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Pollinator supplementation mitigates pollination deficits in smallholder avocado (*Persea americana* Mill.) production systems in Kenya

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Abstract

Avocado (*Persea americana* Mill.) is a major horticultural crop that relies on insect mediated pollination. In avocado production, a knowledge gap exists as to the importance of insect pollination, especially in East African smallholder farms. In this study, conducted in a leading smallholder avocado production region in Kenya, we assessed the dependence of avocado fruit set on insect pollination and whether current smallholder production systems suffer from a deficit in pollination services. Furthermore, we assessed if supplementation with colonies of the Western honey bee (*Apis mellifera* L.) to farms mitigated potential pollination deficits. Our results revealed a very high reliance of avocado on insect pollinators, with a significantly lower fruit set observed for self- and wind-pollinated (17.4%) or self-pollinated flowers (6.4%) in comparison with insect-pollinated flowers (89.5%). We found a significant pollination deficit across farms, with hand-pollinated flowers on average producing 20.7% more fruits than non-treated open flowers prior to fruit abortion. This pollination deficit could be compensated by the supplementation of farms with *A. mellifera* colonies. Our findings suggest that pollination is limiting fruit set in avocado and that *A. Mellifera* supplementation on farms is a potential option to increase fruit yield.

Keywords: Fruit set; Fruit retention; Landscape composition; NDVI; Pollination services; Western honey bee

Introduction

Pollination is an essential ecosystem service for improved quality and yield of crops, contributing to food security (Klein et al., 2007; Dainese et al., 2019). Currently, the demand for pollination services in most pollinator-dependent crops is increasing (Aizen, Garibaldi, Cunningham, & Klein, 2009), and there is a need to incorporate insect pollination in sustainable agriculture systems to enhance food security (Freitas et al., 2016). The economies of most African countries are heavily reliant on agricultural production, but the implementation of sustainable agriculture is a significant challenge, and relatively few studies have explored the relationship between pollination and yields, especially in smallholder farming systems (Freitas et al., 2016).

Using a global analysis based on 29 crops, Dainese et al. (2019) demonstrated increasing evidence of

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insufficient insect pollination, particularly in regions with high land-use intensity, limiting crop production. Managed colonies of the Western honey bee (*Apis mellifera* L.) have been used in agricultural landscapes to supplement pollination services provided by wild bees and improve the yield and quality of many flowering crops (Geldmann & González-Varo, 2018). It is, however, essential to identify and assess pollination deficits in crops to mitigate and protect against crop losses in the event of pollination deficits. Previous studies have been done on pollination limitation in Africa. For instance, Grass et al. (2018) reported pollination limitation in macadamia (*Macadamia integrifolia*) orchards in South Africa. In another study, Dan et al. (2019) demonstrated the importance of insect pollination as an additional input in enhancing the yield and quality of cowpea (*Vigna unguiculata*) and cucumber (*Cucumis sativus*) in Makueni county, Kenya, while Kasina et al. (2007) revealed the influence of insect diversity on the seed yield of sunflower (*Helianthus annuus*) in Kenya.

Avocado (*Persea americana* Mill.), a crop that has seen an increase in worldwide production, is highly dependent on pollination services for enabling fruit set (Vithanage, 1990; Altendorf, 2019). Avocado is an economically important crop in Kenya, and since recently, it has gained popularity as a healthy super food due to its nutritional value for human health, with extensive marketing and wide distribution (Hakizimana & May, 2018). The first commercial avocado orchard in Kenya was established in 1923 on approximately 80 ha. In 1970, an estimated 23 metric tons of avocado were exported. In 1984, annual production increased to 1,400 metric tons and by 2003, over 20,000 metric tons were being exported (Griesbach, 1985; Griesbach, 2005). In 2017, Kenya had a total annual avocado production of 233,933 metric tons; 81,098 metric tons worth $90 million were exported, while the remainder (152,835 metric tons) served the local market. Kenya is currently ranked 6th after Peru, Chile, South Africa, Israel, and Mexico in avocado export volumes (HCDA, 2017).

Avocado has a complete flower, with an unusual behavior known as protogynous dichogamy, whereby the flower has both functional male and female organs in the same flower but opens and closes twice over two days, the first day as functionally female and the subsequent day as functionally male (Ish-Am & Lahav, 2011). Lack of pollination could be one of the limiting factors in commercial avocado production (Alcaraz & Hormaza, 2009). In Israel, California (USA), and South Africa, which experience Mediterranean climates, wind and spontaneous self-pollination of the avocado flowers were found not to be effective in the absence of pollinating insects (Ish-Am, G., 2005). Supplementation of farms with *A. mellifera* effectively enhances fruit production in commercial orchards (Evans et al., 2010). For instance, in New Zealand, the Avocado Industry Council has recommended four to ten hives of honey bees per hectare for avocado pollination (Evans and Goodwin, 2011). In Mexico, stingless bees (Meliponini) and the Mexican honey wasp (*Brachygastra mellifica* Say) have been identified as the primary avocado pollinators (Ish-am et al., 1999). In Australia, many insect species were found to pollinate avocado flowers, but *A. mellifera* played a leading role (Vithanage, 1990). However, little is known about African avocado pollinators, especially in tropical and sub-tropical habitats dominated by smallholder farming systems (Rapsomanikis, 2015). A study conducted by Mulwa et al. (2019) in Kenya found that honey bees were the most abundant and frequent insect flower visitors of avocado. Other insects that were found to be potential avocado pollinators include the tropical African latrine blowfly *(Chrysomya putoria*), drone fly (*Eristalis tenax),* and polistine wasps (*Polistes* sp.) (Okello, Amugune, Mukiama, & Lattorff, 2021).

Natural landscape elements adjacent to crops or in their vicinity can maintain wild pollinator populations and enhance pollination services (Wood, Holland, & Goulson, 2015; Martin, Dainese, Clough, Báldi, & Bommarco, 2019). Various studies have indicates that proximite to remnnant forests is positively associated with the abundance and diversity of pollinators that visit crop species in agroecosystems (Ricketts et al., 2008). In addition, there is a substantial decline in the species richness of bee pollinators with decreasing temperature (Classen et al., 2015), which could exaggerate pollination deficits in higher elevation farming systems. Thus, there is a need to understand how different landscape elements, vegetation, farm size (number of avocado trees on the farm), agricultural habitats in the surrounding landscape, and elevation influence pollination services.

Conserving pollinator-supporting habitats within farmlands for increasing pollination services is beneficial to agriculture (Carvalheiro, Seymour, Veldtman, & Nicolson, 2010). However, the potential of increasing avocado yield and improving quality by supplementing the fields with managed bees outside of large-scale commercial production systems has not been explored. Understanding the extent to which crops depend on pollinators within a specific region and the occurrence of pollination deficits is crucial to provide valuable information to farmers, and to evaluate the current and future conservation plans, and to develop mitigation measures.

This study used manipulative experiments to quantify the pollination deficit in an African crop system and reports, for the first time, the testing of pollinator (managed *A. mellifera)* supplementation in different landscapes to reduce this deficit.

Materials and methods

Study area

This study was conducted in Murang'a County, situated in the central region of Kenya (Fig. 1). The area is located at a latitude of 0°43′0" South and a longitude of 37°9′0" East. The county has a total area of 2,559 km^2 and lies between

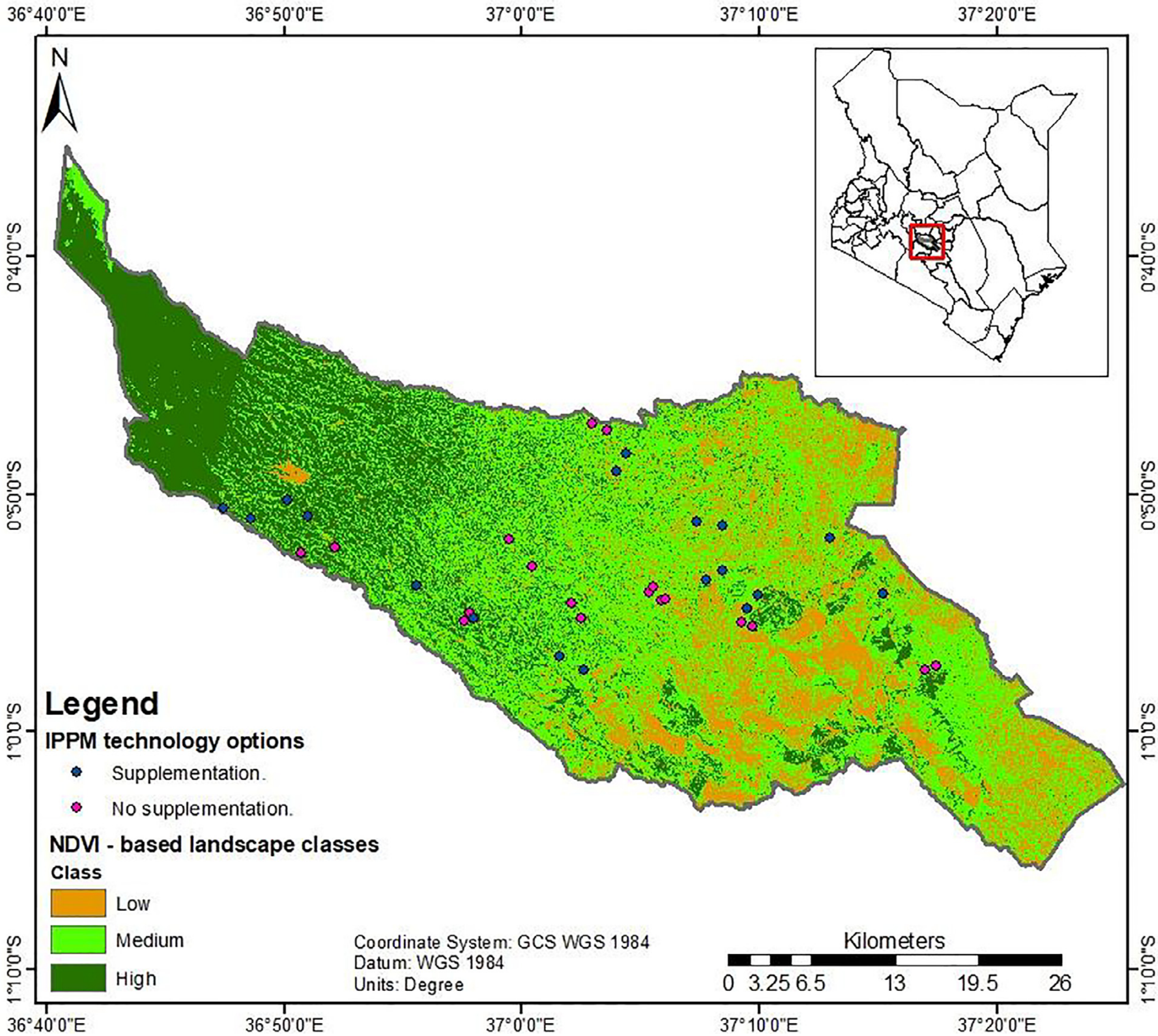

Fig. 1. Map of Murang'a County, Kenya, with the location of the 36 study sites (dots). The color pixels with the map indicate the three levels of normalized difference vegetation index (NDVI), a proxy of the net primary productivity of ecosystems. The blue dots represent avocado farms supplemented with two hives of honey bees per farm while the pink dots represent avocado farms without hives. The inlet figure shows the location of Murang'a County within Kenya (adapted from Adan et al. e, 2021).

914 m above sea level (asl) in the East and 3,353 m asl along the slopes of the Aberdare mountains in the West. The average annual rainfall varies from 1,400 to 2,000 mm, and the mean annual temperature is between 18 and 21°C. The main economic activity in the region is agriculture with small scale farms, excepting large-scale holdings of 6.5 ha (Murang'a County, 2018). The area is one of the essential avocado-growing regions in Kenya. The county is divided into three climatic regions, the western region with an equatorial climate, the central region with a sub-tropical climate, and the eastern region with semi-arid conditions. The western region is generally wet and humid due to the influence of the Aberdares and Mt. Kenya. The eastern region receives less rain and has a higher mean annual temperature. All regions experience a long (March-May) and short (October-November) rainy season. In Murang'a County, there are two avocado flowering seasons in a year. The major one is from August to October, and the minor one is from February to May.

Landscape productivity

The area covering 1630.50 km^2 was classified into three landscape productivity classes based on low, medium, and high net primary productivity according to the normalized difference vegetation index (NDVI), which was used as a proxy for primary productivity. Freely available multi-date Sentinel-2 (S2) satellite data of 10 m spatial resolution was used to create a composite image with images of wet (March to May) and dry (December to February) seasons in the year

2019. Satellite images were processed and analyzed using the Google Earth Engine (GEE) (https://earthengine.google.com, Dublin, Ireland). NDVI was computed as the ratio of the differences between the reflectance at near-infrared (NIR) and red (R) bands and their summation [(NIR−R)/(NIR + R)]. The NDVI range values of each of three classes (i.e., low, medium, and high) were used as thresholds to reclassify the multi-date NDVI imagery. The NDVI threshold for the low class was −0.425 −0.368, while for the medium and high classes, thresholds were 0.368 −0.611 and 0.611−0.864, respectively (Adan et al., 2021). For calculating the NDVI, both areas holding avocado trees and those with other vegetation were considered.

Land use/land cover (LULC) classification

Land use/land cover (LULC) composition was determined in a 3 km radius area around the experimental farms, based on the foraging distance for bees (Visscher & Seeley, 1982) and included the following classes: annual croplands, avocado, built-up, grasslands, perennial croplands, shrub lands, tree cover, and water bodies. The altitude of the farm points was recorded using the global positioning system (GPS). The S2 multi-spectral image was used to determine LULC for its high resolution of 10 m in the visible and near-infrared (VNIR) bands, which comes with three red-edge (RE) bands. A composite image was created in GEE S2 level 1C (images top of atmosphere reflectance). The composite image was used in the calculation of two RE vegetation indices (VIs): RE normalized difference vegetation index (RE−NDVI) and RE enhanced vegetation index (RE−EVI). RE−NDVI and RE−EVI were both derived from the S2 RE band with a 20 m resolution. Thus, resampling was conducted on the respective band to 10 m pixel size. The RE−VIs and reflectance were fused in GEE, and the random forest (RF) algorithm was employed to characterize the landscape. The overall accuracy of the classification was 83.85% with a kappa (total accuracy − random accuracy) / (1 − random accuracy) of 0.7721 (King'ori, unpublished data).

Experimental design

To evaluate the effect of *A. mellifera* supplementation on fruit set and fruit retention, we selected 36 smallholder avocado farms (0.2−0.4 ha). The avocado varieties Hass and Fuerte were dominating, with 21 farms growing Hass, 12 farms growing Fuerte, and three farms growing both varieties. A multi-stage sampling procedure was used to select sub-counties, wards, and small-scale avocado growers. Smallholder avocado farms were selected in different villages to ensure maximized representation of growers in Murang'a County. In each NDVI landscape class (low, medium, and high), the willingness of the farmer to implement pollinator supplementation during the study was considered, and farmers were classified based on the treatment option they preferred (pollinators or control). Several criteria were then applied depending on the treatment: pollinators (supplemented farms) were at least 1.5 km away from each other, and pollinator farms were at least 3.5 km apart from the control sites. In addition, only farms with at least seven avocado trees were selected (Adan et al., 2021). This led to a selection of farms with between seven and 350 avocado trees, typical for African smallholder farms. On farms, all the experimental trees had a minimum distance of 10 m from the edge of the farm in order to minimize the edge effects. Eighteen farmers were selected for each treatment (pollinators or control), with twelve farms per NDVI class, yielding 36 farms. *Apis mellifera* colonies were supplied as additional pollinators in mid-July 2019, just before avocado blooming. The bees were supplied in standard 10-frame Langstroth troth hives (African Beekeepers Ltd., Nairobi, Kenya) headed by naturally mated queens at a density of two colonies per farm. All manipulative experiments were performed during the major flowering period.

Pollination experiments

Field pollination experiments were conducted from August 2019 to December 2019. At each farm, three trees were randomly selected. Approximately two weeks before flowering, four east-orienting branches (pointing eastwards) on each experimental tree bearing dense and mature flower buds were randomly selected, with a total of 432 branches involved in the experiment. Bags for manipulating flower access were put in place 1−6 days before flowering. The four pollination treatments were: i) self-pollination (self), using woven bags that were impermeable to wind, allowing only autogamous self-pollination; ii) wind pollination and spontaneous selfing (self + wind), where insects were excluded by coarse mesh gauze with 0.8−1.0 mm openings; iii) open pollination (open), in which all insects had access to flowers (insect pollination); and iv) hand pollination (hand). For hand pollination, pollen was transferred to stigmas with a paint brush and flowers covered with very fine nylon mesh gauze (10 μm), according to Willmer & Stone, 1989. Sticky glue was applied on the branch beneath the bagged flowers to eliminate insect contamination, such as ants in bagged experiments. Flowers were tagged and left undisturbed. Six weeks after the end of the flowering period, bags were removed from flowers, and the number of green fruits per branch was counted for each treatment. In December 2019, two months after the initial fruit set, all fruits retained were counted to assess fruit drops during development.

Data analysis

Generalized linear mixed-effects models (GLMM) as implemented in the R package *lme4* (Bates, Mächler, Bolker, & Walker, 2015) were used to investigate the effects of treatments on fruit set, fruit retention, and farm treatment within different landscape classes. We used 'Poisson' distribution in the case of count data (i.e., number of fruits) and 'binomial' in the case of proportion data (i.e., the proportion of fruits retained after 14 weeks). Pollination treatment was used as a fixed effect to test for differences in the mean number of fruits between open, self + wind, and self-pollination. We tested for a pollination deficit in the control farms (without honey bee supplementation) by evaluating whether hand pollinated flowers showed a higher fruit set than open-pollinated flowers. For testing, if the pollination deficit is reduced in farms supplemented with honey bee colonies, we first constructed a model testing for the interactive effect of pollination treatment (hand versus open pollination) and honey bee supplementation (with or without additional honey bee colonies). Second, we evaluated whether farms that were supplemented with honey bee colonies exhibited a difference between hand- and open-pollinated flowers in terms of fruit set. If honey bee supplementation reduces the pollination deficit, we would expect a significant interaction term and no significant difference in fruit set in the second model. In all models, we added tree ID nested in farm ID and avocado variety as additive random terms to control for the correlated, hierarchical structure of the data. In the case of over dispersed count data, we added an observation-level random effect to the model (Harrison, 2014). To test if the pollination deficit was dependent on the environment, we added the interaction term pollination treatment (i.e., hand versus open) $\times$ environmental variable to the model. We tested five environmental variables, i.e., the influence of elevation (strongly correlated to temperature); the $\log_e$-transformed number of avocado trees on farms (a measure of the farm size); landscape diversity; the proportion of annual crop land in the surrounding landscape; and landscape productivity based on the NDVI classification. Landscape diversity was calculated by applying the Shannon diversity index formula on the proportional contributions of eight land cover types in the study sites' surrounding (within a 3 km distance from the center of the study site). None of the environmental variables were significantly correlated to the farm treatment (supplementation of honey bee colonies or control) (absolute Spearman's rho < 0.35, $p > 0.05$). If the pollination deficit is higher under certain environmental conditions, we would expect the interaction term to be significant.

Regarding the proportion of fruits that were retained on the trees after 14 weeks, we first analyzed which environmental variable significantly explained the probability of fruit retention. We then tested if the effect was modulated by the supplementation of *A. mellifera* colonies on farms by adding an interaction term open $\times$ environmental variable (i.e., elevation, the proportion of annual crop land, landscape diversity, the number of avocado trees on farms and the landscape productivity based on the NDVI classification) to the model. All analyses were carried out in R statistical software (v 4.0.2, R Foundation for Statistical Computing, Vienna, Austria).

Results

Fruit set

Avocado fruit set was significantly higher in the open pollination treatment (89.5%) (mean $\pm$ SE fruits produced = 19.89 $\pm$ 1.15), where insect pollinators had access to flowers, than in treatments with self + wind pollination (17.4%) (3.71 $\pm$ 1.12, Z = -12.06, $p < 0.001$) or self-pollination only (6.4%) (1.34 $\pm$ 1.17, Z = -17.36, $p < 0.001$) (Fig. 2).

Pollination deficit

On average, there was a 20.7% reduction (Z = -2.749, p = 0.006) in fruit set in avocado trees with open pollination treatment compared with hand pollination (Fig. 3A), indicating a pollination deficit. However, the difference between hand and open pollination treatments strongly varied among trees, with some trees even showing a higher fruit set in the open pollination than in the hand pollination treatment (Fig. 3A). There was no significant influence of elevation (F = 0.07, p = 0.94), NDVI (F = 0.31, p = 0.73), landscape diversity (F = 0.02, p = 0.88), the proportion of annual croplands (F = 0.00, p = 0.98), and the total number of avocado trees on farms (a measure of the farm size) (F = 0.56, p = 0.46) on the pollination deficit. In farms supplemented with *A. mellifera* colonies, there was no significant difference between the open pollination treatment and the hand pollination treatment (Z = 0.24, p = 0.81) (Fig. 3B). A model testing for the interaction between pollination treatments (hand versus open pollination) and the honey bee supplementation treatment revealed a significant interaction effect (Z = 2.06, p = 0.04).

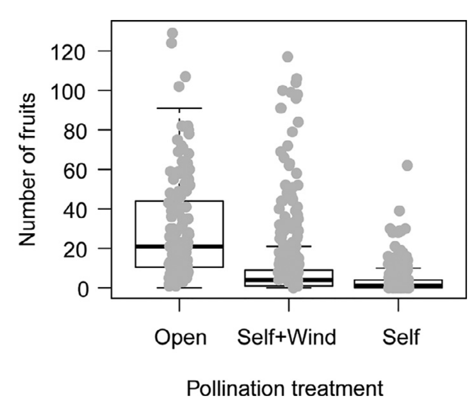

Fig. 2. The number of avocado fruits (fruit set) observed in different pollination treatments (open, self + wind, and self-pollination). Dots show the original measures of the number of fruits produced per tree. Box and whisker plots show the median (bold line), the quartiles (box) and the extreme values (whiskers).

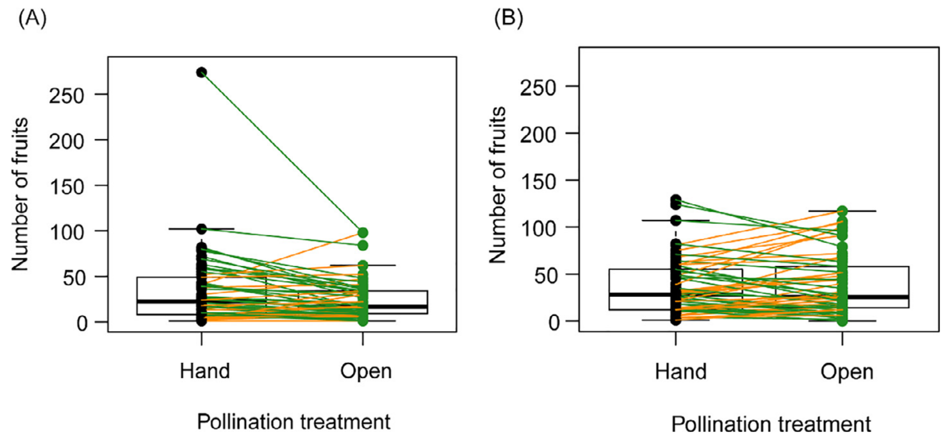

Fig. 3. The number of fruits (fruit set) in hand and open pollination treatments on the same tree. Control farms that were not supplemented with honey bees (A). Farms supplemented with two *A. mellifera* colonies per farm (B). Lines connecting the dots between treatments show observations on the same avocado tree. The green and orange colors indicate lower and higher fruit set, respectively, in open-pollinated flowers in comparison to hand-pollinated flowers. Box and whisker plots show the median (bold line), the quartiles (box) and the extreme values (whiskers).

Fruit retention rate

We found that the number of fruits counted after six weeks was positively correlated to the number of fruits counted after 14 weeks (Fig. 4). On week 14, farms supplemented with honey bees still tended to have a higher fruit set in open-pollinated flowers ($Z = 1.90$, $p = 0.057$) than the control farms. Further, the fruit retention rate was dependent on the number of avocado trees on the farm, whereby farms with a higher number of trees (large farm size) were associated with a lower percentage of fruits retained after 14 weeks ($Z = -2.10$, $p = 0.036$) (Fig. 5). Other environmental variables did not have a significant effect on the fruit retention rate. i.e., elevation, ($Z = 1.32$, $p = 0.19$), landscape diversity ($Z = -0.14$, $p = 0.89$), and proportion of agricultural land ($Z = -1.71$, $p = 0.086$).

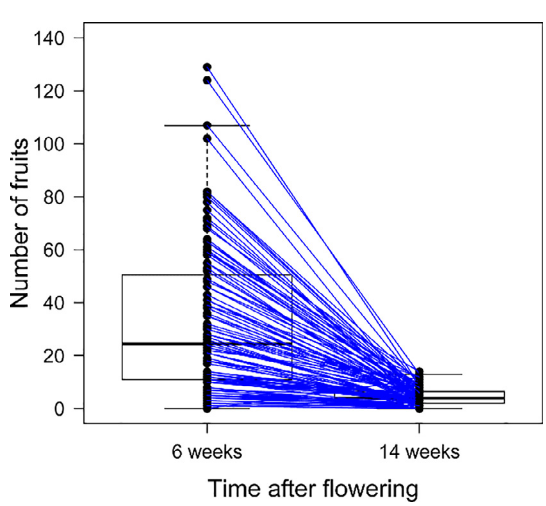

Fig. 4. Fruit retention at six and 14 weeks after avocado flowering. The blue lines connect observations on the same trees studied in the hand pollination treatment.

Discussion

Insect pollination is an essential aspect of crop yield and quality in avocado production. The results from our pollination manipulation experiments show a clear evidence of the importance of insect pollinators on avocado fruit set. When pollinators were excluded from the flowers, the initial fruit set (measured six weeks after pollination) was low in the case of self + wind and self-pollination, compared with open pollination in the presence of insect pollinators. Insect pollination has been reported to increase fruit set in avocado significantly (Read, Howlett, Jesson, & Pattemore, 2017). Similar results have been observed by Ish-am et al., (1999)

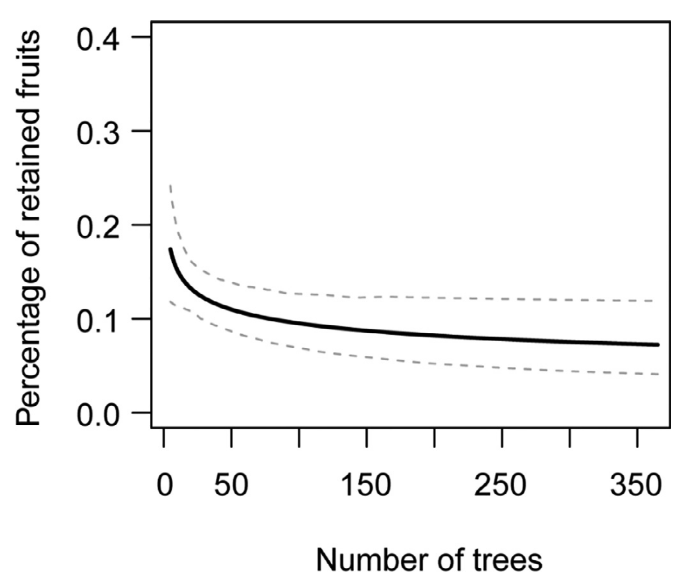

Fig. 5. The relationship between the percentage of fruits retained at 14 weeks after flowering and the number of avocado trees per farm. The bold black line indicates the predicted mean fruit retention while the grey dashed lines delimit the 95% confidence interval.

in Mexico, where only a few or no fruit set was reported after caging avocado to prevent pollination by insects. The shaking of flowers could have caused the observed fruit set in self-pollination due to wind motion, gravity (Ish-Am, 2005), or small insects like thrips inside the flowers (Wragg & Johnson, 2011). Even though pollination treatments affected the fruit set aspects of avocado, different unmeasured factors like pruning, mulching, weeding, fertilization regimes, variation in the age of the avocado trees, the availability of mineral elements and nutrients in the soil, pests, and pathogens, weather and other animal interactions in the orchard, may have caused hidden variations in final fruit set levels between open and supplementary hand-pollinated fruits (Samnegård, Hambäck, & Smith, 2019).

In our experiments, we recorded pollination deficits, whereby trees that received supplementary hand-pollination with pollen from other cultivars had a higher fruit set than open pollination treatments. This indicates that the productivity of the studied system is limited by pollinators (Robbertse et al., 1996; Alcaraz & Hormaza, 2009). There was a 20.7% pollination deficit in the orchards without honey bees, indicating that wild pollinators such as tropical African latrine blowfly, drone fly, and polistine wasps (Mulwa et al., 2019; Okello, Amugune, Mukiama, & Lattorff, 2021) alone could not attain adequate fruit set and this agrees with our preliminary results (R.N.S., unpublished data). Our results highlight for the first time that managed pollinator supplementation can resolve pollination deficits in avocado in East Africa. This was evident as farms supplemented with hives did not significantly differ between open and hand pollination. Most individual trees showed an increase in fruit set under open pollination compared to hand pollination, indicating that *A. mellifera* is a required input to ensure sufficient cross-pollination in this agricultural system. *A. mellifera* has been used successfully and almost exclusively for avocado pollination in commercial orchards in which the native pollinators were absent (Davenport, 1998; Ish-am et al., 1999). Our results on smallholder farms imply that the agricultural system is susceptible to a decrease of pollinators and that farmers will experience meager yields if insect pollinators decline in the study area. It is vital to protect wild pollinators effectively and, in the case of pollination limitation, potentially supplement farms with managed pollinators (Rader, Reilly, Bartomeus, & Winfree, 2013; Garibaldi et al., 2014) to provide enough and stable pollination services to crops and to fill the short-term pollination deficit.

We expected that the pollination deficit would be smaller on farms characterized by high habitat diversity or structural complexity as they were expected to hold more suitable habitats for pollinators resulting in better pollination services (Dainese et al., 2019). However, there was no significant effect of the landscape variables on the pollination deficit. Study sites characterized by high NDVI class, higher landscape diversity, a lower percentage of agricultural habitat in the surrounding landscape, and smaller farms (with fewer avocado trees) did not differ in the pollination deficit from farms characterized by higher habitat diversity or structural complexity. This may have been attributed to other factors like landscape homogenization which has been reported to reduce the abundance and diversity of many taxa due to low foraging resources and lack of nesting site (Tscharntke et al., 2012).

Additionally, we expected that avocado grown in high elevations (strongly correlated to temperature) to be more pollinator-limited than those at low elevations because hymenopterans are known to be dominant pollinators in low-elevation areas (Marini, Quaranta, Fontana, Biesmeijer, & Bommarco, 2012). We failed to detect a significant elevation effect due to differences in the geographical region, climatic zone, and wide range of elevational gradient. A study conducted by Senapathi, Goddard, Kunin, & Baldock, 2017 showed that landscape quality could directly impact pollinator communities and influence abundance and richness through the interaction of multiple drivers such as climate change or increased chemical inputs in land management.

In our study, we observed an early abscission pattern across all the farms. However, less abscission was observed on farms that were supplemented with *A. mellifera* even after two months from the initial fruit set. This suggests that other factors besides lack of pollination contribute to the massive drop of avocado flowers and fruitlets. Among the environmental variables tested, we found that the number of avocado trees in the farm negatively influenced fruit retention, whereby farms with fewer avocado trees showed a higher percentage of fruit retention, than with farms with a high number of trees. This may be associated with reduced resource competition between plants over soil nutrients on smaller farms, better pest control from parasitoids and predators on smaller farms, or a different avocado age structure for smaller farms (Bennett, 2010; Cameron, Wearing, Rohani, & Sait, 2007). Trophic interactions within the soil can influence the aboveground community of plants, which may include fruit retention (Cheng & Gershenson, 2007).

Conclusion

This study shows the existence of pollination deficits in Kenyan smallholder avocado farms that can be resolved by pollinator supplementation. This knowledge can be used to increase avocado production in farms managed by smallholder farmers, which represent most producers in African agriculture. Our results also confirm that bee pollination plays a vital role in avocado production, thus promoting wild colonies of *A. mellifera*, which constitute more than 90% of all colonies in Africa, can be an excellent strategy to ensure enough avocado pollination and hence improved high-quality yields. Notably, protecting or restoring natural habitats in agricultural landscapes could support native pollinator communities and reduce the dependence of avocado pollination on managed honeybees. This would reduce costs for the management of colonies and enhance system resilience. The number of avocado trees on a farm affected fruit retention. Therefore, enhanced fruit retention could be achieved by improved soil management, mixed cropping with other legume crops, and optimizing the number of trees per farm.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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