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HIGHLIGHTS Monasterolo et al.

- Insect visits to mandarin flowers improved their fruit set.

- Mandarin fruit set increased with higher visitation rate by native insects.

- Mandarin quality decreased with higher visitation rate by honeybees.

- Flower visitor diversity increased with higher surrounding forest covers.

Native pollinators increase fruit set while honeybees decrease the quality of mandarins in family farms

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Abstract

Family farms can benefit from the presence of a diverse set of native pollinators and associated pollination services. In the present study we assessed the effect of flower visitor richness and visitation rate by honeybees and native insects on mandarin production (*Citrus reticulata* `Criolla´), in ten citrus family farms located in the Dry Chaco region of northwest Argentina. An exclusion experiment was conducted to explore how pollinators influence the fruit set and quality of `Criolla´ mandarin. The

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influence of features such as local richness and abundance of flowering plants, farm size, and surrounding natural/semi-natural habitats in the diversity of flower visitors was also evaluated. Fruit set in open pollination branches was three times higher than in bagged branches, where flower visitors were excluded. Moreover, the mandarin fruit set increased with a higher native visitation rate, and mandarin quality (fruit weight and size) decreased with a higher honeybee visitation rate. Flower visitor diversity was higher in farmlands with a greater proportion of surrounding natural and semi-natural habitats. Our results demonstrate the negative effects of excessive honeybee visitation on citrus fruit quality and highlight the importance of native pollinators and natural habitat conservation to increase the fruit set and quality of mandarin in family farms.

Keywords

Pollination service, Citrus, Mandarin productivity, Flower visitors, Spatial scales.

Introduction

The intensification of agriculture has led to loss and fragmentation of natural habitats (Foley *et al.* 2005). Conventional farming systems with larger fields of monoculture crops magnify the problem, causing a decline in the populations of many native pollinators and in the ecosystem services they provide (e.g. crop pollination; Batáry *et al.* 2013). As opposed to the large size and intensive management of conventional farms, most family farms have a smaller crop surface, greater crop diversity, and are usually closer to natural and semi-natural habitats, which can benefit pollinator diversity and crop pollination (Garibaldi *et al.* 2017). According to FAO Policies, in these family farms, the farmers and their families are directly involved in the production process through manual labour and do not hire permanent labour (Garner &

de la Campos 2014). Family farms represent 98% of all farms and are responsible for over 53% of the global agricultural production (Graeub *et al*. 2016). Although the size and practices used can potentially differ among family farm holdings, the management of pollinators is poorly developed, and thus they have a strong potential for management (Roubik & Gemmill-Herren 2016).

For numerous crops, increased pollinator visits are associated with improved productivity (Garibaldi *et al.* 2013). Cross-pollination is required in many crops, and to ensure adequate performance, the use of honeybee hives (*Apis mellifera* L.) or sometimes other managed bees remains the most widely used practice (Halder *et al.* 2019), rather than considering maintenance of the native pollinators diversity (Garibaldi *et al.* 2013). However, honeybees are inefficient pollinators of some crops, and excessive beehive densities can even lead to declines of crop productivity in comparison with more diverse pollinator assemblages (Aizen *et al.* 2020).

Local and landscape factors strongly influence the richness and abundance of pollinators (Kennedy *et al.* 2013). Practices enhancing habitat to promote species richness (e.g., nesting and feeding availability) could improve the frequency of pollinator visits to the flowers of the crop (Garibaldi 2014). Pollinator richness and visitation rate in small farms of mass-flowering crops could be higher than in farms with larger productive areas, where pollinator diversity would be more "diluted" (Holzschuh *et al.* 2016). Moreover, farms with higher wild plant richness and floral abundance increase pollinator richness, visitation rate (Williams *et al.* 2015), and consequently pollination service to crops (Carvalheiro *et al.* 2011, Garibaldi *et al.* 2013). At the landscape scale, natural and semi-natural areas surrounding crops can provide greater pollinator diversity and facilitate crop pollination, as they can provide nesting sites and appropriate supplementary resources in times of scarcity (Chacoff &

Aizen 2006; Fijen *et al.* 2019). However, most of the existing literature focuses on specific hymenopteran groups in Europe and North America (Senapathi *et al.* 2017).

In this paper, we focus on pollination service in citrus family farms, specifically in mass-flowering mandarin crops (*Citrus reticulata* `Criolla´ Blanco). Although citrus crops have been extensively studied, the management needed to ensure greater pollination and fruit productivity of numerous varieties is still poorly known (Sanford 2011). Pollinators can increase the productivity of citrus fruits such as orange (Sanford 2011), grapefruit (Chacoff & Aizen 2007) and tangelo (Silva da Santos *et al.* 2021), and fruit set, sugar content, and size in some varieties of mandarins (Wallace & Lee 1999; Yildiz & Kaplankiran 2017). There is evidence showing honeybees to be the most important citrus pollinators, though some varieties benefit more than others (Sanford 2011). Therefore, it is necessary to examine the importance of pollinators in sustaining crop pollination service, and understand which strategies and practices can promote pollination service on family farms (e.g., size of crop area, flower diversity, and landscape diversity).

The present study aimed to (i) evaluate the contribution of honeybees and native pollinators to fruit set and quality of `Criolla´ mandarin and (ii) determine whether local (spontaneous vegetation and citrus cover) and landscape features (surrounding patches of natural or semi-natural vegetation) affect the richness and abundance of flower visitors in family farms. For this purpose, we assessed the potential impact of flower visitors on mandarin fruit through exclusion experiments in farms with a range of surrounding natural/semi-natural covers. We expected the fruit set and quality (fresh fruit weight and size, sugar content, and seed number) of mandarins to increase with higher visitor richness and visitation rates in farms. At local and landscape scales, we expected flower visitor richness and visitation rate in mandarin flowers to increase with

higher richness and abundance of entomophilous flowering plants, particularly in farms with a lower citrus cover and surrounded by a higher proportion of natural and semi-natural habitats. This study helps understand the contribution of insect visits in fruit set and quality of mandarins, and the management scale most appropriate to enhance the pollination service in family farms, with low dependence on external inputs (e.g., agrochemicals, hives).

Materials and methods

Cultivar and study area

The experimental area was located in Capayán county, one of the most important citrus regions of Catamarca province (28º 09' 00" S and 65º 29' 00" O, Fig. 1) in Argentina, where mandarin crops (*Citrus reticulata* `Criolla´) are predominant (INDEC 2021). While hard-peeling citrus fruits (oranges, grapefruits) are being consumed at constant levels, global mandarin consumption has increased in the past decade (Goldenberg *et al.* 2018). The `Criolla´ mandarin is a naturalized variety, cultivated almost exclusively in Argentine farms, many of which are family farms. This variety has a great aroma due to the essential oils of the peel, it is very easy to peel and has numerous seeds (Palacios 2005).

The study area is included in the Arid Chaco, a sub-region of the Dry Chaco, the most extensive dry forest in South America (Morrone 2014). Mean annual rainfall is close to 430 mm/year, concentrated mainly in the summer (Magliano *et al.* 2015). Mean temperatures of the hottest month (January) and the coldest (July) are 26 °C and 12 ºC, respectively (Luti 1979). The landscape in the experimental area is dominated by secondary semi-deciduous forests and shrublands, alternating with patches of old-

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growth forests, fodder crops, fruit trees (mainly citrus and olives), and rural areas,

including family farms.

We selected ten citrus family farms (circles of 200 m diameter, further referred to

as "sites") with a `Criolla´ mandarin patch in the centre. These circles were selected to

have representative samples of local-scale features. The sites were separated from each

other by at least two kilometres (see Fig. 1). The size of the citrus family farms

comprised a gradient of 0.3-24 ha, with a mean of 11 ha.

Influence of pollinators in fruit set and quality

An exclusion experiment was conducted in September 2019 to assess the

contribution of pollinators to fruit set and quality of `Criolla´ mandarin. In each site, ten

trees separated by at least 20 m were randomly chosen. In each tree, two treatments

were assigned on separate branches: "bagged" and "open pollination". Eight branches

with floral buds were marked for each tree, and on four of those all the buds were

enclosed with voile bags for the entire duration of flowering, to prevent pollinator visits

(see Appendix A: Fig. 1). Previously, open flowers were manually removed from both

the bagged and open pollination branches. Then, all floral buds observed on those

branches were counted. From April-May 2020, the number of early fruits for each

treatment was counted and the fruits were collected to measure quality. Five

economically important mandarin traits were measured: fruit/flower (fruit set), fresh

fruit size and weight, sugar content, and seed number (fruit quality) (Goldenberg *et al.*

2018). An electronic digital calliper (Mitutoyo Sul Americana, Ltda.) and a digital Brix

refractometer (Atago Co., Ltda.) were used to evaluate fresh fruit size and sugar

content, respectively.

For statistical analyses, two extreme outliers were removed (representing 0.005% of total observations) due to their high residual value and exerted undue influence (see Appendix A: Fig. 2). Then, generalized linear mixed models were constructed (GLMM; Zuur *et al.* 2013). The fruit set and quality metrics were used as response variables and the exclusion treatment as a fixed factor (bagged vs. open pollination). Also, the "site" was selected as a random factor because we were only interested in the sites as random proxies among a larger number of representative family farms. For fruit set analyses, two models with different random factor structures were fitted: one model with the tree nested in the site and another with only the site identity. Qualitatively, the results did not change (see Appendix A: Table 1), thus we decided to keep the simplest model (with only site identity as a random factor). Based on the previous analysis, we did not include tree as random effect in the analyses of mandarin quality. Although this would probably enhance the model, the results would not change.

Influence of visitor richness and visitation rate in fruit set and quality

Flower visitors of ´Criolla´ mandarin were observed in selected sites from September 16th to October 10th of 2019 bloom. In each site, three flower visitor observation sessions were conducted during the blooming period (citrus blooms for approximately one month, and we sampled once a week during the month). In each session, flower visitation activity was registered for 15-minutes in one randomly selected flowering branch of each of six randomly selected trees, separated by at least 20 m. As the last sampling session had few trees with open flowers, total observation time varied between sites (mean of 3.6 h per site). Owing to possible differential preferences in visitation time across visitor species, the sampling was conducted between 09:00 and 18:00 h. A visit was recorded when a visitor contacted reproductive parts of any of the

flowers within the observed branch, avoiding possible bias. Whenever possible, visitors were identified in flight; otherwise, visitors were collected. To avoid any bias associated with double-counting of visitors that were not immediately collected after a visitation session, whenever a visitor approached and contacted the reproductive parts of any of the flowers within the observed branch, we counted this as a single visit (even when multiple flowers were visited). Flower visitors were identified in the laboratory at the lowest possible taxonomic level, using taxonomic keys and by consulting experts. Also, the visitation rate was estimated as [number of visits / (flowers open per branch *hours of observation)] (Vázquez *et al.* 2005).

For each site, we thus had an overall estimate of visitation rates and visitor richness. Fruit set (fruit/flower) was estimated from the influence of pollinators in fruit set and quality experiment (sample size: 10 per site). To assess fruit quality (fresh fruit size and weight, sugar content and seed number) we used the fruits collected from the influence of pollinators in fruit set and quality experiment. To increase the sample size, ten ripened fruits every week were also collected in all sites from March to July of 2020 (Segura, unpublished data), totalizing 980 fruits.

For statistical analyses, six extreme outliers were removed (representing 0.006% of total observations; see Appendix A: Fig. 2). Also, a correlogram with the Pearson method variables was performed (see Appendix A: Fig. 3), considering a correlation threshold of 0.7. Then, GLMMs were constructed. For this step, the previously mentioned fruit set and quality metrics were used as response variables. The visitor richness and visitation rates by honeybees and natives were used as fixed factors. Based on similar results (see Appendix A: Table 1), we decided to keep the simplest model with only site identity as a random factor. Finally, the effects of visitation rates by

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honeybees and natives on fruit set and quality were assessed through linear and nonlinear fits (quadratic polynomials) (Rollin & Garibaldi 2019).

A full model was constructed including each response variable. The vif.mer function (variance inflation factors for mixed models) was used to evaluate the correlation between fixed factors, considering acceptable values of vif<2 for each variable (Zuur *et al.* 2013). An automated model selection based on Akaike's Information Criterion (function dredge, Barton 2019) was performed, as well as model averaging with the relative importance of fixed factors. Models were considered plausible with ΔAIC<2, and variables with relative importance greater than 0.6 (Burnham & Anderson 2002).

Influence of local and landscape features in visitor diversity

From the centre of each site, three 100 m linear transects were drawn to a random location within the circumference (see Appendix A: Fig. 4). Every 20 m, a 20 m linear transect was performed, alternating the direction (left/right) to cover a larger area. Richness and abundance of entomophilous flowering plants physically touching the transects were recorded "in situ". Transects were drawn three times (before, during, and after `Criolla´ mandarin bloom) per site. Plant species were identified in the laboratory, using taxonomic keys and with the help of experts. For each site, we thus had an overall estimate of the total number of individuals with flowers and the richness of flowering plants per site.

Circular areas of two radii (500 and 1000 m) centred on the sampling sites were used to analyse the surrounding landscape. The radii considered included the mean foraging ranges of most native pollinators (Zurbuchen *et al.* 2010). Polygons were delimited with different types of land cover categories within each circle (citrus and

fruit trees, village areas, forage crops, and natural/semi-natural habitats) using Google

Earth images. Each site showed a gradient of natural/semi-natural cover (5 - 80%; see

Fig 1). Cartographic analyses were carried out with QGIS 3.16.14 Hannover (QGIS

Development Team 2020).

For statistical analyses, a correlogram was performed (see Appendix A: Fig. 3).

The natural/semi-natural cover was the land cover category most correlated with the

response variables. As expected, the landscape covering both radii (500 and 1000 m)

correlated with each other, thus the landscape radius most correlated with the response

variable considered was included in the full model. Then, the fit of alternative models

was compared based on an AIC. Mantel test was conducted to detect spatial

autocorrelation between sites and check for independence, ensuring sampling quality.

No spatial autocorrelation was found between sites in the composition of flower visitors

($r = -0.16$, $p = 0.18$).

GLMMs were constructed (Zuur *et al.* 2013) with the flower visitor richness and

abundance previously estimated as response variables, the local features (richness and

abundance of entomophilous plants, proportion of citrus cover) and landscape variable

(surrounding patches of natural and semi-natural vegetation) as fixed factors, and site

identity was used as a random factor. A full model was constructed including each

response variable and an automated model selection based on AIC was performed (see

previous analyses). Honeybees were excluded from this analysis because their

abundance could be determined by the location of managed hives rather than by

environmental variables (Kremen *et al.* 2004).

The statistical program R v3.6.1 (R Development Core Team 2020) was used for

the analyses. Exploratory analyses were performed according to Zuur *et al.* (2010) and

assumptions for all models were verified according to the graphic validation procedures

recommended by Zuur *et al.* (2013). For the GLMMs, glmer and glmer.nb functions of "lme4″ package version 1.1–12 were used. Binomial negative (due to overdispersion), Normal, and Poisson distributions were used in GLMMs (see Tables). For model selection, dredge, model.avg, and importance function of "MuMin" package version 1.43.6 were used. To create the graphics, "ggplot" version 3.6–4 was used.

Results

From a total of 36 h of observations, 1970 flower visitors were recorded in mandarin flowers in family farms (see Appendix B: Table 1). All observed flower visitors were insects, except for two visits made by a green hummingbird (*Chlorostibon lucidus* Shaw). The honeybee *A. mellifera*, an alien species (Aizen *et al.* 2020), was the most abundant flower visitor species (81.1% of all visits recorded), followed by the stingless bees *Plebeia molesta* Puls (6.9%), and the eusocial bees *Lasioglossum* Curtis (*Dialictus spp.*) Robertson (group with at least 4 morphospecies, 5.8%). *A. mellifera* and *Dialictus spp.* were the only visitors recorded in the ten sites. In 7273 `Criolla´ mandarin flowers, the visitation rate of native insects was lower compared to honeybees (10.9 and 46.6 specimens/h, respectively).

In total, 79 entomophilous plant species were identified (see Appendix B: Table 2) and 10299 flowering plants were counted in orchards. The species with the highest abundance were *Hirschfeldia incana* (L.) Lagr.-Foss (Asteraceae, 15.2% of total plants), followed by *Melilotus albus* Desr., and *Melilotus officinale* (L.) Lam. (Fabaceae, 14.9% and 10.3% respectively).

As expected, mandarin fruit set increased in open pollination branches compared to bagged branches (0.02 ± 0.099 and 0.007 ± 0.014 fruit/flower respectively; Table 1, Fig. 2). The quality of mandarin fruit (weight, size, sugar content and seeds) did not

differ between treatments (Table 1). However, there was some evidence that sugar content increased in open pollination branches (Table 1; see Appendix C).

As expected, mandarin fruit set increased with a higher native visitation rate (Table 2, Fig. 3). On the other hand, the best fit including the honeybee visitation rate was a polynomial (quadratic term) regression $y=0.0006+0.34x-1.44(x^2)$ (Fig. 3). Contrary to what we expected, fruit weight and equator diameter in open pollination branches decreased with a higher honeybee visitation rate (Table 2, Fig. 4A, 4B). In contrast to honeybees, the remaining quality indicators were not affected by the visitation rate of native pollinators.

Flower visitor richness and abundance in `Criolla´ mandarin increased with higher surrounding natural and semi-natural covers within 1000 and 500 m, respectively (Table 3, Fig. 5). Contrary to what we expected, the fruit set and quality variables were not affected by local features (richness and abundance of entomophilous plants, citrus cover; Table 3).

Discussion

Our results show the importance of pollination service in fruit set and the negative effects of excessive honeybee visitation rate in fruit quality of `Criolla´ mandarin. Moreover, this increase in fruit set and quality of mandarins can be supported by a higher diversity of native pollinators associated with the conservation of natural habitats in family farms.

Honeybees were by far the most frequent visitors. We also observed some native visitors that could be promising for citrus pollination, such as stingless bees (Vossler *et al.* 2018) and small Halictidae. Studies on citrus (Chacoff & Aizen 2006; Silva da Santos *et al.* 2021) have found that the relative abundance of honeybees was over 90%

of the total number of visits, with little contribution from native pollinators (about 10%). By contrast, in our study the relative abundance of native pollinator visits was about 20%, so native visitors could be even more relevant.

Flower visitors increase fruit set

The fruit set of open pollination branches was three times higher than that of bagged branches (Fig. 2), evidence of the development of `Criolla´ mandarin by self-compatibility, similar to other citrus varieties (Vithanage 1991; Sanford 2011). However, the number of aborted fruits was higher without the cross-pollination conducted by insects in concordance with numerous mandarin varieties, such as 'Lee', 'Murcott', 'Imperial', 'Ellenor' (Wallace & Lee 1999), and 'Oroval' Clementine (Wallace 2004). Thus, the provision of flower visitors and multiple sources of pollen ('pollen parent') may be beneficial for a greater `Criolla´ mandarin production (Vithanage 1991; Wallace & Lee 1999).

The increase in fruit set did not represent a loss of fruit quality. Studies suggest that bees may increase or keep citrus quality parameters, such as fruit size and weight (Yildiz & Kaplankiran 2017; Halder *et al.* 2019; Silva da Santos *et al.* 2021). Many of these studies have found a positive influence of flower visitors on seed production, however, in the present work we did not find differences in the number of seeds per fruit. The varieties studied were seedless, whereas the `Criolla´ variety has a large number of seeds (about 20 seeds per fruit). Therefore, like other citrus cultivars, seedlessness could not be possible for `Criolla´ mandarin, and the rest of the fruit quality traits such as fruit size, weight, and sugar content become more important (Silva da Santos *et al.* 2021). In this regard, similar to 'Imperial' mandarin (Wallace & Lee

1999) a trend was evidenced to increase sugar content for open pollination flowers exposed to cross-pollination.

Native visitors increase the fruit set and honeybees decrease fruit quality

Native visitors to `Criolla´ mandarin flowers increased the fruit set. Also, the weight and equator diameter of `Criolla´ mandarin decreased with higher visitation rates by honeybees. Fruit size and weight contribute to high economic value for fresh fruit, mainly in small easy-peeling cultivars like some mandarin (Abouzari & Nezhad 2016). This is the first study showing the negative influence of a high honeybee visitation rate on citrus fruit quality. For grapefruit, Chacoff *et al.* (2008) found an asymptotic relation between the number of visits performed by honeybees and the pollen deposited, however, here we found that increasing the abundance of honeybees within the mandarin farms can be detrimental to their production. One explanation for this trend could be that surplus of pollen deposition on the stigmas may cause a negative effect on the fruit set, promoting massive pollen-tube abortion (Sáez *et al.* 2014). Also, the consecutive transfer of pollen to numerous flowers of the same plant by honeybees can result in low-quality pollination (Aizen *et al.* 2020). Therefore, similar to a broad range of crops (Garibaldi et al. 2013), our results show that the contribution of native flower visitor assemblages to the fruit set and quality of `Criolla' mandarin is greater than that of honeybees. Various studies have shown that a high visitation rate can be detrimental to fruit production (Sáez *et al.* 2014; Rollin & Garibaldi 2019; Aizen *et al.* 2020), however, fruit quality has not previously been assessed in relation to visits performed by a single species or by honeybees. Further studies seem necessary to understand the mechanisms of this relation, which can be very important for management purposes in the case of honeybees.

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Our results suggest that to preserve the fruit set, size and weight of `Criolla´ mandarin it is necessary to avoid a high honeybee density, given mainly by the use of managed beehives. Studies have suggested standardized measures of actual honeybee density and crop productivity previous to hive management (Rollin & Garibaldi 2019). Moreover, according to our findings, the populations of wildflower visitors including feral honeybees in low densities may be sufficient to support high levels of fruit set and fruit quality and assure the stability of the pollination service.

Higher natural and semi-natural covers increase visitor diversity

Visitor richness and abundance in `Criolla´ mandarin increased with higher natural and semi-natural covers within 1000 and 500 m of the sites, respectively. Recent evidence has shown that natural and semi-natural habitats prove beneficial to flower visitor diversity (Fijen *et al.* 2019), being a source of food and shelter in the face of adverse situations in cultivated fields. Flower visitor diversity decreases in landscapes with poor quality (low nesting site and food availability) and diversity of surrounding habitats, such as large farms with monoculture crops and intensive management (Kennedy *et al.* 2013). Therefore, the family farms nearer to natural habitats with low agriculture impact, are more likely to sustain long-term biodiversity, and hence require more attention considering the conservation of natural habitats as a part of agroecosystem management (Hipólito *et al.* 2018).

Contrary to our hypothesis, plant richness and abundance, and farm size, were not significantly associated with the richness and abundance of mandarin flower visitors. Mass-flowering mandarins may be more competitive than wildflowers, being able to produce up to 80,000 flowers per tree and a high amount of nectar per flower (about 20 ml based on Palacios 2005). However, the wildflower diversity can be essential mainly

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after the citrus blooming since it may enhance resources available to bees (Rands &

Whitney *et al.* 2011). Moreover, although the visits could be concentrated mainly on

citrus flowers, the increase in flower visitor richness and abundance might have been

"hidden" due to the dilution effect of pollinator density (Veddeler *et al.* 2006) in larger

farms.

Conclusions

Here, we provide evidence of the importance of native pollination service in citrus

family farms. Moreover, we highlight the negative effect of high visitation rates of

honeybees on fruit quality. Based on our results, to increase the pollination service in

this variety and possibly in other citrus plants, we recommend the conservation and

enhancement of natural and semi-natural habitats within at least 500 m surrounding

farms. This would benefit the visitation rate of native pollinators in mandarin flowers.

Moreover, since the high honeybee visitation rate decreases fruit set and quality of

mandarin (weight and size), while the intermediate honeybee visitation rate can increase

the fruit set (Fig. 3), we recommend a visitation rate lower than 0.10 visit$*$flower$^{-1}*$h^{-1}.

For this purpose, it would be appropriate to decrease the number of managed beehives,

at least while the mandarins are in bloom (about 21 days). Our results support the need

for policies of care and preservation of pollination service in small family farms, since

they usually have low impact agriculture, with sustainable management and less

demand for external inputs, helping to maintain biodiversity (Hipólito *et al.* 2018;

Garibaldi *et al.* 2017; Graeub *et al.* 2015) and the ecosystem services they provide in the

long term.

Declaration of interests

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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Table 1. Results of GLMMs analysing the effect of pollinator exclusion on the indicators of fruit set and quality of `Criolla´ mandarin. Error structure, estimator, standard error (ES), the value of Z or t, and P-value are shown.

Fruit set	Negative binomial					
Response variable	**Fixed effects**	**Estimate**	**SE**	**Z**	**P**	
Fruit x flower	(Intercept)	-4.82	0.18	-27	<0.0001	
	Exclusion	0.91	0.16	5.6	<0.0001	
Fruit quality	Normal					
Response variables	**Fixed effects**	**Estimate**	**SE**	**t**	**P**	
Weight	(Intercept)	83.50	3.57	23	<0.0001	
	Exclusion	0.84	2.10	0.4	0.69	
Pole diameter	(Intercept)	46.90	0.72	65	<0.0001	
	Exclusion	0.51	0.44	1.1	0.25	
Equator diameter	(Intercept)	55.60	0,96	58	<0.0001	
	Exclusion	0.63	0,53	1.2	0.24	
Sugars	(Intercept)	9.22	0.19	47	<0.0001	
	Exclusion	0.24	0.13	1.9	0.06	
Seeds	(Intercept)	20.90	0.75	28	<0.0001	
	Exclusion	-0.67	0.53	-1.3	0.20	

Table 2. The best-fitting models resulting from model selection for the indicators of fruit set and quality of `Criolla´ mandarin with fixed factors in citrus family farms. Error structure, estimator, standard error (ES), the value of Z or t, and P-value are shown.

Fruit set	Negative binomial				
Response variable	**Fixed effects**	**Estimate**	**SE**	**Z**	**P**
Fruit x flower	(Intercept)	-4.73	0.22	-21.5	<0.0001
	Native visitation rate	20.21	10.60	1.9	0.05
Fruit quality	Normal				
Response variables	**Fixed effects**	**Estimate**	**SE**	**t**	**P**
Weight	(Intercept)	81.81	2.15	38.0	<0.0001
	Honeybee visitation rate	-5.13	2.14	-2.4	0.05
	Native visitation rate	-0.68	2.17	-0.3	0.76
Pole diameter	(Intercept)	47.73	0.90	52.7	<0.0001
	Honeybee visitation rate	-15.26	10.05	-1.5	0.17
Equator diameter	(Intercept)	55.97	0.42	132.4	<0.0001
	Honeybee visitation rate	-1.62	0.41	-3.9	0.003
Sugars	(Intercept)	9.98	0.11	90.8	<0.0001
	Native visitation rate	0.14	0.11	1.3	0.23
Seeds	(Intercept)	20.48	0.74	27.6	<0.0001
	Honeybee visitation rate	-1.25	0.67	-1.9	0.10

Table 3. The best-fitting models resulting from model selection for flower visitor

richness and abundance with fixed factors in citrus family farms. Error structure,

estimator, standard error (ES), the value of Z and P-value are shown.

Visitor richness	Poisson			
Fixed effects	**Estimate**	**SE**	**Z**	**P**
(Intercept)	2.12	0.11	18.8	<0.0001
Natural/semi-natural cover within 1000m	0.31	0.12	2.7	0.007
Flower visitor abundance	Poisson			
Fixed effects	**Estimate**	**SE**	**Z**	**P**
(Intercept)	-4.46	0.20	-22.9	<0.0001
Natural/semi-natural within 500 m	0.58	0.21	2.7	0.006

Fig. 1. Map of the study area (SA) in northwest Argentina (left) and distribution

of citrus family farms with the surrounding covers within 1000 m buffer (right;
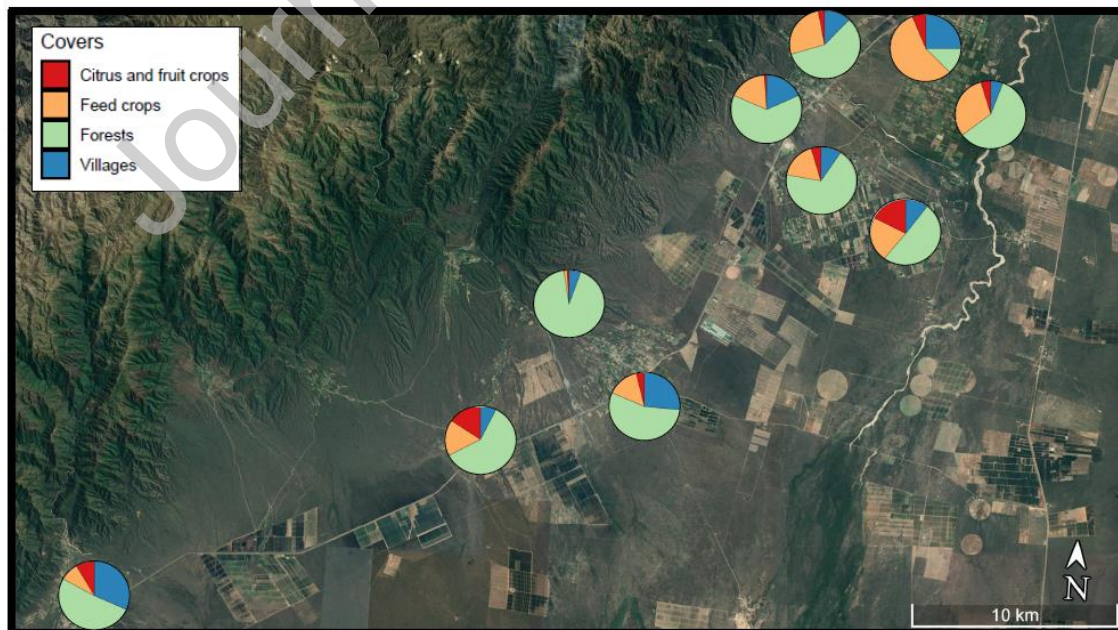
modified from Google Earth 2019).

Fig. 2. Effect of fruit set (fruit/flower) according to the bagged branches and open pollination treatments in selected sites. Boxplots show medians, quartiles (25th and 75th percentiles) and outliers.

Fig. 3. Fruit set (fruit/flower) and rate visitation partitioned into *A. mellifera* (honeybees) and native visitors in selected sites. The lines show the linear and polynomial fit of the models. The gray area is the 95% confidence interval.
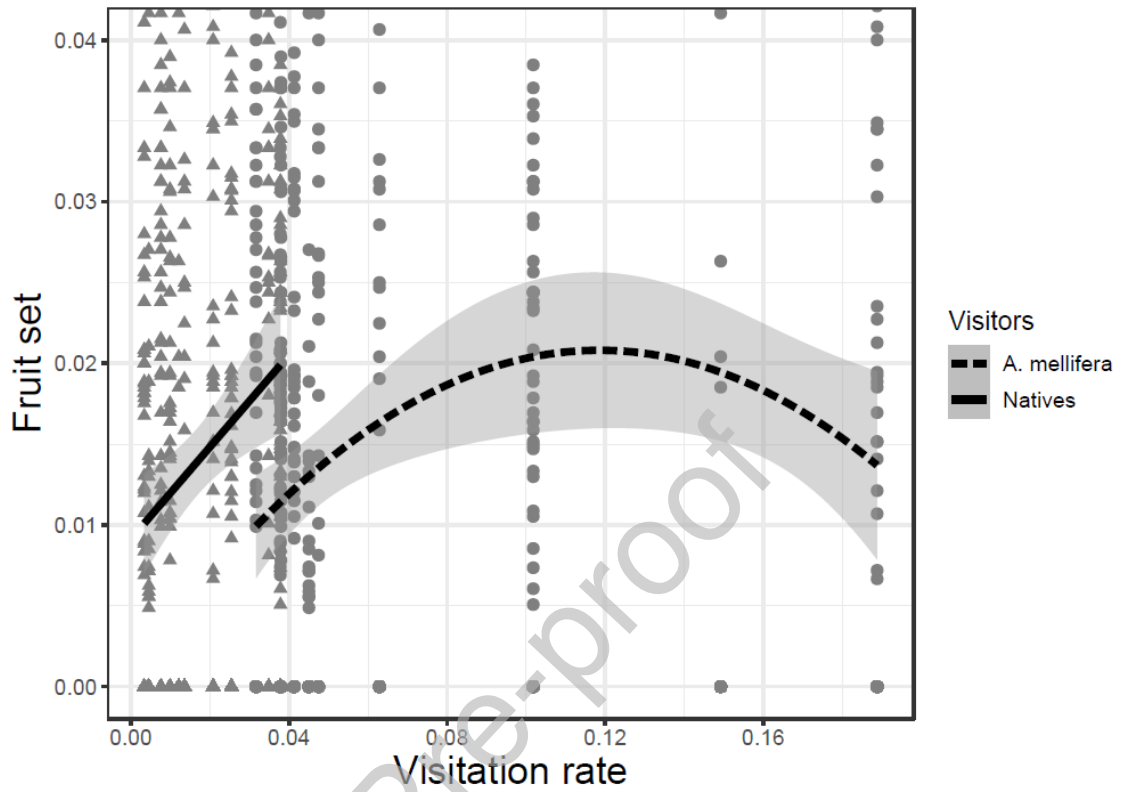
Fig. 4. Weight (A) and equator diameter (B) of mandarin and honeybee visitation rate in selected sites. The lines show the linear fit of the models among variables. The gray area is a 95% confidence interval
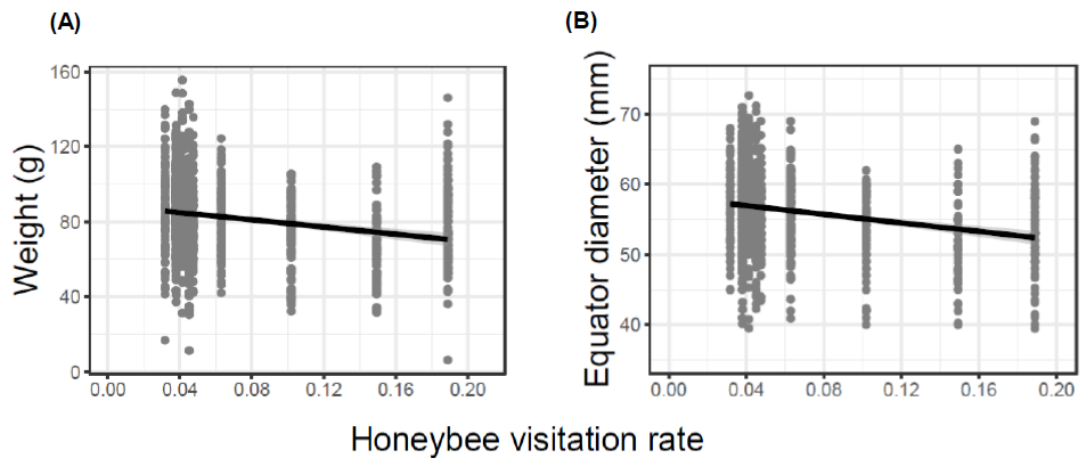
Fig. 5. (A) Visitor species number and natural/semi-natural cover within 1000 m of selected sites; and (B) abundance of flower visitors (*flower^{-1}*h^{-1}) and natural/semi-natural cover within 500 m of selected sites. The lines show the fit of the models among variables. The gray areas are 95% confidence intervals.