Olive Landscape Affects *Bactrocera Oleae* Abundance, Movement and Damage

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Abstract

The olive fruit fly, *Bactrocera oleae* (Rossi) (Diptera: Tephritidae), is a key pest of olive groves. Because of its economic importance and problems associated with chemical control, new approaches to reduce the damage caused by this pest and a deeper knowledge of the biology of the insect and the relationship of landscape structure to different biological parameters are needed. *B. oleae* can fly long distances and its ability to move within the landscape can determine the damage caused to olive groves. This work evaluates the effect of landscape structure on olive fruit fly abundance, movements and damage at three times of year—spring, early autumn and late autumn—in central Spain. This area is less dominated by olive groves than southern Spain, where the relationship between olive grove area and *B. oleae* abundance is already known. A cost-distance analysis is used to evaluate the landscape effect on the movement of the fly along the crop cycle. The olive grove area is the landscape composition factor with the greatest effect on the parameters studied, with a decrease in *B. oleae* abundance in a more complex landscape during spring and early autumn. The cost-distance analysis shows that the olive fruit fly moves mainly in spring, and amongst olive groves. There is no evidence that land uses other than olive groves serve as a summer refuge for *B.oleae* in the studied landscape context. Olive grove area and land use diversity index had significant effects on olive damage in more than one year.

Key Message

- Knowledge about the landscape effects on the biology of *Bactrocera oleae* is incomplete.
- We hypothesise that landscape structure affects *B. oleae* according to the resource concentration hypothesis, and that landscape affects *B. oleae* movement.
- Results indicate that *B. oleae* abundance was greater in areas with high olive grove area resulting in more damage. In addition, a cost-distance study indicated that *B. oleae* moves mainly in spring and amongst olive groves.
- This information can be useful in planning landscapes resilient to the olive fruit fly.

Introduction

The olive fruit fly, *Bactrocera oleae*, is the main pest of olive crops in most olive growing areas worldwide (Daane and Johnson 2010). Control of *B. oleae* has relied mainly on synthetic insecticides such as organophosphates, with associated problems of resistance, side effects on beneficial insects and impacts on human health and the environment (Cardenas et al. 2006; Nobre et al. 2019). Research on alternative control methods for the olive fruit fly has provided more environmentally friendly tools to manage this important pest (Petacchi et al. 2003; Rizzo et al. 2020). However, knowledge on the biology of *B. oleae* is also needed as a basis for its management. In particular, it is necessary to better understand their sheltering in summer, when populations decline, only to reappear when temperatures drop.

Bactrocera oleae 3rd instar larvae pupate in the soil in autumn and adults emerge the following spring, completing a number of generations between two and five, depending on the environmental conditions. The biology of overwintering populations has been studied, showing the presence of a complete generation in the spring (Marchini et al. 2017). During the summer, the number of *B. oleae* adults captured by different trap devices in olive groves decreases to minimum values, and increases from late summer to autumn, when olive fruit fly damage occurs. Thus, studies on *B. oleae* abundance have been carried out mainly on autumn populations, with a need to clarify biological aspects of spring populations (Marchini et al. 2017). It is also important to clarify the biology of *B. oleae* in summer, as it is unclear whether the unfavourable effects of high temperatures and low humidity cause the fruit fly to disperse to cooler sites (Daane and Johnson 2010).

The relationship between the structure of the landscape and the abundance of *B. oleae* has been studied in regions dominated by olive groves (more than 70%) with some complex areas of diverse land uses, such as the province of Jaén in Spain (Ortega and Pascual 2014; Ortega et al. 2016). In this area with a simple landscape due to the dominance of olive groves, it has been shown that the abundance of *B. oleae* in late summer-autumn is lower in olive groves in which the landscape environment is more complex. That is, olive groves around which the olive grove area was smaller and the Shannon landscape diversity index was higher. This landscape effect seems to be mainly direct, as predation of *B. oleae* pupae is more related to local than to landscape factors (Ortega et al. 2018) and parasitism rates are usually low (Fletcher 1987; González-Núñez et al. 2017), although a relationship between parasitism rates and landscape structure has also been reported (Boccaccio and Petacchi 2009). The direct landscape effect on *B. oleae* abundance needs to be studied in depth. It is thought that the "resource concentration hypothesis" would apply in this context (Root 1973), i.e., higher abundances are found in a landscape context with increased available resources. However, landscapes can also favour or hinder the movement of insect pests between crop patches and this relationship has been proposed to extend the 'resource concentration hypothesis' to the landscape scale (O'Rourke and Petersen 2017). The landscape-scale habitat diversity may directly reduce agricultural pest loads by requiring more dispersal activity, which, in turn, can increase mortality and decrease fitness.

At the landscape scale, the role of connectivity between favourable habitat patches for *B. oleae* has not been investigated. Functional connectivity depends on two factors: (i) the landscape-specific structural connectivity of habitat patches and (ii) the species-specific dispersal ability between habitat and non-habitat patches (Tischendorf and Fahrig 2000).

In this work, we used for the first time cost-based modelling to make inferences about the movement of *B. oleae*. This approach assigns different weights to cover types surrounding focal fields to identify spatial arrangements that facilitate or discourage the flow of organisms, and thus can improve our understanding of how landscapes affect ecological processes (Haan et al. 2020). Cost-distance has been applied to measure landscape connectivity mainly in conservation ecology (Wang et al. 2009; Zeller et al. 2012), with some studies on forest pests (Koch and Smith 2008; Roversi et al. 2013). However, to our knowledge, this approach has been used in the field of agricultural pest control only in one study in cotton landscapes (Perović et al. 2010). The authors of this work added cost-distance metrics to the proportional area metrics to identify whether they significantly improved the model. They conclude that cost-distance metrics offered a more or less significant explanation of in-crop density depending on the insect studied. Our approach is somewhat different as we compare significance of the models fitted with area metrics and cost-distance metrics at different times along the season to identify times when movement probably occurs, indicated by significance of the cost-distance metrics being higher than that of area metrics.

In this context, the aim of this work is to gain knowledge on the relationship between landscape structure and *B. oleae* abundance, movement and damage, in a landscape context with a gradient of complexity (dominance of olive groves from 70% to 6%), such as the olive growing area in central Spain, with several hypotheses: a) The area direct landscape effect on *B. oleae* abundance occurs over the complete cropping season, including spring populations. This would confirm the hypothesis of Root 1973. b) Another direct landscape effect occurs on *B. oleae* movement, over the complete cropping season. This would confirm the extended hypothesis of Root 1973 proposed by O'Rourke and Petersen 2017. c) This relationship translates to reduced damage to the olive crop in more complex compared to simple landscapes.

Materials And Methods

Study area

The study was carried out in the olive growing area of south-eastern Madrid (central Spain) (Figure 1), which covers an area of approximately 1,378.13 km². Climate is continental Mediterranean, with long and cold winters (average minimum temperature 0-2.5ºC) and long and hot summers (average maximum temperature 27.5-35ºC) (http://www.aemet.es/es/serviciosclimaticos/datosclimatologicos/valoresclimatologicos). The slopes are moderate, between 1% and 10%, and the altitude ranges between 570 to 700m asl. The dominant natural habitat is a Mediterranean scrubland with plant species adapted to dry climate and gypsiferous soils, and the main crops are olive, vineyards and cereals. Olive groves are generally rainfed and planted in a 10x10 m frame. Olive grove management in the area is mostly integrated, with low application of phytosanitary products. The soil is normally ploughed, but also treated with herbicides for weed control. The main pest in the area is the olive fruit fly (*Bactrocera oleae* Rossi), followed by the olive moth (*Prays oleae* Bernard).

Fifteen olive groves were selected in a 750 km^2 area, to represent a landscape compositional gradient, according to three parameters: landscape diversity index, percentage of olive groves and percentage of natural vegetation. Details of the selection of olive groves can be found in González-Núñez et al. (2015). Olive groves were separated at least 4 km. All of them were quite small in size with an area ranging from one to 11 ha.

Estimation of *Bactrocera oleae* abundance and damage

Yellow sticky traps baited with sex pheromone were used to sample *Bactrocera oleae* adults. Four traps were placed in each olive grove forming a 20 x 20 m square, separated by at least 30 m from the margin of the grove. Samplings were carried out in 2015 from 22nd April to 28th May and from 26th August to 26th November, and in 2016 from 21st April to 9th June and from 25th August to 23th November. The number of *B. oleae* adults were counted and taken off the traps weekly. Pheromone was replaced according to the manufacturer instructions and traps were replaced when their stickiness was reduced. Numbers of *B. oleae* adults were pooled into three time periods each year: In Period A (spring: 22 April-28 May 2015 and 21 April-9 June 2016), adult flies emerge from soil and no olive fruits are available for oviposition. In Period B (early autumn: 26 August-7 October 2015 and 25 August-5 October 2016), olive flies start emerging from fruits but abundance levels are still moderate. In Period C (late autumn: 14 October- 26 November 2015 and 13 October- 23 November 2016), olive fly abundance and damage are at a maximum.

Bactrocera oleae damage was estimated sampling fruits twice each year, except in 2014. Sampling was carried out at an early stage of infestation before treatments (early assessment in second and third week of October) in 2015 and 2016, and at a late stage of infestation after treatments (late assessment at the end of November) in 2014, 2015 and 2016. On each sampling date, an approximate number of 100 fruits were collected from each olive grove. The total number of olives collected was 1500 in 2014, and 3000 in 2015 and 2016. Fruits were collected from trees in the area where traps were placed. Whenever possible, only ten trees were sampled per olive grove, collecting ten fruits from each tree. Two fruits were collected from each cardinal point and two from inside the tree canopy. Fruits were taken to the laboratory, the number of fruits damaged by *B. oleae* was counted, and the number of damaged fruits/number of assessed fruits was calculated.

Landscape metrics

Landscape indices were calculated using the software Patch Analyst for ArcGIS® 10.1 (ESRI, Redlands, CA, USA). Information from the SIOSE project (Information System on Land Occupation of Spain; http://www.siose.es) was used to calculate these indices. Verification and updating of land uses were accomplished by comparing the SIOSE information collected in 2005 with aerial photographs taken in 2015 (provided by National Aerial Orthophotography Plan; https://pnoa.ign.es/) and information provided by SIGPAC (Geographic Information System of Agricultural Plots, 2004; http://sigpac.mapa.es/fega/visor/). Patches were reclassified to obtain a final number of 13 land use classes: Olive grove (O), Field crop (C), Scrubland (S), Scrubland with oaks (SO), Woody crop (W), Artificial (A), Pastures (P), Oak forest (K), Sparse vegetation (SV), Pine forest (F), Riverside vegetation (RB), Landscape 'mosaic' (Z) and Watered crop (W). 'Mosaic' refers to artificial green areas such as parks and housing developments with vegetation that is irrigated. Buffer areas of radii 500, 750, 1000 and 1500 m were established around the selected olive groves. Figure 2 shows the mean percentages of these land uses in the buffer of 1500m. The following landscape structure indices were calculated for these areas: Area of olive groves (CAO), Patch richness (PR) and Simpson landscape diversity index (SIEI).

Cost-distance analysis

The effect of mosaics of patches that make up a landscape on dispersal can be addressed with a cost-distance approach (Chardon et al. 2003) in which different land-use types can be assigned different costs to represent the degree of favourability for a taxon of interest. A standard component of ArcGis software, the 'cost-distance' tool, was used to model the dispersal of a theoretical individual throughout the landscape by identifying paths that maximise the use of favourable land uses between a designated source and destination on a map grid (in this case from perimeter of buffer to central point of circle where *B. oleae* samples were taken). Each cell of the map grid was assigned a cost based on the land uses that occupied that cell. The lowest cost (1) was assigned to those land uses that represent highly preferred habitat patches for a particular taxon, and highly unfavourable land uses, or an inhospitable matrix, was assigned much higher costs (50).

Three different scenarios were hypothesised regarding the suitability of land uses for *B. oleae* and its movement: H1: Olive grove is the only land use highly suitable for *B. oleae*, and the flies move amongst olive groves. H2: Water sources are suitable for *B. oleae*, acting as a summer refuge for the flies and thus, as a source of infestation for olive groves. H3: Scrublands are suitable for *B. oleae*, acting as a summer refuge for the flies and thus, as a source of infestation for olive groves, since in summer olive grove fly populations drop drastically. Cost values were assigned to the different land uses according to these hypotheses (Table 1). Mean Cost distance values were obtained for each olive grove. Hypothesis H1 was tested at all radii. However, to obtain a representative gradient in cost-distance values, hypotheses H2 and H3 were tested at radii 1000 and 1500 only, because of the scarce presence of some land uses around some olive groves at the smallest radii (750 and 500). Other land uses were not tested due to their low frequency in the olive grove plots.

Data analysis

Generalised linear mixed models were built to compare the effect of olive landscape structure on *B. oleae* abundance from two points of view: the first one is the *area* approach and the explanatory variable was olive grove area (CAO); the second point of view is a *dynamic* approach and studies as explanatory variables the values of cost-distance calculated for the different hypotheses (COSTH1, COSTH2 and COSTH3). Olive grove was a random factor in the models. A negative binomial family was considered. All statistical analyses were carried out in R. Generalised linear mixed models were fitted with negative binomial distribution and link function log. The *MuMIn* package was used to obtain estimates of regression coefficients.

The effect of landscape structure on *B. oleae* damage was assessed by fitting Generalised linear models separately for every buffer radius and sampling period. The response variable was number of damaged fruits/number of assessed fruits. Two landscape indices were assessed as explanatory variables because of collinearity problems (vif>4). These were CAO and PR for the early damage assessment, and CAO and SIEI for the late damage assessments. Models were fitted with binomial distribution and link function logit. MuMIn package was used to select models and obtain estimates of regression coefficients.

Results

Assessment of *B. oleae* area versus movement approach

The models were fitted to compare the effect of landscape on *B. oleae* abundance from an *area* approach, i.e. using CAO as a landscape explanatory variable, and from a *dynamic* approach, i.e. using mean cost-distance values (COST) as explanatory variables (Tables 2 and 3).

In the first sampling period (spring), it is remarkable that in 2015 and 2016 the significance of COST H1 is consistently higher than that of CAO. In the second sampling period (early autumn) variables behave the opposite, i.e. significance of CAO was consistently higher than that of COST H1. In fact, in 2015 COST H1 was not significant, while CAO had a significant effect at the smallest radius. In 2016 the effect of CAO was stronger than in 2015 and found at all radii. COST H1 was also significant, but significance was consistently lower than that of CAO, especially at the smallest radii, with a difference in significance about three orders of magnitude or higher. In the third sampling period (late Autumn), only in 2016 did COST H1 have a significant effect at 750 and 1000 m radii.

Regarding the cost values corresponding to hypothesis 2 (COST H2), in 2015 it was only significant at 1000 m radius and the spring sampling period, and its significance was lower than that of COST H1. In 2016 the significance of COST H2 was higher than in 2015, but again its significance was always lower than that of COST H1. In this year, COST H2 was also significant in early autumn and lower than that of COST H1. COST H3 was not significant in any of the fitted models. Thus, the most abundant wild land use (scrubland) does not play an important role in the movement of *B. oleae* flies.

Effect of landscape structure on *B. oleae* damage

Of the landscape variables, the olive grove area (CAO) affected damage assessed at an early stage of infestation, carried out in 2015 and 2016, which was higher as CAO increased (Table 4). This was observed in both years and radii analysed, but the effect was stronger in 2016 than in 2015 and the lowest intensity of this effect was shown at 500 m radius.

In the same analysis regarding damage assessed at a late stage of infestation, carried out in 2014, 2015 and 2016, Simpson landscape diversity index (SIEI) was significantly associated with reduced *B. oleae* damage in 2014 at 750 and 1000 m radii and in 2016 at 500 m radius (Table 5). No significant results were observed for CAO in these late assessments, except in 2014 at 750 m radius, and the behaviour in this case was opposite to the general trend observed for this variable in the early assessments.

Discussion

This work shows that landscape structure affects *B. oleae* abundance along the complete cropping season and affects *B. oleae* movement. The relationship between landscape structure and abundance of *B. oleae* translates to reduced damage to the olive crop in more complex compared to simple landscapes.

Effect of landscape structure on spring **B. oleae** *population*

This work shows that landscape structure (total area of olive groves) positively affects *B. oleae* abundance in a gradient of landscape context from 70% to 6% of olive grove along the complete cropping season, including spring populations. We previously reported a negative relationship between landscape diversity and autumn *B. oleae* abundance in the Jaén province, Spain (Ortega and Pascual 2014; Ortega et al. 2016), an area where olive grove is the dominant land use. According to the Spanish Ministry of Agriculture, Fisheries and Food, the area occupied by olive groves in the Jaén province is 586,921 ha, while in the Madrid province, where the present study was carried out is 26,585 ha (https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/superficies-producciones-anuales-cultivos/). The complexity of the landscape surrounding olive groves has also been shown to be related to lower abundance of another important olive pest, the olive moth (*Prays oleae*, Bernard) (Villa et al. 2020). In addition, several other works indicate a favourable effect of landscape complexity on different biocontrol organisms/processes (Boccaccio and Petacchi 2009; Lantero et al. 2019; Ortega et al. 2018), and general arthropod biodiversity (Cotes et al. 2011; Gkisakis et al. 2018). However, other works did not detect any landscape variables explaining the distribution of olive fruit flies (Picchi et al. 2016).

The olive grove area (CAO) is more strongly related to autumn and spring abundance of *B. oleae* than other parameters, as has been demonstrated in this work. This confirms that olive fruit fly populations follow the “resource concentration hypothesis” (Root 1973) in this gradient of landscape complexity. Taking into account this information can improve agricultural spatial planning enhancing landscape resilience to pest development (Rescia and Ortega 2018). However, we can take this a step further in assessing the extension of the ‘resource concentration hypothesis’ to the landscape scale, as predicted by O'Rourke and Petersen 2017, and determining whether it is posible to understand *B. oleae* movement in the surrounding landscape.

Effect of landscape structure on **B. oleae** *movement*

According to our results, the movement of *B. oleae* flies occurs mainly amongst olive groves in spring, when olive fruits have not yet developed. This seems to indicate that the stimulus for movement in this period could be searching for olive groves with fruits on which to oviposit, thus leading to more active movement amongst olive groves at this time of the year. Additionally, it is possible that adult *B. oleae* flights are also due to a search for food, because while fruit fly larvae are monophagous on olive fruits, adult flies use a variety of food sources. These adults have been found on different plant species, such as fig, lemon, cypress, mulberry and orange tree and they can use different pollens, honeydews, fruit and plant exudates, bacteria and even bird faeces (Michelakis and Neuenschwander 1981; Nobre 2019; Sacchetti et al. 2014; Tsiropoulos 1977). It is likely that flies move around looking for their host plant, following olfactory and visual stimuli (Neuenschwander et al. 1986; Scarpati et al. 1993; Scarpati et al. 1996), and during this search, they can find food sources on other species of vegetables, on which they remain, but only temporarily. Thus, although adults have been found in various plants, their abundance was always lower than on olive groves (Michelakis and Neuenschwander 1981). Interestingly, Michelakis and Neuenschwander (1981) found that in the "white period" (May-June), when there were no fruits susceptible to olive fly attack, there was an increase in numbers of olive flies in other plant species in one of the two locations studied. They explained this difference by the olive varieties in the two locations: in the location with higher numbers outside olive groves, the variety is Tsounati, whose last fruits neglected during the harvest fall before those of the Koroneiki variety, the variety in the other site. Thus, the movement of olive flies outside olive groves to other plant species seems to be due to the lack of fruits on which to oviposit. Our findings that movement happens mainly in spring agree with this behaviour, i.e. *B. oleae* moves searching for olive fruits. In addition, Girolami et al. (1982) describe that the adult behaviour corresponding to the phenological state of "newly formed olives" (not suitable for oviposition) is "dispersion throughout the area".

In this first study period, other land uses apart from olive groves do not seem to be a source of olive fruit flies in our study, as the significance of hypothesis 2 and 3, assigning lower cost to additional land uses, is lower than that of hypothesis 1, or even not significant in the case of hypothesis 3. In our study area, there are plant species that could harbour *B. oleae*, such as fig and walnut trees, as described by Michelakis and Neuenschwander (1981). However, the most abundant use of wild land, namely scrubland, has mainly shrubby plants (*Retama sphaerocarpa* (L.) Boiss., *Teucrium pseudochamaepitys* L., *Thymus vulgaris* L.), with some interspersed oak trees (*Quercus ilex* L.), which are probably not very attractive to the flies. Thus, olive flies at this time of the year are mainly in olive groves and moving amongst them.

Apart from the first period evaluated, it seems that *B. oleae* stays in olive groves throughout the rest of the season. Adults emerging in spring lay eggs on fruits from the previous season (Marchini et al. 2017; Michelakis and Neuenschwander 1981) and it is possible that a substantial amount of these adults do not survive summer. Alternatively, the large drop in the numbers of *B. oleae* captured in summer could be attributed to movement to areas outside of olive groves to different land uses. In a study carried out in Crete, marked flies were released in July-October, and higher dispersion was found in summer than in autumn, probably because of the high temperature and favourable winds (Economopoulos et al. 1978). In addition, movement of *B. oleae* outside of olive groves has been assumed in other works in Italy (Girolami et al. 1982; Scarpati et al. 1996). These studies noted that in the summer the olive flies dispersed throughout the area probably to search for food, and returned to the olive trees after summer rains. It is also noted that this phenomenon is not linked to the emergence of the adults of the preceding spring generation. Our results do not agree with this assumption as in period B the significance of the area metrics (CAO) was higher than that of cost-distance metrics, regardless of the cost hypothesis being tested. In our study area, summer rains are not very frequent; therefore, this and other environmental conditions could be factors explaining this disagreement. On the other hand, Michelakis and Neuenschwander (1981) did not find any plants other than olives acting as a refuge for flies during summer. Thus, in our area it seems that the *B. oleae* adult population at the end of summer starts mainly from larvae developed on fruits of the previous year, although adult immigration from outside the olive groves cannot be completely discarded. Our approach evaluates movement indirectly, and studies assessing movement by direct means would be necessary to confirm this behaviour.

In the last period evaluated, the effect of landscape on *B. oleae* abundance losses significance, both from the area-metrics approach and from the cost-metric approach. In this period abundance reaches the highest levels, when damage to olive fruit is inflicted and when control measures against the olive fly are applied if abundance surpasses economic thresholds. This can explain the area-approach (CAO) loses significance in the two years of study. In addition, the significance of the cost-metric assigned to hypothesis 1 (COST H1), observed only in 2016, indicates movement of *B. oleae* flies again amongst olive groves. As in spring, studies assessing movement by direct means would confirm this behaviour. However, the cost-distance approach to assess insect movement is a relatively easy and affordable tool compared to methods such as marking flies with fluorescent powders (Economopoulos et al. 1978), taking into account the limited number of insects that can be marked (Michelakis and Neuenschwander 1981). In addition, it is important to point out the remarkable consistency of the results found in our work across the two years studied.

Regarding the different radii studied, we did not found any consistent behaviour across all the parameters and time periods studied, although perhaps the most relevant is a lower effect of the landscape structure for the smallest radius studied (500 m). According to other studies, the olive fruit fly can perform seasonal movements of several kilometres (Economopoulos et al., 1978; Neuenschwander et al., 1986; Fletcher, 1987). However, the radius of action that olfactory stimuli may have on *B. oleae* is not exactly known (Scarpati et al., 1993; Scarpati et al., 1996). Our previous work in the Jaén province also found significant effects of landscape structure on *B. oleae* abundance at radii ranging between 500 and 2000 m, depending on the index studied (Ortega and Pascual, 2014; Ortega et al., 2016). Other studies in olive groves used radii ranging from 200 to 2000m (Boccaccio and Petacchi 2009; Gkisakis et al. 2018; Picchi et al. 2016; Villa et al. 2020). In some of this work, one radius is selected because there is previous knowledge on the phenomenon studied (Picchi et al. 2016). Otherwise, multiple scales are examined, as it is not known a priori which are important, and these are chosen based mainly on the dispersal abilities of the studied organisms. However, significant effects have been found in different studies at 1000 m radius (Boccaccio and Petacchi 2009; Ortega and Pascual 2014; Ortega et al. 2016; Villa et al. 2020), and the most predictive scale of response for specialist pests in different crops is around 1000m (Chaplin-Kramer et al. 2011).

Effect of landscape structure on B. oleae *damage*

An important result of our work is that the effect of landscape structure on *B. oleae* abundance results in a reduced damage to the crop, when this is evaluated at an early stage before damage surpasses economic thresholds, since later pesticides are used altering the results. In our previous work in the Jaén province, we did not observe this reduction (Ortega and Pascual 2014). As explained above, the Jaén area is dominated by olive groves, therefore damage produced by the olive fly is probably higher than in central Spain, and thus control measures against *B. oleae* are more intense, which could mask the landscape effect. In addition, Ortega and Pascual (2014) assessed damage without considering the different periods we used in the present work, and this may have masked the landscape effect. Our results also show that the landscape effect is not observed when damage assessment is carried out at a later stage, and even in some cases when a relationship was detected, its meaning was opposite to the general trend.

In conclusion, we note the importance of landscape for the development of olive fruit fly pests, with the area of olive groves in a landscape being the most relevant parameter determining abundance, movement and damage. This information should be taken into account in improving agricultural spatial planning to enhance landscape resilience to pest development. Additionally, this work proposes the cost-distance approach as a useful means to make inferences about insect movement. Using this tool, this work provides new information regarding the biology of *B. oleae*: movement of adults occurs mainly in spring and no other land use apart from olive groves seems to have a significant role as a refuge for the insect during summer in the area studied.

Declarations

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Conflicts of interest

All the authors declare that they have no conflict of interest.

Author Contribution Statement

SP and MO conceived the research, and gathered abundance data. CEF and SP evaluated damage. NM carried out cost-distance analysis. SP analysed data and wrote the manuscript. MO improved the manuscript.

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Tables

Due to technical limitations, table 1, 2, 3, 4 and 5 is only available as a download in the Supplemental Files section.

Figures

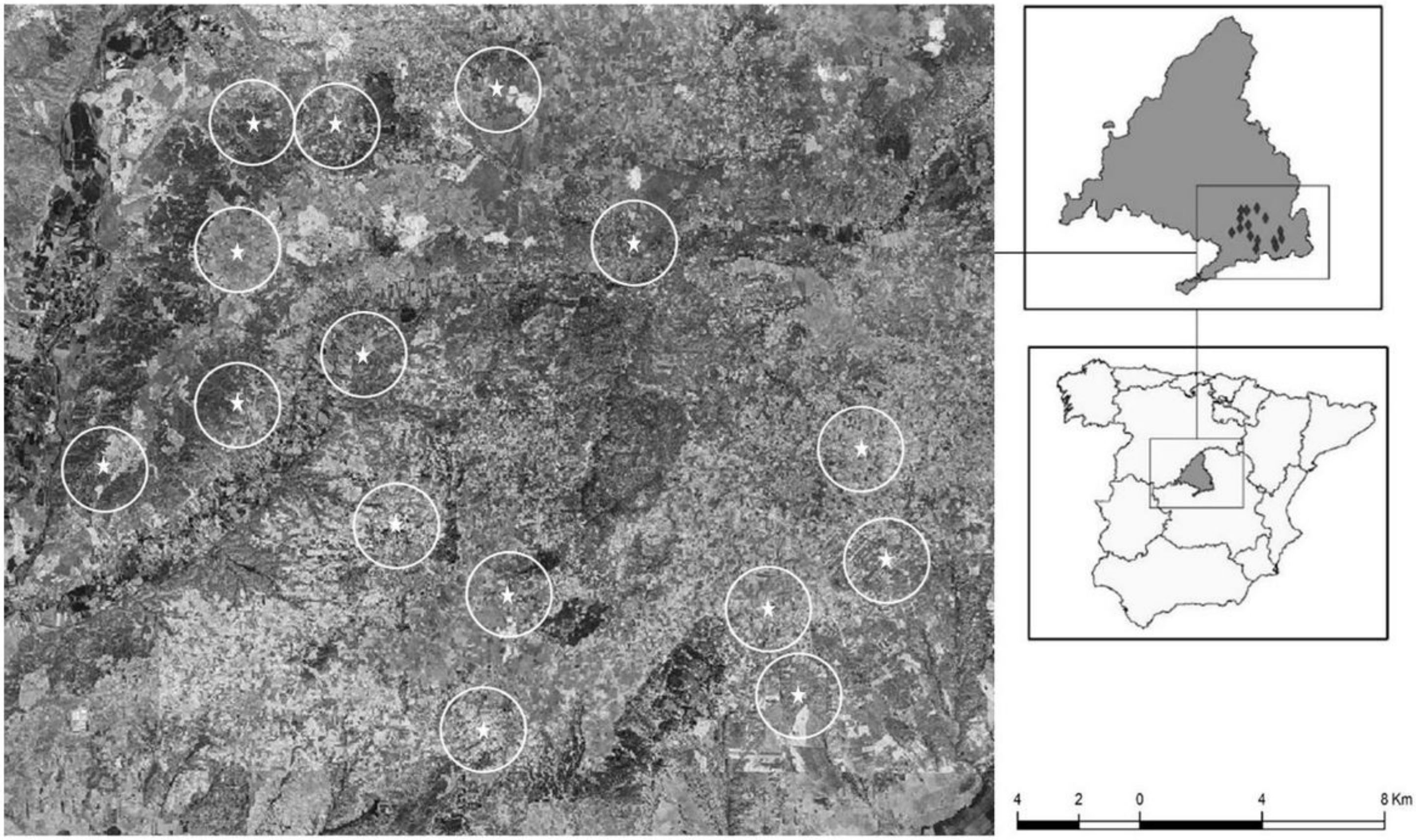

Figure 1

Location and aerial photograph of the study area. Sampled olive groves are indicated, as well as the 1500m radius areas around them. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

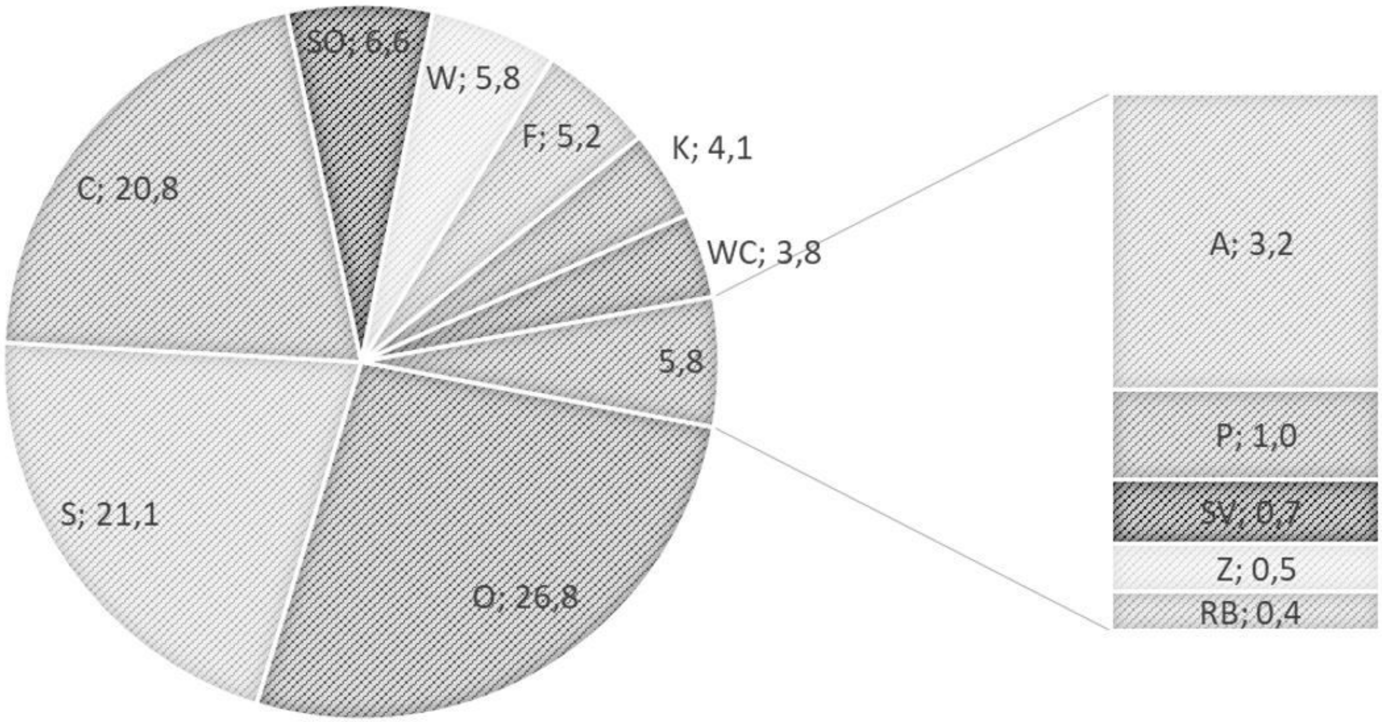

Figure 2

Average percentages of the different land uses in the 1500m radius areas around the sampled olive groves. Olive grove (O), Field crop (C), Scrubland (S), Scrubland with oaks (SO), Woody crop (W), Artificial (A), Pastures (P), Oak forest (K), Sparse vegetation (SV), Pine forest (F), Riverside vegetation (RB), Landscape mosaic (Z) and Watered crop (W)

Supplementary Files

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- Table1.jpg
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