

Article

Are the Interactions between Oaks and Pre-Dispersal Seed Predators Retained in Urban Environments? An Analysis of Two *Quercus* Species in Southern Mexico City

Hilda Díaz-Guzmán, Edgar J. González  and Consuelo Bonfil *

Departamento de Ecología y Recursos Naturales, Facultad de Ciencias, Universidad Nacional Autónoma de México, Ciudad de México 04510, Mexico; hilda_diaz@ciencias.unam.mx (H.D.-G.); edgarjgonzalez@ciencias.unam.mx (E.J.G.)

* Correspondence: cbonfil@ciencias.unam.mx

Abstract: As urbanization proceeds, natural ecosystems surrounding cities are transformed, but usually some elements persist, notably trees from forest ecosystems. However, it is still unknown the extent to which isolated trees, immersed in an urban matrix, maintain their interactions with insects that feed on their seeds. In this work we analyzed pre-dispersal seed predation by the two main groups of insects, weevils (Coleoptera; Curculionidae) and moths (Lepidoptera: Tortricidae), whose larvae feed on the acorns of two oak species (*Quercus rugosa* and *Q. castanea*). We compared these interactions between trees located in a protected forested area and trees isolated in an urban matrix. Our hypothesis was that, since pre-dispersal seed predation depends on insect dispersal, acorns from isolated trees would have lower predation levels than acorns from trees in the forest. A second hypothesis, based on reports that moths exhibit larger dispersal distances than weevils, was that isolated trees would have higher predation levels from moths than from weevils compared to their respective proportions in forest trees. Finally, we expected that moth predation would increase with seed size, as it does in weevils. We collected 1200 acorns of the two oak species (ten trees per species) in a protected oak forest and a nearby highway in southern Mexico City. From the whole sample, 17.3% of the acorns were predated by weevils and 3.8% by moths. The probability of predation was larger in acorns from trees in the forest (0.30) than in those from isolated trees (0.07), which confirmed the first hypothesis; tree species identity did not have a significant effect on the proportion of predated acorns. When only predated acorns were analyzed, predation by weevil larvae was larger than predation by moths in both oak species, although the probability of predation by weevils was higher in the oak species having large acorns (*Q. rugosa*, 0.93), than in the species with small acorns (*Q. castanea*, 0.63). Inversely, predation by moths was higher in *Q. castanea* (0.37) than in *Q. rugosa* (0.07). Seed predation decreased similarly for weevils and moths in isolated trees, so we failed to find support for our second hypothesis. A positive relationship between seed predation by weevils and seed size was found in *Q. rugosa* but not in *Q. castanea*; seed size did not affect predation by moth larvae. Therefore, although isolated trees in the urban matrix harbor smaller populations of pre-dispersal seed predators than forest trees, their interactions with the two main groups of insects feeding on acorns are maintained, which points to their importance for the conservation of urban biodiversity.

Keywords: curculionids; *Cydia*; isolated trees; moths; seed size; urbanization



Citation: Díaz-Guzmán, H.; González, E.J.; Bonfil, C. Are the Interactions between Oaks and Pre-Dispersal Seed Predators Retained in Urban Environments? An Analysis of Two *Quercus* Species in Southern Mexico City. *Diversity* **2022**, *14*, 351. <https://doi.org/10.3390/d14050351>

Academic Editor: Raul Bonal

Received: 11 March 2022

Accepted: 26 April 2022

Published: 29 April 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

As land use change proceeds, natural ecosystems are transformed, but usually some elements persist, notably trees from previously forested areas. Isolated or scattered trees have been considered keystone structures, performing diverse ecological functions, including provision of a distinct microclimate, increasing plant species richness, increasing soil

nutrients and habitats for animals [1]. However, their role in biodiversity conservation has been studied mainly in the context of tropical deforestation and rural landscapes [2–4], and less attention has been given to isolated trees in extremely modified landscapes, such as cities.

Studies on urban trees have been centered on their role in modulating atmospheric pollution [5–7], and microclimatic conditions [8,9], but their contribution to maintaining overall biodiversity is less well known. However, it is expected that some of their interactions with fauna may persist in an urban context, especially in those trees located near protected forested areas.

The main emphasis in the study of biodiversity associated with urban trees has been placed on birds and bats [10–12], and less attention has been paid to arthropods, with a few exceptions (e.g., Helden et al., 2012 [13]). However, arthropods can be good indicators of changes associated with urbanization, because they respond quickly to anthropogenic changes in the soil and vegetation, due to their short generation times [14].

The relative importance of isolated trees immersed in an urban matrix is expected to vary with tree species identity, because very different numbers of arthropod species are associated with different tree species [15]. Among them, oaks harbor high insect diversity. It has been shown that native oaks have more phytophagous insect species than non-native *Quercus* species [16], and that oak trees located in less disturbed sites have higher arthropod diversity than those found in disturbed sites [17].

Certain groups of phytophagous insects feeding on oaks have received more attention, particularly those belonging to the Coleoptera, Hymenoptera and Lepidoptera orders [18]. A relatively well studied interaction between oaks and insects is pre-dispersal seed predation [19–24]. However, most studies on this topic have taken place only in a few regions, notably the Iberian Peninsula and California. In tropical regions of the world, and countries having a high oak diversity, such as China or Mexico, studies on this interaction are still scarce (but see Peguero et al., 2017 [25] and Li et al., 2021 [26]).

With the aim of assessing whether interactions between oaks and pre-dispersal seed predators are maintained in urban trees, in this study we compared seed predation between trees located either in a protected forested area or isolated and immersed in an urban matrix. We analyzed predation by the two main groups of insects whose larvae feed on acorns: (i) weevils (Coleoptera; Curculionidae) and (ii) moths (Lepidoptera: Tortricidae), in two oak species (*Quercus rugosa* and *Q. castanea*) that can be found both in the forest and as isolated trees in the streets. Our hypotheses were: (1) if pre-dispersal seed predation depends on insect dispersal, acorns from isolated trees would have lower predation levels than acorns from forest trees; (2) since previous reports registered larger dispersal distances for moths than for weevils, isolated trees would have higher predation levels from the former compared to their respective proportions in forest trees, and (3) as larger seeds have larger reserves for larvae development, the presence of both curculionid weevils and *Cydia* larvae would be positively related to acorn size.

2. Materials and Methods

Study site and study species—This study was carried out in the piedmont of the Ajusco volcano, in the southern portion of the endorheic watershed where Mexico City is located. Acorns from two oak species (see below) were collected: (a) in the forested protected area “Center for Environmental Education Ecoguardas” (Ecoguardas from now on), which encompasses 132.6 ha of oak forest at an altitude of 2507 m a.s.l. and, (b) in a portion of the Picacho-Ajusco (PA) highway (around Km. 5.6) adjacent to Ecoguardas, where isolated oak trees are found (Figure 1). Mean distance among individual trees (trunks) was 6.85 m (range 3–9 m).

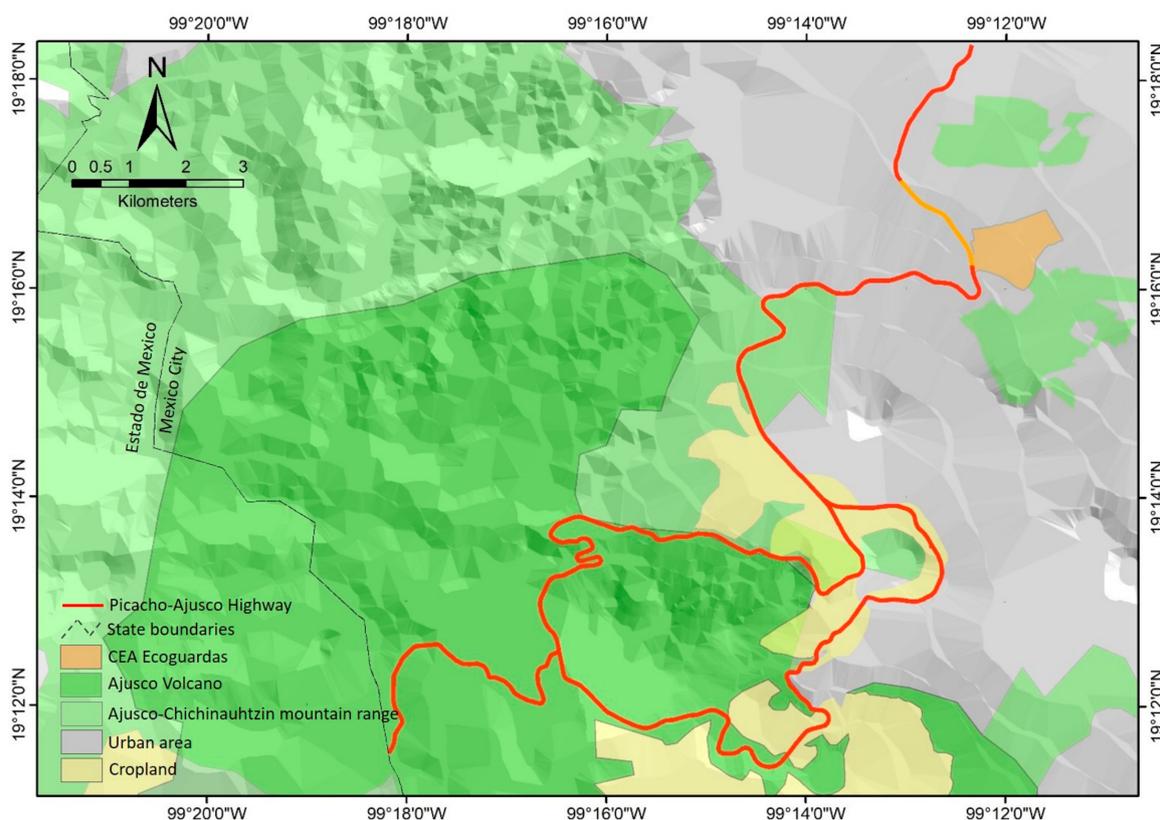


Figure 1. Study area and its location in relation to the Ajusco volcano (dark green) and the Ajusco-Chichinautzin mountain range (light green area surrounding the volcano). The protected forested area, Ecoguardas, and the portion of Picacho-Ajusco highway (where acorns were sampled) are shown in orange.

The Ajusco volcano is part of the Ajusco-Chichinautzin mountain range (Figure 1). In the piedmont of this volcano, older soils, such as Andosols and Phaeozems, intersperse with basaltic lava beds created by the eruption of the Xitle volcano, which occurred approximately 2000 years ago [27,28]. Climate is temperate (mean annual temperature 12–18 °C) and annual precipitation is around 1000 mm, most of which falls during the summer. The two main vegetation types are oak forest and xeric shrubland, the latter growing mainly on lava beds. The dominant oak species found in these forests are *Quercus castanea*, *Q. rugosa* and *Q. obtusata*, while the main shrubland species are *Buddleja cordata*, *Dodonaea viscosa* and *Pittocaulon praecox*. Parts of these lava beds have also been colonized by *Q. rugosa* and *Q. castanea* [27,29–31].

Mexico City, the largest urbanization of the country, has been growing steadily to the piedmont of the mountains surrounding the basin. The fragmentation of the ecosystems in the piedmont of the Ajusco volcano became evident during the 1970s, when oak forests were transformed into urban settlements, and has continued therefrom. At present, there are patches of natural vegetation that have been protected, as well as remaining oak trees that became isolated in the urban matrix, mainly along roads and within gardens.

Two oak species found both in Ecoguardas and on the PA highway were selected for this study. *Quercus castanea* Neé trees are 5–18 m tall, and fruit annually in groups of 2–3 acorns. They are widely distributed in Mexico and Central America, between 1800–2600 m a.s.l. Trees of *Q. rugosa* Neé are 3–25 m tall and fruit annually in groups of 2–13 acorns. The species is found from southern USA to Central America, from 1100 to 3050 m a.s.l.

The two main groups of pre-dispersal acorn predators are weevils (Coleoptera; Curculionidae) and moths of the genus *Cydia* (Lepidoptera: Tortricidae). The first include

mainly species of the genus *Curculio*, but species of *Conotrachelus* may also be found. The Curculionid life cycle is bound to oak phenology, as adults feed on leaves and females lay their eggs inside the acorns. Their large rostrum allows them to bore into the cotyledons and lay eggs through this hole. Female moths place their eggs on, or nearby, the surface of acorns, and when first-instar larvae hatch from eggs, they find their way into the fruits [32]. It is unusual to find more than one larva inside an acorn, but occasionally larvae go from one acorn to another if there is not enough food [33,34]. Since knowledge of curculionid and *Cydia* species is very scarce in Mexico, in this study we will only address their presence naming them as weevil or moth larvae.

Seed sampling and processing—During September 2015 we surveyed trees of both oak species in Ecoguardas and along the PA highway. 10 healthy trees ($\text{dbh} \geq 20$ cm, having immature seeds) per species were chosen (five in the forest and five on the highway), for a total of 20 trees. They were marked and located on a map, and regular visits were made until acorns were mature. All chosen trees in the forested protected area, Ecoguardas, were found in the central area (i.e., far from the border).

During October–November 2015, weekly surveys were made (on 5, 12, 19, 26 October and 2, 9, 16 and 23 November), during which approximately 50 mature acorns per tree were collected from the tree canopy. Acorns were taken to the lab and numbered individually according to their mother tree. Each acorn was measured, registering its length (r_1) and width (r_2), to estimate its volume with the formula of an ellipsoid, which has been widely used to model seed size expressed as volume [35]:

$$V = \frac{4}{3}\pi r_1 r_2^2$$

Each acorn was individually placed in an ice cube plastic tray and daily observations were made for one month to register the emergence of weevil or moth larvae. After this period, each acorn was cut in half to establish whether there were larvae or excrement inside it. Since it is possible to distinguish the excrement of larvae of weevils and moths (the latter having larger pellets), the type of excrement was also registered.

Data analysis—To analyze and estimate the probability of: (a) an acorn being predated and, (b) one type of larva (curculionid or moth) being responsible, generalized linear mixed effects models (GLMMs) were constructed, using binomial distribution, and tree identity as a random factor, with the lme4 package [36] in the R software (version 3.4.2, R Core Team, 2017). For each hypothesis, four models were constructed: a model including the interaction of tree location (forest or isolated) and oak species (*Q. rugosa* or *Q. castanea*), a model without this interaction, and two models including only one of the abovementioned variables each. These models were compared, using maximum likelihood ratios, and observed as to whether the removal of one variable caused significant differences among them (critical value $p = 0.05$).

Estimates obtained from the chosen models were transformed to obtain values in the correct scale (i.e., between 0 and 1) using the formula of a logistic regression [37]:

$$Y = \frac{1}{1 + e^{-z}}$$

where Y is the probability of an acorn being predated by a weevil larva and z is the lineal model selected for this type of predation. Thus, the predation probability by a moth larva is $1 - Y$. Confidence intervals (95%) were obtained for the estimates of each model, which were also transformed with the abovementioned formula.

To evaluate the effect of acorn size and *Quercus* species on predation by weevil and moth larvae, GLMMs were constructed with binomial distribution. A full model was constructed (including all variables and their interactions) for each larva type, and from this, subsequent models were simplified and compared using likelihood ratios. Two models were constructed for predation by weevil larvae (one with, and another without, interaction) and five models for predation by moth larvae (one without, and another with, interaction,

a null model, and one for each independent variable). For this analysis, two sets of acorns were considered. One, including undamaged acorns and those predated by weevil larvae, was used to evaluate the effect of seed size on pre-dispersal predation by weevils. The second set included all acorns predated by moth larvae and undamaged acorns, and was used to analyze predation by moths. In all models the independent variables were *Quercus* species and seed size (volume), and the tree was a random factor (19 trees included, as one did not have predated acorns). The dependent variable was acorn predation with two categories (undamaged or predated).

3. Results

Out of 1200 acorns, 22.3% were predated: 17.3% by weevil larvae, 3.8% by moth larvae, and 1.1% by both of them. Acorns of *Quercus rugosa* accounted for 54.4% of the total sample and had a higher predation rate (26.9%) than acorns of *Q. castanea* (45.6% of the total sample; predation rate 16.8%). The sample was slightly imbalanced, with a mean of 65 acorns per tree for the first species and 55 acorns per tree in the second.

In both oak species, predation by weevils was higher (23.3% and 10.2% in *Q. rugosa* and *Q. castanea*, respectively) than predation by moths (1.8% and 6.21%, respectively); percentages of acorns predated by both types of insects were 1.8% and 0.3%, respectively. Due to the low number of acorns in the latter category, they were excluded from the analysis.

To analyze overall predation, the models with, and without, interaction were compared (Table 1). Since they did not differ significantly, the model without interaction was chosen, as it is more parsimonious. We then eliminated location and oak species from the model, using a stepwise procedure, which allowed us to establish that the best model only included location as a fixed factor. Predation probability of acorns of trees in the forest was significantly higher (0.299) than that of isolated trees (0.071; Figure 2A).

Table 1. Generalized linear mixed effects models (GLMMs) used to analyze predation probability of acorns of two *Quercus* species. In each model the effects of tree location and *Quercus* species were included. The *p*-values indicate the significance of the likelihood ratio test among pairs of models (*n* = 1186).

| Response Variable | GLMM Model | <i>p</i> |
|----------------------------|--|----------|
| Total predation proportion | (undamaged, predated) = location × species | 0.706 |
| | (undamaged, predated) = location + species | |
| | (undamaged, predated) = location + species | <0.001 |
| | (undamaged, predated) = species | |
| | (undamaged, predated) = location + species | 0.113 |
| | (undamaged, predated) = location | |

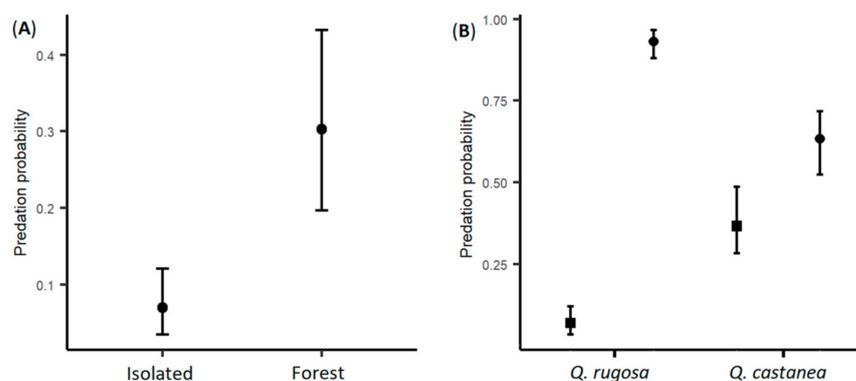


Figure 2. (A) Acorn predation probability of isolated trees and trees in the protected forest area Ecoguardas. (B) Acorn predation probability of *Quercus rugosa* and *Q. castanea*. Circles: predation by weevils, squares: predation by moths. Bars represent 95% confidence intervals.

When analyzing the effect of tree location and *Quercus* species on the proportion of acorns predated by weevils and moths, we found no differences between the models with, and without, interaction (Table 2), so the latter was chosen. Then two models were compared, one including both variables and one in which location was removed. As there were no differences among them, location was removed. However, when the effect of oak species was removed there were significant differences (Table 2), so the best model included only *Quercus* species as a fixed factor. Although in both oak species predation levels by weevil larvae were higher than those of moth larvae, the probability of predation by weevils was higher in *Q. rugosa* (0.93), than in *Q. castanea* (0.63). Conversely, predation probability by moth larvae was higher in *Q. castanea* (0.37) than in *Q. rugosa* (0.07). There were significant differences in predation by insect species among *Quercus* species (Figure 2B).

Table 2. Generalized linear mixed effects models (GLMMs) used to analyze the differences in the proportion of acorns predated by weevil and moth larvae between locations (forest and isolated trees) and oak species. The *p*-values indicate the significance of the likelihood ratio test among pairs of models (*n* = 254).

| Response Variable | GLMM Model | <i>p</i> |
|-----------------------------|---------------------------------------|----------|
| Predation proportion | (weevils, moths) = location × species | 0.402 |
| | (weevils, moths) = location + species | |
| | (weevils, moths) = location + species | 0.154 |
| | (weevils, moths) = species | |
| | (weevils, moths) = location + species | |
| (weevils, moths) = location | <0.001 | |

To analyze the effect of seed size on predation by weevil larvae, we included undamaged acorns and those predated only by weevils (*n* = 1140). Mean seed volume of *Q. rugosa* was almost three times higher ($1.51 \pm 0.8 \text{ cm}^3$, mean \pm SD) than seed volume of *Q. castanea* ($0.56 \pm 0.3 \text{ cm}^3$). There were significant differences between the models with, and without, interaction (Table 3), so the former was used. The significant interaction in the selected model is explained because the effect of acorn size differed among oak species: while in *Q. rugosa* predation by weevils increased with seed size, in *Q. castanea* there was a slight tendency (i.e., with a small slope) for it to decrease with seed size (Figure 3).

Table 3. Generalized linear mixed effects models (GLMMs) used to analyze the effects of seed volume and oak species in pre-dispersal predation by weevils. The *p*-value indicates the significance of the likelihood ratio test among the pair of models (*n* = 1140).

| Response Variable | GLMM Model | <i>p</i> |
|----------------------|--|----------|
| Predation by weevils | (undamaged, predated) = volume × oak species | 0.016 |
| | (undamaged, predated) = volume + oak species | |

When predation by moth larvae alone was analyzed, no differences were found among the models (Table 4), and thus the explanatory variables were not significant. This implies that, in contrast to weevils, moths do not select acorns based on seed size, and do not seem to have a marked preference for an oak species. Thus, arrival and seed infestation appear to be random phenomena. However, since this analysis included a low number of acorns attacked by moth larvae (*n* = 46) in relation to the total sample used (*n* = 978), there was a strong disparity between undamaged and moth-predated acorns.

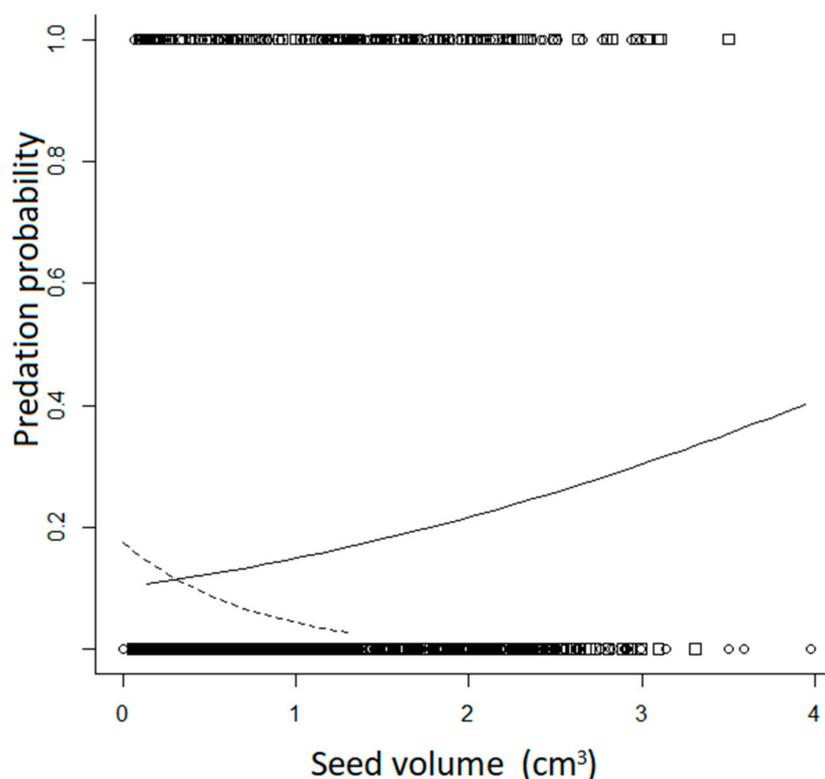


Figure 3. Acorn predation probability vs. acorn volume in *Quercus rugosa* (continuous line) and *Q. castanea* (dotted line).

Table 4. Generalized linear mixed effects models (GLMMs) used to analyze the effects of seed size (volume) and oak species on pre-dispersal predation by moth larvae. The *p*-values indicate the significance of the likelihood ratio test among pairs of models (*n* = 978).

| Response Variable | GLMM Model | <i>p</i> |
|--------------------|--|----------|
| Predation by moths | (undamaged, predated) = volume × oak sp. | 0.277 |
| | (undamaged, predated) = volume + oak sp. | |
| | (undamaged, predated) = volume + oak sp. | 0.124 |
| | (undamaged, predated) = volume | |
| | (undamaged, predated) = volume | |
| | (undamaged, predated) = 1 | 0.622 |
| | (undamaged, predated) = volume + oak sp. | |
| | (undamaged, predated) = oak sp. | |
| | (undamaged, predated) = oak sp. + tree | |
| | (undamaged, predated) = 1 + tree | 0.783 |
| | 0.112 | |

4. Discussion

Changes in biodiversity in small patches of remnant vegetation, such as isolated trees, have been associated with time elapsed since they became isolated, as well as with their connectivity to large, forested areas [38]. However, the role of isolated trees for biodiversity conservation has received less attention in urban contexts, where most studies have addressed interactions of native plants and birds [39–41], and to a lesser degree, arthropods [13,42].

In this study, we showed that isolated oak trees in an urban matrix harbor populations of the two main groups of pre-dispersal acorn predators, even though they have been isolated for approximately 40–50 years. Larvae were missing only in one out of ten urban trees, and insect presence did not seem related to distance to the forest, since this tree

was close to the Ecoguardas forest, and acorns from the farthest tree had larvae of both types of insects. Although the Ecoguardas is not a large forested area, and the surrounding urban matrix may have some impact on it, it was protected soon after the PA highway was constructed and has kept its original composition and structure since then.

In the two oak species studied, the proportion of acorns having both weevil and moth larvae was very low. In other studies, these proportions were also very low [43] or slightly higher [33]. According to Rohlf (1999) [32], moth larvae get inside the acorn through a softened surface caused by infections in the pericarp. Our results show that moths do not require the previous presence of holes made by weevils to enter the seeds. In *Q. rugosa*, there were as many acorns having only moth larvae as there were of those with both types of insects. In *Q. castanea*, acorns having only moth larvae were more common than those having the two types of insects (6.2% and 0.3%, respectively). Perhaps in the smaller acorns of *Q. castanea* it is easier for female weevils to detect the presence of a moth larva and avoid oviposition. It has been shown that oviposition by curculionids is reduced in seeds of *Castanea sativa* already having a moth larva [44], because female weevils can detect a chemical marker that the larvae leave when entering the acorn [45]. Future studies will establish if the simultaneous presence of both types of larvae is more likely in large-seeded oak species. To our knowledge, this is the first time that a species with such small acorns has been included in a study of pre-dispersal seed predation.

Our results supported our first hypothesis, as pre-dispersal seed predation was reduced in isolated trees compared to predation levels in forest trees, and this reduction was not affected by oak species identity. Fragmentation and isolation reduce pre-dispersal predation by coleoptera and lepidoptera in various tree species [46,47]. In isolated *Quercus ilex* trees, in the dehesas in Spain, increases in acorn size and/or acorn production have been reported [22,48], which may render them more attractive to weevils. In this study, changes in acorn abundance or size in isolated trees were not documented, but even if this were the case, larvae abundance decreased. The limitations imposed by an urban matrix on weevil and moth dispersion probably make it difficult for them to reach isolated trees, and thus the permanence of *in situ* populations could be more important than immigration. However, additional studies are needed to address whether *in situ* population maintenance is more important than immigration in urban trees that are located close to protected forest patches.

The prediction that the relative proportion of acorns infested by moth larvae would be higher in isolated trees than in forest trees was not supported by our data. This hypothesis was based on reports of *Cydia pomella* and *C. fagiglandana* being capable of large flight distances, while curculionids are considered low-mobility predators [49,50]. Although differences in dispersal ability among species of *Curculio* have been reported [51], at present it is not known how significant unusually long travelling distances (displayed by a few individuals and recorded in experimental devices) are for population persistence. In this study, the relative proportions of both types of larvae were affected by oak species, but not by tree location.

Preference for an oak species has been documented in weevils [52], but to our knowledge this is the first time that moth preferences have been found. The probability of predation of *Quercus castanea* acorns by moths was five times larger than the same probability for *Q. rugosa* acorns (means 0.366 and 0.070, respectively). These figures were calculated by including only infested acorns, so proportions are higher than those reported when considering the whole acorn sample.

Our results show that weevil predation is affected by oak species and acorn size (Table 3). The higher weevil predation of acorns of *Q. rugosa* than those of *Q. castanea* (23.3% and 10.2%, respectively) is partially explained by the larger acorns of the former species. Espelta et al. (2009) [52] also found that an oak species with larger acorns experienced stronger predation by *Curculio* larvae than another species with smaller acorns. Moreover, a previous study including three oak species in the study area showed higher acorn predation by weevils in the two large-seeded species (*Q. rugosa* and *Q. obtusata*), and higher super-

infestation (i.e., presence of more than one larva) in *Q. obtusata*, the species having the largest acorns [53].

Our third hypothesis—namely that moth larvae would increase with seed size, as is the case with weevils—was not supported. Our results pointed to seed predation by these insects being a random process, since it was not affected by seed size or tree species. This result conflicts with our previous finding that predation probability by moth larvae was significantly higher in *Quercus castanea* than in *Q. rugosa*. We believe that the probability estimation is more solid in the first analysis, since, in this last one, sample size was very low; it included only 46 acorns (4.7% out of 978) with evidence of predation by moth larvae, whereas the rest of them were undamaged. This renders an unbalanced, less robust, model than that used in the first analysis. The absence of a positive relationship between seed predation by moths and seed size conflicts with results from Mezquida et al. (2021) [24], who found that moths preferred *Quercus faginea* trees producing larger acorns in one year, and the following year they preferred trees producing larger acorns when the incidence of weevils was low. In their study, moth larvae were much more abundant (>15% of the acorns) than in this case. However, they did not find a relationship between the number of moth larvae and acorn mass. More research is needed on the relationship between acorn size and moth predation before generalizations can be made regarding their presence, and relative importance, in various oak species. Abundances of the different species whose larvae feed on acorns vary across years and in response to acorn production (including mast years, [24,54]). Thus, long term studies are needed to quantify variation in populations of the different species, and to establish clear trends in insect feeding preferences.

As reported in studies with other *Quercus* species, predation probability of weevils increased with seed size in *Q. rugosa*. However, in *Q. castanea*, this probability had a slight tendency to decrease with seed size. This was unexpected and at present it is not possible to draw conclusions from this result. Factors not analyzed in this study, such as differences in phenology among oak species, diversity of weevil species, or variation in tannin concentration in acorns of different oak species, may affect acorn predation by these insects [55]. Our field observations showed a later fructification in *Q. castanea* than in *Q. rugosa*, but it is not known how weevil abundance changed through the fruit development period. Furthermore, at present, it is unknown how many species of Curculionidae are found in the oak forests of the basin of Mexico. Unpublished research by our group points to the presence of various species in other oak species in the Ajusco-Chichinautzin mountain range. High diversity of acorn weevils, and variation in host specificity, have been reported in a high oak diversity region in China [26], and it has also been shown that tropical weevil species are highly specialized, and larval body size is highly correlated with size of the infested acorns [25]. A similar pattern could be present in the oak forests of Mexico, which harbor the highest diversity of *Quercus* species in America [56]. Future research on diversity and ecology of weevil species of the oak forests of central Mexico will help to refine these results.

Author Contributions: Conceptualization and methodology C.B.; investigation H.D.-G. and C.B.; data curation H.D.-G.; formal analysis E.J.G., H.D.-G. and C.B.; writing—original draft preparation C.B. and H.D.-G.; writing—review and editing C.B. and E.J.G.; funding acquisition C.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by program UNAM-DGAPA-PAPIIT IN218815 and Facultad de Ciencias, UNAM.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are openly available in FigShare at DOI 10.6084/m9.figshare.19670724.

Acknowledgments: Bruno Barrales helped during field work; the staff of Centro de Educación Ambiental Ecoguardas provided facilities for seed sampling.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Manning, A.D.; Fischer, J.; Lindenmayer, D.B. Scattered trees are keystone structures—implications for conservation. *Biol. Conserv.* **2006**, *132*, 311–321. [[CrossRef](#)]
- Dunn, R.R. Isolated trees as foci of diversity in active and fallow fields. *Biol. Conserv.* **2000**, *95*, 317–321. [[CrossRef](#)]
- Laborde, J.; Guevara, S.; Sánchez-Ríos, G. Tree and shrub seed dispersal in pastures: The importance of rainforest trees outside forest fragments. *Ecoscience* **2008**, *15*, 6–16. [[CrossRef](#)]
- Cadavid-Florez, L.; Laborde, J.; Mclean, D.J. Isolated trees and small woody patches greatly contribute to connectivity in highly fragmented tropical landscapes. *Landsc. Urban Plan.* **2020**, *196*, 103745. [[CrossRef](#)]
- Nowak, D.J.; Crane, D.E. Carbon storage and sequestration by urban trees in the USA. *Environ. Pollut.* **2002**, *116*, 381–389. [[CrossRef](#)]
- Nowak, D.J.; Crane, D.E.; Stevens, J.C. Air pollution removal by urban trees and shrubs in the United States. *Urban For. Urban Green.* **2006**, *4*, 115–123. [[CrossRef](#)]
- Grote, R.; Samson, R.; Alonso, R.; Amorim, J.H.; Cariñanos, P.; Churkina, G.C.; Calfapietra, C. Functional traits of urban trees: Air pollution mitigation potential. *Front. Ecol. Environ.* **2016**, *14*, 543–550. [[CrossRef](#)]
- Georgi, N.J.; Zafiriadis, K. The impact of park trees on microclimate in urban areas. *Urban Ecosyst.* **2006**, *9*, 195–209. [[CrossRef](#)]
- Linden, J.; Fonti, P.; Esper, J. Temporal variations in microclimate cooling induced by urban trees in Mainz, Germany. *Urban For. Urban Green.* **2016**, *20*, 198–209. [[CrossRef](#)]
- Galindo-González, J.; Guevara, S.; Sosa, V.J. Bat-and bird-generated seed rains at isolated trees in pastures in a tropical rainforest. *Conserv. Biol.* **2000**, *14*, 1693–1703. [[CrossRef](#)]
- Fischer, J.; Lindenmayer, D.B. The conservation value of paddock trees for birds in a variegated landscape in southern New South Wales. 1. Species composition and site occupancy patterns. *Biodivers. Conserv.* **2002**, *11*, 807–832. [[CrossRef](#)]
- Lumsden, L.F.; Bennett, A.F. Scattered trees in rural landscapes: Foraging habitat for insectivorous bats in south-eastern Australia. *Biol. Conserv.* **2005**, *122*, 205–222. [[CrossRef](#)]
- Helden, A.J.; Stamp, G.C.; Leather, S.R. Urban biodiversity: Comparison of insect assemblages on native and non-native trees. *Urban Ecosyst.* **2012**, *15*, 611–624. [[CrossRef](#)]
- McIntyre, N.E. Ecology of urban arthropods: A review and a call to action. *Ann. Entomol. Soc. Am.* **2000**, *93*, 825–835. [[CrossRef](#)]
- Kennedy, C.E.J.; Southwood, T.R.E. The number of species of insects associated with British trees: A re-analysis. *J. Anim. Ecol.* **1984**, *53*, 455–478. [[CrossRef](#)]
- Southwood, T.R.E.; Wint, G.W.; Kennedy, C.E.; Greenwood, S.R. Seasonality abundance, species richness and specificity of the phytophagous guild of insects on oak (*Quercus*) canopies. *Eur. J. Entomol.* **2004**, *101*, 43–50. [[CrossRef](#)]
- Tovar-Sánchez, E.; Cano-Santana, Z.; Oyama, K. Canopy arthropod communities on Mexican oaks at sites with different disturbance regimes. *Biol. Conserv.* **2004**, *115*, 79–87. [[CrossRef](#)]
- Valencia-Cuevas, L.; Tovar-Sánchez, E. Oak canopy arthropod communities: Which factors shape its structure? *Rev. Chil. de Hist. Nat.* **2015**, *88*, 15. [[CrossRef](#)]
- Bonal, R.; Muñoz, A. Seed weevils living on the edge: Pressures and conflicts over body size in the endoparasitic *Curculio* larvae. *Ecol. Entomol.* **2009**, *34*, 304–309. [[CrossRef](#)]
- Yi, X.F.; Yang, Y.Q. Large acorns benefit seedling recruitment by satiating weevil larvae in *Quercus aliena*. *Plant Ecol.* **2010**, *209*, 291–300. [[CrossRef](#)]
- Bonal, R.; Espelta, J.M.; Vogler, A. Complex selection on life-history traits and the maintenance of variation in exaggerated rostrum length in acorn weevils. *Oecologia* **2011**, *167*, 1053–1061. [[CrossRef](#)] [[PubMed](#)]
- Bonal, R.; Hernández, M.O.; Muñoz, A.; Espelta, J.M. Positive cascade effects of forest fragmentation on acorn weevils mediated by seed size enlargement. *Insect Conserv. Divers.* **2012**, *5*, 381–388. [[CrossRef](#)]
- Bonal, R.; Espelta, J.M.; Muñoz, A.; Ortego, J.; Aparicio, J.M.; Gaddis, K.; Sork, V.L. Diversity in insect seed parasite guilds at large geographical scale: The roles of host specificity and spatial distance. *J. Biogeogr.* **2016**, *43*, 1620–1630. [[CrossRef](#)]
- Mezquida, E.T.; Caputo, P.; Acebes, P. Acorn crop, seed size and chemical defenses determine the performance of specialized insect predators and reproductive output in a Mediterranean oak. *Insects* **2021**, *12*, 721. [[CrossRef](#)] [[PubMed](#)]
- Peguero, G.; Bonal, R.; Sol, D.; Muñoz, A.; Sork, V.L.; Espelta, J.M. Tropical insect diversity: Evidence of greater host specialization in seed-feeding weevils. *Ecology* **2017**, *98*, 2180–2190. [[CrossRef](#)] [[PubMed](#)]
- Li, Q.Y.; Hu, X.H.; Liu, D.C.; Ouyang, A.; Tong, X.; Wang, Y.J.; Chen, X.Y. High diversity and strong variation in host specificity of seed parasitic acorn weevils. *Insect Conserv. Divers.* **2021**, *14*, 367–376. [[CrossRef](#)]
- Carrillo-Trueba, C. *El Pedregal de San Ángel*, 1st ed.; Universidad Nacional Autónoma de México: Mexico City, Mexico, 1995; p. 177.
- Palma, M.; Cram, S.; Bocco, G.; Velázquez, A. Caracterización abiótica de la región de la montaña del sur de la Cuenca de México. In *Biodiversidad de la cuenca de México*; Universidad Autónoma Metropolitana: Mexico City, Mexico, 1999.
- Bonfil, C.; Soberón, J. *Quercus rugosa* seedling dynamics in relation to its re-introduction in a disturbed Mexican landscape. *Appl. Veg. Sci.* **1999**, *2*, 189–200. [[CrossRef](#)]

30. González-Hidalgo, B.; Orozco-Segovia, A.; Diego-Pérez, N. La vegetación de la reserva ecológica Lomas del Seminario, Ajusco, México. *Bol. Soc. Bot. Mex.* **2001**, *69*, 77–99. [[CrossRef](#)]
31. Cano-Zantana, Z.; Pisanty, I.; Segura, S.; Mendoza-Hernández, P.E.; Martínez-Ballesté, A. Ecología, conservación, restauración y manejo de áreas naturales y protegidas del Pedregal del Xitle. In *Manejo, Conservación y Restauración de Recursos Naturales en México*; Oyama, K., Castillo, A., Eds.; Universidad Nacional Autónoma de México and Siglo XXI: Mexico City, Mexico, 2006; pp. 203–226.
32. Rohlf, D.A. A Study of Acorn Feeding Insects: Filbert Weevil (*Curculio occidentalis* (Casey)) and Filbertworm (*Cydia latiferreana* (Walsingham)) on Garry Oak (*Quercus garryana* (Dougl.) in the Southeastern Vancouver Island Area. Master's Thesis, Faculty of Graduate Studies, University of British Columbia, Vancouver, BC, Canada, April 1999.
33. Lewis, V.R. Within-Tree Distribution of Acorns Infested by *Curculio occidentalis* (Coleoptera: Curculionidae) and *Cydia latiferreana* (Lepidoptera: Tortricidae) on the Coast Live Oak. *Environ. Entomol.* **1992**, *21*, 975–982. [[CrossRef](#)]
34. Jiménez, A.; Soria, F.; Villagrán, M. Seguimiento del ciclo biológico de *Cydia fagiglandana* (Zeller) (Lepidoptera: Tortricidae) en un encinar del sur de España. *Boletín De Sanid. Veg. Plagas* **2006**, *32*, 157–168.
35. Ganhao, E.; Siva Dias, L. Seed volume dataset—An ongoing inventory of seed size expressed by volume. *Data* **2019**, *4*, 61. [[CrossRef](#)]
36. Bates, D.; Maechler, B.; Bolker, B.M.; Walker, S. Fitting linear mixed-effects models using lme4. *J. Stat. Softw.* **2015**, *67*, 1–48. [[CrossRef](#)]
37. Trexler, J.C.; Travis, J. Nontraditional regression analyses. *Ecology* **1993**, *74*, 1629–1637. [[CrossRef](#)]
38. Santos, T.; Tellería, J. Pérdida y fragmentación de hábitat: Efecto sobre la conservación de las especies. *Ecosistemas* **2006**, *15*, 3–12.
39. Fernández-Juricic, E. Bird community composition patterns in urban parks of Madrid: The role of age, size and isolation. *Ecol. Res.* **2000**, *15*, 373–383. [[CrossRef](#)]
40. Burghardt, K.T.; Tallamy, D.W.; Gregory Shriver, W. Impact of native plants on bird and butterfly biodiversity in suburban landscapes. *Conserv. Biol.* **2009**, *23*, 219–224. [[CrossRef](#)]
41. MacGregor-Fors, I.; Escobar-Ibáñez, J.F.; Schondube, J.E.; Zuria, I.; Ortega-Álvarez, R.; Sosa-López, J.R.; Vega-Rivera, J.H. The urban contrast: A nationwide assessment of avian diversity in Mexican cities. *Sci. Total Environ.* **2021**, *753*, 141915. [[CrossRef](#)]
42. Helden, A.J.; Leather, S.R. Biodiversity on urban roundabouts—Hemiptera, management and the species–area relationship. *Basic Appl. Ecol.* **2004**, *5*, 367–377. [[CrossRef](#)]
43. Soria, F.; Jiménez, A.; Villagrán, M.; Ocete, M. Influencia de la infestación de *Cydia fagiglandana* (Zeller) (Lepidoptera:Tortricidae) en la caída del fruto de la encina. *Boletín de Sanid. Veg. Plagas* **2002**, *28*, 213–216.
44. Debouzie, E.; Desouhant, E.; Oberli, F.; Menu, F. Resource limitation in natural populations of phytophagous insects. A long-term study case with the chestnut weevil. *Acta Oecol.* **2002**, *23*, 31–39. [[CrossRef](#)]
45. Debouzie, D.; Heizmann, A.; Desouhant, E.; Menu, F. Interference at several temporal and spatial scales between two chestnut insects. *Oecologia* **1996**, *108*, 151–158. [[CrossRef](#)] [[PubMed](#)]
46. Chacoff, N.; Morales, J.Y.; Vaquera, M. Efectos de la fragmentación sobre la aborción y depredación de semillas en el Chaco Serrano. *Biotropica* **2004**, *36*, 109–117. [[CrossRef](#)]
47. Savilaakso, S.; Koivisto, J.; Veteli, T.; Roininen, H. Microclimate and tree community linked to differences in lepidopteran larval communities, between forest fragments and continuous forest. *Divers. Distrib.* **2009**, *15*, 356–365. [[CrossRef](#)]
48. Morán-López, T.; Forner, A.; Flores-Rentería, D.; Díaz, M.; Valladares, F. Some positive effects of the fragmentation of holm oak forests: Attenuation of water stress and enhancement of acorn production. *For. Ecol. Manag.* **2016**, *370*, 22–30. [[CrossRef](#)]
49. Schumacher, P.; Weyeneth, A.; Weber, D.; Dorn, S. Long flights in *Cydia pomonella* L. (Lepidoptera:Tortricidae) measured by a flight mill: Influence of sex, mated status and age. *Physiol. Entomol.* **1997**, *22*, 149–160. [[CrossRef](#)]
50. Díaz, M. Distribución del arbolado y persistencia a largo plazo de las dehesas: Patrones y procesos. *Rev. Ecosistemas* **2014**, *23*, 5–12. [[CrossRef](#)]
51. Pélisson, P.F.; Bernstein, C.; Debias, F.; Menu, F.; Venner, S. Dispersal and dormancy strategies among insect species competing for a pulsed resource. *Ecol. Entomol.* **2013**, *38*, 470–477. [[CrossRef](#)]
52. Espelta, J.M.; Bonal, R.; Sánchez-Humanes, B. Pre-dispersal acorn predation in mixed oak forests: Interspecific differences are driven by the interplay among seed phenology, seed size and predator size. *J. Ecol.* **2009**, *97*, 1416–1423. [[CrossRef](#)]
53. Díaz-Guzmán, H.; Bonfil, C. Depredación y dispersión en tres especies de *Quercus* del pie de monte del Ajusco. *Rev. Mex. de Biodivers.* **2020**, *91*, e91.3242. [[CrossRef](#)]
54. Pérez-Ramos, I.M.; García de la Cruz, Y.; Gómez-Aparicio, L. Contrasting responses of insects and vertebrates as seed consumers in two neotropical oak species: The interactive effects of individual crop size and seed mass. *For. Ecol. Manag.* **2017**, *401*, 99–106. [[CrossRef](#)]
55. Weckerly, F.W.; Sugg, D.W.; Semlitsch, R.D. Germination success of acorns (*Quercus*): Insect predation and tannins. *Can. J. For. Res.* **1989**, *19*, 811–815. [[CrossRef](#)]
56. Valencia, S. Diversidad del género *Quercus* (Fagaceae) en México. *Boletín de La Soc. Botánica De México* **2004**, *75*, 33–53. [[CrossRef](#)]