Forest Habitat Variables Predict Detection and Elevation Predicts Occupancy of *Rhaphidophoridae*

by

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ABSTRACT

The wide-spread use of insecticides has contributed to the rapid decline of insect diversity and abundance. In light of recent guidance from international and governmental organizations, other non-chemical control methods are necessary to control insect pest populations. In my study, I used occupancy modeling techniques and found that environmental variables could predict the presence of *Rhaphidophoridae,* in Hidalgo, Mexico. The results showed that variables associated with forested habitats increase the probability of *Rhaphidophoridae* detection, and higher elevation increases the probability of *Rhaphidophoridae* occupancy. Understanding the specific habitat variables associated with human detection and occupancy of *Rhaphidophoridae* give people the ability to utilize the Integrative Pest Management (IPM) strategy of cultural control to prevent *Rhaphidophoridae* pest populations in my study region.

ACKNOWLEDGMENTS

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INTRODUCTION

Overview and Purpose of Study

Climate change, driven by economic growth and anthropogenic disturbance, is no longer a problem for the future, but a crisis of the present (Caro et al., 2022; Habibullah et al., 2022; Rosales, 2008; Santer et al., 2003). As we turn our focus from how do we prevent a climate crisis to how do we mitigate the impacts of climate change and preserve biodiversity and ecosystem services, we are faced with the realization that a multidisciplinary approach shows the most promise (Amolegbe et al., 2022; Schipper, Dubash, & Mulugetta, 2021; Zayan, 2019). It is exceedingly unlikely that one strategy or area of research will be able to solve the current climate change crisis (Burroughs, 2007; Grasso & Markowitz, 2015; Falardeau & Bennett, 2019; Middleton, 2011; Urban, 2015). In 2018, the Intergovernmental Panel on Climate Change issued a special report on the problems that governments, researchers, and the public face if global climate temperatures rise 1.5°C above pre-industrial levels (IPCC, 2018). In this report, the IPCC also discussed how climate change could impact pest control by decoupling prey and predator species due to habitat degradation, reducing pollinator populations, and greatly limiting seed dispersal (IPCC, 2018). Insects comprise approximately 80% of named life on the planet with an estimated total of 1 million insect species named and 80% that remain to be discovered (Baillie et al., 2012; Scheffers et al., 2012; Stork, 2018). However, insect species have seen a significant decline in biodiversity due to factors related to climate change, wide-spread use of pesticides, and other anthropogenic disturbances (Harvey et al., 2023). Invertebrate species are less studied and less understood than vertebrate species, even though Hexapoda make up approximately two-thirds of all terrestrial biomass on the planet (Bánki et al., 2021; Eggleton, 2020; Rosenburg et al., 2023). Despite this gap in the literature, arthropods play a crucial role in ecosystems and ecosystem services. Insects are the primary food source of many terrestrial species, including but not limited to many birds, reptiles, amphibians, and small mammals, and they are the most common pollinator of most angiosperms and agricultural crops (Forister et al., 2019; Noriega et al., 2018).

While insect biodiversity loss may seem significant to conservationists and wildlife biologists, the importance of protecting biodiversity is often juxtaposed against economic and agricultural needs (Kremen & Chaplin-Kramer, 2007; Onstad & Crain, 2019; Samways et al., 2020). Arthropods that have been identified as economic pests can cause significant monetary losses. Researchers have estimated that worldwide 10-16% of agricultural yields are lost before harvest due to insect pests (Bradshaw et al., 2016; Dhawan, 2019). Diamondback moth management alone is estimated to cost 4 to 5 billion USD, per year, globally (Zalucki et al., 2012). At the same time, climate change is also impacting viability and output of economically significant crops, and food scarcity is an urgent issue in many developing areas around the world. Using the most severe climate change models, scientists predict a 7-23% crop yield loss due to growing extremes in climate conditions (Rezaei et al., 2023). Insect pests also can negatively impact the balance of ecosystems, which may require the use of control methods (Boyd, 2013). The need to balance both immediate economic and humanitarian needs with environmental priorities is a critical field of research (Gvozdenac et al., 2022; Ovawanda, Witjaksono, & Trisyono, 2016).

For my study, I wanted to determine if I could predict the presence or absence of an insect that is currently identified as a nuisance pest, not generally considered agriculturally detrimental, not a vector of disease, but is the subject of chemical control. The risks of broad-spectrum pesticide have been known for quite some time, many emerging countries are still struggling with environmental and health consequences as a result of broad-spectrum pesticide use (Konradsen et al., 2003; Sarkar et al., 2021). Currently, the Mexican government still authorizes the use of many insecticides that have been classified as Persistent Organic Pollutants (POPs) by the Stockholm Convention resulting in adverse health and environmental impacts such as unintended poisonings, pollution of drinking water sources and aquatic habitats, ecosystem degradation, and biodiversity loss (Cortez, 2023; FAO and WHO, 2022; Martínez et al., 2022; OECD, 2013; Salas, Duran & Wiener, 2000). Pesticide use often impacts vulnerable communities (Garcia, 2021; Payán-Rentería et al., 2012; Wright, 1986). However, the use of Integrated Pest Management (IPM) principles has the ability to bridge the gap between human economic needs and the health and safety of people and the environment (Muneret et al., 2018).

In response to the risks associated with chemical control, IPM and IPM principles were introduced as a more environmentally conscious alternative before resorting to pesticide use (Ehler, 2006; Koppenhöfer et al., 2013). In 1972, IPM officially became accepted terms within the scientific community (El-Shafie, 2018; Kogan, 1998). IPM is a multidisciplinary approach and combines knowledge and practices from many different areas of study (Dara, 2019; Lamichhane, 2016). However, historically, pest control practices have been a tumultuous field (Bergvinson, 2004; Bueno et al., 2021; Deguine et al., 2021; Zalucki, Adamson & Furlong, 2009). In the United States and Canada, pest management has relied heavily on a western perspective and has historically excluded Indigenous and traditional pest management strategies (Allen et al., 2014). While the official IPM name didn't make it into the scientific literature until the 1970s, Indigenous populations have employed integrated pest management strategies for thousands of years (Allen et al., 2014; Kogan, 1998; Rathore et al., 2021; Tesfahun, Bayu & Tesfaye, 2000). IPM is a multi-tiered approach to pest management with chemical control being used as a last resort. Cultural control is the first line of defense in IPM. Cultural control is designed to create an environment that is less suitable for a particular pest. Understanding the environmental variables that predict the presence or absence of a pest can reduce the need for use of pesticides needed to control a pest population (Bajwa & Kogan, 2004; Vreysen et al., 2007; Barzman et al., 2015).

I wanted to identify an insect that not only was the subject of chemical control, but also an insect that could also possibly be controlled through the IPM principle of cultural control, reducing the amount of chemical control needed, while also not increasing stress on agricultural practices or human health. I identified *Rhaphidophoridae* as an insect family that meets these criteria for our study. *Rhaphidophoridae* can be considered a nuisance, living in basements of homes in suburban areas, drains, sewers, and wells (Allegrucci, Todisco & Sbordoni, 2005). These insects are omnivorous, but they are not generally considered to cause significant agricultural damage or be a human disease vector (Gorochov, 2010; Hubbell & Norton 1978). Occupancy modeling is a statistical tool that allows researchers to estimate the probability of an organism's occurrence among sampled sites, while also considering environmental variables such as habitat, vegetation, disturbance, etc. that are thought to influence the organism's occurrence among sampled sites. Occupancy modeling also takes into consideration imperfect detection (MacKenzie et al., 2017). Using occupancy modeling my study aimed at finding environmental variables that could be controllable through IPM practices and can predict the presence of *Rhaphidophoridae* in the environment. Based off of previous studies of *Rhaphidophoridae* in other regions, I hypothesized that leaf litter and herbaceous plants would predict the occupancy or detection of *Rhaphidophoridae* in the study region (Taylor, Krejca & Denight, 2005).

METHODS AND MATERIALS

Study Area

We conducted fieldwork for this study from mid-May to mid-June 2023, as part of a larger study focused on identifying habitat factors relevant to *Sceloporu*s lizard species (Flores et al., 2023). The study region was in central-eastern Mexico in the Sierra Madre Oriental Mountain range. The region hosts abundant biodiversity and comprises of a wide range of landscapes ranging from deserts to tropical broadleaf forests where pine-oak forests dominated most of the study region (Villaseñor & Ortiz, 2022). We selected 75 one-hectare sites, and the site locations extended in a spoke-like fashion around the town of Calnali in the state of Hidalgo (Figure 1 & 2). Each site was a minimum of 1 km distance from any other site to ensure the independence of each site. We selected the sites to include a wide range of environmental variables and habitat characteristics. The elevation of the sites ranged from 111 to 2,181 meters above sea level.

Habitat Surveys

The fieldwork team visited approximately four sites each day over the course of the month. The number of sites visited each day depended on the distance between sites, terrain, and weather variables. A wide range of weather conditions occurred during site visits. However, we did not collect data during periods of thunderstorms and heavy precipitation because of the low likelihood of locating or detecting *Sceloporus* lizard species. The field crew team walked quietly to the center of the site to attempt to not disturb local wildlife. We then determined the center of the site with a rangefinder. At each center point, I used a 4 in 1 environmental meter to measure air temperature (°C), relative humidity (%), wind speed (m/s), and light (LUX). I also recorded percentage of site disturbance, type of disturbance, time of day, location of the site, type of terrain, and other notable features. I calculated the percentage of site disturbance based on the level of observed human development such as agricultural development, trails, roads, human-made structures, or any time of anthropogenic disturbance.

We conducted habitat surveys for each site. Each observer began at a start point and recorded habitat variables at two random points along their transect. Recorded habitat variables included vegetation cover, ground cover, tree cover height and diameter, and leaf litter depth. The height and circumference of these habitat variables were measured by the six field crew members, at two random points each, in the site using a measuring tape and range finder. Vegetation cover was classified as either tree, shrub, or herbaceous plant cover. We considered ground cover to be anything covering the bare soil surface, such as grass, gravel (0.2-25.6 cm), rock, cement, woody debris, and leaf litter.

Insect Collection and Identification

I used pitfall trap data for our *Rhaphidophoridae* occupancy modeling. The fieldwork team placed four pitfalls at each site, on the outermost corners of the one-hectare site. Due to the topography, the one-hectare site areas were not always consistent in shape or side measurements. However, traps placed in this fashion reduced bias when attempting to identify the insect abundance and diversity of the site. Some accommodations were made in trap placement to reduce disturbance from livestock or to take into account site features, such as streams, man-made structures, and cliff faces. In these instances, we placed the trap as close to the correct placement as possible.

The pitfall traps consisted of a 500 mL white plastic cup with a 10 cm opening placed flush with the ground. The pitfall traps also had a lid made from a 16 cm plastic plate with four plastic legs. The lid was placed approximately 2.5 – 3 cm above the substrate to prevent bycatch. The pitfall trap contained a detergent solution. I recorded the time of placement and picked up the traps approximately 24-hours later after we had placed pitfalls and collected the habitat data for our planned sites for the day. Once the pitfall traps were collected, I put the contents in an ethanol solution for preservation. I collected the traps even if weather conditions were poor and recorded any trap disturbance or loss. The most common cause of trap disturbance was either weather or livestock related. In July 2023, we identified insect specimens collected during field season with the assistance of entomologists at the collections department at the Universidad Nacional Autónoma de México (UNAM).

Data Analysis

The species-occupancy modeling I used for this study contains two distinct sub-models with one model being a function of site-level covariates and the other model representing detection probability. To determine significant environmental characteristics of the study sites, I began by running a principal component analysis (PCA) in R v4.3.1 (R Core Team, 2023). The environmental variables that the fieldwork team collected in the field included elevation, disturbance, refuges, tree height, tree cover, shrub cover, herbaceous plant cover, and litter depth (Table 2). I excluded soil density and tree diameter due to missing data points. Including these data would reduce the number of sites included in my analysis. I ran PCAs to identify correlated habitat variables and to combine these correlated variables into individual Principal Components (PCs) for use in our occupancy-modeling analysis (Figure 5). I then standardized each habitat variable to a mean of 0 and a variance of 1. I included variables that were highly correlated with a correlation coefficient greater than 0.5 in value in our PC (MacKenzie, 2017).

I then used the R package Unmarked (v1. 0.1; Fiske & Chandler, 2011) to identify environmental variables that predict the presence of *Rhaphidophoridae* at our study sites. I was interested in estimating both detection probability (p) and occupancy probability (ψ) of *Rhaphidophoridae* by running single-species and single-sampling-season occupancy models. I recorded data from each of the four traps as independent observations at each site (Fiske & Chandler, 2011). For the response variable, I recorded either zeroes and ones with “0” indicating a member of the *Rhaphidophoridae* family did not appear in the pit-fall trap, or a “1”, indicating that they were detected and later identified as a member of this family from the traps at each site. I found

Rhaphidophoridae at a total of 33 out of 75 of our study sites. I ran models for only detection, only occupancy, and both detection and occupancy combined, as well as a model for the null. I ran a total of sixteen models to take into consideration all relevant possibilities of our habitat and vegetation variables, in regard to detection and occupancy predictors. After running our models, I selected the model with the smallest Akaike information criterion (AIC) score as the best-fit model (MacKenzie, 2017).

RESULTS

Principal Component Analysis

The principal component analysis reduced the eight habitat variables into two principal components that described the variation across sites. I found that only two principal components had eigenvalues greater than one and together described 62% of the inter-site variation (Table 1). PC1 included 7 of the variables: negative site disturbance, negative herbaceous plant cover, positive tree cover, shrub cover, average tree height, leaf litter depth, and refuges. Positive values of PC1, therefore, represent less disturbed areas that are forested. Only a single habitat variable, elevation, loaded strongly on PC2. Because elevation was the only variable of interest in PC2, I instead used negative elevation as a single variable in my occupancy modeling analysis (Figure 5).

Species Occupancy Modeling

Using the PC1 and Elevation variables, I ran 16 occupancy models and found that several models fit better than our null model. Three models fit particularly well: (1) PC1 plus elevation as predictors of detection with elevation as a predictor of occupancy; (2) PC1 plus elevation as predictors of both detection and occupancy; and (3) PC1 as a predictor of detection and elevation as a predictor of occupancy (Table 2; Figure 3a, 3b, 4a). I concluded that the best supported model was the third model, because it was within two ΔAICc units of the top model and was the simplest model. The third model showed that variables associated with forested areas predicted that the insects would fall into the pitfall traps in the sampled sites, disturbance and herbaceous plant cover were negatively correlated with detection, and elevation above 1,000 meters above sea level predicts the occupancy of *Rhaphidophoridae* (Table 2; df = 4, AICc = 324.57, $\Delta\mathrm{AICc} = 0.62$).

DISCUSSION AND CONCLUSION

Summary of Findings

The results of the best fitting occupancy model showed that habitat variables associated with forested areas predicted detection of *Rhaphidophoridae* at the study sites, and an increase in elevation above 1,000 meters above sea level predicted the occupancy of *Rhaphidophoridae.* Sites with less disturbance, higher elevation and tree canopy, shrubs, leaf litter, and refuges predicted if *Rhaphidophoridae* would fall into the pitfall traps at the study sites. I was surprised to discover that low herbaceous plants were negatively correlated with detection, as I hypothesized that herbaceous plant ground cover would aid in the insects falling into our pitfall traps. However, because herbaceous plants are negatively correlated with tree cover, it appears that tree canopy and leaf litter may be more important in detection of *Rhaphidophoridae.* This also may be due to the cooling effect that trees and forests have on the surrounding area. However, I did not include ground or ambient air temperature in our analysis, because only one temperature data point was taken during the day. Further studies may want to consider utilizing temperature data from an entire 24-hour period and utilize this variable in their occupancy models.

Detection: More Than a Nuisance Variable

Researchers have often considered detection variables in occupancy modeling to be nuisance variables (Karavarsamis, 2015; Richmond, Hines & Beissinger, 2010; Stewart et al., 2023). This is because many ecologists are primarily interested in the occupancy of organisms despite imperfect detection (MacKenzie et al., 2003; Guillera-Arroita, 2017). However, some researchers have begun using detection variables to look at human and organism interactions and, more specifically, removal of invasive or unwanted species. When knowledge of occupancy, or total eradication, are not the main priorities, but instead, control is the desired result, our detection rate does not need to be maximized. We only need to detect to the level of the desirable removal rate (Christy et al., 2010; Reynolds et al., 2010; Waldron et al., 2013). In this study, I was looking at a family of insects that are primarily targeted for insecticide use, because they are detected in homes or near manmade structures, and this detection is considered undesirable. If there is no detection, insecticides are not used. Detection in this study is therefore not a nuisance variable but just as important of a consideration as occupancy.

Implications for IPM

Common insect control methods include biological, mechanical, chemical, and cultural control methods. However, chemical control is an extremely common method of control due to ease of use, effectiveness, and cost (Dent & Binks, 2020; Pedigo, Rice, & Krell, 2021). The use of chemical control to regulate arthropod pest populations has a long history, and Dichlorodiphenyltrichloroethane (DDT) was one of the first widely used synthetic insecticides, an organochlorine pesticide, designed to control agricultural and disease vector pests (Morris, 2019). Rachel Carson wrote *Silent Spring* in 1962 sounding the alarm to the world about the havoc this insecticide was wreaking on the environment (Carson, 1996; Hajjar et al., 2023; Krebs, 1999). In 1972, the United States and many countries around the world banned DDT due to its harmful impact on biodiversity and the environment (Epstein, 2014; Morris, 2019; Turusov, 2002). However, even before DDT was banned, the scientific and agricultural community had recognized the indiscriminate use of insecticides as an environmental concern (Ehler, 2006). Researchers have recognized that organosynthetic pesticides, and other more recent insecticides, can cause insecticide resistance, resurgence of primary pests, increases of secondary pests, loss of biodiversity, risk environmental contamination, ecological degradation, and threats to human health (Brogdon & McAllister, 1998; Chagnon et al., 2015; Hemingway, Field & Vontas, 2002; Kogan, 1998; Pereira, 2009; Mew et al., 2004). Organophosphates (OPs), such as fenitrothion used in roach bait and phosmet, which is commonly used for controlling moth populations on fruit trees, were designed as hopeful alternatives to DDT and organochlorine insecticides (Adeyinka et al. 2023; Zaim & Guillet, 2002). However, OPs have also been shown to cause significant, poor health outcomes in humans and other vertebrates, even when exposed to small quantities (Iyer, Iken & Leon, 2015; Holstege & Baer 2004; Muzinic et al. 2018).

Research has shown that educating individuals on IPM practices to reduce nuisance pests has been effective (Lowe et al., 2019). In one study, researchers educated staff and residents in New York apartment buildings on IPM strategies with the goal of reducing cockroach populations (e.g. steam cleaning, closing food containers, and minimizing entry points for pests). At the end of the study, the IPM practices were more effective at reducing pests than traditional chemical control (Kass et al., 2009). While many of these strategies may seem simplistic, or like common sense, it is important to remember that many individuals have no education or knowledge on what may cause insect pests to infiltrate a space, thus resorting to chemical control. However, many IPM strategies can not only be effective but also be simple and cost effective. Education on preventative measures is crucial to IPM success, and further research into occupancy and detection variables is essential. Based on my study results, I would recommend that individuals wishing to reduce unwanted pests, such as *Rhaphidophoridae,* and live at elevations greater than 1000 meters above sea level, near forested environments, consider clearing a perimeter around their home of leaf litter, shrubs, and refuges that *Rhaphidophoridae* can use as shelter. Individuals may also want to consider building structures and homes away from tall trees and avoid planting tall trees and vegetation near their home.

One reason for why I found a significant difference in detection of *Rhaphidophoridae* in forested areas versus sites that had greater disturbance could be because chemical control was already being utilized in those sites. Many of the study sites were also agricultural fields and livestock pasture sites. Previous research has shown that livestock grazing areas significantly impact insect communities (Basto-Estrella et al., 2014; Debano, 2006; Fenster et al., 2021; Figueroa, Galicia & Suárez, 2022). Researchers in future studies should consider including study sites in areas that are known to be subject to chemical control. Occupancy models that include sites with known chemical control, and other sites with no chemical control, would potentially help tease out if the results of my study were due to forest habitat variables and elevation or due to insecticides already used in the area.

Time constraints also prevented me from identifying down to the species level of *Rhaphidophoridae* collected in our pitfall traps from the study site locations. However, while species level environmental occupancy would be an interest for future studies, species level occupancy knowledge is not necessary for the purpose of my study since pest identification and chemical application most often happens at the family level for this insect. *Rhaphidophoridae* habitat literature is sparse for this region of Mexico, and *Rhaphidophoridae* are a largely understudied group of insects. My study adds to the body of literature, for not only this insect family, but also contributes to occupancy and detection data that can be used for IPM methods and potentially reduce broad-spectrum pesticide use (Hegg, Morgan-Richards & Trewick, 2019).

Table 1. Rotated principal component results for all eight habitat variables: Loadings with an absolute value > 0.5 are considered high loading results. Only principal components with eigenvalues > 1 were included for detection and occupancy model analysis. Since elevation was the only high loading in PC2, it was analyzed separately during detection and occupancy model analysis.

Habitat Variables	PC1	PC2
Elevation	0.14	- 0.82
Disturbance	-0.68	0.22
Tree Cover	0.90	- 0.19
Shrub Cover	0.54	0.04
Herbaceous Plant Cover	- 0.76	- 0.39
Average Tree Height	0.81	- 0.23
Leaf Litter Depth	0.76	- 0.01
Refuges	0.63	0.49
Proportion Variance Explained (%)	47.24	14.99
Cumulative Variance Explained (%)	47.24	62.23
Eigenvalue (λ)	3.78	1.20

Table 2. 16 model results for detection (p), occupancy (ψ), AICc, ΔAICc, and null model

Model	df	AICc	ΔAICc	Weight
p(PC1 + Elevation)ψ(Elevation)	5	323.95	0.00	0.28133
p(PC1 + Elevation)ψ(PC1 + Elevation)	6	324.27	0.32	0.23983
p(PC1)ψ(Elevation)	4	324.57	0.62	0.20663
p(PC1)ψ(PC1 + Elevation)	5	326.27	2.32	0.08834
p(Elevation)ψ(PC1 + Elevation)	5	326.81	2.85	0.06757
p(.)ψ(PC1 + Elevation)	4	327.74	3.79	0.04231
p(.)ψ(Elevation)	3	328.29	4.33	0.03222
p(Elevation)ψ(Elevation)	4	328.29	4.34	0.03213
p(Elevation)ψ(.)	3	334.36	10.41	0.00154
p(PC1)ψ(.)	3	334.50	10.54	0.00145
p(Elevation)ψ(PC1)	4	334.68	10.73	0.00132
p(PC1 + Elevation)ψ(.)	4	334.74	10.79	0.00128
p(.)ψ(PC1)	3	334.86	10.91	0.00120
p(.)ψ(.)	2	334.89	10.93	0.00119
p(PC1)ψ(PC1)	4	335.41	11.46	0.00092
p(PC1 + Elevation)ψ(PC1)	5	335.79	11.84	0.00076

Figure 1. Map of study region in the Mexican State of Hidalgo

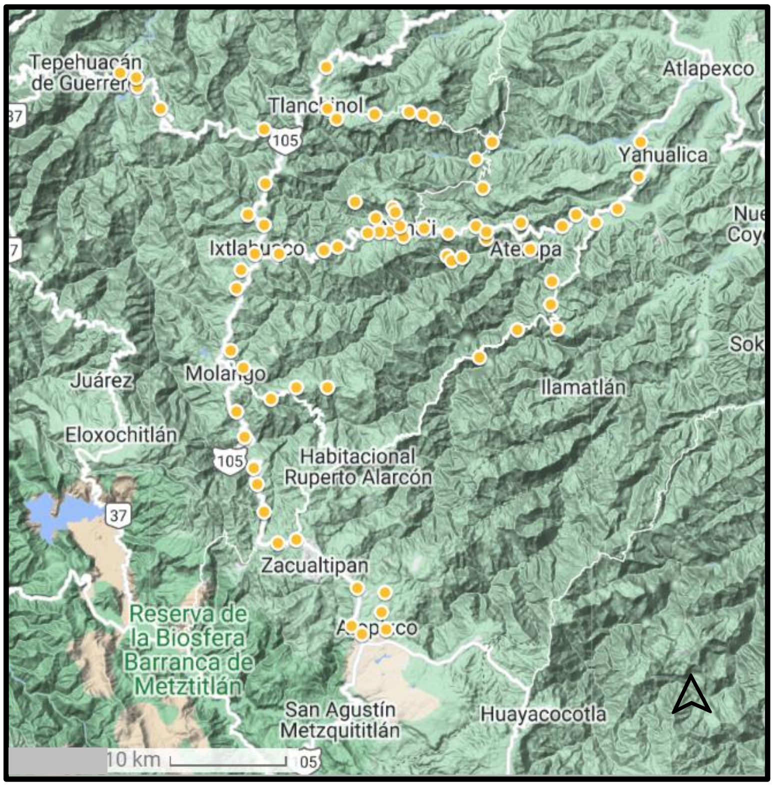

Figure 2. Map of 75 sites in the Mexican state of Hidalgo

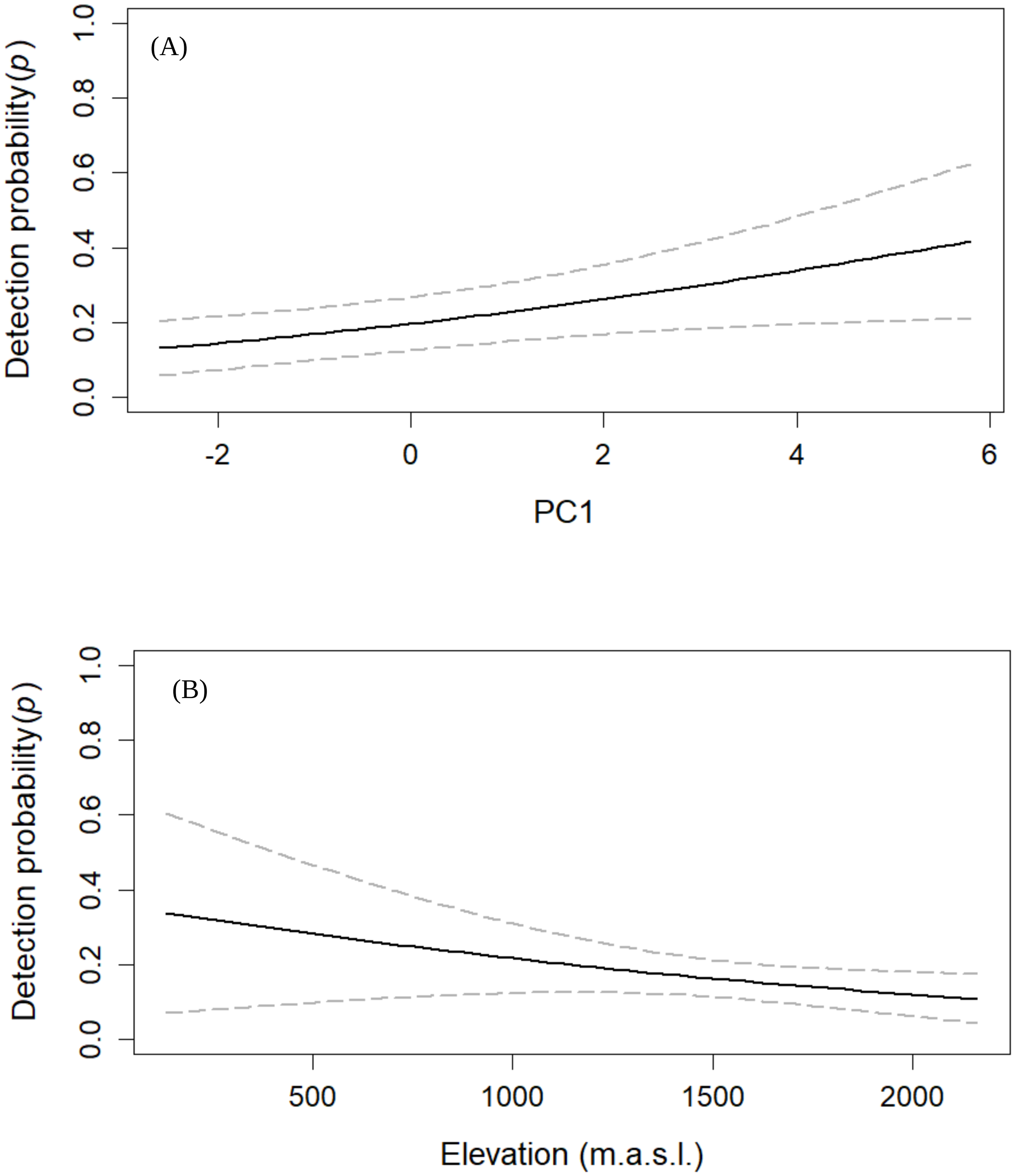

Figure 3. Best-fit detection model results, in standardized form, for *Rhaphidophoridae* detection: Elevation is shown in meters above sea level. The solid lines indicate the detection estimate, and the broken lines indicate the 95% CIs.

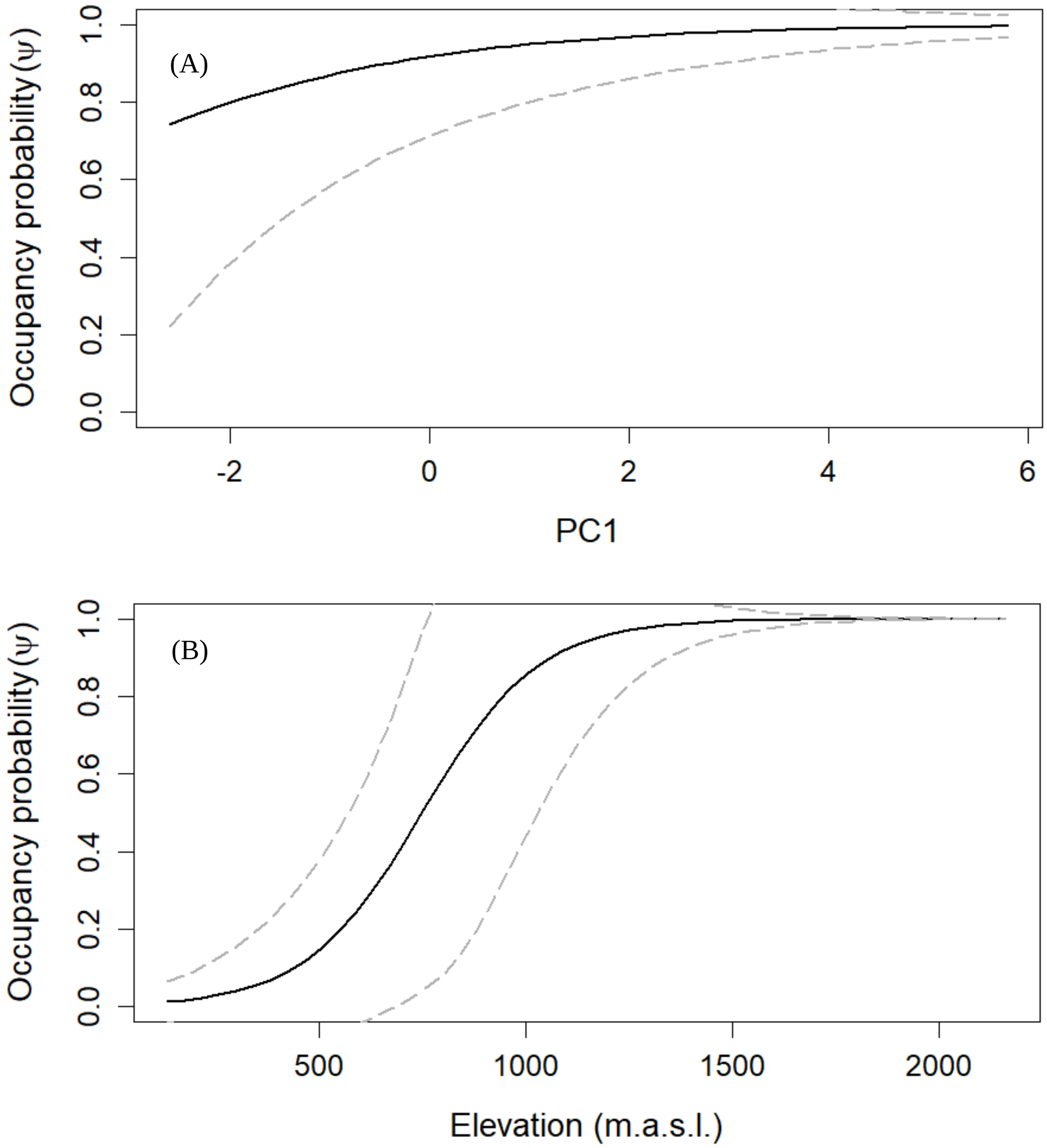

Figure 4. Best-fit occupancy model results, in standardized form, for *Rhaphidophoridae* occupancy: Elevation is shown in meters above sea level. The solid lines indicate the detection estimate, and the broken lines indicate the 95% CIs.

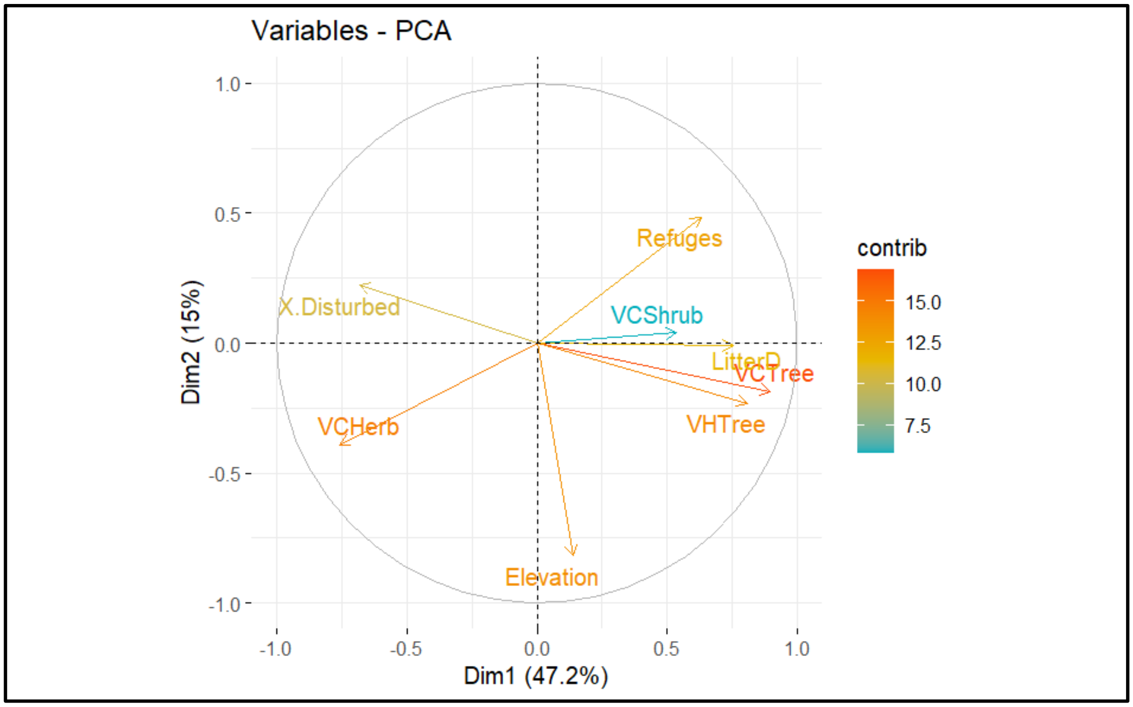

Figure 5. Loading plot shows how strongly each habitat variable influences the principal component analysis. Loadings closer to 1 or -1 indicate that the habitat variable strongly influences the PC. PC1 and PC2 loadings are on different axes. PC1 is represented by Dim1, and PC2 is represented by Dim2. We see that positive refuges, shrub cover, litter depth, tree height, tree cover, negative disturbance, and negative herb cover influence PC1. Negative elevation influences PC2. Vectors that have a small angle represent habitat variables that are positively correlated. Vectors closer to 180° are negatively correlated.

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