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HABITAT EFFECTS ON SCORPION DENSITIES AND MICROHABITAT USE BY CENTRUROIDES VITTATUS AND VAEJOVIS WAUERI IN SOUTH TEXAS

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A Thesis

by

JONATHAN BELTRAN

Submitted to Texas A&M International University
in partial fulfillment of the requirements
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MASTER OF SCIENCE

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ABSTRACT

Habitat Effects on Scorpion Densities and Microhabitat Use by *Centruroides vittatus* and *Vaejovis waueri* in South Texas (November 2022)

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Co-existence between *Centruroides vittatus* and *Vaejovis waueri* is influenced by environmental factors that shape their habitats. Differences in surface activity frequency between the two species suggest differential microhabitat use. The observed frequency of scorpions using microhabitats in the Martinez Ranch and La Union Ranch were not significantly different from the expected frequencies. Frequency of scorpions observed using microhabitats in La Union South was significantly different from the expected frequency ($P<0.001$). Microhabitat use of catclaw was lower than expected and higher than expected for other vegetation. Conditional comparisons of microhabitats were significantly different among habitats ($P<0.001$), size classes were significantly different among microhabitats ($P<0.001$), and size classes were significantly different among habitats ($P<0.01$). Microhabitat use by scorpions on the ground was higher among all habitats. Scorpion use of ground and grass were different among size classes. Size class I-II scorpions had a higher frequency than size class III. Scorpion density for *C. vittatus* was significantly different among habitats ($P<0.0001$) and scorpion density for *V. waueri* was significantly different among habitats ($P<0.0001$). *Centruroides vittatus* was significantly higher in the Martinez Ranch and in La Union South. *Vaejovis waueri* was significantly higher in La

Union South. Associations between plant densities and scorpion size classes were tested. Plant densities had a significant association with *C. vittatus* size classes I and II in the Martinez Ranch. Association between plants had a significant correlation with *C. vittatus* size classes I and IV in La Union Ranch. Association between plants had a significant correlation with *V. waueri's* total density. These associations may suggest plant densities may have a synergistic effect on scorpion densities. Soil type composition for the different habitats was hypothesized to influence scorpion densities. Maps for each site were created to show soil type compositions. Soil type findings suggest that La Union South had the soil types with the lowest soil strength. *Vaejovis waueri* was shown to have a higher density in La Union South where soils are sandier. Results indicate that co-existence between *C. vittatus* and *V. waueri* is possible because competition is low through minimal overlap in microhabitat use and intraguild predation avoidance.

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INTRODUCTION

The co-existence between scorpion species can occur when they have distinct habitat specializations and different prey preferences (Hadley and Williams 1968). Understanding the distinctions that influence scorpion densities are of important ecological significance when discerning how scorpion species may co-exist. It is suggested that when co-existing predators have similar preferences, one species tends to be superior at acquiring resources, resource utilization, and controlling time and space (Polis and Myers 1989), thus, allowing the superior species to suppress the density of other species. One example is the association between predaceous anthocorid bugs and parasitoid braconid wasps, in which both feed on pyralid moths. When anthocorid bugs prey on braconid wasps, the pyralid moth population increases indirectly (Polis and Myers 1989). This increase in pyralid moths is likely to benefit the population of both predators. Scorpion species may have similar prey preferences, but how they obtain their prey may vary. For instance, Vaejovids do not stalk their prey but sit-and-wait for random contact with potential prey (Hadley and Williams 1968). Buthids, on the other hand, not only rely on sit-and-wait but are also capable of active searching (Hadley and Williams 1968). A study on wandering spiders determined that co-existence may occur if individuals of competing species occupy space at different times and hunt different-sized prey (Uetz 1977). This is possible especially when intraguild predators mature at different rates and sizes. Competition may be more at play at different life stages, or may result from ontogenetic shifts in microhabitats. For instance, Polis (1980a) suggests that surface occupancy by immature scorpions may be an evolutionary response to long-term exposure to cannibalistic pressure from larger scorpions. McReynolds (2012) suggests that smaller size classes of scorpions should avoid microhabitats

This thesis follows the model of *The American Naturalist*

preferred by larger scorpions. This can explain a change in behavior throughout the different life-stages of scorpions. Although resource utilization may occur in this study, the association scorpion species have with each other can persist if their responses to environmental factors are not the same. This can be expected from species that obtain their prey through distinct foraging techniques. A study on a guild of five raptorial spider species concluded that intraguild competition was relatively unimportant because overlap in resource utilization was too low (Turner and Polis 1979). This study does not focus on resource utilization, but perhaps the densities obtained may provide insight as to how time and space are controlled by a particular species. The purpose of this study was to interpret how scorpion densities vary under different environmental conditions and how the same conditions may affect scorpion size classes and microhabitat preferences.

Scorpion densities may be influenced by many environmental factors such as temporal changes, environmental variability and microhabitat preferences, predation risk, prey preference, plant density, and soil types (Hadley and Williams 1968; Polis 1980a; Bradley and Brody 1984; Polis et al. 1985; McReynolds 2004; Cala-Riquelme and Colombo 2011). For example, the nightly and seasonal surface activity of *Smeringurus mesaensis* varied depending on age- and sex-specific responses to environmental factors (Polis 1980a). Similarly, it was hypothesized that surface activity of scorpions in our study varied. Bradley (1988) reported *Paruroctonus utahensis* initial emergence in the spring to be a response to higher temperatures with temporal changes. Apparent changes in temperature, plant productivity, and an increase in prey availability may result from temporal changes. Low ambient temperatures were reported to constrain the social spider, *Stegodyphus mimosarum*, foraging activity (Crouch and Lubin 2000). Similarly, scorpion surface activity during the winter months may be limited due to the low

temperature and low luminescence. Temperature shows to play a major influence on density patterns. *Paruroctonus utahensis* was reported to retreat back into its burrows when temperatures fell under 6-8 °C (Bradley 1988). Crouch and Lubin (2000) also reported body size growth of *S. mimosarum* during the winter season to be 5% but 13-16% during the summer season. Body size growth in *S. mimosarum* may suggest that prey abundance, during the summer, is greater. This further suggests that species diversity and scorpion activity increase with an increase in temperature. Surface densities of *Vaejovis waueri* and juvenile and female *Centruroides vittatus,* in the western region of Texas, showed significant monthly variation (Brown et al. 2002). Although, temperature was reported to have little effect on their density, surface density variation for these groups was greatest during the spring and fall (Brown et al. 2002). High air temperature and relative humidity had a strong influence on the foraging activity of scorpions in the Aegean archipelago (Kaltsas et al. 2008). A study on *C. vittatus* and the effects temperature has on its behavior reports findings that temperature has a major influence on their sprint speed and sting frequency (Carlson and Rowe 2009). This suggests that scorpions may exhibit riskier behavior when temperature is warmer. It also suggests that scorpions with errant behavior become less active as temperature decreases (Carlson and Rowe 2009). *Centruroides. vittatus* showed higher ground activity than on vegetation when the temperature was greater than 30°C (McReynolds 2008). McReynolds (2008) suggests that the low activity of scorpions on vegetation may be due to low prey activity on vegetation (Figure 1). Hypothetically, scorpion densities should fluctuate with temperature. However, it is possible that microhabitats with higher plant densities may be more resistant to temperature change and more suitable habitats for scorpion prey. Thus, scorpions should select microhabitats with the greatest resistance to change or insulation from low temperatures.

Figure 1: *C. vittatus* on huisachillo feeding on caterpillar.

Photo taken by Dr. N. McReynolds

Environmental variability or having distinct microhabitat preferences may result in higher prey availability and lower predation risk (Hallander 1970). Similar species may co-exist without direct competition (Turner and Polis 1979). Coexistence may be possible by reducing predation risk and increasing environmental variability (Turner and Polis 1979). Habitats with high abundance of vegetation often have high prey availability and can provide protection from predators (McReynolds 2004). With higher prey availability, it is possible that competition between intraguild predators may be diminished allowing for an increase in scorpion density. Similarly, predators having distinct microhabitat preferences may also reduce interactions between similar species. For example, females of the scorpion species, *Mesobuthus gibbosus,* were shown to forage under bushes more often than juveniles and adult males where wind speeds and lunar luminosity were low (Kaltsas et al. 2008). Observations on *Paraphidippus basalis,* a jumping spider, reported seeing individuals moving around agave plants to facilitate locating their prey from a distance. They were also observed shifting to parts of the plant which provided the most protection from sunlight where they may be at a greater risk of predation (Cobbold and O'Donnell 2021). Scorpions can also reduce predation risk by choosing microhabitats with plant cover during nights with high moon illumination (McReynolds 2004). For instance, burrowing scorpions can benefit from a shift in microhabitat by errant scorpions during nights with high moon illumination. McReynolds (2004) showed *C. vittatus* microhabitat shift to vegetation during the waxing gibbous and after moon rise during the waning gibbous lunar phases. McReynolds (2004) also suggested that such microhabitat shift onto vegetation may provide protection from predators on nights with high lunar illumination. Change in microhabitat preference throughout the night may be a contributing factor to the co-existence of scorpion species. Although, microhabitat shift in *C. vittatus* may be due to a trade-off between foraging

success and predation risk (McReynolds 2004), burrowing scorpions may become more active when errant scorpions become less active. Therefore, scorpion individuals should choose habitats with environmental variability that maximize resources while minimizing risk of predation (Fet et al. 1998) and competition (Polis et al. 1987, Polis 1980a, McReynolds 2012).

Scorpion size class, or age group, may also influence scorpion density. There are two major factors that can cause changes in density of size classes: predation risk and prey preference. For instance, a study showed that when wolf spider populations are low, wolf spider mortality rate increases due to cannibalism (Hallander 1970). Polis (1980b) reported smaller size classes of *P. mesaensis* to be the most vulnerable to cannibalism. Polis (1980b) also showed adult male scorpions to be the predator in fifty percent of all cannibalistic events. It can be predicted that avoiding overlap between smaller and larger size classes of scorpions may result in a decrease in mortality by cannibalism (Figure 2). Size classes of *C. vittatus* showed shifts in activity that suggest younger scorpions are possibly avoiding larger conspecifics in preferred microhabitats (McReynolds 2012). This suggests that as scorpions grow, the influence of cannibalism on scorpion density decreases. Because small individuals are at greater risk of cannibalism, it is likely that they may alter their behavior in response to larger conspecifics. A response to such change can be the altering of foraging frequency (Rudolf 2007). Juveniles may also choose to forage when environmental conditions pose a greater predation risk or low prey availability (Kaltsas et al. 2008) or forage on vegetation to avoid encounters with predators (Brown and O'Connell 2000). Hence, it is likely for smaller size classes to be more active at times when larger size classes are less active.

Figure 2: Cannibalism. Size class III *C. vittatus* feeding on size class IV *C. vittatus*.

Intraguild predation has been shown to reduce population growth of some guild members (Polis et al. 1986) (Figure 3). Predation-competition systems predict that the co-existence between competing predators may occur when one species is superior at resource utilization and the other at withstanding predation (Polis et al. 1989). Polis and McCormick (1986) reported that intraguild predation is sometimes directed towards the more superior intraguild predator. This combination of competition and predation can take place when species share the same resources (Polis and Holt 1990). Polis and Holt (1990) suggested that intraguild predation may result in several possible outcomes such as exclusion, coexistence, priority effects, alternative stable states, and an increase in resource levels. The exclusion or decrease in population by means of exclusion competition may result in the increase of a shared resource, thereby, allowing intraguild predators to coexist (Polis and Holt 1990). Exclusion through intraguild predation can also take place at different size classes. For example, a study done on predatory mites, adults of two species were observed feeding, almost exclusively, on each other's juveniles (Marques 2018). This study specifically shows an increase in female reproduction when their diet includes juveniles of guild member species (Marques 2018). Reducing the number of competing predators may, in turn, reduce the probability of a cannibalistic encounter (Cisneros and Rosenheim 1997). Directing intraguild predation towards a competing species, may free up resources that can allow dispersion among competing species (Polis and Myers 1988).

Figure 3: Intraguild predation. *C. vittatus* on tree trunk feeding on solifugae.

Photo taken by Dr. N. McReynolds

In *C. vittatus,* as females grow larger, so does their reproductive investment (Formanowicz and Shaffer 1993). This suggests that larger size class females require more resources. In turn, a shift in microhabitat when resources are scarce may occur. Adult male, *P. mesaensis,* were observed traveling long distances during breeding seasons (Polis et al. 1985). Although, distances within their home range may not be great, searching for mates can result in a change of scorpion density as male scorpions move throughout the night. Growth necessitates and allows changes in diet, either gradually or radically (Polis 1991). Change in body size can also affect competition, cannibalism, and predation by altering resource utilization (Armsby and Tisch 2006). A study done on, *Smeringurus mesaensis*, showed a direct correlation between adult scorpions and prey abundance, but an inverse correlation between juveniles and prey abundance (Polis 1980a). It was suggested that larger size classes forage during times of high prey activity or are rather more efficient foragers than their smaller counterparts (Polis 1980a). It is also possible that the risk of predation is too high for smaller size classes, hence, being less active during periods of high prey activity (Polis 1980a). Because foraging may take place at different times throughout the night, scorpion surface activity by the different size classes may vary on a night-to-night basis. For other species of scorpions, switching to active search may not be an option. Fossorial scorpions may opt to remain inactive during periods of low prey availability rather than seek out prey (Brand 1983). It may be that on nights with low prey availability, burrowing scorpions and adult errant scorpions, may have low surface activity.

Two factors that are believed to be of great importance to the co-existence and survival of scorpion species were plant densities and soil types. A variation in plant density may have different effects on the density of active scorpions. Variation in soil types may have other effects on soil types, plant densities and scorpion densities. Identifying an association between plant

density, soil types, and scorpion density can be vital to our understanding of how smallers size or age classes are shaped and how the co-existence of scorpion species is possible. For example, it has been suggested that high winds may create a 'jamming' effect on the sensory mechanism of scorpions (Bradley 1988). Choosing habitats with plant cover or choosing to remain in a burrow can maintain scorpion sensory mechanisms functional. It has also been reported that the presence of certain plant species may serve as refuge against predation risk and high temperatures (McReynolds 2008). Habitats with greater plant density may reduce predation risk while still offering protection from extreme weather. Foraging success may also be influenced by plant density. The conditional strategy of a spider's approach to prey was shown to depend on the prey's ability to escape and the predator's ability to detect prey (Bartos 2008). Plant density can have an effect on both aspects of a predator's conditional strategy to capture prey. Hypothetically, scorpions should show a preference towards plant densities that reduce preys' escape ability while raising their prey capture ability. A hypothesis of this study was that scorpions would appear in greater densities in habitats with greater plant densities. In part, because greater plant densities may allow scorpions greater foraging success. Hence, scorpions should favor behavior that raises their hunting success (Bartos 2008). The amount of plant cover is an important factor in creating a more diverse environment for predators and prey. A study on the influence of plant cover on macroinvertebrates showed that areas with dense emergent plants had greater diversity of macroinvertebrates and areas with low plant cover had less diversity (De Szalay and Resh 2000). Another study on the importance of plant cover against predation risk showed isopods protected by plant cover had more surviving individuals than those without plant cover (Segoli et al. 2016). Errant scorpions are predicted to choose microhabitats with greater

plant density because it provides them with plant cover, but also creates a more diverse microhabitat for prey and foraging sites.

Soil strength may be a limiting factor for burrowing scorpions (Lamoral 1978). Without their ability to dig, burrowing scorpions are unlikely to be found in habitats with high soil strength. As an example, a study on caecilians reported the effects compact soil has on their ability to construct burrows (Formanowicz et al. 1993). It supports the idea that individuals may be restricted from habitats with high soil strength by limiting their ability to dig their burrows (Formanowicz et al. 1993). Soil types are predicted to have a direct effect on burrowing scorpions but not on non-burrowing scorpions. Non-burrowing scorpions use other structures as shelter such as cracks in soil, under rocks, or occupying burrows of other animals (McReynolds 2008). They are also more commonly seen actively foraging on vegetation (Polis 1990). An effect on plant densities can have an indirect effect on non-burrowing scorpions. For instance, high soil strength was also reported to limit plant growth due to a possible constraint on the roots supplying water to the shoot system (Masle and Passioura 1987; Passioura 2002). This effect on plant growth can represent a change in plant density with a change in soil types. It could also mean that some plant species that thrive on certain soil types may not be adequately adapted to living on other soil types. High soil strength may reduce shoot growth for some plant species (Lanaku 2013). It is possible that early restriction in root growth can eventually lead to nutrient deficiency, limiting shoot growth in the long term (Masle and Passioura 1987 ; Lanaku 2013). Different soil types may contain different biotic communities that also affect plant growth. These soil communities can exert control over plant community structure (Lanaku 2013) which can have an indirect effect on scorpion densities.

The association between sympatric species, *C. vittatus* and *V.waueri,* will be tested to identify distinctions in microhabitat use, or other environmental preferences. Prey preferences appear to be similar, both choosing to feed on smaller prey and switching to larger prey as their size increases. Generally, *C. vittatus* is more active throughout the year than *V. waueri.* Intraguild predation and cannibalism, as in many arachnids, are a likely cause for scorpion mortality in both species. I, however, was interested in determining the differences in effects caused by the aforementioned environmental factors and how different size classes may respond to them. I am most interested in identifying differences between *C. vittatus* and *V. waueri* that may allow them to co-exist. Measuring their densities and identifying microhabitats where their densities vary may help explain why co-existence between the two scorpion species is possible.

The primary objectives for this study were to, (1) identify soil types that form the ranches that make up our sites, (2a) determine potential microhabitat preferences by the different scorpion size classes, (2b) determine whether different size class densities varied within habitats, (2c) determine whether microhabitat availability varied within habitats, (3) determine whether scorpion densities were affected by the densities of the different groups of plants, (4a) and compare densities between *C. vittatus* and *V. waueri* to determine possible factors that affect the co-existence between both species, (4b) or possibly the lack of competition. Meeting our objectives may provide an understanding of how scorpion species may respond differently to similar environmental conditions permitting them to co-exist within the same habitats. It may also demonstrate possible synergistic effects plant densities may have on scorpion densities. These objectives can also help in testing several hypotheses:

1. Habitats with higher plant densities will have an important effect on the density of *C. vittatus.*

2. *Centruroides vittatus* will prefer climbing on vegetation and *V. waueri* will have a preference for being on the ground.

3. Smaller size classes of scorpions will have a higher density on succulents and larger size classes of scorpions will have a higher density on legumes.

4. Habitats with soil types of low soil strength will have an important effect on the density of *V. waueri* due to its burrowing nature.

5. Co-existence between *C. vittatus* and *V. waueri* occurs because they use different microhabitats.

METHODS

Habitats

This study was conducted in four sites: Texas A&M International University (27°.57, -99°.43), Martinez Ranch (27°.32, -99°.37), located a few miles south of Laredo, Texas, La Union Ranch (27°.09, -99°.28) and La Union South (27°.1, -99°.29) both located east of San Ygnacio, Texas. Most of the habitats have been exposed to anthropogenic disturbances such as construction of roads, oilfield work, and ranching. There was ongoing oilfield work at the Martinez Ranch and La Union South throughout the time of research. Oilfield work usually took place during the day time. Caliche roads ran through all sites. All habitats can be described as thornscrub (McReynolds 2004; McReynolds 2008; McReynolds 2012; McReynolds 2020). The vegetation in these areas consists of mostly succulents and legumes. Vegetation in the four sites include plant species such as leather stem (*Jatropha dioica*), blackbrush (*Vachellia rigidula*), spanish dagger (*Yucca treculeana*), tasajillo (*Opuntia leptocaulis*), guajillo (*Senegalia berlandieri*), honey mesquite (*Prosopis glandulosa*), huisachillo (*Vachellia tortuosa*), strawberry cactus (*Echinocereus enneacanthus*), cenizo (*Leucophyllum frutescens*), lotebush (*Ziziphus obtusifolia*), guayacan (*Guaiacum angustifolium*), Texas prickly pear cactus (*Opuntia engelmannii*) and other plant species.

Study animals

The population of scorpions observed during my study were found within our four sites. *Centruroides vittatus* (Say 1821) (Figure 4), the striped bark scorpion, is very common in south Texas. For example, in the Webb and Zapata Counties, *C. vittatus* was the most abundant scorpion species (unpublished data). *Centruroides vittatus* is a nocturnal errant scorpion and is

not known to dig its own burrows (Polis 1990). It keeps to its refuge during the day time, hidden away under rocks, vegetation or in crevices on the ground. Rather, it chooses to usurp burrows built by other arachnid species such as wolf spiders (personal observations). *Vaejovis waueri* (Gertsch and Soleglad 1972) (Figure 5) is also commonly found in Texas. Due to its fossorial nature (Figure 6), *V. waueri* sits-and-waits rather than actively search for prey. Identifying factors that may contribute to habitat discrimination can allow for the prediction of habitats occupied by certain scorpion species.

Figure 4: *Centruroides vittatus* on blackbrush. Size class measured from the beginning of the prosma (P) to the end of the mesosoma (M).
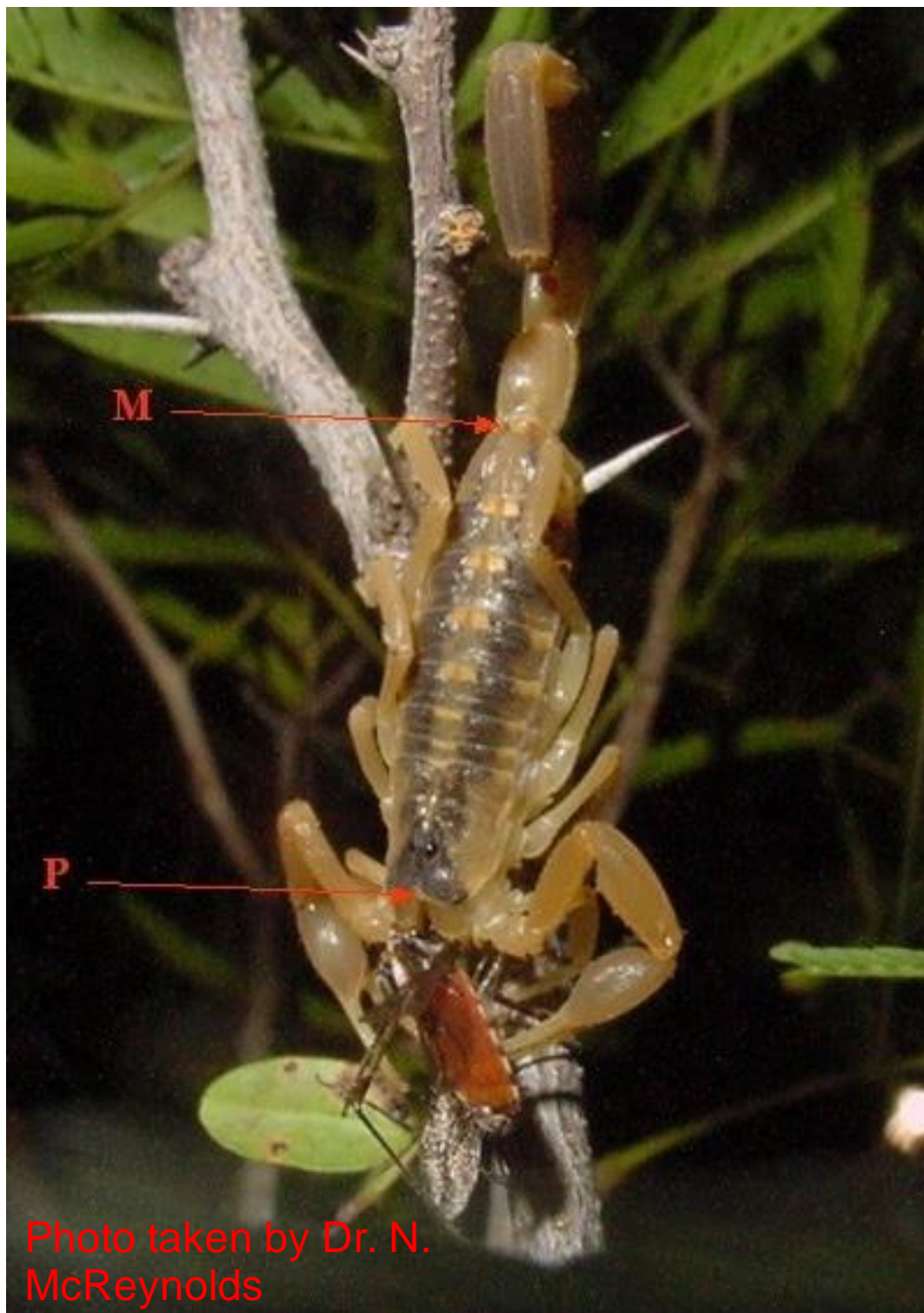
Figure 5: *Vaejovis waueri* on sandy ground.

Figure 6: *Vaejovis waueri* in a sandy burrow.

Photo taken by Dr. N. McReynolds

Data collection

Fieldwork took place from February 2016 to June 2018. The collection of data included scorpion data, spatial data, vegetation data and GPS data for five plots per night. Non-biased plots were created by throwing flags in random directions. Each plot had a center point from which we searched for scorpions within the four-meter radius of the plot (~ 50 square meters). GPS positions were recorded at the flag's location. Having a high density of scorpions per plot meant less plots per night were sampled. Sampling for data was suspended on nights with no scorpion activity or severe weather. Data collection ceased during the winter months when temperatures and scorpion activity became too low. We searched for scorpions using Xenopus Electronix ultraviolet rechargeable flashlight (Hadley 1969). Head lanterns were used for the identification of scorpion species and size classes. Scorpions were then classified into four size classes. Size classes of scorpions were determined by visually estimating the length of scorpions from the anterior of the prosoma to the posterior of the mesosoma. Size class I was <5mm in length; size class II scorpions between 5-10mm; size class III scorpions between 10-15mm; and size class IV scorpions >15mm (McReynolds 2012) (Figure 4). Data on each individual scorpion included date and time observed, species and size class of scorpion, microhabitat in which scorpion is found, the height of scorpion if found above ground (if on the ground, the height is zero centimeters), and prey captured.

Once scorpion data was collected, the point quarter method was implemented for each of the plots, which focused on collecting data on the surrounding vegetation (Cottam and Curtis 1956). For each plot we created four quadrants around the center point. Data collected at each quadrant for the point quarter method included: distance (cm) from center point to nearest plant, plant species, plant height (cm), and plant width (cm). A total of 120 plots were sampled in the

TAMIU campus. A total of 200 plots were sampled for the Martinez Ranch. A total of 94 plots were sampled for La Union South. A total of 82 plots were sampled in La Union Ranch. A total of 496 plots were sampled during the entire data collection period.

Soil types for GIS use were obtained from Texas National Resource Information System (TNRIS). Soil types are obtained through the Soil Survey Geographic (SSURGO) Database that provide a depiction of where the soil types are located and the identification of the soil types.

Data Analyses

Scorpion plant preferences were analyzed using a G-test for Goodness of Fit (Sokal and Rohlf 2011). A contingency table was created for this test to determine whether the observed scorpion frequency was different from the expected frequency on microhabitats. This allowed for the comparison in the frequency of scorpions between habitats of the four sites. Spatial data acquired through the point-quarter method was used to obtain an expected value. Microhabitats with a low frequency of scorpions were pooled when the expected frequency was lower than 5. Frequency of observed plant species was divided by the total plants observed. The value obtained was multiplied by the total number of scorpions observed using plants. Ground and grass were not part of the expected values because the point-quarter method does not account for the two microhabitats. Expected values for this test were obtained once these calculations were performed. The frequency of scorpions observed using each plant species determined the observed values for this test. A three-way G-test of independence (Sokal and Rohlf 2011) was also used to determine an association between scorpion size classes, microhabitats, and habitats. A three-way contingency table was created using Microsoft Excel that allowed us to compare the frequency distribution of scorpion size classes. Size classes I and II were pooled for this analysis

because the data collected on smaller size classes included many zeros when compared to the two larger size classes.

An analysis of variance (ANOVA) was used to compare scorpion activity in different habitats. The comparison was made using a non-parametric ANOVA, or the Kruskal-Wallis test because the assumptions of normality and equal standard deviation between classes were violated for this test (Sokal and Rohlf 2011). This comparison was done for each of the two scorpion species found within the four sites. A comparison using the Dunn's Multiple Comparisons Test was used to identify the sites that were significantly different.

Linear mixed-effect models were conducted using MATLAB (Gelman and Hill 2007) to determine if there was an association between scorpion densities and plant densities. Associations were tested within three of the four habitats. Associations between scorpion densities and plant densities were not tested for in the TAMIU Campus because insufficient data was collected. Scorpion size class data was pooled to identify associations between total scorpion density and plant densities. Succulent species were pooled to create a fixed-effect for the models. Legume species were pooled to create a second fixed-effect. Vegetation that was not succulents or legumes were pooled in the third fixed-effect and labeled other vegetation. The benefit of using linear mixed-effects models is that it allows the identification of an effect between the response variable and fixed-effects when random-effects were present. Scorpion densities represented the response variables. Plant densities represented the fixed-effects. Plots represented the random-effects. Scorpion size classes were tested against plant type densities and total plant densities. These tests were done for both scorpion species observed for this study. If there was a significant association between them, a positive or negative association was determined by obtaining the slope for each of the fixed-effects. The coefficient of determination (R^2) and the

Akaike Information Criterion (AIC) were calculated for each of the models. An AIC provides a measure for the quality of a model (Ljung 1999). The AIC of different models can be compared for accuracy. The model with the lowest AIC is considered the most accurate model. We constructed each model by using the function *lme* (linear mixed-effect model) and *rsquared*.

Geographic Information Systems

ArcGIS Pro was used with two objectives in mind, (1) GPS coordinates obtained through our data collection were used to create maps of the four sites. Scorpion data and plant community data were added as layers to create points on the maps. Points on the map were represented by the date in which that data was collected. The soil type layers were obtained through the Texas Natural Resources Information System website (TNRIS). I used the soil layer to identify the soil types that form my four study sites. Soil data was broken down further into their soil compositions. This breakdown provided the make-up of each soil type with percentages. For example, plot points surveyed on June 15th, 2018 were obtained from the soil type NSC. The NSC soil type had a soil composition of sand, silt, and clay. Because I was interested in comparing densities between burrowing scorpions and non-burrowing scorpions, we required a further breakdown of the sandy soils, where burrowing scorpions were predicted to have greater densities. This breakdown in sand compositions gave percentages for the different types of sand (Soil Survey Geographic Database). Using this information, we were able to compare the different scorpion densities and plant densities for 'within sites' and 'between sites'. Scorpion data was collected prior to identifying soil types. Microhabitats with deeper, or low soil strength were predicted to have a greater abundance of *V. waueri*. Microhabitats with a high density of plants were predicted to have low soil strength. Therefore, *C. vittatus* was predicted to have a greater distribution in habitats with greater plant density and soils with high soil strength.

RESULTS

In the Martinez Ranch, plant community data was collected on 704 plants. Scorpion data was collected from 27 plant species. Three plant species appeared in the data collected with more frequency than the other 17 species (Table 1). A total of 440 scorpions were observed (Table 1). *Centruroides vittatus* made up the large majority with 437 scorpions to 3 of *V. waueri* (Table 1). In La Union South, spatial data was collected on 314 plants. A total of 26 plant species were observed. Catclaw appeared more frequently than the other 12 plant species. 299 scorpions were observed (Table 2). *Centruroides vittatus* had a frequency of 284 scorpions to 15 of *V. waueri* (Table 2). In La Union Ranch, plant data was collected on 158 plants. A total of 23 plant species were observed (Table 3). Approximately 281 scorpions were observed (Table 3). *Centruroides vittatus* had a frequency of 270 scorpions to 11 of *V. waueri* (Table 3). In TAMIU Campus, plant data was collected on 84 plants. A total of 19 plant species were observed (Table 4). Approximately, 72 scorpions were observed (Table 4). *Centruroides vittatus* had a frequency of 70 scorpions to 2 of *V. waueri* (Table 4).

The observed proportion of scorpions (%) on microhabitats was compared to the expected proportion of microhabitat use. The observed proportion of scorpions on vegetation was not significantly different from the expected scorpion proportion (Figure 7). The proportion of scropions observed on vegetation was significantly different than the expected proportion (Figure 8). Scorpions in La Union South were observed on catclaw at a much lower frequency than the expected proportion of microhabitat use (Figure 8). Scorpions on mesquite, succulents, and other vegetation were observed at a higher frequency than the expected proportion of microhabitat use (Figure 8). The observed proportion of scorpions on vegetation was not significantly different from the expected scorpion proportion (Figure 9).

Table 1. Frequency of microhabitats (%) surveyed through the point-quarter method in the Martinez Ranch. Total number of plants (n = 702). Microhabitats not surveyed through the point-quarter method are shown (-). The number of scorpions on microhabitats is shown. Proportion of scorpions (%) found on microhabitat is provided.

Species	Microhabitat Frequency (%)	# of *C. vittatus* on microhabitats	# of *V. waueri* on microhabitats	Proportion of scorpions (%)
Mesquite	24.64	31	0	7
Huisachillo	22.08	23	0	5
Prickly Pear	17.38	11	0	3
Blackbrush	10.4	10	0	2
Goldenweed	9.26	21	0	5
Huisatche	3.85	0	0	0
Hogplum	3.42	0	0	0
Tasajillo	2.85	1	0	0
Lotebush	1.42	1	0	0
Leather stem	0.85	0	0	0
Yucca	0.71	0	0	0
Coyotillo	0.71	1	0	0
Desert Hackberry	0.71	2	0	0
Coma	0.43	4	0	1
Desert Olive	0.28	0	0	0
Ebony	0.28	0	0	0
Lime Prickly Ash	0.28	0	0	0
Whitebrush	0.14	0	0	0
Soapbush	0.14	0	0	0
Palo Verde	0.14	0	0	0
Allthorn Goatbush	0	3	0	1
Herb	0	11	0	3
Termite Tubes	0	6	0	1
Unknown	-	3	0	1
Ground	-	193	3	44
Grass	-	94	0	22
Dead Vegetation	-	20	0	5
Total	99.97	437	3	100

Table 2. Frequency of microhabitats (%) surveyed through the point-quarter method in La Union South. Total number of plants (n = 314). Microhabitats not surveyed through the point-quarter method are shown (-). The number of scorpions on microhabitats is also shown. Proportion of scorpions (%) found on microhabitat is provided.

Species	Microhabitat Frequency (%)	# of *C. vittatus* on microhabitats	# of *V. waueri* on microhabitats	Proportion of scorpions (%)
Catclaw	21.66	1	0	0.33
Mesquite	10.83	6	0	2.01
Allthorn Goatbush	9.87	9	0	3.01
Prickly Pear	7.32	2	0	0.67
Coma	7.01	7	0	2.34
Goldenweed	6.37	4	0	1.34
Whitebrush	5.73	0	0	0
Yucca Constricta	5.41	0	0	0
Spanish Dagger	4.46	14	0	4.68
Lotebush	4.14	0	0	0
Soapbush	2.87	0	0	0
Lime Prickly Ash	2.87	0	0	0
Aster	2.23	4	0	1.34
Cenizo	2.23	0	0	0
Leather stem	1.59	0	0	0
Tasajillo	1.59	0	0	0
Blackbrush	0.96	0	0	0
Desert Hackberry	0.96	0	0	0
Hogplum	0.64	0	0	0
Huisachillo	0.64	1	0	0.33
Coyotillo	0.32	0	0	0
Desert Olive	0.32	0	0	0
Herb	0	15	0	5.02
Ground	-	168	15	61.2
Grass	-	43	0	14.38
Dead Vegetation	-	10	0	3.34
Total	100.02	284	15	99.99

Table 3. Frequency of microhabitats (%) surveyed through the point-quarter method in La Union Ranch. total number of plants (n = 158). Microhabitats not surveyed through the point-quarter method are shown (-). The number of scorpions on microhabitats is also shown. Proportion of scorpions (%) found on microhabitat is provided.

Species	Microhabitat Frequency (%)	# of *C. vittatus* on microhabitats	# of *V. waueri* on microhabitats	Proportion of scorpions (%)
Goldenweed	38.61	17	0	6.3
Allthorn Goatbush	14.56	9	0	3.3
Leather stem	14.56	2	1	0.7
Mesquite	9.49	7	0	2.6
Huisachillo	3.16	5	0	1.9
Desert Olive	3.16	3	0	1.1
Tasajillo	2.53	0	0	0
Soapbush	2.53	3	0	1.1
Catclaw	2.53	1	0	0.4
Coma	1.9	4	0	1.5
Lotebush	1.9	2	0	0.7
Desert Hackberry	1.27	0	0	0
Blackbrush	1.27	0	0	0
Prickly Pear	1.27	1	0	0.4
Ephedra	0.63	0	0	0
Lime Prickly Ash	0.63	1	0	0.4
Ratany	0	1	0	0.4
Yucca	0	3	0	1.1
Strawberry Cactus	0	1	0	0.4
Herb	0	5	0	1.9
Ground	-	152	7	56.3
Grass	-	31	2	11.5
Dead Vegetation	-	22	1	8.1
Total	100	270	11	100.1

Table 4. Frequency of microhabitats (%) surveyed through the point-quarter method in the TAMIU campus. Total number of plants (n = 84). Microhabitats not surveyed through the point-quarter method are shown (-). The number of scorpions on microhabitats is also shown. Proportion of scorpions (%) found on microhabitat is provided.

Species	Microhabitat Frequency (%)	# of *C. vittatus* on microhabitats	# of *V. waueri* on microhabitats	Proportion of scorpions (%)
Blackbrush	36.90	9	0	12.5
Tasajillo	16.67	2	0	2.8
Prickly Pear	10.71	5	0	6.9
Leather stem	9.52	0	0	0
Desert Olive	7.14	2	0	2.8
Soapbush	4.76	1	0	1.4
Lotebush	3.57	0	0	0
Mesquite	2.38	0	0	0
Desert Hackberry	2.38	0	0	0
Palo Verde	2.38	1	0	1.4
Coyotillo	2.38	0	0	0
Huisachillo	1.19	0	0	0
Guajillo	0	1	0	1.4
Strawberry Cactus	0	1	0	1.4
Allthorn Goatbush	0	1	0	1.4
Yucca	0	1	0	1.4
Ground	-	40	2	58.3
Grass	-	4	0	5.6
Dead Vegetation	-	2	0	2.8
Total	99.98	70	2	100.1

Figure 7: Proportion of scorpions (%) among the different microhabitats in the Martinez Ranch. The frequency of scorpions on microhabitat use was not significantly different between the expected and the observed proportions (G=6.76, P<ns, df=4, n=111).
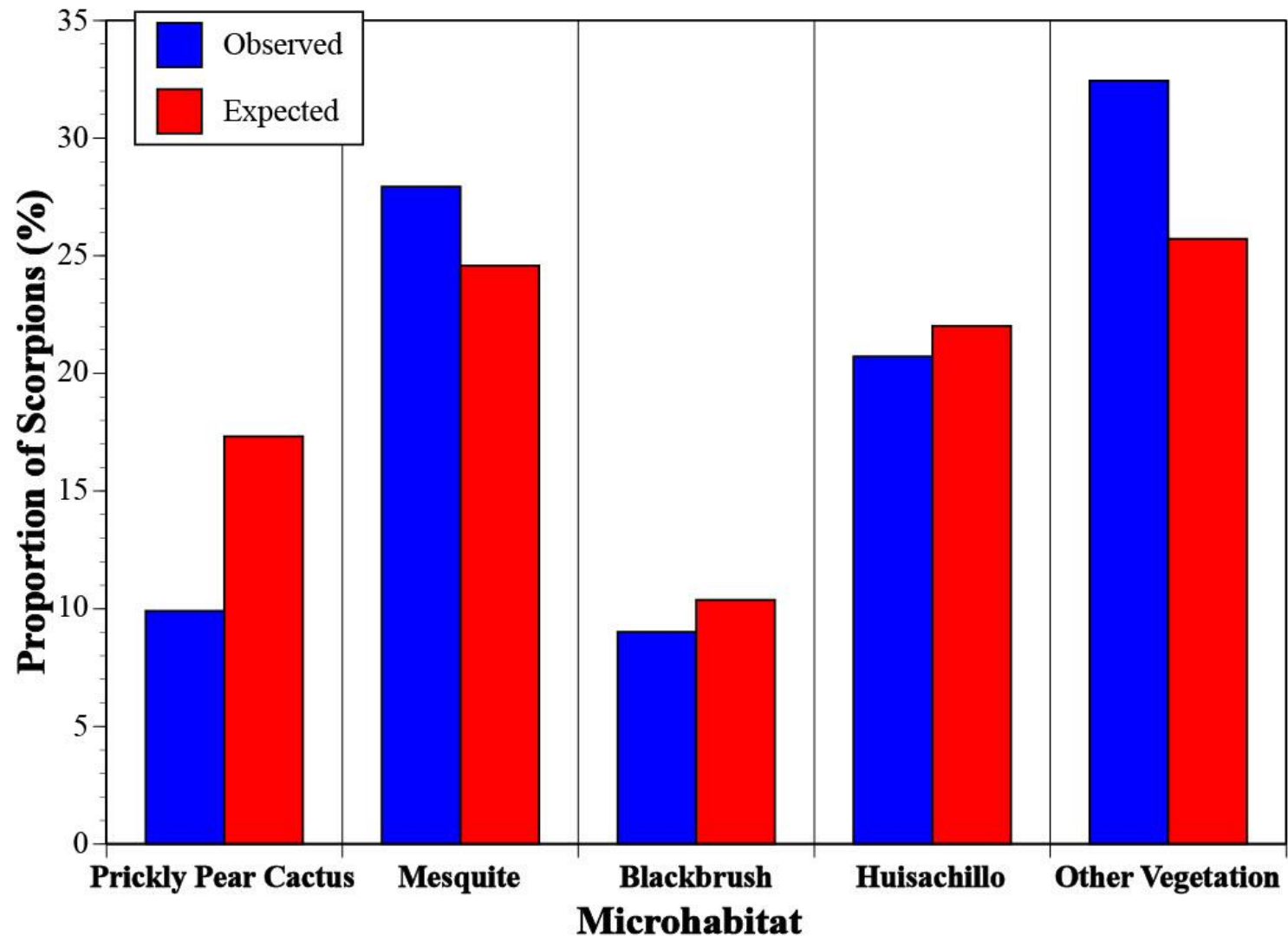
Figure 8: Proportion of scorpions (%) among the different microhabitats in La Union South. The frequency of scorpions on microhabitat use was significantly different between the expected and the observed proportions (G=18.72, P<0.001, df=3, n=48).
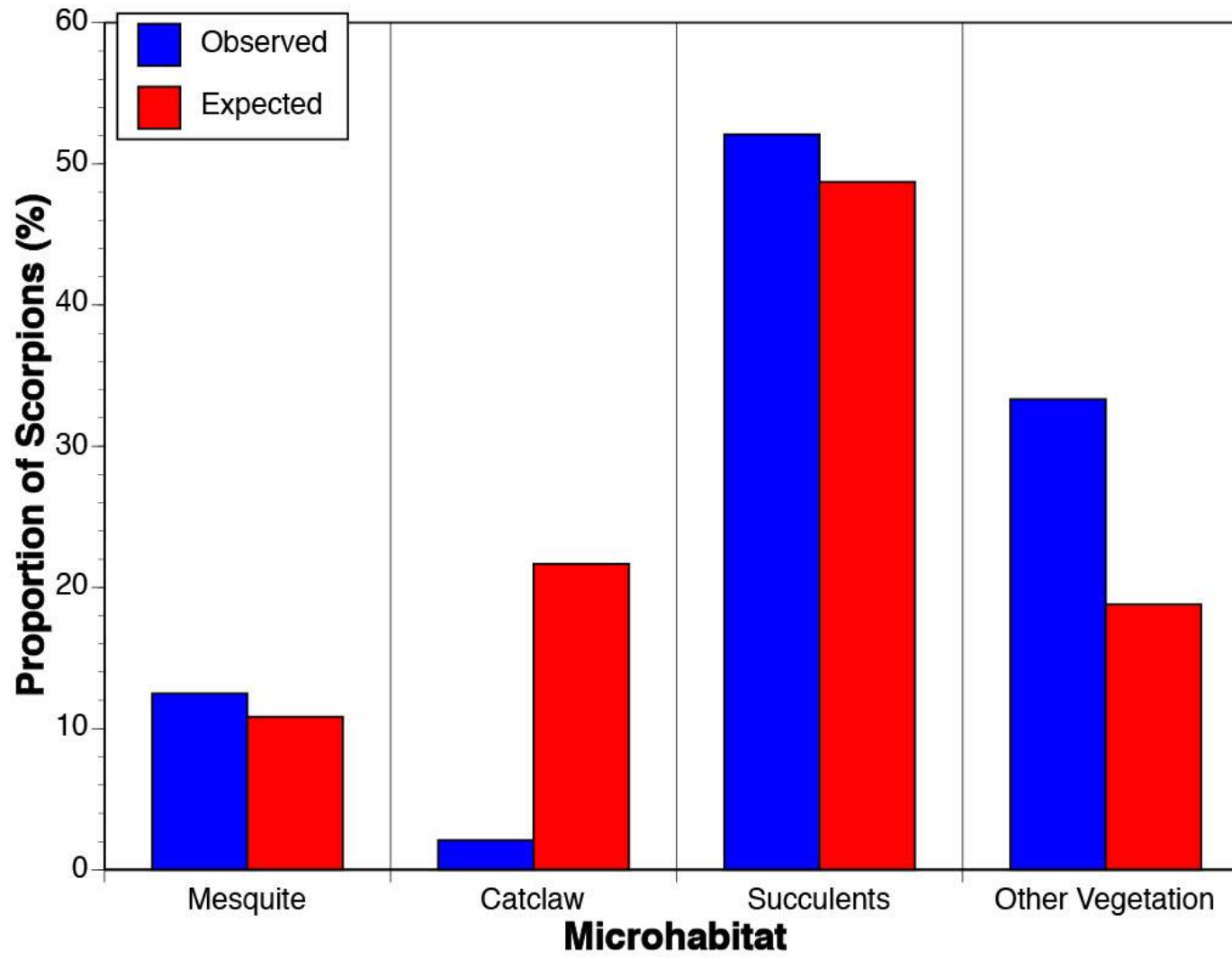
Figure 9: Proportion of scorpions (%) among the different microhabitats in La Union Ranch. The frequency of scorpions on microhabitat use was not significantly different between the expected and the observed proportions (G=0.93, P<ns, df=2, n=37).
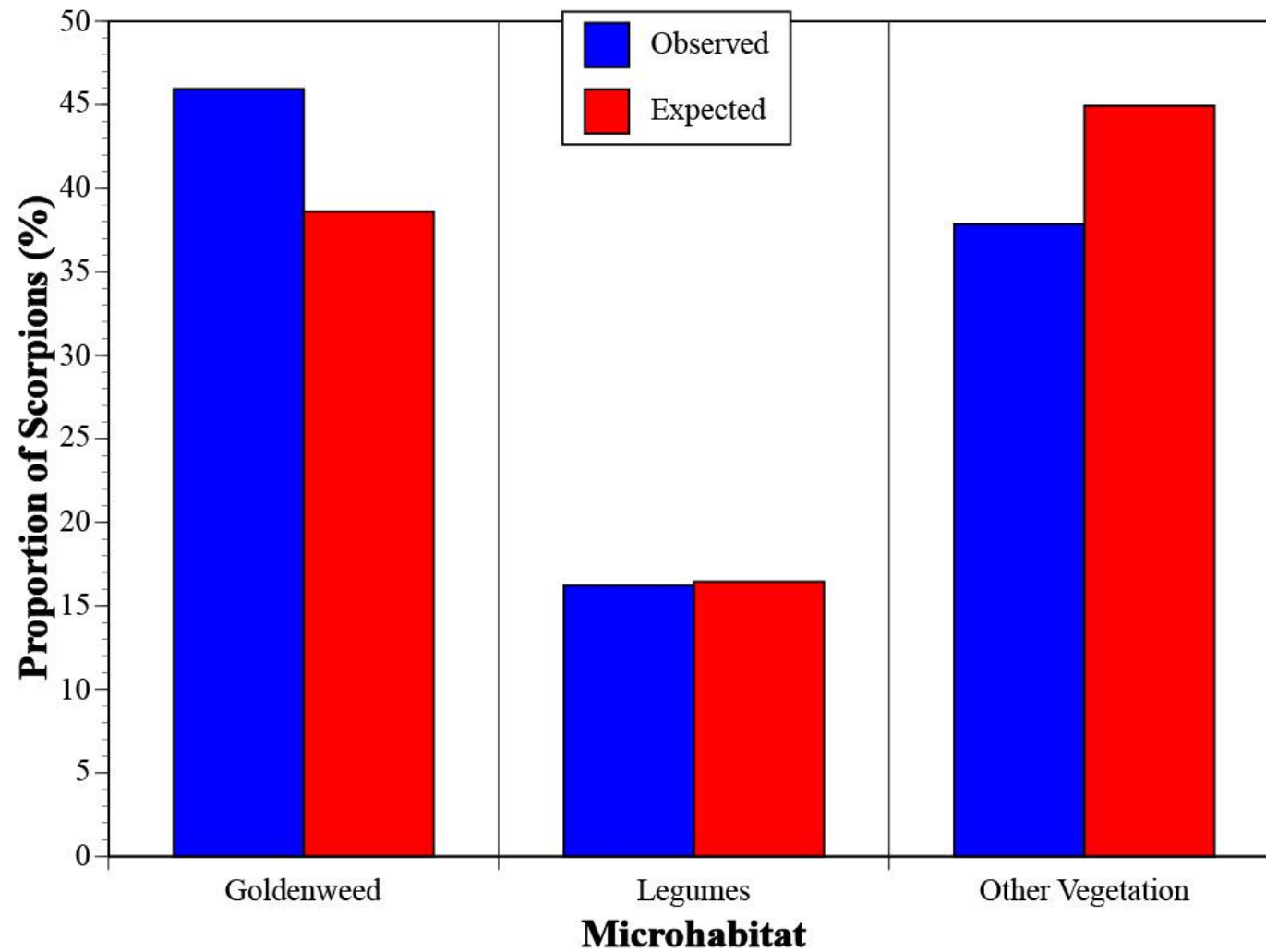
A three-way G-test of independence was used to compare the scorpion frequency between habitats, microhabitats, and size classes (Table 5). In the interaction comparison between habitats, microhabitats, and size classes was not significantly different. In a conditional comparison, microhabitat use in the different habitats, given the level size classes, was significantly different (Figure 10). There was a significant difference between scorpions on the ground versus scorpions on vegetation (Table 5). There was a significant difference in the orthogonal comparison between scorpions on grasses and all vegetation (Table 5). There was also a significant difference in the orthogonal comparison between scorpions found on legumes versus scorpions found on other vegetation.

In a conditional comparison, size classes were significantly different among microhabitat use, given the level of habitats (Figure 10). In an orthogonal, comparison there was a significant difference among size classes of scorpions found on the ground versus scorpions found on all vegetation (Table 5). In a second orthogonal comparison, there was a significant difference among size classes of scorpions found on grasses versus scorpions found on all other vegetation (Table 5). There was no significant association between size classes of scorpions found on legumes versus scorpions found on other vegetation. The habitat use by the various size classes was significantly different (Table 5). Scorpion use of legumes versus other vegetation was not significantly different among size classes.

In the conditional comparison, there was a significant difference between scorpion size classes among habitats, given the level of microhabitats (Figure 10). In an orthogonal comparison, size class III scorpions were sampled at a significantly lower rate than size class I-II

(Table 5). Size class IV scorpions were not significantly different among habitats than the other size classes.

Figure 10: Number of scorpions for each size class observed in three habitats. Size classes I and II were pooled for statistical analysis. The number of scorpions observed in different microhabitats was significantly different among habitats (G=68.653, P<0.0001, df=18, n=943). The number of scorpions for each size class was significantly different amongst microhabitats (G=46.889, P<0.001, df=18, n=943). The number of scorpions of different size classes was significantly different between habitats (G=34.825, P<0.01, df=16, n=943).
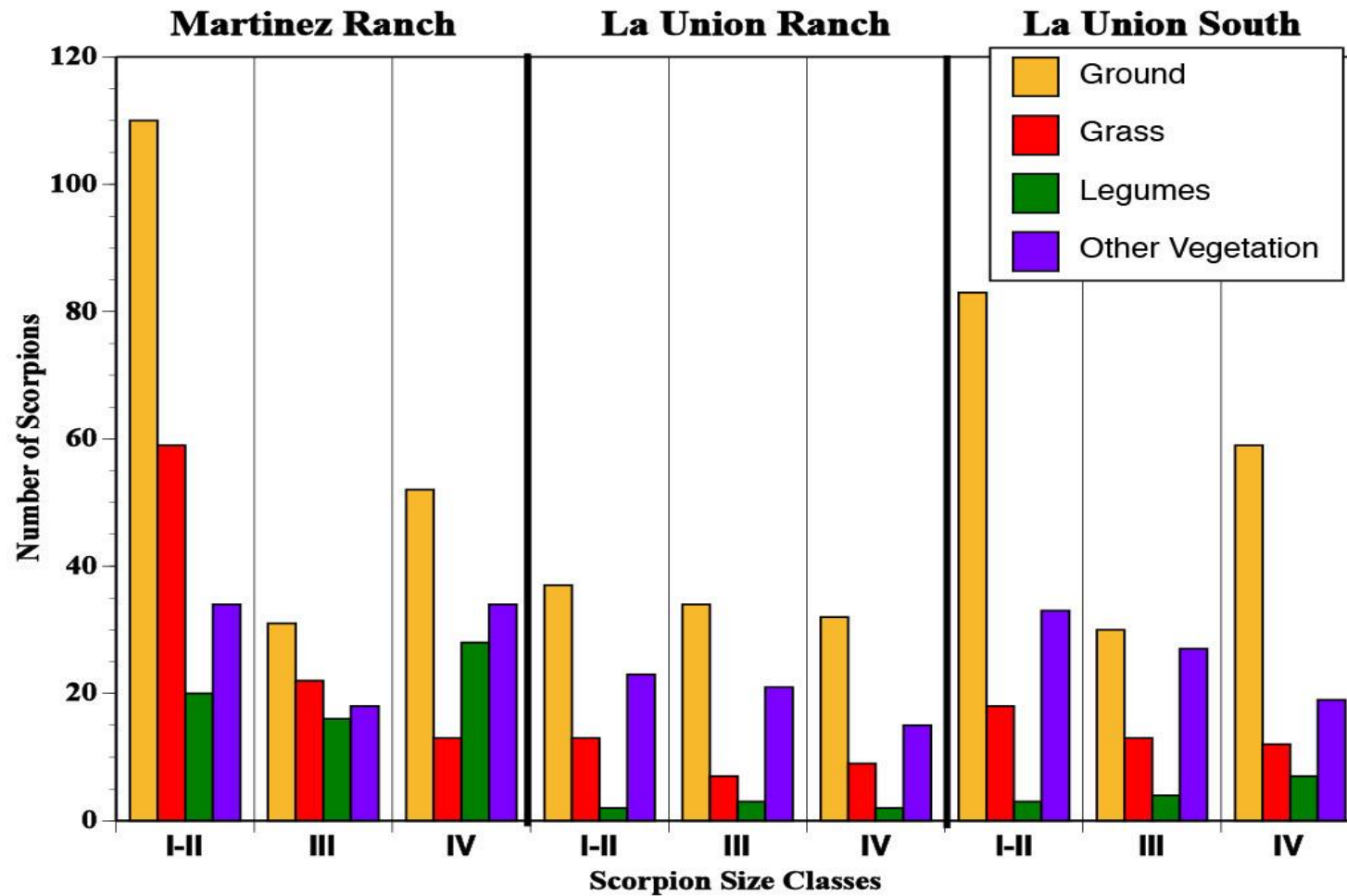
Table 5. Three-way G tests of independence of the contingency tables for habitats vs. microhabitats vs. scorpion size classes.

	Comparisons	G	df	P
Interaction		17.676	12	ns
Conditional	Microhabitat vs Habitat	68.653	18	<0.001
Orthogonal Comparison	Ground vs All other vegetation	18.468	6	<0.01
	Grass vs All other vegetation	14.475	6	<0.05
	Legumes vs Other Vegetation	35.71	6	<0.001
Conditional	Microhabitat vs Size Classes	46.889	18	<0.001
Orthogonal Comparison	Ground vs All other vegetation	15.215	6	<0.05
	Grass vs All other vegetation	26.224	6	<0.001
	Legumes vs Other Vegetation	5.45	6	ns
Conditional	Habitat vs Size Class	34.825	16	<0.01
Orthogonal Comparison	Size Class IV vs I-III	14.703	8	ns
	Size Class III vs I-II	20.122	8	<0.01

A comparison of the median scorpion densities for both species showed an extremely significant difference among habitats using a non-parametric ANOVA. The median density of *C. vittatus* among habitats was significantly different (Figure 11). The Martinez Ranch and La Union South were significantly higher than the median densities of La Union Ranch and TAMIU Campus using the Dunn's Multiple Comparisons Test but not significantly different from each other. The median density of *C. vittatus* for La Union Ranch was significantly higher than the median density of TAMIU Campus using the Dunn's Multiple Comparisons Test. The density of *V. waueri* for La Union South was significantly higher than the mean densities of the other habitats using the Dunn's Multiple Comparisons Test (Figure 12).

Linear mixed-effects models were used to identify the association between plant densities and scorpion densities. In the Martinez Ranch, eight models were constructed for *C. vittatus* total scorpion density. None of the models yielded a significant model for the association between scorpion density and plant densities (Table 6). Seven models were constructed for *C. vittatus* size class I. A significant between scorpion density and plant densities was obtained for one model. Model 1 showed a significant association and a positive slope between scorpion size class I and succulent densities (Table 7). Model 4 showed an almost significant association between scorpion size class I and the densities for succulents and legumes (Table 7). The R^2 and AIC values were used to demonstrate the direct association with the line of regression for these models and evaluate how well a model fits the data it was generated from, respectively. Models with the highest R^2 and lowest AIC value are the best-fit models. Model 4 had the highest R^2 and Model 1 has the lowest AIC value (Table 7). Seven models were constructed for *C. vittatus* size class II. A significant positive association between scorpion size class II density and other vegetation density was obtained through Model 3 (Table 8).

Figure 11: The mean and median density of *C. vittatus* at each of the four habitats. Standard error bar (± 1 SE) and sample size (n) were shown for the mean of each habitat. Median scorpion density was significantly different among habitats (Kruskal-Wallis Statistic: KW=136.87 (corrected for ties), P<0.0001). Medians with the same letter were not significantly different in a pairwise comparisons.
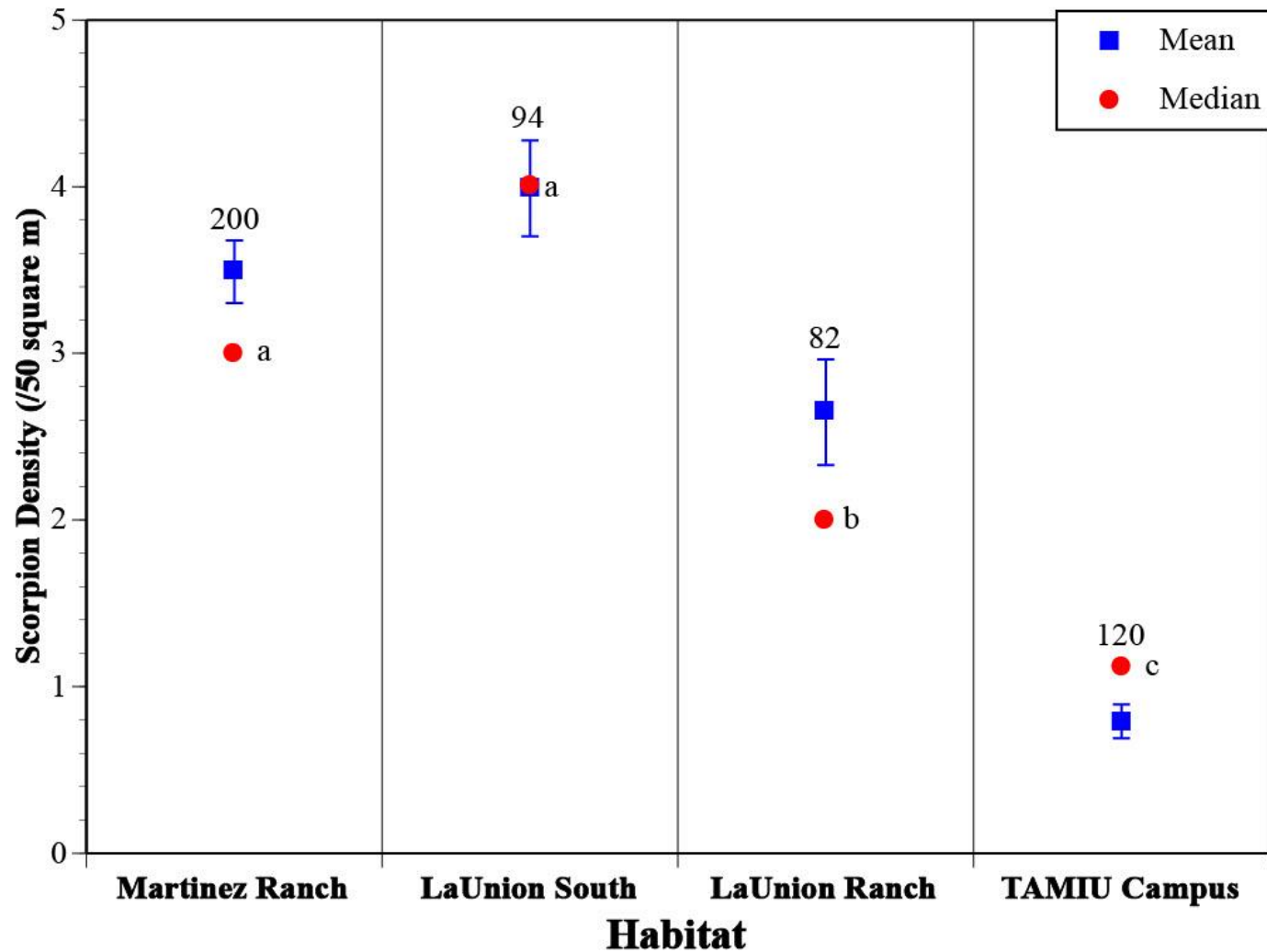
Figure 12: The mean and median density of *V. waueri* at each of the four habitats. Standard error bar (± 1 SE) and sample size (n) were shown for the mean of each habitat. Median scorpion density was significantly different among habitats (Kruskal-Wallis Statistic: KW=46.542 (corrected for ties), P<0.0001). Medians with the same letter were not significantly different in a pairwise comparison.
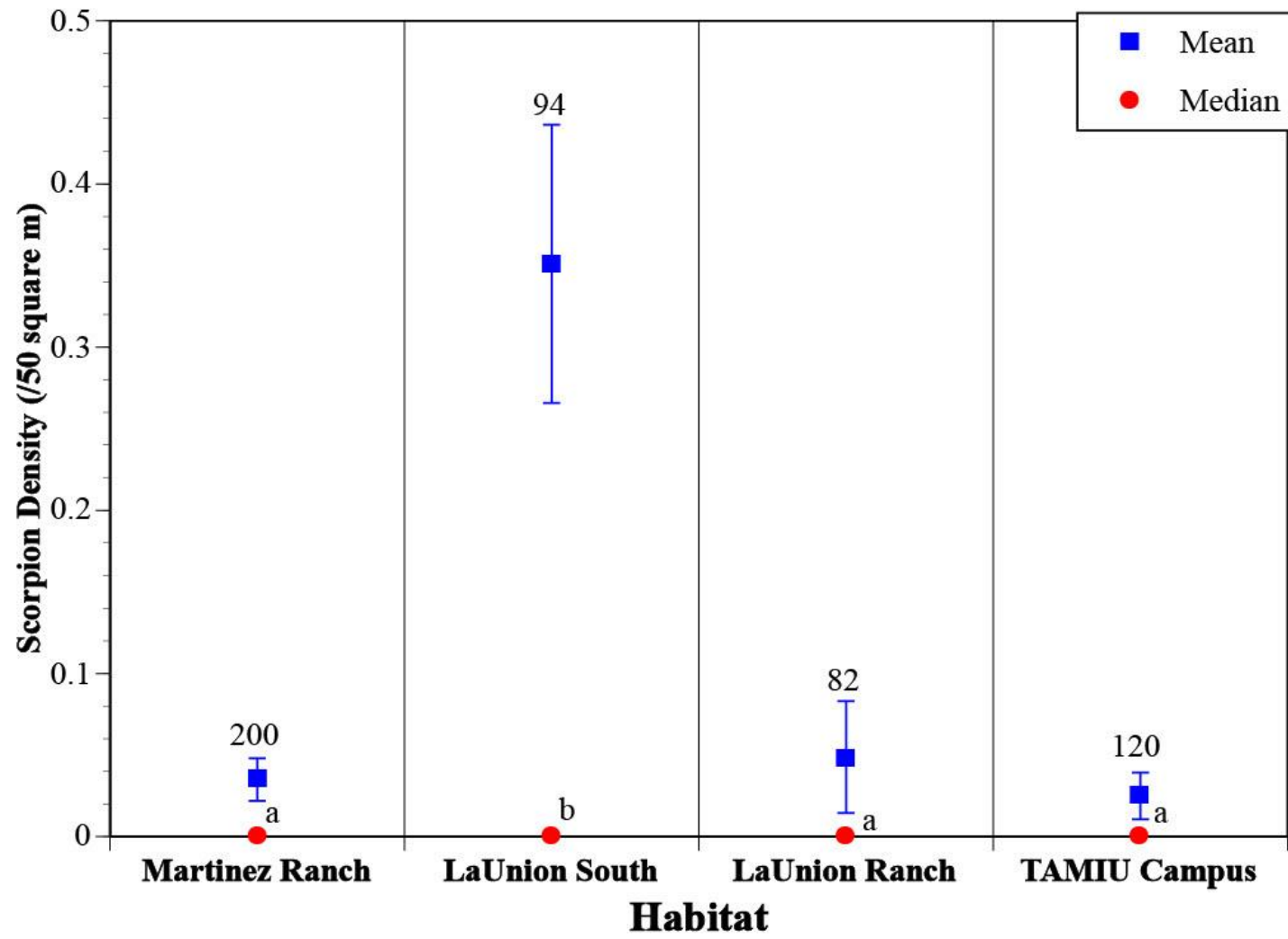
Model 7 had the highest R^2 and Model 3 had the lowest AIC value (Table 8). Seven models were constructed for *C. vittatus* size class III. No models showed a significant association between scorpion density and plant densities (Table 9). Seven models were constructed for *C. vittatus* size class IV. None of the models showed a significant association between scorpion density and plant densities (Table 10).

In La Union South, eight models were constructed for *C. vittatus* total size classes. None of the models showed a significant association between scorpion density and plant densities (Table 11). Eight models were generated for *C. vittatus* size class I. None models showed a significant association between scorpion density and plant densities (Table 12). Eight models were generated for *C. vittatus* size class II. None of the models showed a significant association between scorpion density and plant densities (Table 13). Eight models were generated for *C. vittatus* size class III. No models showed a significant association between scorpion density and plant densities (Table 14). Eight models were generated for *C. vittatus* size class IV. None of the models showed a significant association between scorpion density and plant densities (Table 15).

Table 6. Linear mixed-effects models for total scorpion density of *C. vittatus* vs. plant densities at the Martinez Ranch. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Total Scorpion Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.64601	0.020305	0.10794	-0.067328	0.4964	376.84
2	Succulent density	0.44233	0.12181	0.43573	-0.19211	0.5010	376.46
3	Legume density	0.78137	0.013066	0.10643	-0.080298	0.4948	376.98
4	Other vegetation density	0.89829	-0.047452	0.68891	-0.78381	0.4940	377.04
5	Succulent density + Legume density	0.43826 0.76711	0.12288 0.013897	0.43677 0.10696	-0.19102 -0.079169	0.4958	378.38
6	Succulent density + Other vegetation density	0.44873 0.9945	0.122 0.0025882	0.44093 0.74809	-0.19692 -0.74292	0.4948	378.46
7	Legume density + Other vegetation density	0.7539 0.84625	0.015131 -0.073772	0.11085 0.68088	-0.080589 -0.82843	0.4889	378.94
8	Succulent density + Legume density + Other vegetation density	0.45155 0.76262 0.95233	0.1212 0.01453 -0.023017	0.44005 0.10995 0.74096	-0.19766 -0.080893 -0.78699	0.4895	380.37

Table 7. Linear mixed-effects models for scorpion size class I density of *C. vittatus* vs. plant densities at the Martinez Ranch. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size class I Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Succulent density	**0.049616**	0.13263	0.26504	0.00022787	0.5380	233.16
2	Legume density	0.2251	-0.02447	0.015359	-0.64299	0.5114	235.56
3	Other vegetation density	0.6535	-0.071659	0.24478	-0.3881	0.4963	236.84
4	Succulent density + Legume density	**0.05086** 0.23157	0.13082 -0.023585	0.26214 0.01535	-0.00050141 -0.062521	0.5474	233.72
5	Succulent density + Other vegetation density	0.055587 0.91055	0.1313 -0.017806	0.26581 0.29661	-0.0032105 -0.33223	0.5324	235.15
6	Legume density + Other vegetation density	0.25323 0.85054	-0.023614 -0.030582	0.01722 0.29136	-0.064448 -0.35252	0.5057	237.53
7	Succulent density + Legume density + Other vegetation density	0.051253 0.22977 0.87683	0.13264 -0.024272 0.024965	0.26602 0.015645 0.34454	-0.00073978 -0.064188 -0.29461	0.5419	235.70

Table 8. Linear mixed-effects models for scorpion size class II density of *C. vittatus* vs. plant densities at the Martinez Ranch. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size Class II Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R²	AIC
1	Succulent density	0.22449	-0.1021	0.063867	-0.26807	0.5115	270.67
2	Legume density	0.23946	0.029325	0.078561	-0.019911	0.5104	270.76
3	Other vegetation density	**0.034482**	0.4118	0.79278	0.030828	0.5446	267.65
4	Succulent density + Legume density	0.23095 0.24645	-0.099899 0.028649	0.064799 0.077481	-0.2646 -0.020182	0.5208	271.31
5	Succulent density + Other vegetation density	0.37775 0.052101	-0.073453 0.38168	0.091349 0.76691	-0.23825 -0.0035552	0.5470	268.87
6	Legume density + Other vegetation density	0.45305 0.05609	0.018711 0.37926	0.068096 0.7686	-0.030673 -0.01009	0.5448	269.08
7	Succulent density + Legume density + Other vegetation density	0.36936 0.44208 0.082244	-0.074509 0.019081 0.34805	0.089758 0.068241 0.74163	-0.23878 -0.030079 -0.045528	0.5474	270.27

Table 9. Linear mixed-effects models for scorpion size class III density of *C. vittatus* vs. plant densities at the Martinez Ranch. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Scorpion Size Class III

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Succulent density	0.72812	0.025016	0.1677	-0.11767	0.4953	245.57
2	Legume density	0.65698	0.0094729	0.051759	-0.032813	0.4962	245.50
3	Other vegetation density	0.33279	-0.16252	0.16936	-0.49441	0.5446	267.65
4	Succulent density + Legume density	0.72014 0.65094	0.025758 0.0096471	0.16833 0.051919	-0.11682 -0.032625	0.4915	247.37
5	Succulent density + Other vegetation density	0.85568 0.35641	0.013223 -0.1571	0.15744 0.18001	-0.13099 -0.49421	0.5470	268.87
6	Legume density + Other vegetation density	0.49762 0.2732	0.014739 -0.18816	0.057787 0.15123	-0.028309 -0.52755	0.5448	269.08
7	Succulent density + Legume density + Other vegetation density	0.8641 0.49941 0.29396	0.012411 0.014677 -0.182960	0.15628 0.057732 0.16174	-0.13146 -0.028377 -0.52767	0.5474	270.27

Table 10. Linear mixed-effects models for scorpion size class IV density of *C. vittatus* vs. plant densities at the Martinez Ranch. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size Class IV Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Succulent density	0.51536	0.06626	0.26804	-0.13551	0.4990	303.09
2	Legume density	0.96672	-0.0012615	0.058716	-0.061239	0.4938	303.52
3	Other vegetation density	0.34383	-0.22507	0.24524	-0.69538	0.5046	302.62
4	Succulent density + Legume density	0.51588 0.97848	0.066198 -0.00081387	0.26806 0.059038	-0.13567 -0.060665	0.4927	305.09
5	Succulent density + Other vegetation density	0.62082 0.39694	0.050934 -0.20418	0.25504 0.27292	-0.15317 -0.68129	0.5014	304.37
6	Legume density + Other vegetation density	0.86365 0.33651	0.0052949 -0.23428	0.066456 0.24791	-0.055866 -0.71648	0.4988	304.59
7	Succulent density + Legume density + Other vegetation density	0.62274 0.86989 0.38852	0.050655 0.0050438 -0.21307	0.25479 0.066136 0.27604	-0.15348 -0.056048 -0.70218	0.4954	306.35

Table 11. Linear mixed-effects models for total scorpion density of *C. vittatus* vs. plant densities at the La Union South. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Total Scorpion Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.9316	0.011034	0.2736	-0.25153	0.4795	145.8
2	Succulent density	0.44034	-2.4572	4.0061	-8.9206	0.5027	145.2
3	Legume density	0.85322	0.061257	0.73729	-0.61478	0.4806	145.78
4	Other vegetation density	0.96221	0.006437	0.28389	-0.2710Soil du2	0.4793	145.81
5	Succulent density + Legume density	0.43735 0.83594	-2.8116 -0.077072	4.5467 0.68413	-10.17 -0.83827	0.4828	147.16
6	Succulent density + Other vegetation density	0.22921 0.3549	-6.1892 -0.20073	4.176 0.23907	-16.554 -0.64052	0.5137	146.33
7	Legume density + Other vegetation density	0.85454 0.96755	0.060765 0.0055291	0.73879 0.28363	-0.61726 -0.27257	0.4581	147.78
8	Succulent density + Legume density + Other vegetation density	0.11686 0.30327 0.17197	-11.675 -0.47967 -0.37719	3.1589 0.46404 0.17685	-26.51 -1.4234 -0.93123	0.5297	147.24

Table 12. Linear mixed-effects models for scorpion size class I density of *C. vittatus* vs. plant densities at the La Union South. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size Class I Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.22424	0.048871	0.12972	-0.03198	0.5349	84.554
2	Succulent density	0.21243	-1.2477	0.76256	-3.2581	0.5375	84.475
3	Legume density	0.77856	0.029498	0.24359	-0.18459	0.4824	85.985
4	Other vegetation density	0.22234	0.051844	0.13725	-0.033563	0.5353	84.542
5	Succulent density + Legume density	0.20607 0.72162	-1.4372 -0.041212	0.84766 0.19515	-3.7221 -0.27758	0.9419	86.345
6	Succulent density + Other vegetation density	0.63883 0.69425	-0.75154 0.026689	2.5172 0.16538	-4.0203 -0.112	0.5229	86.317
7	Legume density + Other vegetation density	0.80695 0.22586	0.024927 0.051472	0.23353 0.13703	-0.18368 -0.034089	0.5196	86.481
8	Succulent density + Legume density + Other vegetation density	0.67103 0.88755 0.82735	-0.9912 -0.020954 0.01898	3.7839 0.28282 0.19733	-5.7663 -0.32473 -0.15937	0.5020	88.296

Table 13. Linear mixed-effects models for scorpion size class II density of *C. vittatus* vs. plant densities at the La Union South. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size Class II Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.53402	0.029521	0.12608	-0.067039	0.9401	93.787
2	Succulent density	0.39336	-1.0059	1.3826	-3.3943	0.5078	93.437
3	Legume density	0.24017	0.14235	0.38628	-0.10158	0.5315	92.771
4	Other vegetation density	0.82971	0.010821	0.11353	-0.09189	0.9389	94.135
5	Succulent density + Legume density	0.72916 0.37991	-0.45414 0.12001	2.2263 0.39729	-3.1346 -0.15728	0.5154	94.648
6	Succulent density + Other vegetation density	0.26434 0.45168	-2.1306 -0.060494	1.7216 0.10296	-5.9828 -0.22394	0.5079	94.858
7	Legume density + Other vegetation density	0.24318 0.85907	0.14158 0.0087052	0.38608 0.10899	-0.10293 -0.091581	0.5122	94.738
8	Succulent density + Legume density + Other vegetation density	0.69124 0.60045 0.79204	-1.0866 0.09128 -0.026913	4.5128 0.4475 0.1822	-6.686 -0.26494 -0.23605	0.4960	96.577

Table 14. Linear mixed-effects models for scorpion size class III density of *C. vittatus* vs. plant densities at the La Union South. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size Class III Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.29566	-0.032646	0.030377	-0.095669	0.9424	71.601
2	Succulent density	0.6732	0.33059	1.9285	-1.2674	0.4864	72.538
3	Legume density	0.2968	-0.083904	0.078465	-0.24627	0.5211	71.606
4	Other vegetation density	0.48942	-0.022927	0.044476	-0.090329	0.4982	72.231
5	Succulent density + Legume density	0.93499 0.338449	-0.071281 -0.087411	1.7169 0.097572	-1.8595 -0.27239	0.5005	73.599
6	Succulent density + Other vegetation density	0.84138 0.55999	-0.2533 -0.031405	2.3355 0.078438	-2.8421 -0.14125	0.4780	74.190
7	Legume density + Other vegetation density	0.30441 0.50452	-0.081976 -0.021702	0.079455 0.044511	-0.24341 -0.087914	0.5167	73.150
8	Succulent density + Legume density + Other vegetation density	0.15489 0.082088 0.11709	-2.5307 -0.19912 -0.10466	1.0321 0.027533 0.028406	-6.0934 -0.42577 -0.23772	0.5635	73.066

Table 15. Linear mixed-effects models for scorpion size class IV density of *C. vittatus* vs. plant densities at the La Union South. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size Class IV Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.66909	-0.034712	0.13085	-0.20028	0.4866	121.83
2	Succulent density	0.79188	-0.53421	3.5979	-4.6663	0.4820	121.94
3	Legume density	0.89865	-0.026688	0.40121	-0.45459	0.9388	122.00
4	Other vegetation density	0.69805	-0.033301	0.14174	-0.20835	0.4853	121.86
5	Succulent density + Legume density	0.71212 0.77349	-0.84894 -0.068455	3.8516 0.4178	-5.5495 -0.55471	0.4630	123.86
6	Succulent density + Other vegetation density	0.3494 0.32817	-3.0538 -0.13552	3.5596 0.14509	-9.6672 -0.41612	0.4979	122.96
7	Legume density + Other vegetation density	0.90955 0.70137	-0.023762 -0.032946	0.40417 0.14258	-0.4517 -0.20847	0.9367	123.84
8	Succulent density + Legume density + Other vegetation density	0.13328 0.23661 0.13236	-7.0669 -0.35088 -0.2646	2.3342 0.24719 0.086519	-16.468 -0.94894 -0.61572	0.5269	123.52

In La Union Ranch, eight models were generated for *C. vittatus* total scorpion density. None of the models had a significant association between scorpion density and plant densities (Table 16). Seven models were generated for *C. vittatus* size class I. Significant association between scorpion density and plant densities were obtained for four models. Model 2 showed a positive slope and a significant association between the scorpion density of size class I and succulent density (Table 17). Model 3 showed a positive slope and a significant association between scorpion density size class I and legume density (Table 17). Model 6 showed a positive slope and a significant association between scorpion density of size class I and the density of succulents but not with other vegetation (Table 17). Model 7 showed a significant association between scorpion density of size class I and the density of legumes but not with other vegetation (Table 17). Models 5 through 7 had the highest R^2 and lowest AIC values (Table 17). Seven models were generated for *C. vittatus* size class II. None of the models showed a significant association between scorpion density and plant densities (Table 18). Seven models were generated for *C. vittatus* size class III. None of the models showed a significant association between scorpion size density and plant densities (Table 19). Seven models were generated for *C. vittatus* size class IV. Significant associations between scorpion density and plant densities were obtained for six models. Model 1 showed a negative slope and a very significant association between scorpion density of size class IV and total plant density (Table 20). Model 3 showed a negative slope and a very significant association between scorpion density of size class IV and legume density. Model 4 showed a negative slope and a very significant association between scorpion density for size class IV and other vegetation density (Table 20). Model 5 showed a significant association between scorpion density for size class IV and the densities of succulents and other vegetation (Table 20). The slope in Model 5 for scorpion density and

succulent density was negative, while the slope for scorpion density and legume density was a positive one. Model 6 showed a significant association between scorpion density for size class IV and the density of other vegetation but not with succulents (Table 20). Model 7 showed a significant association between scorpion density for size class IV and the density of other vegetation but not with legumes (Table 20). Models 5 through 7 had the highest R^2 and lowest AIC value (Table 20).

In La Union South, eight models were generated for *V. waueri.* All size classes were pooled together as total scorpion density due to the low surface activity displayed by this burrowing scorpion and low sampled numbers. A total of eight models were generated for *V. waueri*. Model 5 showed a positive slope and a significant association between total scorpion density and the density of legumes but not with succulents (Table 21). Model 8 showed a positive slope between total scorpion density and succulents (Table 21). Model 8 also showed a positive slope and a significant association between total scorpion density and legumes (Table 21). Model 5 had the highest R^2 and Model 8 had the lowest AIC value (Table 21).

In La Union South, eight models were constructed for *C. vittatus* total size classes. None of the models showed a significant association between scorpion density and plant densities (Table 11). Eight models were generated for *C. vittatus* size class I. None models showed a significant association between scorpion density and plant densities (Table 12). Eight models were generated for *C. vittatus* size class II. None of the models showed a significant association between scorpion density and plant densities (Table 13). Eight models were generated for *C. vittatus* size class III. No models showed a significant association between scorpion density and plant densities (Table 14). Eight models were generated for *C. vittatus* size class IV. None of the models showed a significant association between scorpion density and plant densities (Table 15).

Table 16. Linear mixed-effects models for total scorpion density of *C. vittatus* vs. plant densities at the La Union Ranch. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Total Scorpion Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.086832	-0.044396	0.008073	-0.096865	0.6807	54.9
2	Succulent density	0.41777	-0.1511	0.25675	-0.55895	0.5092	57.422
3	Legume density	0.46256	0.13701	0.5465	-0.27248	0.4973	57.548
4	Other vegetation density	0.11135	-0.039303	0.011348	-0.089954	0.6571	55.349
5	Succulent density + Legume density	0.12063 0.12923	-0.33084 0.32126	0.11199 0.76308	-0.77367 -0.12055	0.6389	56.832
6	Succulent density + Other vegetation density	0.49009 0.12923	-0.11423 -0.037152	0.25667 0.013941	-0.48513 -0.088246	0.6389	56.832
7	Legume density + Other vegetation density	0.49009 0.12063	-0.16942 -0.056745	0.38068 0.019208	-0.71952 -0.1327	0.6389	56.832

Table 17. Linear mixed-effects models for scorpion size class I density of *C. vittatus* vs. plant densities at the La Union Ranch. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size Class I Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.82274	0.001963	0.021518	-0.017592	0.4462	35.16
2	Succulent density	**0.022001**	-0.12297	-0.02292	-0.22302	0.7842	29.317
3	Legume density	**0.023978**	-0.12133	-0.02064	-0.22203	0.7789	29.492
4	Other vegetation density	0.43411	0.0063958	0.024306	-0.011515	0.5047	34.557
5	Succulent density + Legume density	0.12745 0.14039	-0.080024 -0.076766	0.029423 0.03243	-0.18947 -0.18596	0.8216	28.877
6	Succulent density + Other vegetation density	**0.011453** 0.14039	-0.13178 0.0088776	-0.04011 0.021505	-0.22345 -0.0037504	0.8216	28.877
7	Legume density + Other vegetation density	**0.011453** 0.12745	-0.19545 -0.013725	-0.05949 0.005047	-0.33141 -0.032497	0.8216	28.877

Table 18. Linear mixed-effects models for scorpion size class II density of *C. vittatus* vs. plant densities at the La Union Ranch. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size Class II Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.63042	0.0063595	0.035679	-0.02296	0.4643	43.261
2	Succulent density	0.76613	0.027019	0.22947	-0.17543	0.4480	43.414
3	Legume density	0.87003	-0.014848	0.18781	-0.2175	0.4407	43.48
4	Other vegetation density	0.66328	0.0054369	0.033176	-0.022302	0.4596	43.306
5	Succulent density + Legume density	0.63972 0.69066	0.051315 -0.043426	0.2994 0.20409	-0.19677 -0.29094	0.3899	45.243
6	Succulent density + Other vegetation density	0.8092 0.69066	0.022035 0.005022	0.22982 0.033646	-0.18575 -0.023602	0.3899	45.243
7	Legume density + Other vegetation density	0.8092 0.63972	0.032681 0.0088013	0.34086 0.051352	-0.2755 -0.033749	0.3899	45.243

Table 19. Linear mixed-effects models for scorpion size class III density of *C. vittatus* vs. plant densities at the La Union Ranch. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size Class III Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.8626	0.001963	0.027292	-0.023366	0.4411	40.335
2	Succulent density	0.093371	-0.12297	0.025953	-0.2719	0.6739	32.273
3	Legume density	0.097566	-0.12133	0.027844	-0.27051	0.6698	37.352
4	Other vegetation density	0.54757	0.0063958	0.029885	-0.017093	0.4786	39.98
5	Succulent density + Legume density	0.31497 0.33264	-0.080024 -0.076766	0.094808 0.097665	-0.25485 -0.2512	0.6818	38.245
6	Succulent density + Other vegetation density	0.070875 0.33264	-0.13178 0.0088776	0.014651 0.02905	-0.27822 -0.011294	0.6818	38.245
7	Legume density + Other vegetation density	0.070875 0.31497	-0.19545 -0.013725	0.021729 0.016261	-0.41263 -0.043712	0.6818	38.245

Table 20. Linear mixed-effects models for scorpion size class IV density of *C. vittatus* vs. plant densities at the La Union Ranch. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Size Class IV Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	**0.0033021**	-0.054681	-0.02414	-0.085219	0.8725	44.075
2	Succulent density	0.6583	0.067825	0.40842	-0.27277	0.4603	53.817
3	Legume density	**0.0012664**	0.39452	0.58197	0.20707	0.9015	41.92
4	Other vegetation density	**0.00032054**	-0.057532	-0.03545	-0.079614	0.9316	39.745
5	Succulent density + Legume density	**0.014321** **0.00012961**	-0.22211 0.51822	-0.05984 0.68012	-0.38438 0.35632	0.9495	36.754
6	Succulent density + Other vegetation density	0.062359 **0.00012961**	0.1273 -0.059929	0.26321 -0.04121	-0.0086148 -0.078652	0.9495	36.754
7	Legume density + Other vegetation density	0.062359 **0.014321**	0.1888 -0.038095	0.39038 -0.01026	-0.012777 -0.065927	0.9495	36.754

Table 21. Linear mixed-effects models for total scorpion density of *V. waueri* vs. plant densities at the La Union South. Models were constructed to determine whether there was a synergistic relationship between plant densities and scorpion densities. Models that were significant (P<0.05) and those that were not significant were included for comparison.

Total Scorpion Density

Model	Variable	P-value	Slope	Upper 95%	Lower 95%	R^2	AIC
1	Total plant density	0.8506	0.0062217	0.073666	-0.061223	0.4832	75.126
2	Succulent density	0.42263	-0.656	1.0036	-2.3156	0.5045	74.505
3	Legume density	0.095829	-0.13826	0.026348	-0.30287	0.5770	72.319
4	Other vegetation density	0.36511	0.031387	0.10156	-0.038784	0.5112	74.324
5	Succulent density + Legume density	0.051606 **0.015295**	-1.6692 -0.22039	0.01264 -0.046402	-3.3511 -0.39437	0.9555	70.412
6	Succulent density + Other vegetation density	0.88428 0.65587	-0.19181 0.024967	2.5043 0.13936	-2.8879 -0.08943	0.4908	76.302
7	Legume density + Other vegetation density	0.083955 0.30709	-0.14124 0.033497	0.020503 0.099837	-0.30298 -0.032842	0.5898	73.25
8	Succulent density + Legume density + Other vegetation density	**0.027418** **0.0054159** 0.14232	-3.8404 -0.319 -0.09239	-0.46907 -0.10453 0.033524	-7.2117 -0.53347 -0.2183	0.6885	70.194

Geographic Information Systems (GIS) was used to identify the different soil types that make up the four habitats (SSURGO) (Table 22). The site at Texas A&M International University was made up mainly by three soil types: CpB, JQC (gravelly sandy clay loam), and MgC. The CpB had a moderately deep rooting zone. Rooting zone for this soil type was shallow. The MgC had a deep rooting zone. This soil type had lower soil strength than the JQC soil but higher than the CpB (SSURGO). The habitat in the Martinez Ranch was composed of a single soil type, CpB (Figure 13). Although, wildlife is common on this type of soil, plants can still provide thick brush that can be used as cover by scorpions (SSURGO). Different soil types surrounded the Martinez Ranch. Because of its low soil strength, it was inferred that it may be a suitable habitat for burrowing and errant scorpions. The site in La Union South had a combination of soil types with low and extremely low soil strength (Figure 14). This habitat was composed by five soil types: CoB, FaC, HeB, VMD, and NSC (Table 22). The CoB is mostly loamy sand with a deep rooting zone. A major use for this soil type is rangeland and wildlife habitat. The lack of water in this type of soil may limit bird populations from inhabiting this soil (SSURGO). The FaC is mostly fine sand with a deep rooting zone. Typical vegetation found on this soil type were grasses and live oaks (SSURGO). Like CoB, HeB appeared to be an adequate soil type for scorpion habitats. Soil types in this habitat had mostly low soil strength, except for small areas where caliche roads had been overgrown by grasses (SSURGO). The NSC has mostly low soil strength, composed by mainly fine sand. Soil type is well suited for wildlife. Some woody plants and grasses can be found on this type of soil. Soils types with low soil strength in this ranch may allow for burrowing by scorpions (SSURGO). The VMD is a shrubby with short to medium grasses. Prickly pear cactus, mesquite, and leather stem are some of the common plants found in this soil type. This soil type can be used for livestock production and

make for good wildlife habitats (SSURGO). The habitat in La Union Ranch had a combination

of high and low soil strengths. This habitat was composed by three soil types: BeB, CpC, and

HeB (Figure 15). The BeB has major use in livestock grazing, forage production and wildlife

habitat. Common plant species in this soil type were mesquite trees, Texas ebony, desert

hackberry and grasses (SSURGO). The CpC is a major use for livestock production and wildlife

habitat. Vegetation provides adequate cover and food plants. Wildlife animals are common on

this soil type (SSURGO). The HeB is mostly loamy fine sand with a deep rooting zone. A major

use for this soil type is rangeland and wildlife habitat. The lack of water may inhibit bird

populations (SSURGO).

Table 22. Soil types for the four habitats. Sand composition (%) in each of the soil types. Proportion of sand breakdown (%) relative to total soil type: Very coarse sand (VCS), Coarse sand (CS), Medium sand (MS), Fine sand (FS), Very fine sand (VFS).

Habitats	Soil Types	Sand %	VCS %	CS %	MS %	FS %	VFS %
TAMIU	Jimenez-Quemado Complex	53	4	10	12	16	11
	Copita Fine Sandy Loam	64	0	2.2	13.7	31.8	16.3
	Moglia Clay Loam	30	0.2	0.5	1.8	15.6	11.9
Martinez Ranch	Copita Fine Sand	64	0	2.2	13.7	31.8	16.3
La Union South	Falfurias Fine Sand	97	0	1.3	18.3	63.2	14.2
	Nueces-Sarita Complex	92	0.044	0.844	11.722	67.333	11.722
	Comitas Loamy Fine Sand	86	0	2	14.9	45.3	23.8
	Hebbronville Loamy Fine Sand	80	2	3	20	35	20
	Verick-Copita-Maverick association	57	0.367	2.311	12.189	27.911	14.433
La Union Ranch	Hebbronville Loamy Fine Sand	80	2	3	20	35	20
	Brennan Fine Sandy Loam	67	0.1	3.1	15.2	32.1	16.5
	Copita Fine Sandy Loam	64	0	2.2	13.7	31.8	16.3

Figure 13. Map of the Martinez Ranch showing soil type and data collection plots. Plots are labeled by the dates in which data was collected. Plots surveyed on the same day are color coded with the same color.

Figure 14. Map of La Union Ranch showing soil type and data collection plots. Plots are labeled by the dates in which data was collected. Plots surveyed on the same day are color coded with the same color.

Figure 15. Map of La Union South showing soil type and data collection plots. Plots are labeled by the dates in which data was collected. Plots surveyed on the same day are color coded with the same color.
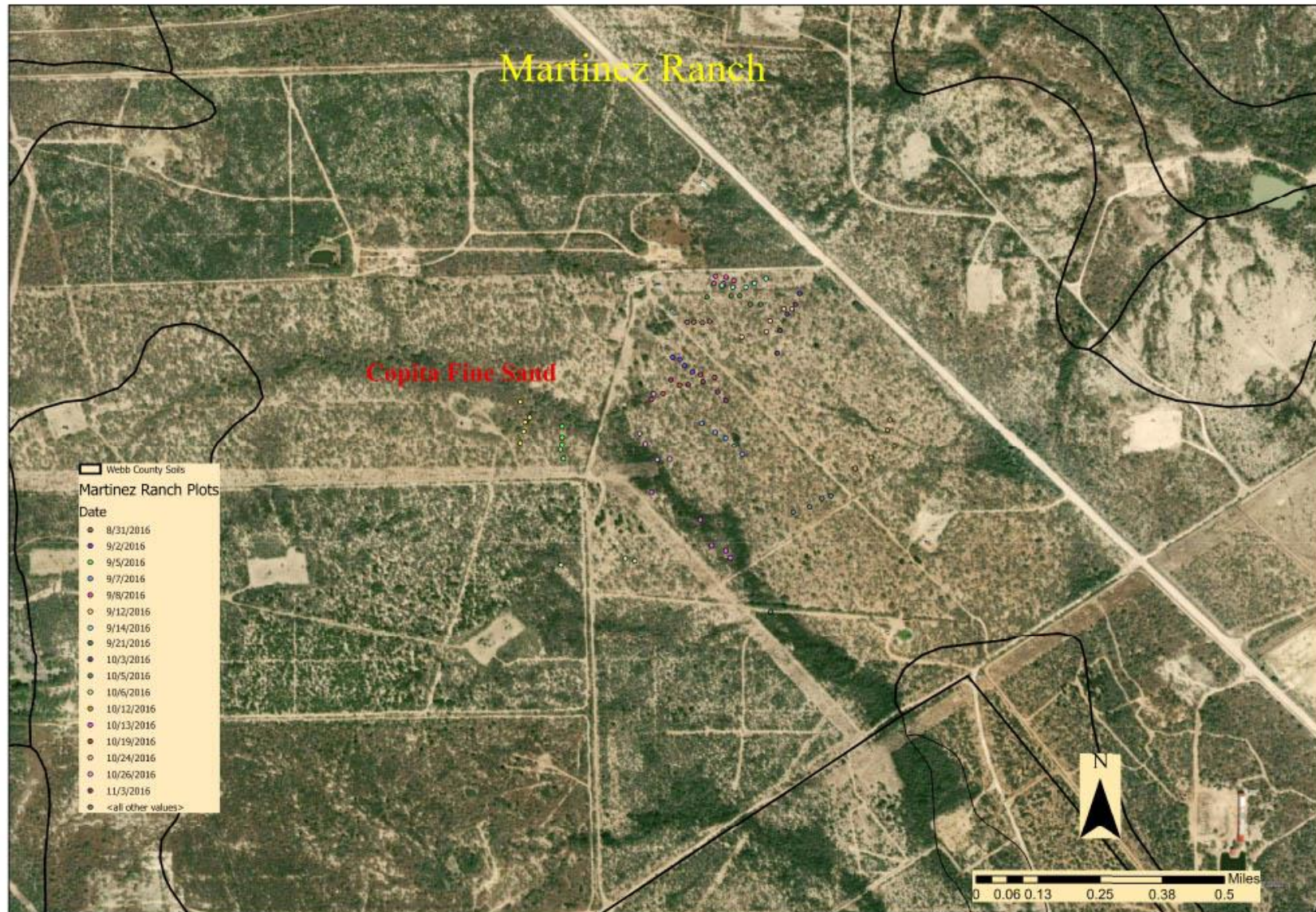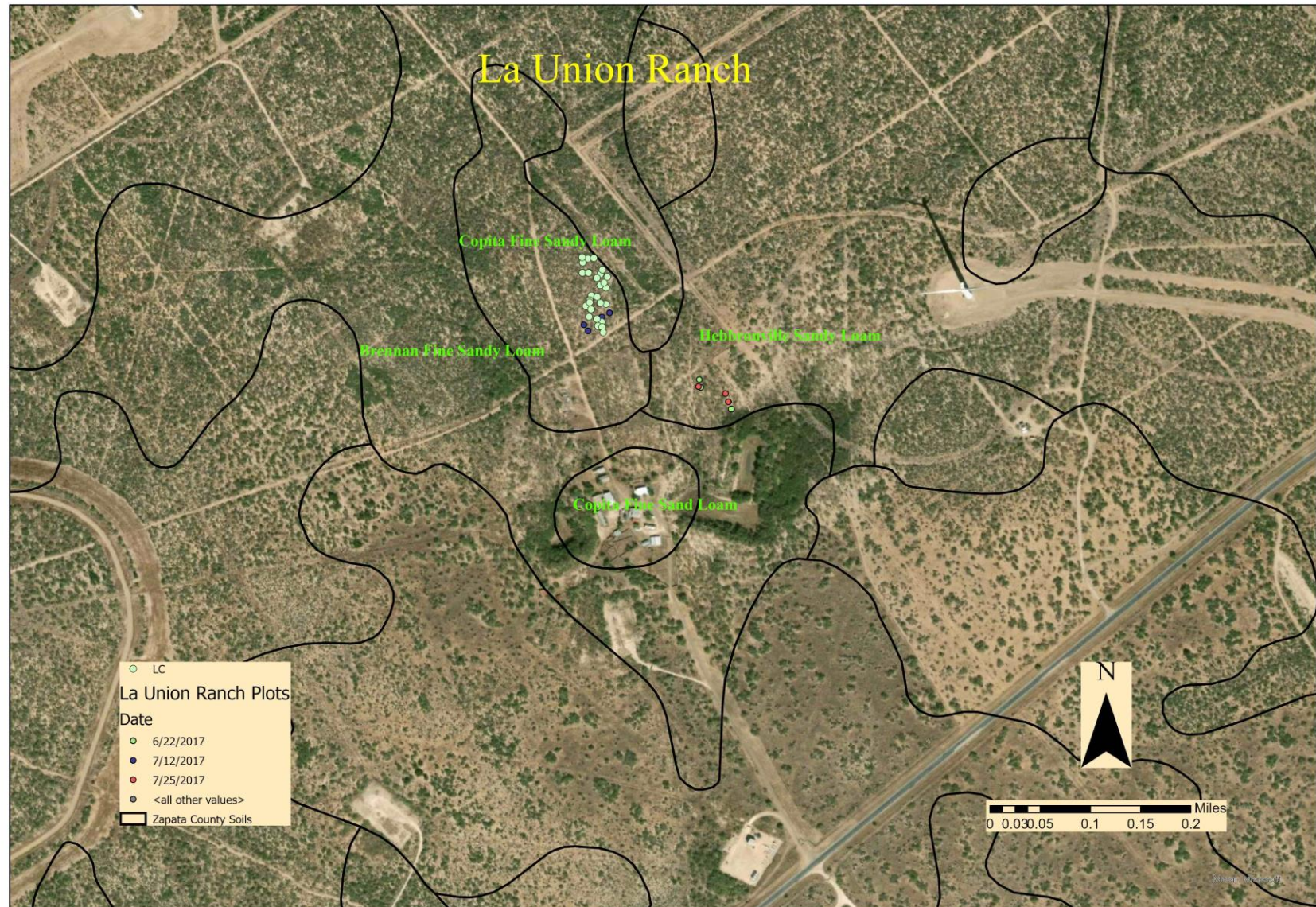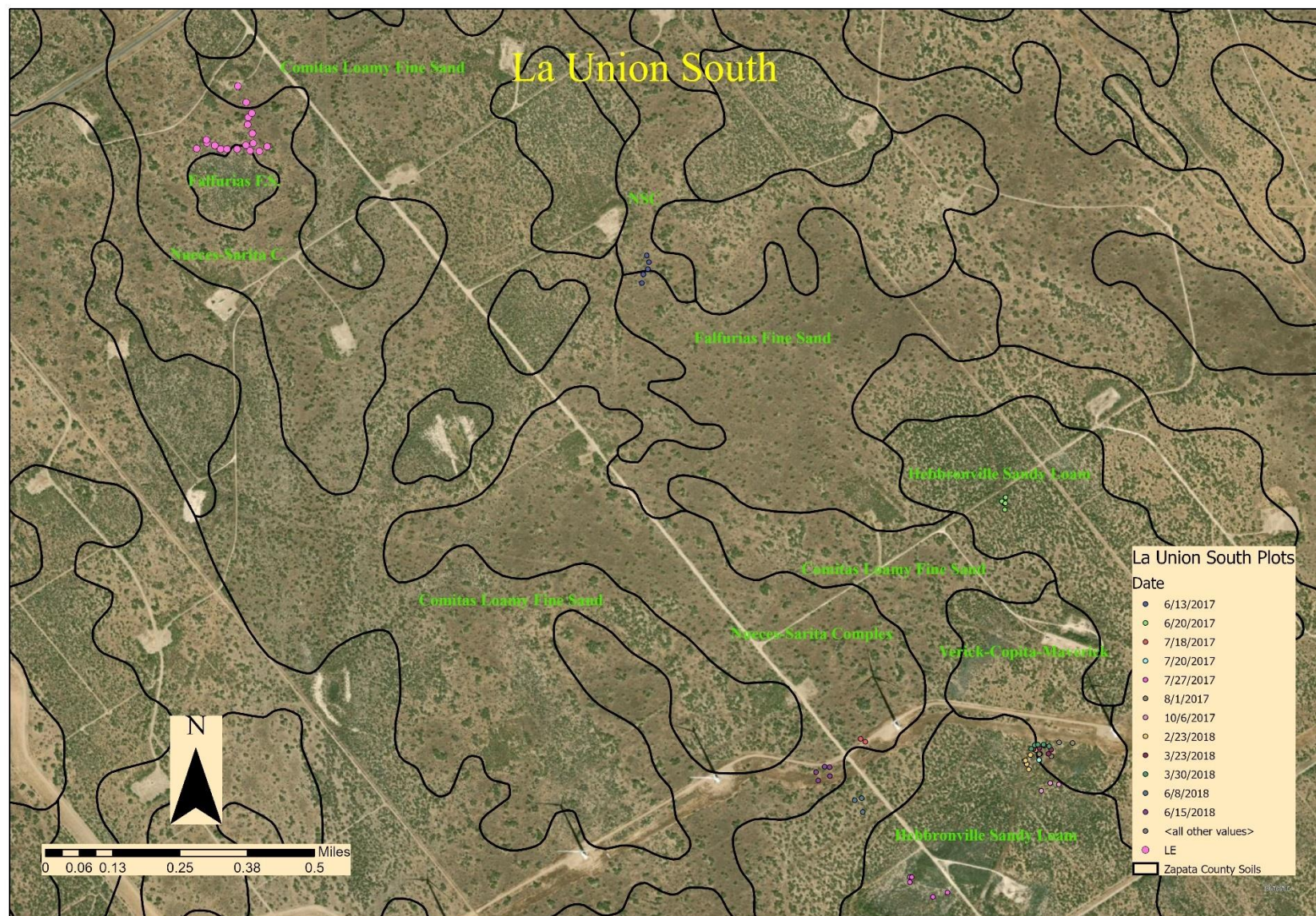
DISCUSSION

Martinez Ranch

Co-existence between *C. vittatus* and *V. waueri* was shown to occur in the four habitats. Co-existence can be made possible through the difference in microhabitat use among habitats. Microhabitat use by scorpions shows that there is no preference for the use of any microhabitat in the Martinez Ranch. Other studies have shown a higher than the expected frequency of *C. vittatus* on strawberry cacti and prickly pear cacti (McReynolds 2008); however, my results show no preferred microhabitat use in the Martinez Ranch (Table 1). It is suggested that scorpions may climb on vegetation when avoiding predation risk or when foraging (Brown and O'Connell 2000, McReynolds 2008, 2012). Showing no preference for any microhabitat may mean predation risk may be reduced no matter what plant species a scorpion climbs. Another possibility may be that the foraging success rate may be similar among all plant species. A third possibility can be that scorpions are climbing vegetation in search of moths and other nocturnal flying insects (McCormick and Polis 1990; McReynolds 2022). They may also be climbing on vegetation to feed on prey captured on the ground (McReynolds 2022). Perhaps caterpillar and other prey availability were low on vegetation.

The frequency table (Table 1) for the Martinez Ranch shows the frequency of *C. vittatus* and *V. waueri* on microhabitats. It also shows the microhabitats survey. Mesquite was the most abundant microhabitat (n = 173) (Table 1). Mesquite also had the highest frequency of *C. vittatus* (n = 31) (Table 1). Previous studies have found vegetation important for errant scorpions (McCormick and Polis 1990) but not so much for burrowing scorpions (Polis 1979). Blackbrush was considered an important foraging plant for *C. vittatus* because of its high abundance of caterpillars (McReynolds 2008, 2012, 2022). However, the frequency of scorpions on mesquite

in the Martinez Ranch does not support that claim. A possible explanation may be that plants with the highest abundance have a higher probability of being used as microhabitats. This can mean that prey availability may have little influence on the frequency of scorpions in microhabitats. Perhaps the higher availability of mesquite trees in the Martinez Ranch increases the frequency of mesquite trees encountered. My result for mesquite trees was not consistent with previous studies conducted on the TAMIU campus in which mesquite trees comprised 2 of the 180 (1.1%) surveyed plants (McReynolds 2008). Ground (n = 193) and grass (n = 94) (not surveyed) had the highest frequency of *C. vittatus* of all microhabitats; *V. waueri* was only observed on the ground (n = 3). McReynolds (2022) reported a high frequency of scorpions on the ground. Possibly foraging for prey or seeking refuge (McReynolds 2022). Ground and grass were important microhabitats for scorpions in the Martinez Ranch, with 44% on the ground, 22% on grass, and only 17% on trees. McReynolds (2008) reported very different frequencies of microhabitat use by *C. vittatus* in the TAMIU campus, with more than half of the scorpions using trees as microhabitats. Microhabitat use between habitats can be further investigated to determine causation for such variation. Other plants, such as huisachillo and prickly pear cacti, were important microhabitats for *C. vittatus*. Huisachillo and prickly pear cactus were the second and third most frequently surveyed microhabitats (n = 155 and 122, respectively). They were also the second and third most frequently occupied by *C. vittatus.* Again, the high frequency of huisachillo and prickly pear may lead to a higher encounter rate by *C. vittatus;* therefore, prey availability may be of very little influence on the frequency of scorpions on microhabitats.

La Union South

Microhabitat use by scorpions shows catclaws being used at a much lower frequency than expected (Figure 8). This is particularly interesting because, like mesquite trees; one would

assume that a greater abundance of catclaws may present more microhabitats for scorpions; this, however, is not shown to be true. Catclaw grows sharp prickles on its stem. Unlike catclaws, mesquite trees grow spines at the base of leaves in place of stipules. Internodes in catclaws are covered in alternating sharp prickles, while mesquite trees are not. Catclaw stems may make it difficult for scorpions to climb. This may be especially challenging when scorpions are carrying or capturing prey, making it more difficult for them to climb. Further studies can seek to determine other explanations as to why catclaw is being used at a much lower proportion than expected.

Other legumes, such as blackbrush, have been reported to make suitable habitats for caterpillars, an important prey for scorpions in South Texas (McReynolds 2008, 2020). This is an important comparison because it may explain why scorpions may choose to climb some legumes at a higher frequency than catclaws. Studies report scorpions using vegetation as a foraging site or refuge; thus, catclaws may have a negative effect on their ability to do so (Brown and O'Connell 2000; McReynolds 2008, 2012). *Centruroides vittatus* was previously reported to have a lower-than-expected frequency on tasajillo (McReynolds 2008). It was suggested that tasajillo did not provide a suitable refuge for scorpions due to its thin stems and low prey availability (McReynolds 2008). McReynolds (2012) reported a low frequency of size class IV scorpions on tasajillo, suggesting that it may not be a suitable refuge for scorpions. Through future studies, I would seek to compare arthropod diversity on plants with prickles versus plants without prickles. I would also be interested in testing the hypothesis that scorpions, especially the larger ones, discriminate against plants such as catclaw and tasajillo with thin and prickled stems.

Microhabitat use by scorpions showed other vegetation being used in a significantly higher proportion than what was expected (Figure 8). Allthorn goatbush and coma were

important microhabitats for *C. vittatus* in La Union South (Table 2). Blackbrush was not considered an important microhabitat for scorpions (Table 2). A previous study predicted that scorpions foraging on blackbrush would increase when caterpillar availability would also increase (McReynolds 2008). However, my findings suggest that *C. vittatus* has no microhabitat preference for blackbrush in La Union South. I wish to focus future work on measuring prey availability to determine a possible reason why scorpion may choose some plant types over other.

The frequency table shows catclaws being the most abundant microhabitat in La Union South (Table 2). However, scorpions rarely used catclaws as microhabitats (Table 2). Spanish dagger was an important microhabitat for *C. vittatus* (Table 2). Spanish dagger had the highest frequency of scorpions, making it the most important microhabitat for scorpions in La Union South (Table 2). Spanish daggers have been reported to be host to many species, including a variety of prey species (Garcia-Salas 2001). Other succulents like prickly pear cactus have been suggested to serve as a buffer against temperature changes (McReynolds 2008). A high number of potential prey and a buffer from temperature change may explain why spanish daggers frequently served as microhabitats for *C. vittatus*. Ground (Table 2) and grass (Table 2) had the highest frequency of *C. vitttatus*. *V. waueri* had the highest observed activity in La Union South, with all observed scorpions on the ground (n = 15). The higher frequency of *V. waueri* may be possible because of the soils with low soil strength that form La Union South (see Results). The higher frequency of *V. waueri* in La Union South should lead to a higher encounter frequency with *C. vittatus*. I am especially interested in observing the interaction rate between both scorpion species in La Union South. I hypothesize that the interaction rate should be minimal due

to distinct foraging in microhabitats; however, the interaction rate will fluctuate throughout the year as temporal changes force *C. vittatus* to exhibit a higher frequency of activity on the ground.

La Union Ranch

The proportion of scorpions observed on microhabitats was not significantly different in La Union Ranch. Microhabitat use by scorpions shows that there is no preference for the use of any microhabitat. The frequency table shows goldenweed being the most abundant microhabitat for La Union Ranch (Table 3). Goldenweed also had the highest proportion of scorpions in the surveyed microhabitats (Table 3). Allthorn goatbush was the second most frequently surveyed plant species (Table 3). It also had the second-highest proportion of scorpions in the surveyed microhabitats (Table 3). As previously suggested, plants with the highest abundance may have a higher probability of being used as a microhabitat by *C. vittatus*. Ground (Table 3) and grass (Table 3) had the two highest proportions of microhabitat use by both scorpion species.

TAMIU Campus

During the data collection period, scorpion numbers at TAMIU were extremely low. Due to the low sample size, I was unable to perform a goodness of fit test on the TAMIU data. The frequency table shows blackbrush being the most abundant microhabitat in the TAMIU campus (Table 4). Blackbrush also had the highest frequency of scorpions of all surveyed microhabitats (Table 4). This is consistent with my results for the Martinez and La Union Ranch, in which the most abundant plant species has the highest frequency of microhabitat use. The high frequency of scorpions on blackbrush is consistent with previous reports for the TAMIU campus (McReynolds 2004, 2008, 2012, 2020). However, the scorpion preference for blackbrush or plant species is inconsistent with this study. According to McReynolds (2008), blackbrush is a

preferred microhabitat for scorpions between the months of January-April when caterpillar availability is highest. He also suggested that seasonal shifts in microhabitats may be due to seasonal shifts in prey availability (McReynolds 2004, 2020, 2022). Further research comparing seasonal shifts in microhabitats can help identify differences between the different populations for each habitat. Comparing seasonal shifts in prey availability between the different habitats can also explain shifts in microhabitat use by the scorpions.

Frequencies of scorpions in microhabitats are different among the habitats. *Centruroides vittatus* has a high frequency on the ground and grasses but also occupies microhabitats on vegetation. *Vaejovis waueri* is less common, mostly always occupying ground microhabitats. My results have shown that a high abundance of one plant species may result in a higher frequency of scorpion occupancy of that plant, as is the case with mesquite trees in the Martinez Ranch and goldenweed in La Union Ranch. Exceptions to this interpretation of my results are possible. For example, scorpions did not choose catclaws proportionate to their abundance in La Union South. An explanation for this contradiction may be that not only do scorpions choose microhabitats based on availability but suitability as well. I am interested in testing this hypothesis to determine whether scorpions have evolved an innate behavior that allows them to discriminate unsuitable plants from those suitable before climbing them or if there may be an environmental cue that allows them to discriminate between plants. Brown and O'Connell (2000) suggested that *C. vittatus* walks randomly in its habitat following an increasing resource gradient in response to certain cues. Another speculation that may explain the high frequency of scorpions on the ground and grass was that during a period of low precipitation, scorpions are forced to forage away from the more common plant species. McReynolds (2004, 2008, 2022) suggested that the low activity of scorpions on vegetation may result from low prey activity. Periods with low precipitation

result in no new foliage on trees. Without new foliage, herbivorous insect activity on plants will also be low. This may push potential prey species to shift their microhabitat preferences to those plants that remain available during periods of low precipitation for plant cover or food. Hence, scorpions will follow wherever prey activity is highest (McReynolds 2008).

<p style="text-align:center">*Scorpion Size Class Frequencies*</p>

Scorpion densities can be influenced by predation risk and prey preferences. Size classes are affected by predation risk differently (Polis 1980a; Kaltsas 2008; McReynolds 2012). For instance, *P. mesaensis's* smaller classes were identified as the most vulnerable to cannibalism (Polis 1980b). A possible response by smaller classes of scorpions may be altering foraging frequency (Rudolf 2007). Additionally, it was suggested that juveniles choose to forage during sub-optimal conditions in order to avoid cannibalism (Kaltsas 2008). My results showed that the frequency of scorpions for each size class differed significantly among microhabitats for *C. vittatus*. The Martinez Ranch had a very high frequency of ground use. Size classes I and II used grasses more frequently than size classes III and IV. Results for size classes on grasses were consistent with other findings (McReynolds 2012). Legumes and other vegetation were used at a similar rate. Interestingly, a pattern between size classes can be seen that resembles a top-down effect. The frequency of size class IV on the ground, legumes, and other vegetation is higher than in size class III. The frequency of scorpions in all microhabitats was higher for size class I-II than size class III. Size classes I-II and III had a higher frequency on grasses than size class IV. A possible interpretation for this pattern may be that when the frequency of size class IV scorpions increases in a microhabitat, the risk of cannibalism increases for size class III. Size class III scorpions may respond to an increase in cannibalistic risk by shifting microhabitat use

towards a less optimal microhabitat. As the shift in microhabitats by size class III scorpions occur, size classes I-II may remain in microhabitats where the risk of cannibalism by size class III scorpions becomes lower. Intermediate-size classes have been shown to have low surface activity overlap with the largest-size classes (Polis 1980b), perhaps to avoid a risk of cannibalism. It may be possible that scorpions size class I-II may be more at risk of cannibalism by the intermediate size class III than by the larger size class IV scorpions. McReynolds (2012) suggested that younger scorpions avoid larger conspecifics in cacti. Brown and O'Connell (2000) indicated that juveniles should forage on vegetation to prevent encounters with predators. Perhaps size class III scorpions forage on grass at a higher frequency to facilitate the detection of larger conspecific. I suggest that the size class most at risk for predation is the intermediate size class, not the smallest. Future studies on cannibalism may seek to determine the frequency of cannibalism between size classes. This can help determine whether a top-down effect can occur in microhabitat use.

Microhabitat use in La Union Ranch showed a different distribution of scorpions from that at the Martinez Ranch. The number of scorpions on the ground and other vegetation showed a descending trend from the smallest size class to the largest in which size class I-II had the highest frequency, size class II the intermediate frequency, and size class IV the lowest. The number of scorpions on grass and legumes showed no apparent trend. Very few scorpions were found on grass and legumes. No evidence supports a top-bottom effect due to a risk of cannibalism in La Union Ranch; however, I suggest that a low frequency of size class IV microhabitat use may allow for a higher frequency of microhabitat use by the intermediate and smallest size classes of scorpions.

In La Union South, microhabitat use among scorpion size classes showed a similar pattern as in the Martinez Ranch. My results again show size classes I-II and IV using ground as a microhabitat at high frequencies. Scorpions size class III used ground at a much lower frequency. This may be an example of scorpions choosing to forage in sub-optimal environmental conditions when prey availability is low (Polis 1980a, McReynolds 2012). Further investigation is needed to determine the level of prey availability. Scorpions on grass and other vegetation were highest for size class I-II, intermediate for size III, and lowest for size IV. Scorpion size class IV showed a greater frequency of microhabitat use on legumes than the smaller size classes. It is important to recognize that the largest size class showed a tendency to occupy two microhabitats with the highest prey availability. McReynolds (2008, 2022) suggested that caterpillars were an important prey item for *C. vittatus* in south Texas. He also reported that scorpions used more blackbrush and captured more caterpillars during January-April (McReynolds 2008, 2022). Larger scorpions may occupy legumes at a higher frequency when prey availability is high (McReynolds 2008). However, during a period of low precipitation, prey availability tends to be lower on vegetation. Hence, scorpions are forced to shift to foraging on the ground instead.

I have discussed evidence that may provide insight into how scorpions use microhabitats. I have also discussed distinctions between scorpion size classes. I have offered possible explanations for why scorpion numbers vary between habitats and what may influence such trends. Understanding distinctions about microhabitat occupancy is essential when discerning how scorpion species may co-exist. For example, *C. vittatus* is an errant scorpion that actively forages on plants and ground (Hadley and Williams 1968; Polis 1990; Brown and O'Connell 2000; McReynolds 2008). However, as different size classes occupy different microhabitats, the

effects on other scorpion species may vary depending on the size class foraging each

microhabitat. On the contrary, *V. waueri* is a burrowing scorpion that infrequently leaves its

burrow to capture prey or find mates (Hadley and Williams 1968). Understanding the

microhabitat occupancy for each habitat by size classes can help discern whether these scorpion

species co-exist in competition or if one species is superior at using resources. Next, I will

discuss the densities of both scorpion species in the four habitats and provide possible

explanations for the differences in densities.

Scorpion densities

When discerning how *C. vittatus* and *V. waueri* may co-exist when using similar

resources in their habitats, an important characteristic to compare them by is their densities. For

example, intraguild predation has been shown to reduce the population growth of some guild

members (Polis et al. 1986). Hypothetically, if guild members are in direct competition with each

other, then the increase in density by one species can negatively affect the density of the other

(Polis et al. 1986). Polis and Holt (1992) reported that competition and predation might occur

when species share the same resources. Possible outcomes from the competition and intraguild

predation may be the exclusion of a species, coexistence, or habitat shift by the subordinate

species (Polis and Holt 1992). An interesting point was made by Cisneros and Rosenheim

(1997), suggesting that reducing the number of competing predators should reduce the

probability of cannibalistic encounters because there is less competition for prey. This leads me

to hypothesize that evolution, in this case, should favor intraguild predation over cannibalism

when prey availability is low. Polis (1980b) suggested that cannibalism is a responsive change to

a decrease in prey availability. In other words, cannibalism should increase only during low prey

availability periods and decrease when prey availability increases (Polis 1980b). For this reason,

intraguild predation by scorpions should be prioritized over cannibalism. This would mean that during a period of low precipitation when prey availability is low, competing species should increase the rate of intraguild predation. If this was the case, and a superior species was involved, the inferior species should respond by avoiding encounters with intraguild predators. Scorpion densities may be indicative of such evolutionary shifts in behaviors. Hence, co-existence between *C. vittatus* and *V. waueri* may continue to occur when one species is superior at intraguild predation and the other better at avoiding it by utilizing a different microhabitat.

Scorpion densities for both species varied significantly. *Centruroides vittatus* was significantly higher for the Martinez Ranch and La Union South than La Union Ranch and TAMIU campus. *Vaejovis waueri* also had the highest average density in La Union South. Although the density of *C. vittatus* was much greater than that of *V. waueri*, it is interesting that both species can be found in greater abundance in La Union South. It is possible that La Union South may provide more resources or may make for a better scorpion habitat than the other habitats. Scorpion density for *C. vittatus* was not significantly lower at the Martinez Ranch than at La Union South.

Scorpion densities for *C. vittatus* at La Union Ranch and the TAMIU campus were significantly lower than the two previously mentioned ranches. Average scorpion densities for *V. waueri* were extremely low for all habitats. All habitats had average scorpion densities lower than 1 per 50 square meters. A possible explanation for the low densities is that *V. waueri* may be excluded from those habitats by competition, intraguild predation, or other predators (Bradley and Brody 1984). Another possible reason can be that *V. waueri* spends most of its time within its burrow and only emerges to capture prey or find a mate (Hadley and Williams 1968). If their surface activity depends on the rate at which they metabolize meals and mating opportunities,

then could their burrowing behavior be an evolutionary response to predation risk and/or

competition (Hadley and Williams 1968; Polis 1980a)? It would be interesting to know whether

V. waueri's densities are consistently low, especially when intraguild predation risk is low.

Additional studies may seek to explain whether the densities of burrowing scorpions on the

surface can be influenced by lower competition and predation risk.

Scorpion densities may be evaluated for patterns showing an association that can

contribute to the co-existence between species. Associations such as competition and intraguild

predation can affect densities (Polis et al. 1989; Polis and Holt 1992). Therefore, it is possible to

understand how scorpion species may co-exist by evaluating scorpion densities in habitats.

Synergy: Association between plants and C. vittatus

I suggest there must be a synergistic effect placed on scorpion densities by the

composition of plant populations. I believe that individual plants provide varying effects

depending on their size and foraging benefit. For example, larger plants may offer more cover

protection from predatory risk (McReynolds 2004, 2008; Segoli et al. 2016). Plants with denser

foliage may also provide a higher diversity of prey availability. I focused my study on

identifying possible association between groups of plants and how they can affect scorpions'

densities at different size classes. My results have showed variation in microhabitats use among

habitats. They have also shown that densities of the different size classes vary in microhabitat

use. Synergy between plants may show the effects of plant densities on the densities of the

different size classes and species. The strength of the synergistic effect depended on plant

species composition and the densities of each plant group. Each model in my results shows how

significant the synergistic effect was on scorpion density. It is important to compare models that

are not significant to those that were significant because they can offer no effect with one plant type on its own but a significant effect when combined with a second or third plant type.

In the Martinez Ranch, when succulent density was modeled alone, it showed a positive association with *C. vittatus* size class I. However, when analyzed with legumes or other vegetation, succulent density had no significant effect on size class I density. A possible explanation for this is that an increase in succulent density may allow for size class I scorpion densities to increase. Perhaps under conditions presented in the Martinez Ranch, higher densities of succulents can provide microhabitats with lower predation risk or higher prey availability. When modeled alone, other vegetation density showed a positive synergistic effect on *C. vittatus* size class II scorpions. When analyzed with succulent or legume densities, other vegetation had no significant effect on size class II scorpion density. Contrary to size class I scorpions, higher succulent density can lead to a lower density of *C. vittatus* size class II. On the other hand, an increase in other vegetation may lead to an increase in size class II density. Segoli et al. (2016) reported that isopod survivorship in plots with plant cover was higher than in plots without plant cover. This suggests that scorpions' survivorship may be directly correlated with plant cover or density. Another possibility may be that smaller scorpions avoid microhabitats occupied by larger scorpions (McReynolds 2012, 2022); hence, succulents and other vegetation may offer smaller scorpions refuge from cannibalism. Consistent with previous studies, some succulents have been shown to have higher than the expected frequency of *C. vittatus* (McReynolds 2008). However, McReynolds (2012) reports a higher frequency of size class IV scorpions on succulents, not size class I.

Plant densities in La Union South did not have a strong synergistic effect on any of the *C. vittatus* size classes. Synergistic effects on scorpion size classes were not observed. Perhaps

other environmental factors such as temporal changes, environmental variability, predation risk, or soil types (Hadley and Williams 1968; Polis 1980a; Bradley and Brody 1984) may influence scorpion densities in La Union South.

Plant densities had a significant effect on *C. vittatus* in La Union Ranch. When modeled separately, succulents and legumes have a strong synergistic effect on the density of size class I scorpions (Table 17). Both plant densities showed a negative association with scorpion densities. Something noteworthy is that when modeled together, the negative effects became weaker. Interestingly, the negative synergistic effect was not there when plant densities were modeled as total density. One possible explanation for this phenomenon may be that succulents and legumes have higher prey availability or may serve as refuges (Brown and O'Connell 2000; McReynolds 2008); therefore, larger size classes may occupy those plants. Polis (1980b) suggested that cannibalism may contribute to population regulation. He reported that cannibalism increases due to increasing densities (Polis 1980b). In other words, cannibalism helps adjust the population size to the habitat's resource base (Polis 1980b). The risk of cannibalism may explain the lower density of size class I scorpions on succulents and legumes as a response to the cannibalism risk. High prey availability may also explain why the negative synergistic effect is weakened when succulent and legume densities increase.

There was no evidence of a synergistic effect on size class II and III scorpion densities. However, the synergistic effect on size class IV scorpion density was significant (Table 20). Total plant density had a significant negative association with size class IV scorpion density. Interestingly, the effect was a negative one. A possible explanation for this can be that prey availability may have been low on succulents and other vegetation in La Union Ranch (McReynolds 2022). However, it has been reported that prey availability is not the only reason

adult scorpions are active (McReynolds 2022). Scorpions may be active on the ground when males are searching for mates, courting, or when females are carrying young (McReynolds 2020). Legumes had a strong positive association with size class IV. Other vegetation densities had a strong negative association with scorpion density. One possible factor is that size class IV had a stronger association with legumes because they could have had higher prey availability. Succulents and other vegetation could have had low prey availability; thus, size class IV scorpions did not use those microhabitats.

Synergy: Association between plants and V. waueri

Plant densities had a significant effect on *V. waueri* in La Union South (Table 21). When modeled alone, succulent density showed a weak negative effect on scorpion density; however, when analyzed in synergy with legumes, the synergistic effect exhibited by succulents increased in significance. Legumes had a strong negative effect on the scorpion density throughout (Table 21). Results show an interesting change in the synergistic significance between plant densities. The synergy between succulents and legumes reveals an important association. It is important to understand this association because it can identify legume density as a hotspot for competition, intraguild predation risk, or other environmental factors that may exclude *V. waueri*. Perhaps *C. vittatus* is better at utilizing space near succulents and legumes which leads to the exclusion of *V. waueri* (Polis et al. 1989). Another possibility is that plant density might have been extremely low where *V. waueri's* density was highest resulting in a negative association. *Vaejovis waueri* is more commonly preyed upon by *C. vittatus*. Perhaps *V. waueri* segregates itself from *C. vittatus* (Polis and Holt 1992). Segregation from an intraguild predator may result as an evolutionary response or a short-term behavioral avoidance (Polis and Holt 1992). Therefore, occupying different microhabitats may explain how *V. waueri* and *C. vittatus* may co-exist.

Effects of soil types on scorpion densities

Burrowing scorpions may be restricted from habitats with high soil strength by limiting their ability to construct burrows (Formanowicz et al. 1993). Soil strength was, therefore, an important environmental factor to consider when comparing scorpion densities. The co-existence between *C. vittatus* and *V. waueri* could be indirectly affected by the soil types that make up a habitat. Previously, I discussed the higher average frequency of *V. waueri* in La Union South. Even though *V. waueri* was present in all habitats, La Union South showed a higher density of these scorpions. Comparing the soil types among habitats was an essential part of this study because it provided evidence for future studies to investigate and compare habitats where the abundance of *V. waueri* varies. Adequate habitats for *C. vittatus* were those with plenty of vegetation for foraging and refuge (Brown and O'Connell 2000; McReynolds 2004, 2008). Suitable habitats for *V. waueri* were predicted to be those with low soil strength that could facilitate digging (Polis 1980a).

Soil types are important environmental factors that may influence animal and plant densities. This study was used to compare soil types among habitats. Habitats composed by a higher sand percentage were hypothesized to have a higher abundance of *V. waueri*. This is because *V. waueri* is burrowing scorpions and requires sandy soils for digging (Polis 1980a). Although soil types were mapped and identified, my results are not conclusive in determining the effects on scorpion densities. Scorpion data provides a premise from which to develop further studies on the effects soil types have on scorpion densities. Studying the effects soil types can have on scorpion densities will require soil sampling and a comparison between habitats. I recommend further studies be conducted in La Union South and in the La Union Ranch. These

two study sites were shown to have the highest frequency of *V. waueri.* Enough variation in soil types exists among the two study sites for comparisons. Furthermore, other studies can focus on studying *V. waueri's* burrowing behavior and soil type preferences.

In some habitats, soil types may play a minor role in determining scorpion densities. In other habitats, soil types may be a more significant driver of densities. Through comparing the synergistic effects that plants can have on scorpion densities, I conclude that plant densities are a more important influence on *C. vittatus* densities in the Martinez Ranch and La Union Ranch. The association between plants, however, was not shown to have a significant effect on *C. vittatus* densities in La Union South. However, the association between plant densities and *V. waueri* density was significant. Soil types may have an influence on scorpion densities for *V. waueri*. Further investigation can seek to determine why plant densities had no significant association with the densities of *C. vittatus*. I predict the high sandy soils in La Union South may have a strong association with plant densities.

Co-existence between *C. vittatus* and *V. waueri* can be made possible by using different microhabitats, having distinct foraging patterns, or having a high enough prey availability (Hadley and Williams 1968; Polis and Turner 1979; Polis 1989). For example, the different size classes of *C. vittatus* were heavily influenced by plant densities in the Martinez Ranch and La Union Ranch. In La Union South, synergy between plants was less important, and soil types can be more important in influencing scorpion densities. Future studies can attempt to quantify the strength of synergistic associations between environmental factors such as the effects of different soil types, moon illumination, and plant cover, or association between scorpion size classes. A measurement of synergy can be an important factor in predicting changes in populations, dispersion patterns, and implementing conservational practices.

Competition appears to be insignificant between the two scorpion species. The overlap in microhabitats was minimal between the scorpion species. Although *C. vittatus* had a very high frequency on the ground, *V. waueri's* surface activity was too low to make encounters with *C. vittatus* frequent. Predation avoidance may be an important behavior that limits the overlap between species. Observations suggest intraguild predation between the two species does occur (pers. Observation by C.N. McReynolds). Perhaps the most important factor in limiting competition is the distinct foraging techniques adopted by the two species. McReynolds (2012) suggested that smaller scorpions should avoid microhabitats preferred by larger scorpions. Competing species should avoid direct competition, especially when one species is superior at utilizing resources. Polis (1980a) suggested that surface occupancy by immature scorpions may be an evolutionary response to long-term exposure to cannibalistic pressure from larger scorpions. I suggest that the distinct foraging strategies displayed by species that utilize the same resources may be an evolutionary response to the long-term exposure to high levels of competition between species, intraguild predation, or cannibalism.

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