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# The Influence of Habitat Diversity on Bat Species Richness and Feeding Behavior in Chilean Vineyards: Implications for Agroecological Practices

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**Abstract:** Agriculture is a leading cause of biodiversity loss, making the transition to sustainable agroecological practices crucial. Insectivorous bats play a crucial role as biological controllers in regard to agricultural crops, serving as important insect predators. The purpose of this study is to assess bat communities in three distinct habitats, namely the interior of a vineyard, native vegetation, and the transitional edge between them, by analyzing the echolocation patterns of different species. Generalized linear mixed models were used to evaluate the influence of landscape characteristics on bat communities and at the species level, allowing the incorporation of variables at different scales (at 10 m, 100 m, and 1000 m radius) from each sampling site. Our results show that edges enhance bat richness, their general activity, and feeding patterns, and are of particular benefit to certain species: *Tadarida brasiliensis*, *Myotis chiloensis*, and *Lasiurus varius*. Implementing agroecological practices, such as the maintenance of tree hedgerows at the landscape scale, along with native vegetation at the landscape scale, can amplify feeding activity in vineyards, thereby enhancing the provision of ecosystem services in agroecosystems. The edges of vineyards and natural vegetation are crucial for providing habitats for bats and increasing their foraging activity, as well as providing a way to enhance agroecological practices in vineyards to bolster ecosystem services.

**Keywords:** biodiversity conservation; Chiroptera; Mediterranean type ecosystems; sustainability; *Vitis vinifera*

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## 1. Introduction

Chile's wine industry is of great economic and environmental importance, being the fourth largest wine exporter in the world. The industry includes 130,000 hectares of Vitis vinifera and over 12,000 vineyard farms, contributing 15–18% of the total national export revenue [1,2]. However, agriculture is a leading cause of biodiversity loss, and transitioning to sustainable agroecological practices is crucial [3]. Sustainable viticulture practices are vital for maintaining soil health, conserving water, and preserving biodiversity, all of which are essential for long-term agricultural productivity [4,5]. Embracing sustainable practices is key to meeting global environmental goals and significantly reducing the ecological impact of agricultural activities on biodiversity [6,7]. The reduction in bat habitats in central Chile, due to changes in land use in relation to working landscapes (e.g. agroecosystems), raises concerns about their ability to adapt to these new environments.

Insectivorous bats play a crucial role as biological controllers in regard to agricultural crops, serving as important insect predators [8–11]. Currently, 17 bat species have been identified in Chile [12]. In central Chile, six bat species have been described, including

*Lasiurus varius* (Poeppig, 1835) (red bat), *Lasiurus villosissimus* (É Geoffroy Saint-Hiliare, 1806) (hoary bat), *Myotis chiloensis* (Waterhouse, 1840) (southern mouse-eared bat), *Histiotus macrotus* (Poeppig, 1835) (big-eared bat), *Histiotus montanus* (s Philippi y Landbeck, 1861) (small big-eared bat), and *Tadarida brasiliensis* (I. Geoffroy St.-Hilaire, 1824) (Brazilian free-tailed bat) [13]. Bats produce distinct echolocation calls that allow for species-level identification and the inference of their ecological niches in native vegetation [14–17].

Sclerophyllous shrubland and forests are important for global biodiversity conservation [18–20]. Over the past 50 years, increased agricultural, forestry, and livestock activities have led to changes in land use, resulting in a significant reduction in and fragmentation of native vegetation [21,22]. This fragmentation creates edge effects, which are changes in the biological and physical conditions between two different, adjacent communities, leading to microclimatic changes [23–25]. The consequence is that the intermediate conditions of these habitats determine which species can inhabit them [26,27].

Research on bats has revealed that certain species exhibit increased activity at the edges of vineyards [17,28,29]. For example, [28] demonstrated that the overall bat activity was 2.3 times higher next to native vegetation at vineyard edges compared to the interior of vineyards. Additionally, [30–32] found that vineyard edges adjacent to native vegetation support a higher amount of overall bat activity than the interior of vineyards, with no discernible differences in the bat species richness between the two sites. Despite significant progress in this field in central Chile, there is currently a lack of reports that quantify the comparison between vineyard edges, the interior of vineyards, and adjacent native vegetation.

Along with fragmentation and edge effects, landscape composition and its heterogeneity can impact bat activity and diversity. For instance, increased bat activity has been observed in agroecosystems, as vegetation cover diversity increases at the landscape scale [31]. The landscape composition, especially native forests, holds more significance than the landscape configuration for bat communities, leading to an increase in the number of rare species [33]. Rodríguez-San Pedro et al. (2015) propose that fragmented landscapes with native forest patches that are surrounded by a low-contrast matrix can maintain higher insectivorous bat activity compared to high-contrast matrices [34]. Consequently, the diversity of this group increased in landscapes with intermediate levels of forest fragmentation [35].

The purpose of this study is to assess bat communities in three distinct habitats, namely the interior of a vineyard, native vegetation, and the transitional edge between them, by analyzing the echolocation patterns of different species. It is expected that there will be variations in the bat communities present in these habitats, with higher richness and foraging activity at the edges, due to the increased availability of resources. Generalized linear mixed models were used to evaluate the influence of landscape characteristics on bat communities and at the species level, allowing the incorporation of variables at different scales (at 10 m, 100 m, and 1000 m radius) from each sampling site.

## 2. Materials and Methods

### 2.1. Study Area

The study took place in vineyard landscapes located in the metropolitan region, south of the city of Santiago, Chile. These sites were situated between latitudes 33°39′ S and 33°48′ S and longitudes 70°31′ and 71°14′12, approximately (Figure 1). Acoustic surveys were conducted in eleven vineyards within this area, in native vegetation, and at the edges, between both areas. The region has a Mediterranean climate, with an average maximum and minimum temperature during the summer period of 29.7 °C and 13 °C, respectively, while during the winter, the average maximum temperature reaches 14.9 °C and the minimum temperature is 3.9 °C. Additionally, the annual precipitation is 312.5 mm, which is mainly concentrated during the winter months [36]. Regarding the landscape, it is mainly composed of vineyards and native vegetation, the latter dominated by sclerophyllous shrubland and forests [37].

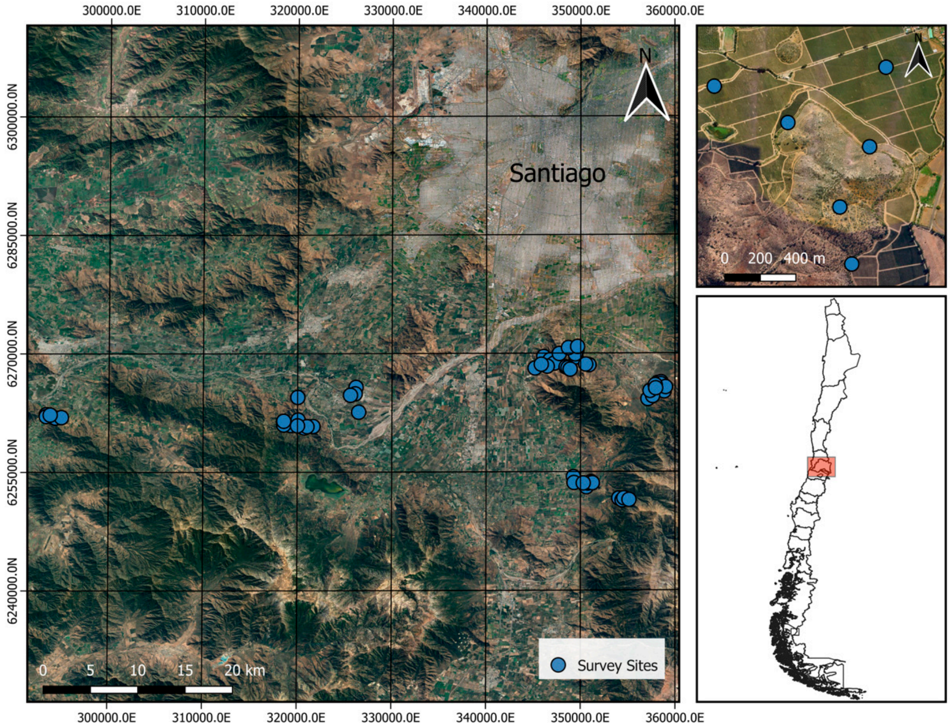

**Figure 1.** Study area in Chile showing the vineyard, edge, and native vegetation habitats (top right inset). Metropolitan region in Central Chile (down right inset).

### 2.2. Land-Cover Characterization

The land cover in the study area was analyzed using QGIS software (v2.0). The surface area of the different types of land cover within a 10 m (field observation), 100 m, and 1 km radius from each sampling site were measured to assess the relationship between these types of land cover and the total foraging activity of bats and the foraging activity related to individual species, as well as the feeding activity of bats. This approach is similar to the approach adopted in other studies [28,31]. The selection of the types of land cover was based on Pearson's correlation, excluding highly correlated variables ($|r| > 0.50$) and those with lesser ecological relevance for bats [38,39].

### 2.3. Bat Monitoring

In order to assess bat diversity and activity, we utilized stationary ultrasonic acoustic recorders, known as AudioMoths (version 1.1.2). These recorders were programmed to capture one minute of sound followed by a one-minute pause, continuously over a period of approximately 28 days, from 8:30 pm to 2:30 am. We analyzed the first 15 s of each recording. This acoustic sampling took place during the spring and summer seasons, as these periods are characterized by peak activity by insectivorous bats in temperate regions [34,40,41]. For the summer period of the season 2022–2023 (January to February 2023), we deployed 48 AudioMoths during the first year of the study, with 38 positioned on bat boxes, at a height of approximately 3.5 m. Of these, 18 were positioned inside vineyards, 20 at the edge adjacent to native vegetation, and the remaining 10 within shrubland and sclerophyllous forest, at a height of approximately 2 m in trees and shrubs, such as *Vachellia caven*, *Quillaja saponaria*, and *Peumus boldus*, among others. During the spring season in the years 2023–2024 (September to November 2023), we used 56 AudioMoths, with 38 placed on bat boxes, at the same height as before. Of these, 20 were positioned inside vineyards, 18 at the edge adjacent to native vegetation, and the remaining 18 within the native vegetation. Furthermore, we established a minimum distance of 200 m from the edge to the interior of the vineyard and native vegetation for the placement of the AudioMoths, with a minimum of 200 m between each sampling point. This distance enabled the differentiation of the bat communities present in the three habitats [28,42].

Bat activity was assessed by accounting for the number of passes and feeding buzzes recorded per night [28]. A pass was defined as a sequence of two or more echolocation pulses in each audio file. This count was used to estimate the relative abundance as an indicator of foraging activity (number of passes per night) and feeding activity (number of feeding buzzes per night) [34]. To accurately quantify bat activity, a 5 min interval was considered in regard to files containing sequences by a particular species, per night [43]. The Batch Scrubber tool in the Sonobat 4.4.5 software (Santa Cruz, CA, USA) was utilized to separate the audio files containing bat calls from the background noise. Manual filtering of the files was then conducted to count the clear bat sequences for species identification and to ensure precise results. Furthermore, a comparison of the call parameters (duration, initial and final frequency, and frequency of maximum energy) was carried out with the reference echolocation call library of bats in central Chile compiled by [13] and other relevant documents [44–47]. The identified files were categorized into specific folders by species, the presence of feeding buzzes, and unidentified bat calls (No ID). The "No ID" folder corresponds to calls that could not be classified at the species level and were only considered in terms of the general activity analysis.

### 2.4. Biodiversity Indices

The biodiversity indices were chosen to evaluate the structure and composition of the bat community in each habitat. The Shannon–Weaver index assesses diversity in terms of relative abundance and expresses community evenness, assuming that individuals are randomly selected and that all species are represented in the sample [48]. Smaller values indicate lower evenness in terms of species abundance. Meanwhile, the Simpson index (1-D) reflects species dominance in a specific site. Values close to 0 represent high dominance and low diversity, while values near 1 indicate low dominance and high diversity [48–51].

### 2.5. Statistical Analysis

Generalized linear mixed models (GLMMs) were used to evaluate the bats at both the community and species level, across the three habitats. In total, we gathered information from 104 survey sites, from eleven vineyard farms, for two seasons, for the GLMMs and biodiversity indices analysis. The GLMMs utilized the Poisson, Negative Binomial, and Zero-Inflated (ZI) functions, and were selected based on a model comparison, based on the results of Moran's I and overdispersion tests (Supplementary Materials). A post hoc Tukey pair test analysis was performed to conduct pairwise comparisons between the sampling sites (vineyard, edge, and native vegetation) in the GLMMs. The independent variables were standardized, with a mean of 0 and a standard deviation of 1, to allow comparisons between the explanatory variables across the different scales. Julian day numbers (factor with 99 levels) and sampling points (factor with 60 levels) nested in the field where the sampling took place (factor with 11 levels) were used as random effects, and the site (factor with 3 levels: vineyard, edge, and native vegetation), season (factor with 2 levels: summer and spring), and the area of the different types of land cover selected based on the Pearson correlation coefficient were used as fixed effects. The longitude of the survey site was used as a fixed effect to account for spatial autocorrelation.

The landscape variables selected for implementation in the models, after removing highly correlated ones, were as follows: herbaceous 10 m, trees 100 m, annual crop/grassland 100 m, rural 100 m, water 1 km, forest 1 km, and shrubland 1 km (Table 1). For the general foraging activity in the GLMMs, the sum of the foraging activity by each species was used. Since *T. brasiliensis* was the most abundant species in the study, an analysis excluding this species from the general foraging activity was conducted to assess whether there were changes in the overall abundance pattern of other species in the three habitats. The aim was to avoid extrapolating rare occurrence patterns, which could be linked to misclassified calls or incidental records [52]. All the analyses were performed using the R program (4.2.3 Vienna, Austria) [53].

**Table 1.** Land cover description of the categories used in the GLMMs.

| Land Cover | Description |
|---|---|
| Tree_hedgerows_100 m | Linear trees that are used to separate properties, for shade, and as a wind breaker. Includes exotic and native trees. |
| Annual_crop_100 m | Vegetables (lettuce, tomatoes, peppers) and cereal crops (wheat, corn), including naturally and naturalized grasslands (annual and perennial), mainly from the Poaceae family. Species include *Holcus lanatus*, *Dactylis glomerata*, *Festuca* sp. |
| Rural_100 m | Areas in the countryside that include farm buildings, greenhouses, and asphalted roads, within 100 m radii. This category includes some green areas, such as gardens, squares, and recreational areas. |
| Water_1 km | Watercourses, including irrigation channels, ponds, and the Maipo River. |
| Forest_1 km | Native sclerophyllous forest trees over 2 m high. These hard-leaved species have thick, leathery leaves, designed to reduce water loss during long dry seasons. Species include *Peumus boldus*, *Quillaja saponaria*, *Lithraea caustica*, *Cryptocarya alba*, *Crinodendron patagua*, and *Prosopis chilensis*, among others, as coexisting species. |
| Shrubland_1 km | Native shrubs less than 2 m high. This shrubland community features a mix of drought-deciduous and evergreen shrubs and small trees, as well as cacti and bromeliads, including species such as *Vachellia caven*, *Colliguaja odorifera*, and *Trevoa trinervis*, among others, and succulents (*Puya* sp., *Echinopsis chiloensis*), as coexisting species. |
| Herbs_10 m | Spontaneous vegetation at 10 m radii, including grasses, weeds, and native herbaceous plants. |

## 3. Results

Over the course of 2601 nights of sampling at three study sites, 452,459 audio files in WAV format were recorded. After completing two filtering processes, 22,781 bat detections were registered (Table 2). Out of these, 22,781 passes were identified at the species level: *T. brasiliensis* with 13,645 passes (59.90%), *M. chiloensis* with 5619 passes (24.67%), *L. varius* with 705 passes (3.09%), *H. montanus* with 139 passes (0.61%), *L. villosissimus* with 117 passes (0.51%), and *H. macrotus* with 38 passes (0.17%). Additionally, 2518 passes (11.05%) could not be identified at the species level. The mean recorded foraging activity was 8.74 ± 0.16 (standard error) passes per sampling night, while the mean feeding buzzes recorded was 1.02 ± 0.03.

**Table 2.** Acoustic monitoring indicates the number of ultrasonic recorders (AudioMoths), number of nights (Nights), number of recording files (Recordings), bat passes with foraging activity (Activity), and bat passes with feeding buzzes (Feeding) in each habitat.

| Habitat [1] | Number of Ultrasonic Recorders (AudioMoths) | Nights | Recordings (%) | Foraging Activity (%) | Feeding (%) |
|---|---|---|---|---|---|
| V | 38 | 961 | 159,987 (35.36) | 8376 (36.77) | 888 (33.25) |
| E | 38 | 965 | 147,260 (32.55) | 9857 (43.27) | 1444 (54.06) |
| N | 28 | 675 | 104,813 (23.17) | 4548 (19.96) | 339 (12.69) |
| Total | 104 | 2601 | 452,459 | 22,781 | 2671 |

[1] Vineyard interior (V), edge (E), and native vegetation (N).

*T. brasiliensis* and *M. chiloensis* were the two species with the highest relative frequency across the three habitats. The former exhibited the highest proportion of activity within the sites, mainly in the vineyard, as compared to the edge and native vegetation (Table 3). *M. chiloensis* displayed a stronger preference for edge habitats and native vegetation, similar to *L. varius* (Table 3). *L. villosissimus*, *H. macrotus*, and *H. montanus* demonstrated different activity patterns, with the lowest proportion of search calls recorded.

**Table 3.** Percentage of calls by species for each sampling habitat (%).

| **Habitat** [1] | ***Tadarida brasiliensis*** | ***Myotis chiloensis*** | ***Lasiurus varius*** | ***Lasiurus villosissimus*** | ***Hystiotus macrotus*** | ***Hystiotus montanus*** |
|---|---|---|---|---|---|---|
| V | 81.64 | 15.65 | 1.44 | 0.76 | 0.30 | 0.20 |
| E | 58.32 | 36.44 | 4.57 | 0.26 | 0.02 | 0.39 |
| N | 61.14 | 30.64 | 4.77 | 0.92 | 0.33 | 2.18 |
| Total | 67.34 | 27.73 | 3.48 | 0.58 | 0.19 | 0.69 |

[1] Vineyard interior (V), edge (E), and native vegetation (N).

The species richness was significantly higher at the edges (1.82 ± 0.02) than in the vineyards (1.46 ± 0.02), partially higher than between the edges and native vegetation (1.54 ± 0.03) (Figure 2a). The overall foraging activity was significantly higher at the edges (10.19 ± 0.31) than in native vegetation (6.72 ± 0.27), with no differences between the edges and the vineyard (8.7 ± 0.24) (Figure 2b). Foraging activity, excluding the dominant species *T. brasiliensis* (Figure 2c), was consistently higher at the edges (4.8 ± 0.21) than in the vineyard (2.47 ± 0.12), and higher at the edges in comparison to the native vegetation (2.9 ± 0.17). Feeding activity per night (Figure 2d) was significantly higher at the edges (1.49 ± 0.08) than in the native vegetation (0.5 ± 0.04), with no significant differences between the edges and the vineyard (0.92 ± 0.05).

At the species level, the foraging activity of *T. brasiliensis* (Figure 2e) was significantly higher in the vineyard (6.23 ± 0.18) than in the native vegetation (3.73 ± 0.19), with no differences between the edge (5.31 ± 0.2) and the vineyard. The foraging activity of *M. chiloensis* (f) was significantly higher at the edges (3.32 ± 0.18) than in the native vegetation (1.87 ± 0.11), with partial differences between the native vegetation and the vineyard (1.19 ± 0.08) or the vineyard and the edges. *L. varius* showed significantly higher activity at the edges (0.41 ± 0.03) than in the vineyard (0.11 ± 0.01) and between the vineyard and the native vegetation (0.29 ± 0.03), but no differences between the edges and the native vegetation. *L. villosissimus* did not show significantly different results between the vineyard (0.05 ± 0.01), the edges (0.02 ± 0.005), and the native vegetation (0.05 ± 0.01).

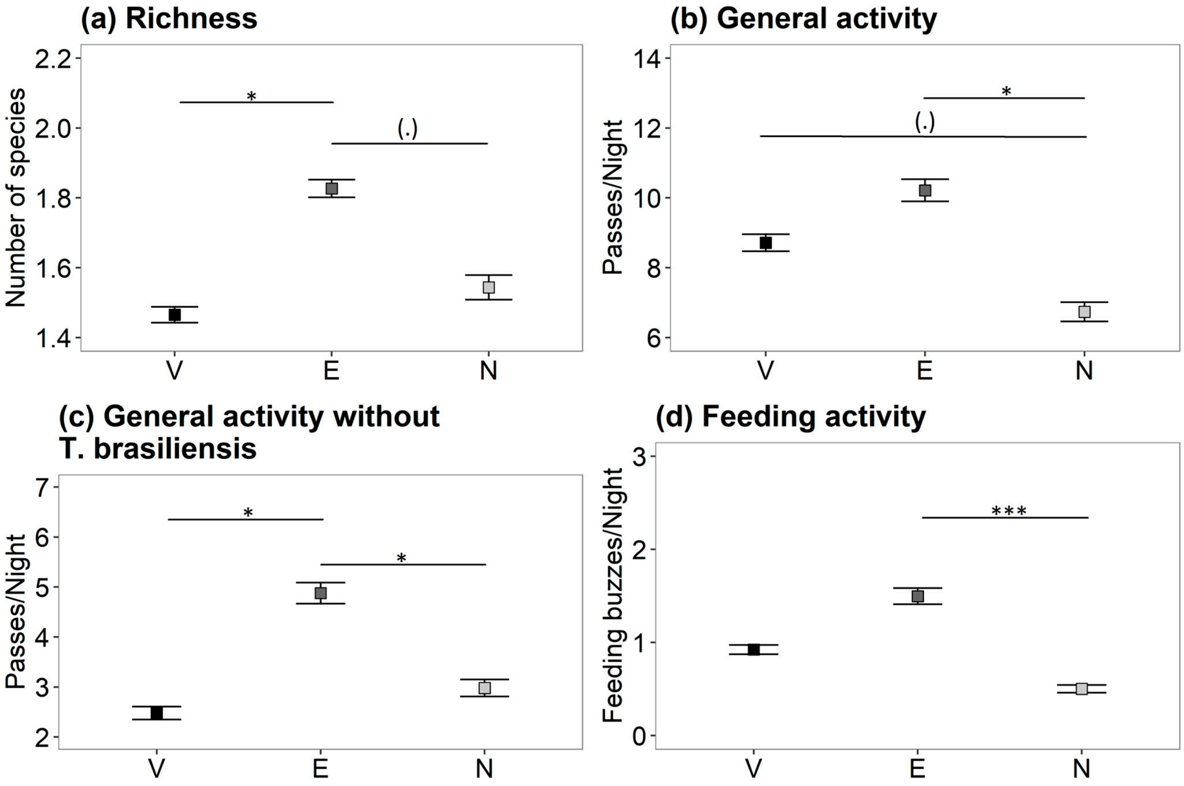

**Figure 2.** *Cont.*

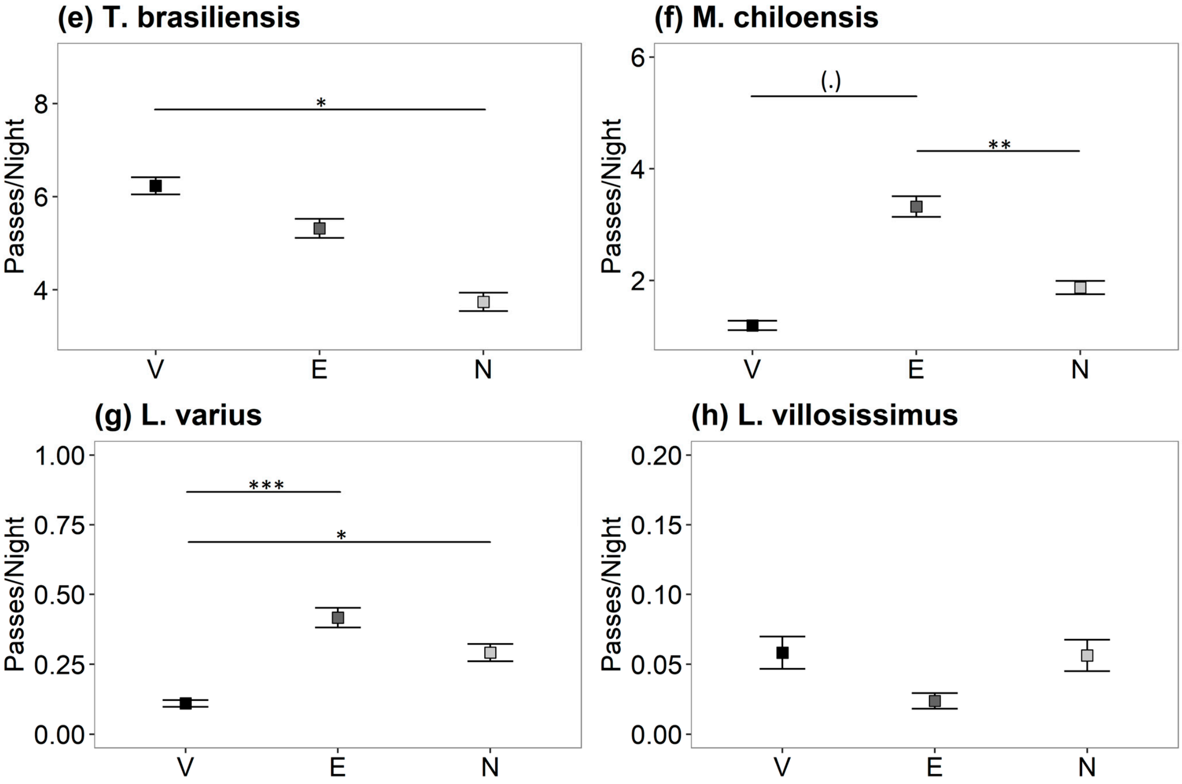

**Figure 2.** Comparison (mean and standard error) between pairs at the 3 sites (vineyard (V, black), edge (E, dark grey), and native vegetation (N, light grey)) per night: (**a**) bat species richness, (**b**) overall foraging activity, (**c**) foraging activity excluding *T. brasiliensis*, (**d**) feeding activity. Foraging activity by species: (**e**) *T. brasiliensis*, (**f**) *M. chiloensis*, (**g**) *L. varius*, and (**h**) *L. villosissimus*. Post hoc Tukey in GLMMs: ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$; (.), $p < 0.1$).

The Shannon–Weaver index shows the diversity of species based on their foraging activity at various sampling sites (Table 4). It was observed that the bat community in the vineyard (0.58) exhibited lower species diversity and distribution in comparison to the edges (0.86) and the native vegetation (0.82). Similarly, the Simpson index indicated higher dominance in the bat community in the vineyard (0.31) as opposed to the edges (0.52) and the native vegetation (0.47). This dominance in the vineyard can be attributed to the presence of *T. brasiliensis*, which is less prevalent in other habitats (see Table 3).

**Table 4.** Comparison of species diversity and dominance between sites using the Shannon–Weaver diversity index and the Simpson equity index. Vineyard interior (V), edge (E), and native vegetation (N).

| Survey Site | Shannon | Simpson (1-D) |
|---|---|---|
| V | 0.58 | 0.31 |
| E | 0.86 | 0.52 |
| N | 0.82 | 0.47 |

The models (Table 5) that evaluated the landscape-scale variables revealed that bat species richness was significantly favored by shrubland coverage (1 km). The overall bat activity was significantly favored by water 1 km, tree hedgerows 100 m, forest 1 km, and herbs 10 m, while the annual crop 100 m and the spring season negatively influenced the general bat activity. The general activity without *T. brasiliensis* was positively and significantly influenced by the spring season, tree hedgerows 100 m, herbs 10 m, shrubland 1 km, and rural 100 m. The feeding activity was positively and significantly influenced by tree hedgerows 100 m and rural 100 m.

**Table 5.** Generalized linear mixed model results. The results of the generalized linear mixed models (GLMMs) evaluate the influence of landscape variables on bat species richness, general activity, general activity excluding *Tadarida brasiliensis*, and feeding activity. Individual models were also created for specific species, including *T. brasiliensis*, *Myotis chiloensis*, *Lasiurus varius*, and *Lasiurus villosissimus*. Significant effects ($p < 0.05$) are highlighted in bold for clarity. The levels of significance are indicated as follows: ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$; (.), $p < 0.1$.

| **Guild** | **Environmental Variables** | **Estimate (±SE)** | ***p* Value** | **$R^2$ Adjusted (%)** |
|---|---|---|---|---|
| Richness<br>(N = 4213; 6 species) | Season_spring | −0.032 ± 0.034 | 0.353 | 7.70 |
| | Longitude | 0.003 ± 0.034 | 0.929 | |
| | Tree_hedgerows_100 m | 0.024748 ± 0.018 | 0.180 | |
| | Annual_crop_100 m | −0.037 ± 0.029 | 0.204 | |
| | Rural_100 m | 0.02 ± 0.032 | 0.522 | |
| | Water_1 km | −0.019 ± 0.031 | 0.539 | |
| | Forest_1 km | −0.011 ± 0.031 | 0.732 | |
| | Shrubland_1 km | 0.076 ± 0.036 | **0.033** * | |
| | Herbs_10 m | −0.034 ± 0.029 | 0.241 | |
| General activity<br>(N = 22,781) | Water_1 km | 0.095 ± 0.033 | **0.004** ** | 96.86 |
| | Tree_hedgerows_100 m | 0.084 ± 0.042 | **0.048** * | |
| | Forest_1 km | 0.173 ± 0.048 | **<0.0001** *** | |
| | Annual_crop_100 m | −0.629 ± 0.09 | **<0.0001** *** | |
| | Herbs_10 m | 0.096 ± 0.017 | **<0.0001** *** | |
| | Rural_100 m | 0.026 ± 0.016 | 0.11 | |
| | Season_spring | −0.357 ± 0.069 | **<0.0001** *** | |
| | Shrubland_1 km | 0.061 ± 0.11 | 0.581 | |
| | Longitude | −0.057 ± 0.105 | 0.586 | |
| General activity without *T. brasiliensis*<br>(N = 9100) | Season_spring | 0.188 ± 0.073 | **0.01** ** | 40.90 |
| | Longitude | 0.064 ± 0.164 | 0.696 | |
| | Tree_hedgerows_100 m | 0.212 ± 0.071 | **0.003** ** | |
| | Annual_crop_100 m | −0.13 ± 0.116 | 0.261 | |
| | Rural_100 m | 0.143 ± 0.045 | **0.001** ** | |
| | Water_1 km | 0.079 ± 0.086 | 0.357 | |
| | Forest_1 km | 0.168 ± 0.11 | 0.129 | |
| | Shrubland_1 km | 0.402 ± 0.169 | 0.018 * | |
| | Herbs_10 m | 0.114 ± 0.054 | 0.033 * | |
| Feeding activity<br>(N = 2671) | Season_spring | 0 ± 0.098 | 0.997 | 29.00 |
| | Longitude | 0.1 ± 0.118 | 0.396 | |
| | Tree_hedgerows_100 m | 0.218 ± 0.063 | **0.001** *** | |
| | Annual_crop_100 m | −0.128 ± 0.103 | 0.215 | |
| | Rural_100 m | 0.21 ± 0.058 | **<0.0001** *** | |
| | Water_1 km | 0.06 ± 0.089 | 0.496 | |
| | Forest_1 km | −0.144 ± 0.104 | 0.166 | |
| | Shrubland_1 km | 0.086 ± 0.125 | 0.49 | |
| | Herbs_10 m | 0.041 ± 0.071 | 0.566 | |
| *T. brasiliensis*<br>(N = 13,645) | Annual_crop_100 m | −0.515 ± 0.1 | **<0.0001** *** | 95.36 |
| | Herbs_10 m | 0.037 ± 0.02 | 0.064 . | |
| | Rural_100 m | −0.128 ± 0.026 | **<0.0001** *** | |
| | Season_spring | −0.689 ± 0.093 | **<0.0001** *** | |
| | Forest_1 km | 0.048 ± 0.045 | 0.278 | |
| | Tree_hedgerows_100 m | −0.083 ± 0.081 | 0.306 | |
| | Water_1 km | −0.018 ± 0.038 | 0.632 | |
| | Longitude | 0.033 ± 0.14 | 0.817 | |
| | Shrubland_1 km | −0.02 ± 0.129 | 0.88 | |

**Table 5.** *Cont.*

| Guild | Environmental Variables | Estimate (±SE) | *p* Value | $R^2$ Adjusted (%) |
|---|---|---|---|---|
| *M. chiloensis* (N = 5619) | Season_spring | 0.27 ± 0.087 | **0.002** ** | 41.90 |
| | Longitude | −0.041 ± 0.181 | 0.822 | |
| | Tree_hedgerows_100 m | 0.133 ± 0.089 | 0.132 | |
| | Annual_crop_100 m | −0.152 ± 0.151 | 0.312 | |
| | Rural_100 m | 0.252 ± 0.053 | **<0.0001** *** | |
| | Water_1 km | −0.274 ± 0.13 | **0.036** * | |
| | Forest_1 km | 0.342 ± 0.148 | **0.021** * | |
| | Shrubland_1 km | 0.224 ± 0.188 | 0.234 | |
| | Herbs_10 m | −0.174 ± 0.071 | **0.015** * | |
| *L. varius* (N = 705) | Season_spring | 0.808 ± 0.136 | **<0.0001** *** | 29.88 |
| | Longitude | 0.072 ± 0.249 | 0.773 | |
| | Tree_hedgerows_100 m | 0.147 ± 0.085 | 0.0818 . | |
| | Annual_crop_100 m | −0.005 ± 0.131 | 0.971 | |
| | Rural_100 m | 0.176 ± 0.142 | 0.215 | |
| | Water_1 km | 0.147 ± 0.146 | 0.315 | |
| | Forest_1 km | 0.012 ± 0.162 | 0.938 | |
| | Shrubland_1 km | 0.604 ± 0.263 | **0.0218** * | |
| | Herbs_10 m | −0.102 ± 0.13 | 0.433 | |
| *L. villosissimus* (N = 117) | Water_1 km | −27.13 ± 5802 | 0.062 . | 13.58 |
| | Forest_1 km | −0.577 ± 0.3088 | 0.127 | |
| | Herbs_10 m | −0.333 ± 0.218 | **0.042** * | |
| | Longitude | 0.414 ± 0.2032 | **0.011** * | |
| | Shrubland_1 km | 0.592 ± 0.2313 | **<0.0001** *** | |
| | Rural_100 m | 0.939 ± 0.2369 | 0.996 | |
| | Season_spring | −327.7 ± 68370 | 0.993 | |
| | Tree_hedgerows_100 m | −36.38 ± 4041 | 0.662 | |
| | Annual_crop_100 m | −0.0546 ± 0.1246 | 0.841 | |

At the species level, *T. brasiliensis* was partially, positively influenced by herbs 10 m, and negatively and significantly influenced by annual crop 100 m, rural 100 m, and the spring season. *M. chiloensis* was significantly, positively influenced by forest 1 km, rural 100 m, and the spring season, while partially, positively influenced by tree hedgerows 100 m and shrubland 1 km. However, it was significantly, negatively related to water 1 km and herbs 10 m. *L. varius* was significantly favored by shrubland 1 km and the spring season, and partially, positively influenced by tree hedgerows. Finally, *L. villosissimus* was significantly favored by herbs 10 m, shrubland 1 km, and longitude and partially, negatively influenced by water.

## 4. Discussion

This study uncovered the significance of edges as crucial habitats for bats in Chilean vineyards. The edges where native vegetation and vineyards meet were found to enhance bat richness, their general activity, and their feeding activity, particularly benefiting the *T. brasiliensis*, *M. chiloensis*, and *L. varius* species. Bat communities at these edges resembled those in native vegetation more closely than those in vineyards, displaying higher diversity and decreased dominance, similar to native vegetation. The edges between vineyards and native vegetation play a vital role for bats, increasing their richness, overall activity, and feeding, likely due to the greater abundance of prey in these areas [54]. Specifically, native vegetation, such as sclerophyllous scrubs and forests, promotes general bat activity, the presence of more species, and reduces the dominance of *T. brasiliensis*. These findings are consistent with prior research [28,31] that identifies native vegetation cover as the primary predictor of bat diversity, benefiting rare species, such as *L. villosissimus*, *L. varius*, *H. montanus*, *H. macrotus*, and *M. chiloensis*, which are associated with forested areas [31,55].

Our study included a comparison of the edges and native vegetation in terms of the bat communities associated with vineyards in Chile, carrying out a comprehensive assessment of this agroecosystem. The findings of our study on bat species richness and abundance contrast with another study that found no significant difference between the interior of vineyards and their edges [30]. This difference may be due to the distance from the edge that we utilized (200 m), which is greater than the 75 m distance from the edge to the vineyard's interior used in the other study [30]. Interestingly, both studies concur that there is higher activity at the edges than in the interior [30], indicating a consistent trend.

Our study aligns with others in the same region, indicating that bat activity trends depend on the species. In regard to vineyard–forest interface landscapes, another study identified the presence of *L. varius*, *L. villosissimus*, *M. chiloensis*, *H. montanus*, and *T. brasiliensis* [29,54]. Certain species, like *H. macrotus*, are rare in central Chile and tend to be solitary [40]. Another report found that *T. brasiliensis*, *M. chiloensis*, and *L. varius* were significantly more active at the edges, while *H. montanus* and *L. villosissimus* did not show significant differences between the two habitat types [56]. The ecology and biology of the species enable them to adapt to various environmental conditions, including tolerance to anthropogenic conditions, such as agricultural management in rural areas and cities. *T. brasiliensis* is adapted to open environments, including working landscapes, such as vineyards, and is utilized in regard to seasonal migration [44,55–57]. However, at the species level, our results show a negative relationship between annual crops and rural land cover at the plot scale (100 m), highlighting the relevance of the landscape context. On the other hand, *M. chiloensis* is considered a short-distance traveler due to the high energy needed for flight [40,55,57,58], where forests are key to supporting this species.

At the species level, three species showed increased activity at the edges. *T. brasiliensis* was significantly more active in vineyards compared to other species, while *M. chiloensis* and *L. varius* were more active at the edges than in vineyards. The dominance of *T. brasiliensis* could influence the overall activity of the entire community. Therefore, we decided to assess this parameter both with and without *T. brasiliensis*.

The findings align with those of other publications that have also observed that edges are relevant habitats for bats in vineyards [28,54]. These results suggest the important role bats play in preying on insects in vineyards. Some of the pests that can be found in vineyards in Chile include the European grapevine moth *Lobesia botrana* (Tortricidae) and the Chilean fruit leaf roller *Proeulia auraria* (Tortricidae) [54]. *T. brasiliensis* bats can establish habitats in vineyards, while species like *M. chiloensis* and *L. varius* can be supported in vineyards through the use of hedgerows or edges. This is supported by [28], who found that the overall bat activity was higher near native vegetation along vineyard edges compared to the interior, likely due to the abundance of prey. Chaperon et al. (2022) [54] highlight that the edges between vineyards and native vegetation harbor a higher overall abundance of insects compared to the vineyard interior [54]. Additionally, that study showed that there is a greater abundance of dipterans and fewer lepidopterans compared to the vineyard interior [54]. However, they did not find a significant relationship between the total bat activity and insect abundance, but there was a significant negative relationship between bat activity and the abundance of coleopterans and lepidopterans [54].

Our findings emphasize the significance of edges in agroecosystems and align with prior research indicating an increase in the richness and abundance of wildlife in temperate ecosystems. It is important to note that the heightened activity of bats in edge habitats may not necessarily be linked to favorable conditions for reproduction or roosting. Recent research on bats in agroecosystems showed that bat activity and pest predation services increased near native vegetation where bats roost, decreasing their biological control far away from the native vegetation, coinciding with our results [59]. It is probable that successful reproduction and roosting are associated with the conservation of native vegetation at larger scales than those examined in this study. When it comes to bat conservation, it is crucial to recognize that these edges can enhance the suitability of habitats for wildlife. However, the preservation of roosting and reproductive areas is essential for ensuring the population's viability and the provision of ecosystem services. It is likely that these areas are situated within the surrounding native vegetation [60].

Our study supports the evidence that diversified farming systems can increase the provision of ecosystem services in agroecosystems [61,62]. Our results show that agroecological practices, such as maintaining herbs, hedgerows at the plot scale, and native vegetation at the landscape scale, support a more diverse bat community in terms of their general activity, but not for all the species in the studied area. Herb features can provide food resources and shelter, contributing to habitats in working landscapes, like agroecosystems [54,63–66]. Tree hedgerows used as windbreakers have been shown to increase the activity of insectivorous bats in Canada [64]. Additionally, the remnants of native vegetation have been found to increase bat species richness and activity in vineyards [31]. The landscape composition also influences bat communities, particularly rare species [33]. Water sources can also contribute to the presence and activity of bats [55]. However, our study partially supports the effect of water, which has a positive effect on general bat activity, but is negatively related to *M. chiloensis* and partially, negatively related to *L. villosissimus*. More studies should be conducted in this area to assess its effect.

The study area reported potential species that were not recorded or were detected very few times, such as *L. villosissimus*. This suggests that working landscapes may not provide a suitable habitat for all these species. For example, gregarious bat colonies may require caves to host a large number of individuals, as seen in the case of *T. brasiliensis* [52], while solitary bats may need old trees with crevices and holes in their bark for daytime resting. For instance, *L. varius* was found to use bark crevices in trees for daytime roosting, while *L. villosissimus* was found to hang on trees for daytime roosting [55,67].

We observed a seasonal effect on bat activity. The overall activity of bats and *T. brasiliensis* decreased during the spring, while the general activity of bats, without including *T. brasiliensis* and the activity of *M. chiloensis* and *L. varius*, increased during the spring. This difference in seasonal use could be linked to the migratory behavior of *T. brasiliensis* [44,55–57]. However, more consistent data from a single season could provide additional information about these seasonal patterns. Our results are based on a large amount of data analyzed (22,781) over 2601 nights, which is not a limitation compared to other studies [31,68]. Our analysis provides insights for future research in this area.

This study has some limitations that need to be considered. We did not measure the influence of agricultural management (e.g., agroecological, organic, conventional) that can affect bat activity [30]. Instead, we focused on the relevance of native vegetation, which is also important for an area that is primarily managed by conventional agriculture. The measurement of herbs at the 10 m scale reflects only one moment during the entire recording period at each survey site. This means that it is likely that some of the herbs changed their phenology during the study, so it cannot be considered a constant variable. However, we propose to factor in this variable in future studies, especially since changes in plant phenology also provide different habitats for insects, which are the main food source for bats.

## 5. Conclusions

The edges between native vegetation and vineyards positively influence bat activity and species diversity, particularly in vineyards located in central Chile. Native vegetation plays a vital role in enhancing bat abundance and species richness and could contribute to important ecosystem services, like pest control in agroecosystems. Tree hedgerows consistently favor bat activity and feeding activity. To promote the feeding activity of bats in vineyards, an agroecological practice that favors diversified cropping systems could involve creating and restoring hedgerows, conserving native vegetation around vineyards, and implementing practices that support agricultural sustainability. This approach will help in striking a balance between production and conservation in this crucial biodiversity hotspot.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14111896/s1, Table S1: Legend of the different acronyms in used in the analysis; Table S2: Results of the Pearson correlation of the final variables used in the

GLM and GLMM models; Table S3: Detailed results of the GLMM used in the analysis, including the results of the Spatial autocorrelation test (Moran's I) and Overdispersion test.

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