Perspectives in Ecology and Conservation 22 (2024) 196–204

Perspectives in ecology and conservation

Supported by the National Council for Scientific and Technological Development - CNPq

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Research Letters

Conserving biodiversity in coffee agroecosystems: Insights from a herpetofauna study in the Colombian Andes with sustainable management proposal

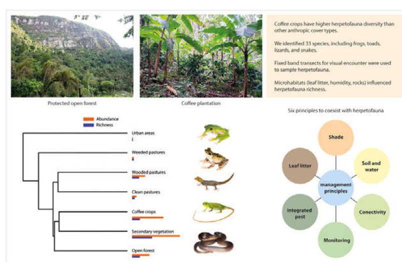
Juan Camilo Ríos-Orjuela[a,b,*], Nelson Falcón-Espitia[a,b,*], Alejandra Arias-Escobar[c], Dennys Plazas-Cardona[d]

[a] Laboratorio de Biología Evolutiva de Vertebrados, Departamento de Ciencias Biológicas, Universidad de los Andes, 111711 Bogotá, Colombia
[b] Grupo de Morfología y Ecología Evolutiva, Instituto de Ciencias Naturales, Universidad Nacional de Colombia, 111321 Sede Bogotá, Colombia
[c] Independent researcher
[d] Grupo de investigación ORNIS: Evolución y Ecología de Aves, Instituto de Ciencias Naturales, Universidad Nacional de Colombia, 111321 Sede Bogotá, Colombia

HIGHLIGHTS

- Coffee crops have higher herpetofauna diversity than other anthropic cover types.
- We identified 33 species, including frogs, toads, lizards, and snakes.
- Fixed band transects for visual encounter were used to sample herpetofauna.
- Microhabitats (leaf litter, humidity, rocks) influenced herpetofauna richness.
- Six principles of sustainable management are proposed to coexist with herpetofauna.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 March 2023
Accepted 3 April 2024
Available online 3 May 2024

Keywords:
Coffee agroecosystems
Herpetofauna diversity
Sustainable management
Anthropogenic impacts
Conservation

ABSTRACT

Amphibians and reptiles are important indicators of ecosystem health, yet their populations are declining worldwide due to habitat loss and climate change. Agroecosystems, such as coffee plantations, can provide important habitat for these species. We conducted field surveys in the Sumapaz region of Colombia to identify the habitat structural variables that influence the diversity and abundance of herpetofauna in coffee crops. The canonical correspondence analysis revealed that abundance of leaf litter, leaf litter moisture, shade percentage, plantation area, and plantation age category were the most important variables for determining herpetofauna diversity. Our findings suggest that shaded coffee plantations can sustain herpetofauna diversity, and maintaining a thick layer of leaf litter is critical for establishing complex and structured animal communities. This study proposes a set of sustainable agricultural management principles to promote the existence of amphibians and reptiles in coffee crops. By adopting these practices, it is possible to prevent the decline in the population of amphibians and reptiles due to the expansion of the agricultural frontier, as seen in other coffee-growing regions. The findings of this study contribute to a better understanding of how to balance agricultural production and biodiversity conservation in the context of agroecosystems.

* Corresponding authors.
E-mail addresses: jcriosor@gmail.com (J.C. Ríos-Orjuela), ngfalcone@unal.edu.co (N. Falcón-Espitia), aariase@unal.edu.co (A. Arias-Escobar), deplazasc@unal.edu.co (D. Plazas-Cardona).

https://doi.org/10.1016/j.pecon.2024.04.001

Introduction

Land use change for agriculture is one of the main drivers of biodiversity loss in the world (Manson et al., 2008). As coffee is an economically important crop in world agriculture, the impact of coffee cultivation on the ecology and diversity of specific animal groups has been investigated in working landscapes (Philpott et al., 2008; Şekercioglu et al., 2019). Regarding herpetofauna, research assessing the effect of different crops on species turnover and local extinction risk in Latin America has mainly focused on amphibians (Murrieta-Galindo et al., 2013; Santos-Barrera and Urbina-Cardona, 2011a), with limited reports on reptiles (Mendenhall et al., 2014). In Colombia, a country with high amphibian and reptile diversity as well as a broad coffee production culture, there is a lack of studies on the impact of coffee agroecosystems on herpetofauna.

Amphibians and reptiles are known for being species with limited mobility that exhibit a strong correlation with microhabitat structural characteristics, influencing their habitat selection and geographic distribution (Cortés-Gómez et al., 2013). Thus, the structural attributes of habitats directly determine the available resources for these species. Therefore, understanding the specific structural characteristics crucial for each species is a need for comprehending the habitat use of amphibians and reptiles, particularly within altered environments such as the coffee agroecosystems.

The Cerro Quininí Protected Forest Reserve (RFPCQ) is a vital conservation area in the Sumapaz province (Cundinamarca, central Colombia). Despite RFPCQ being a protected area, approximately 90% of the associated land is privately owned and has been utilized for cropping and grazing, with coffee agroecosystems occupying around 242,3 ha, corresponding to 13.2% of the total RPFCQ area (Alcaldía Tibacuy, 2016; CAR, 2023). Thus, shaded polyculture-based production methods have become relevant in agroecosystems such as the RFPCQ, as they hold a diverse range of species and have been historically overlooked by conservation efforts (Rojas Sánchez et al., 2012). Given the environmental conditions typical of the tropical mid-mountain zones, with average temperatures and high humidity, the RFPCQ holds the potential for high species diversity, but habitat loss impact has not been evaluated at the ecosystem or species level. Available data suggest that 29 amphibian and 88 reptile species are present in the RFPCQ, including 11 threatened amphibians and three reptiles (IUCN, 2021; Morales-Betancourt et al., 2015; Rueda-Almonacid et al., 2004). Thus, further research and conservation efforts are needed to protect the RFPCQ's diverse array of species.

Coffee agroecosystems are found in the middle of considerably transformed and heterogeneous vegetation matrices, where the forest is often found in isolated remnants (Hoyos-Hoyos et al., 2012). Nevertheless, such agroecosystems act as reservoirs of biodiversity from degraded natural ecosystems, maintaining important ecosystem services in the region, since they resemble to some extent the natural forest (Perfecto et al., 2007; Tscharntke et al., 2011). In Colombia, coffee agroecosystems have shifted from crops under the shade of native or cultivated trees ("shaded crops") to intensive cropping without any shade at all ("non-shaded crops"). The latter presents a higher yield, but also a greater demand for supplies and fertilizers, in addition to directly impacting the populations of amphibians and reptiles by altering the availability of refuges, food and decreasing the number of optimal microhabitats for these animals (González-Prieto, 2018; Jha et al., 2014; Perfecto et al., 1996; Rojas Sánchez et al., 2012).

Agricultural intensification is a trend in Colombia, with 48% of coffee-growing municipalities in the country experiencing production changes due to replacing shaded crops with unshaded crops (Guhl, 2006; Rice, 1999; Rojas Sánchez et al., 2012). Shaded coffee plantations in RFPCQ may serve as connection zones between less intervened ecosystems since they help maintain complex floristic and ecological structures, harboring wildlife species (Manson et al., 2008; Moorhead et al., 2010; Pineda et al., 2005), and even showing comparable diversities between shaded coffee plantations and natural forests (Tejeda-Cruz and Sutherland, 2004). However, limited research exists on herpetofauna diversity in agroecosystems in Latin America and Colombia (Hoyos-Hoyos et al., 2012; Moguel and Toledo, 1999; Murrieta-Galindo et al., 2013; Pineda et al., 2005). Therefore, to mitigate the negative impact of human activity on local fauna and preserve Andean ecosystems, it is essential to document the diversity and interaction of amphibians and reptiles with local production systems, as well as the characteristics of the crops that promote the occurrence of herpetofauna within coffee plantations.

Our goal was to assess the relative impact of coffee agroecosystems on the herpetofauna diversity in the RFPCQ. To achieve this, three objectives were considered: (1) assess the herpetofauna diversity across different landcover units in the region with special emphasis on communities in coffee crops at the RFPCQ; (2) evaluate the relationship between the structural characteristics of coffee plantations and the amphibian and reptile diversity; and (3) propose a management strategy for coffee production systems that supports the presence of herpetofauna.

Methods

Study area

The Cerro Quininí Protected Forest Reserve (RFPCQ) forms part of the crucial Chingaza-Sumapaz-Guerrero corridor in the Eastern Cordillera of the Andes (Sguerra et al., 2011). It is located in the municipalities of Nilo, Tibacuy, and Viotá (Cundinamarca, central Colombia), between 1050 and 2133 m.a.s.l (Castellanos-Menjura et al., 2019). The region has a humid mountain climate, with an average temperature of 19.2 °C and a bimodal rainfall pattern (CAR, 2016). According to Holdridge's classification (1947), the RFPCQ is in the low-montane rainforest and low-montane dry forest life zones to a lesser extent. With an approximate area of 1830 ha, it is one of the largest conservation areas in Cundinamarca (CAR, 2023; Sguerra et al., 2011).

Despite being a protected area, most lands associated with the RFPCQ (about 90%) are privately owned and used for mixed crops and grazing (Alcaldía Tibacuy, 2016; CAR, 2016; CAR and Andina, 2013; Castellanos, 2015). In 1987, the area was declared a Protective Forest Reserve to conserve natural resources and the environment, particularly important water sources at the request of the inhabitants (Ministerio de Agricultura de Colombia, 1987).

Data collection

To cover the rainy and dry seasons in the region, a total of six field trips (three effective sampling days each) were conducted between June and December 2021. Sampling localities in the RFPCQ were established beforehand based on the natural, semi-natural, and transformed land covers (including coffee crops), using vegetation cover units defined by (IDEAM, 2010) (a complete description of the included vegetation cover units can be found in Box 1). Two of the sampling points were outside the RFPCQ, in the villages of Pueblo Nuevo and Buenos Aires (Viotá municipality), selected due to the absence of conserved forest cover units in the reserve, while keep-

Table 1
Alpha diversity indices for vegetation cover units. This table presents the alpha diversity indices used to estimate the diversity of vegetation cover units. The first line states the number of polygons and the total area of the analyzed vegetation units. The value highlighted in bold indicates the highest diversity unit following Shannon's index.

Index	Secondary vegetation	Open forest	Coffee plantations	Wooded pastures	Clean pastures	Weeded pastures	Urban areas
Number of polygons/Total Area	7 Polygons/90.72 ha	3 polygons/68.12 ha	6 polygons 5.97 ha	6 polygons/39.16 ha	1 polygon/0.8 ha	1 polygon/0.49 ha	1 polygon/0.07 ha
Species	23	9	9	8	3	2	1
Individuals	55	20	36	15	5	2	1
Margalef	5.49	2.67	2.232	2.585	1.243	1.443	0
Simpson (1-D)	0.915	0.755	0.6	0.835	0.56	0.5	0
Shannon	**2.776**	1.799	1.41	1.934	0.950	0.693	0

ing equivalence with the slope and the altitudinal range in which the RFPCQ is located.

Using the software QGIS 3.22 (QGIS Development Team, 2023), coffee crops were characterized spatially according to their proximity to water bodies, frequency of maintenance, use of agrochemicals, total plantation area, adjacent vegetation cover units, presence of microhabitats such as leaf litter and rocks, and shading (Table 2). To evaluate the incidence of coffee shading on herpetofauna, we established shade categories taking as a reference those plantations with more shade proportion (C4 and C5) and those with less shade proportion (C1 and C3). Thus, we assigned shade values to each plantation in three categories, no shade, medium shade, and high shade. We decided to use shade as a categorical variable due to the impossibility of establishing the actual percentage of shade for each plantation. Finally, we categorized the plantations into four age categories, based on plant height as follows: stage 1 up to 50 cm height; stage 2 between 50 and 100 cm height; stage 3 between 100 and 150 cm height and stage 4 plants with 150 cm height or more. However, these categories do not have a direct relationship with the date of establishment of the plantation, since coffee plants must usually be replaced due to low production, and it was not possible to collect precise information on this.

During the sampling phase, the protocol of Villarreal et al. (2006) was followed using the techniques of visual and auditory encounter survey (VES) for a limited time and fixed band transects (2×50 m) in which each encounter was counted individually for abundance estimation during a sampling event. Sampling was conducted between 8:00 and 12:00 and between 18:00 and 22:00 h, and potential habitats were searched for species, including vegetation, edges of ponds, streams, roads, and leaf litter, with a maximum limit of 5 m above the ground (Cortés-Gómez et al., 2008).

In addition to the field trips conducted in 2021, historical records from surveys between 2015 and 2019 were also included in the diversity analyses. These records were collected by the authors of this study and the herpetology group of Universidad Nacional de Colombia (Herpetos UN) following the VES methodology described above. During all the field trips, data were collected on the site of observation, habitat, body measurements, and photographic records for all individuals. The individuals were released at the same location where they were captured.

Data analysis

To determine the representativeness of the sampling, the species accumulation curve was used as per the guidelines established by Villarreal et al. (2006) using the CHAO 1, ACE, and Cole's Rarefaction estimators, with data based on abundance for the species accumulation function. Alpha diversity was calculated using the Margalef (specific richness), Simpson (dominance), and Shannon-Wiener (evenness) indices. The Jaccard similarity index was used for beta diversity. All diversity indices were calculated using the vegan package (Oksanen et al., 2012) in R software (R Core Team, 2023), with the entire herpetofauna community as the unit of analysis.

To evaluate the relationship between the structural variables of coffee plantations previously defined (Table 2) and the diversity of herpetofauna, a canonical correspondence analysis (CCA) was performed using the CCA package in R software (Gonzalez et al., 2008; ter Braak, 1986). The CCA was performed over the entire herpetofauna community, and the amphibian and reptile community separately. The structural characteristics evaluated included plantation area, distance to the nearest water body, plantation age category, shading, leaf litter abundance, leaf litter moisture, and distance to nearest plantation (Table 2). To ensure statistical robustness, the eigenvalue reliability criterion (Eigenvalue) $\geq$ 50% was used.

Results

We captured a total of 134 individuals belonging to 14 species of frogs, 12 species of snakes, and 7 species of lizards (Supplementary table 1) which represent 48.3% of the amphibian and 13.63% of the reptile species with potential presence in the study area. The species accumulation curve (Fig. 1) indicates that the sampling effort in the RFPCQ is considerably representative, as it shows a tendency to reach the asymptote for the estimators used (ACE, CHAO 1, and Cole).

The diversity of herpetofauna in the RFPCQ was analyzed by considering seven different vegetation cover units (Box 1). Secondary vegetation had the higher diversity and abundance, with more than twice the number of species reported for the following more diverse vegetation cover units, open forest, and coffee plantations. This trend was maintained for the other indices calculated (Margalef, Simpson and Shannon), showing a considerable difference between the diversity achieved in secondary vegetation and that of the other vegetation cover analyzed (Table 1). In contrast, weeded pastures and urban areas were consistently the less diverse units.

In terms of beta diversity, the Jaccard grouping index showed differences in the composition of the species identified in the different vegetation cover units. Regarding the composition of the herpetofauna community, urban areas and weeded pastures presented the lowest richness and abundance among the evaluated vegetation cover units and were therefore very different from the others. Clean and wooded pastures were grouped together because they shared two species (*Boana platanera* and *Atractus* cf. *werneri*). Finally, the cluster formed by the remaining vegetation cover units was structured based on those units that presented the greatest diversity; in these, coffee crops and secondary vegetation grouped the highest abundance of individuals, also showing assemblages with similar compositions, which made them the most similar coverages with 24% similarity (Fig. 1).

The canonical correspondence analysis (CCA) evaluating the relationship between the structural characteristics of the coffee

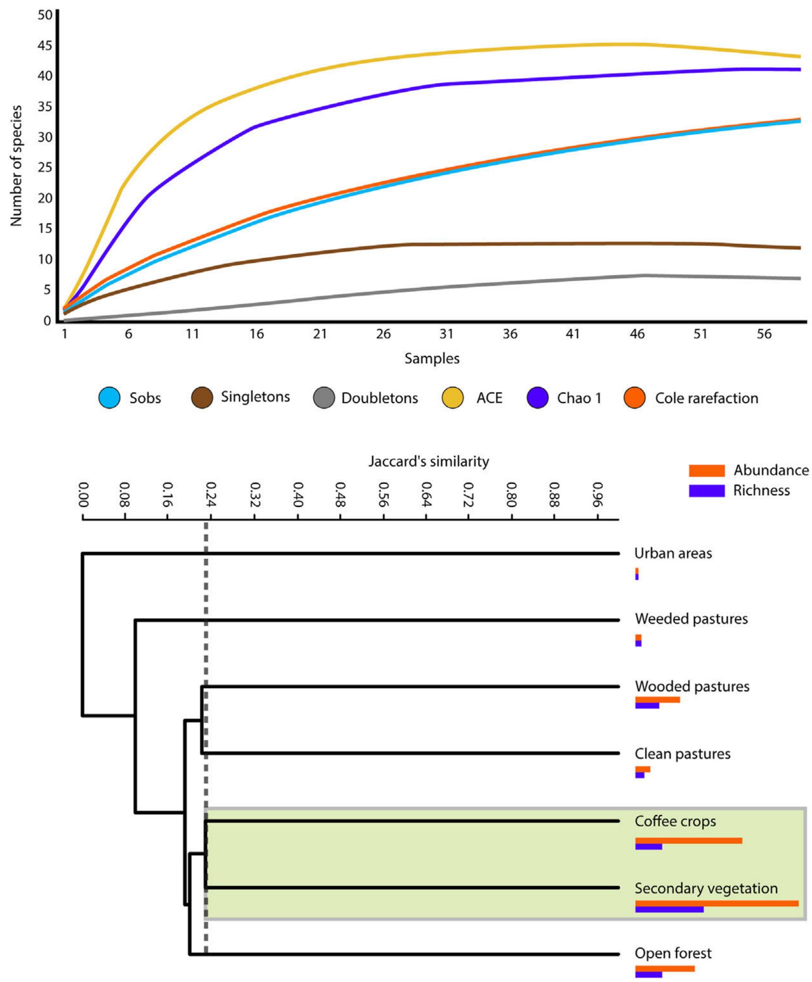


Fig. 1. Sampling representativeness and species diversity across vegetation cover units. The curves depicted above approach the asymptote, indicating that the sampling is representative of the studied area. Representativeness percentage ranges from 77 to 100% (Villarreal et al., 2006). The Jaccard similarity index is presented for each vegetation cover unit to illustrate species diversity. The colored lines correspond to each unit's absolute abundance (orange) and species richness (purple). The shaded area in the figure represents the clade with the highest Jaccard similarity value, which is approximately 24%. The dotted line indicates the cut-off point for the similarity of the most similar group.

Table 2

Structural and maintenance features of coffee plantations. This table presents the characteristics of the six sampled coffee crops. Periodicity of irrigation was not considered as all crops rely only on the natural rainfall regime. Distance to the nearest urban area was also not considered, as all crops were located at least 2.3 km away from the urban center.

	C1	C2	C3	C4	C5	C6
Plantation Area (ha)	0.303	1.874	0.905	1.546	1.056	0.288
Distance to nearest water body (m)	377.806	74.482	0	0	0	0
Plantation age category	4	3	3	4	4	4
Shading	No	Medium	No	High	High	No
Distance to nearest plantation (m)	189.753	130.867	0	277.946	0	24.056
Shade species	NA	*Musa x paradisiaca*	NA	*Musa x paradisiaca*	*Musa x paradisiaca*	NA
Abundance of leaf litter	Low	Low	High	Medium	Medium	Medium
Leaf litter moisture	Medium	Low	Low	Medium	High	Medium
Neighboring Vegetation cover units	Secondary vegetation, wooded pastures	Wooded pastures, weeded pastures	Wooded pastures, clean pastures, coffee crops	Secondary vegetation, wooded pastures	Wooded pastures, clean pastures, coffee crops	Secondary vegetation, wooded pastures
Presence of rocks	Yes	Yes	No	Yes	Yes	No
Other microhabitats	No	No	No	Trees and trunks	Creek	No
Does it use agrochemicals or fertilizer additives?	No	No	No	Yes	No	No

crops and herpetofauna diversity grouped 57.62% of the entire community variation in the first two axes (Fig. 2A). When analyzing the amphibian community individually, 93.48% of the diversity was grouped by the CCA (Fig. 2B), while when analyzing only the reptiles, the first two axes of the CCA grouped 60.06% of the species (Fig. 2C). This means that the structural variables evaluated explain very well the distribution of amphibians in coffee plantations (close to 93%), while these same variables only explain

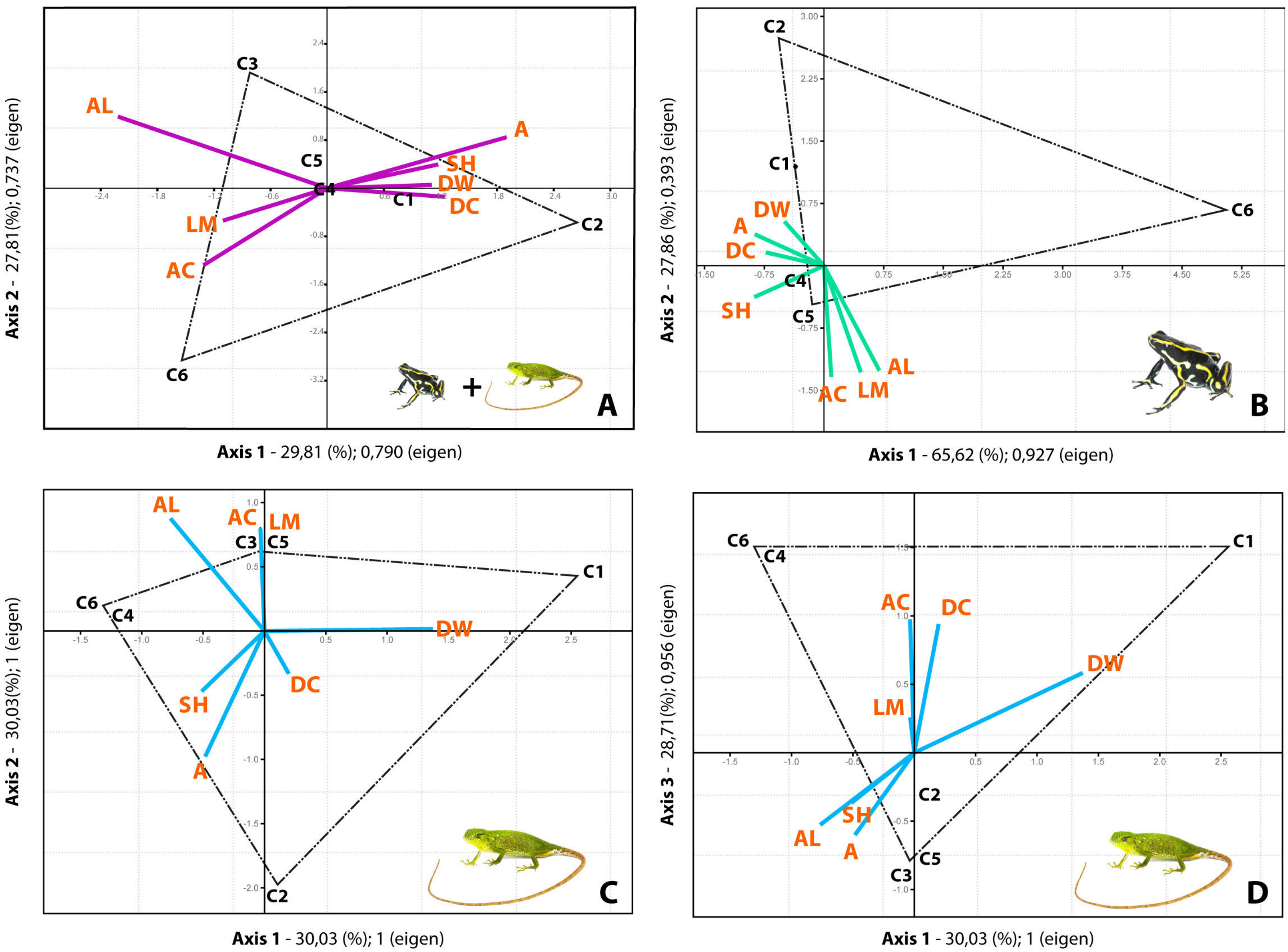


Fig. 2. Canonical Correspondence Analysis (CCA). The diagram shows the herpetofauna community (A), amphibian (B) and reptile (C and D) species diversity relationship with the structural variables of 6 coffee crops in the RFPCQ. The length of the colored lines indicates the relative importance and direction of change of the structural variables. The title of each axis shows the cumulative percentage of variance explained (%) and the eigenvalue (eigen). Conventions: AL: abundance of leaf litter, LM: leaf litter moisture, AC: age category, A: plantation area (ha), SH: shade percentage, DW: distance to nearest body water (m), DC: distance to nearest crop (m), C1-C6: coffee crops.

about 60% of the variance in the distribution of reptiles. Thus, the result shows a greater dependence of amphibians on the variables analyzed. In general, the most important structural variables for determining herpetofauna diversity in the plantations were leaf litter abundance, plantation area and plantation age category. Leaf litter abundance was consistently highly significant for amphibian and reptile groups when analyzed separately (Fig. 2B–D). For amphibians, leaf litter moisture and crop age were also important, while for reptiles, plantation area and distance to the nearest body of water were added as variables of importance in the community structure within coffee plantations.

Discussion

The RFPCQ in the Sumapaz region has a diverse herpetofauna, with the great majority of species associated with secondary vegetation, followed by open forest and coffee plantations (Table 1). Within the coffee plantations, the most important structural variables for the herpetofauna were the abundance of leaf litter, the area of the plantation and the age of the plantation. However, there are slight differences in the importance of structural variables when amphibians and reptiles are analyzed separately (Fig. 2).

The higher diversity and abundance in secondary vegetation indicates its importance as a hotspot for herpetofauna richness and abundance (Fig. 1). This could be attributed to the structural complexity and diverse microhabitats often present in this successional habitat, which increases its potential to offer optimal conditions for reproduction, foraging, and shelter (Leyte-Manrique et al., 2019; Macip-Ríos and Muñoz-Alonso, 2008). Open forests, coffee plantations and wooded pastures presented similar diversity between them, and this could be related to the presence of more generalist species. These species could exhibit behavioral or physiological adaptations that allow them to exploit diverse habitats and resources, leading to similar diversity in apparently distinct environments (Flores et al., 2023). In contrast, weedy pastures and urban areas exhibit lower diversity, potentially reflecting the limited availability of suitable microenvironments for these taxa.

As previously reported, shaded coffee plantations can provide a complex vertical structure with different layers of vegetation (González-Prieto, 2018; Perfecto et al., 1996), resembling the understory of a secondary vegetation area. This structural similarity could offer diverse microenvironments that amphibians and reptiles use to live, which could lead to the presence of similar species in these two habitat types. Second, the ecological niches of certain amphibian and reptile species might be more adaptable and flexible than previously thought. Some species that are ecologically versatile and can thrive in a range of habitat conditions could potentially be present in both secondary vegetation and coffee plantations (e.g. *Pristimantis taeniatus* and *Anolis tolimensis*) (Thompson and Donnelly, 2018).

Moreover, the observed low herpetofauna community similarity (less than 24%) across different vegetation cover units (Fig. 1) can be attributed to a combination of factors that includes habitat preferences, specialized ecological requirements, microhabitat variations, resource availability, and historical human activities and disturbances, that could have created varying conditions to favor certain species while limiting others. Secondary vegetation in the RFPCQ have been subjected to human activities such as soil transformation and selective forest thinning that could relate to the structural characteristics of coffee plantations (CAR, 2023), this could create more convergent habitat conditions between these two vegetation cover units. Future studies exploring species traits, behavior, and ecological preferences in the study habitats could provide insights into the specific factors that lead to the observed similarity in herpetofauna richness and abundance.

Our study underscores the significance of secondary vegetation and coffee plantations in supporting herpetofauna richness and abundance within the studied landscape. However, this does not strictly mean that these are ideal habitats for amphibian and reptile diversity. While secondary vegetation and coffee plantations offer valuable habitats for certain herpetofauna species, the preservation and restoration of forest should remain a primary conservation goal (González-Prieto, 2018). This is particularly crucial for specialist species, such as those strongly associated with forest microhabitats (e.g. creeks, only present in open forest), like *Centrolene daidalea*, *Pristimantis savagei* and *Micrurus mipartitus*, which were exclusively found in forested habitats.

The observed trends in the canonical correspondence analysis (Fig. 2), which highlight the differential importance of environmental traits for amphibians and reptiles within the coffee agroecosystems, may be attributed to several underlying factors rooted in the distinct natural histories, reproductive modes, and ecological adaptations of these two groups. However, the higher abundance of leaf litter appears as a variable of great importance in the structure of the herpetofauna community due to its function as microhabitat, offering refuge, food, thermoregulatory sites, and movement corridors for both amphibians and reptiles (Urbina-Cardona et al., 2006; Wanger et al., 2009).

Amphibians' heightened sensitivity to environmental changes could explain their strong response to factors such as the abundance of leaf litter, leaf litter moisture, plantation age category, and shade percentage. These species often rely on damp and shaded microhabitats for breeding, hydration, and protection, which may relate with a greater dependence on these traits (Roach et al., 2020; Urbina-Cardona et al., 2006). Also, our data shows that species that are less sensitive to dehydration can use unshaded crops, as seen with *R. horribilis*, identified in coffee crop 6 (C6 in Fig. 2B) (Díaz-Ricaurte et al., 2020; Wanger et al., 2010).

Reptiles, on the other hand, exhibit distinct life history strategies, related to their activity periods, food requirements and reproductive modes, that affect their habitat requirements and interaction with environmental factors. The importance of traits like abundance of leaf litter, distance to nearest body of water, plantation area, plantation age category, and leaf litter moisture for reptiles suggests their sensitivity to a combination of factors that influence their thermoregulation, foraging, and reproductive success (Fig. 2C,D). The strong influence of distance to nearest body of water on reptile diversity (and not in amphibian diversity) is surprising, given the amphibians dependence on water sources for survival (Cortés-Gómez et al., 2008; Pineda et al., 2005), and its aligns with their propensity for oviposition near aquatic habitats, underscoring their dependence on water bodies for reproduction and survival (Flores et al., 2023; Ryan et al., 2016).

The strong relation between distance to nearest body of water and reptiles and not amphibians is probably explained because the most abundant amphibian species found in the samples was *Pristimantis taeniatus*, a direct development species that does not depend on water pounds to reproduce (Murrieta-Galindo et al., 2013; Pineda et al., 2005). Moreover, the significance of plantation area for reptiles highlights the potential role of habitat size in shaping reptile communities within the agroecosystems (Ghosh and Basu, 2020; Urbina-Cardona et al., 2006).

Among the coffee crops sampled, only one reported the use of agrochemicals (C4 in Table 2). In general, there was a low relationship between the environmental variables measured and the diversity of herpetofauna in this crop (Fig. 2), which could show a response to the use of insecticides and herbicides that prevent the growth of vegetation within the crop and affect the interaction networks within it, resulting in the loss of resources necessary for amphibians and reptiles, such as refuge and food (Beaumelle et al., 2023; Roach et al., 2021). There is a correlation between the amount of leaf litter and the shaded/unshaded conditions of the crops (Table 2), which shows a direct relationship between the potential for harboring herpetofauna diversity (Cortés-Gómez et al., 2008), and the coffee shade practices, through the formation of leaf litter. A thick layer of leaf litter within the crops could favor the establishment of complex and structured animal communities (Rojas Sánchez et al., 2012; Tejeda-Cruz and Sutherland, 2004), increasing the levels of diversity observed in agricultural environments.

Recent studies in northern Colombia have shown that the expansion of the agricultural frontier and the intensification of coffee production (i.e., less shade) can promote population decline in amphibians due to the decrease in habitat quality and quantity (Roach et al., 2021, 2020). By encouraging and maintaining shade-grown cultivation practices in the RFPCQ, which is directly related to the production and maintenance of a leaf litter layer, the negative impact of intensive agricultural practices on amphibian and reptile population declines could be mitigated. This approach could also provide benefits to local communities by promoting environmentally friendly and socially responsible coffee production practices.

The divergent responses of amphibians and reptiles to environmental traits underscore the need to consider their unique ecological requirements in conservation strategies. These trends emphasize the importance of preserving diverse microhabitats within coffee agroecosystems, tailored to the needs of both groups. By integrating this understanding into management practices, we can foster sustainable coexistence and enhance biodiversity conservation in agricultural landscapes. Further investigations into specific behavioral, physiological, and reproductive adaptations will provide deeper insights into the mechanisms driving these trends and enable more targeted conservation efforts.

A set of sustainable management principles to promote herpetofauna coexistence

The findings of our study are in line with previous research indicating that shaded coffee plantations, through the structural offer of microhabitats and the production of leaf litter, can provide suitable habitats for herpetofauna, including amphibians and reptiles. However, it is important to note that the use of agrochemicals, such as pesticides and fertilizers, can have negative impacts on these animals and their habitats (Beaumelle et al., 2023; Wagner et al., 2013). A recent study by Wagner et al. (2017) found that the use of glyphosate-based herbicides could induce morphological changes

Box 1
Vegetation cover units and their characteristics in the study area. Summary of the vegetation cover units and their characteristics in the study area. The box includes the vegetation unit's definition based on (IDEAM, 2010), the total area sampled, and the number of polygons sampled in each unit.

Open Forest: Is a vegetation community dominated by regularly spaced trees forming a dispersed canopy, with a height greater than five meters. This type of forest cover has either not been disturbed or has undergone selective intervention, preserving its original structure and functional characteristics. In this study, three open forest polygons with a total area of 68.12 ha were sampled in the villages of Buenos Aires (Nilo), Atalá (Viotá), and La Vuelta (Tibacuy). The Buenos Aires and Atalá polygons are larger and correspond to continuous forests, while the La Vuelta polygon is surrounded by secondary vegetation.

Secondary Vegetation: this vegetation type is a result of the natural succession process that occurs after the intervention or destruction of primary vegetation. It can be found in areas cleared for different uses, in abandoned agricultural areas, and in areas where natural events have destroyed the natural vegetation. Within the study area, this unit occupies a total area of 90.72 ha, distributed in seven polygons located in the villages of La Vuelta, Bateas, Albania, Capotes, and El Cairo (Tibacuy). The cover in these areas is characterized by mainly shrub and herbaceous vegetation with an irregular canopy and occasional presence of trees and creepers. These areas are usually surrounded by other coverages such as pastures and coffee plantations.

Clean pastures: these are defined as lands covered mostly by dense grasses such as those of the Poaceae family and are used for permanent grazing for two or more years. In our study area, we conducted sampling in a single 0.8 ha polygon located on the La Vuelta trail in Tibacuy, which is used for livestock maintenance.

Wooded pastures: these are areas of pastureland with trees irregularly distributed over the land and forming 30%–50% of the total area. These areas were selected for sampling in six polygons covering a total area of 39.16 hectares, located in Buenos Aires (Nilo), Capotes, La Vuelta, and Bateas (Tibacuy).

Weeded pastures: these are areas where grasses and weeds form associations of secondary vegetation, which are typically less than 1.5 m. For this study, sampling was carried out in a single polygon with an area of 0.49 hectares located in the village of La Vuelta, Tibacuy.

Coffee plantations: these areas are characterized by developing in patches under shade, which could be temporary or permanent, generated by arboreal elements or with free exposure to sunlight. Six crops were selected, including five in La Vuelta (Tibacuy) and one in Buenos Aires (Nilo). The study considered crop maintenance variables, such as the use of agrochemicals, periodicity of irrigation and maintenance, as well as the type of crop, which could be with or without shade, monoculture, or mosaic. In addition, four age classes were established for the crops according to the average plant height: Stage 1 (plants with heights less than 50 cm), Stage 2 (heights between 50 and 100 cm), Stage 3 (heights between 100 and 150 cm) and Stage 4 (heights greater than 150 cm). The abundance and humidity of leaf litter were recorded, as well as the presence of rocks, trunks, and other potential microhabitats.

Urban areas: these are composed of buildings and surrounding green spaces. In the study area, a private property located in the Buenos Aires (Nilo) neighborhood with an area of 0.068 ha was included. This site is surrounded by a rural road, gardens, and green spaces. Although urban areas were not part of the initial experimental design due to its anthropized nature with low diversity potential, they were included due to the incidental observation of *Hemidactylus* sp. during logistical activities associated with the field stage.

and increase malformation rates in amphibians, especially in areas with low forest cover. Therefore, it is crucial to adopt sustainable agricultural practices that minimize the use of agrochemicals and promote the maintenance of natural habitats.

Several principles and practices can be implemented to promote sustainable agricultural management of coffee crops that support the existence of amphibians, reptiles, and other terrestrial animals in the Andes. We propose the following 6 principles of management:

- Shade management: Maintaining a shade cover that mimics the natural forest structure can provide suitable habitats for herpetofauna and other animals, as well as promote soil health and prevent erosion (Tscharntke et al., 2011; Urbina-Cardona et al., 2006).
- Leaf litter management: Maintaining a thick layer of leaf litter can provide a moist and structured environment that supports a diverse community of animals (Tejeda-Cruz and Sutherland, 2004), even in the dry season, which is crucial for their survival. However, it is important to avoid excessive accumulation of leaf litter, as this can lead to an increased risk of fire and pest outbreaks (Balch et al., 2015).
- Soil and water management: Practices such as the use of cover crops, composting, and reduced tillage can improve soil health and promote the retention of moisture and nutrients, which can benefit plant and animal communities (Bach et al., 2020). Also, implement sustainable water management practices, such as rainwater harvesting and irrigation systems that minimize water use and runoff, and avoid contamination of nearby water sources.
- Connectivity management: Promote landscape connectivity by preserving and restoring natural areas around coffee plantations, such as forests, wetlands, and other important habitats for terrestrial animals. These practices improve resource availability and favors the coexistence of plant and animal communities (González-Prieto, 2018; Howell et al., 2018; Perfecto et al., 2007).
- Monitoring management: Implement monitoring and management plans to ensure that the above practices are being followed and that the health of the ecosystem is being maintained. This can include regular surveys of the herpetofauna and other wildlife and soil and water quality testing.
- Integrated pest management: Adopting pest control strategies that prioritize non-chemical methods, such as crop rotation, intercropping, and biological control, can reduce the negative impacts of agrochemicals on the environment and promote the natural regulation of pest populations (Crowder and Jabbour, 2014).

By implementing these sustainable practices, coffee farmers can contribute to the conservation of biodiversity and the maintenance of ecosystem services in coffee-growing regions, while also promoting the economic viability of their crops.

Furthermore, the promotion of agricultural practices that maintain the quality and quantity of microhabitats is crucial. Maintaining the structural variables of leaf litter abundance, planting area and crop age as long as possible, as well as the influence of leaf litter humidity and distance to other crops will promote the presence of amphibians and reptiles. However, it is important to clarify that the landscape approach is also important to maintain diversity, therefore, promoting diverse matrices containing different land covers could support the long-term survival of herpetofauna and the general biodiversity of the landscape region, since maintaining preserved vegetation around coffee plantations has been positively associated with maintaining connectivity and relative humidity (Santos-Barrera and Urbina-Cardona, 2011b).

In conclusion, the results of this study highlight the importance of agroecosystems, such as shade coffee plantations, in providing habitats for herpetofauna in highly fragmented landscapes such as the Sumapaz region. It was found that the diversity and abundance of amphibians and reptiles was influenced by several microclimatic variables, with leaf litter abundance being the most important. The findings have important implications for conservation strategies in the Sumapaz region and other areas with similar characteristics. Future research could focus on better understanding the dynamics of herpetofauna populations in agroecosystems and the interactions between agricultural practices, the specific role of litter depth and moisture in coffee agroecosystems, land use change and the conservation of biodiversity in these environments.

Funding

This work was supported by the Asociación Colombiana de Herpetología (ACH) through the Botas al Campo grant, 2019.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank the Asociación Colombiana de Herpetología for funding through the Botas al Campo grant (2019) and APRENAT for their logistical support. We also acknowledge the cooperation of various individuals and organizations, including the Castillo Urrego family, Bernal Méndez family, Maria Rosa Gaona de Chacón, Mayelly Liévano, Gabriel Garzón, Fray José María Sepúlveda, the Province of Nuestra Señora de Gracia de Colombia and the members of Herpetos UN, for their hospitality, collaboration throughout the field phase and for their valuable contributions in the development of this project. To Nataly Casas, Carolina Martínez, Juan Diego Rodríguez, and Sebastián Pérez for their help during the field phase and species identification. Thanks to Kelley Crites and Robin Davies for the English writing advising and to our reviewers for their valuable comments. Finally, we appreciate the ongoing efforts of the communities of La Vuelta, Capotes, El Cairo, Albania, and Buenos Aires in developing and conserving the RFPCQ.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.pecon.2024.04.001.

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