RESPONSES OF HERPETOFAUNAL ASSEMBLAGES TO DIFFERENT HABITATS IN WEST AFRICA

A CASE STUDY IN NORTHERN GUINEA-BISSAU

Master's Programme in Ecology and Evolutionary Biology

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Abstract:

Land-use change stands behind the current biodiversity crisis and all it entails in terms of ecosystem services. Guinea-Bissau, in West Africa, is originally characterized by a forest-savanna mosaic biome. However, while savannas have long been planted with rice, both rice paddies and forest remnants are now being converted into cashew monocultures – the only cash crop in the country – at unprecedented rates. The ecological impact of such rapid change is largely unknown. To help fill this gap, we examined how three diversity metrics – rarefied species richness, abundance and composition – varied across forest remnants, cashew orchards and rice paddies for amphibians and reptiles in northern Guinea-Bissau. To do so, visual encounter surveys were carried across 21 sampling sites, seven of each habitat type. A total of 703 amphibian and 266 reptile encounters was recorded from nine and 14 taxa, respectively. The results show class-specific responses to habitat type. Amphibians' diversity in forest remnants and cashew orchards was similar across all metrics, but rice paddies had a higher abundance and unique composition compared to forest remnants. Reptiles' abundance was highest in cashew orchards and this habitat had a distinct composition, when compared to forest remnants. Rice paddies sustained both lower reptile richness and abundance. Overall, our results are not in agreement with the expected detrimental impacts of cashew expansion, which might be due to the still high heterogeneity of habitat types within the landscape. Rice paddies proved particularly important for amphibians, and for open-habitat reptiles, boosting overall species diversity. In face of the eminent habitat conversion,

maintaining heterogeneous landscapes, including the persistence of both forest remnants and rice paddies, will allow minimizing biodiversity loss in West Africa.

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1. INTRODUCTION

Land-use change and related pressures stand behind the current biodiversity crisis that characterizes the Anthropocene (Dirzo et al., 2014; Newbold et al., 2015; Powers & Jetz, 2019; Sala et al., 2000). Today, agriculture occupies about 38% of the world's land surface (FAO, 2020). As the human population grows, that number is expected to increase further, as a response to the growing demand for food (Foley et al., 2011; Godfray et al., 2010; Pendrill et al., 2022, but see Delabre et al., 2021; Leclère et al., 2020). However, the distribution of human-modified landscapes is not even throughout the globe, with the tropics seeing more habitat loss due to land-use change than other regions (Hansen et al., 2020; Newbold et al., 2020; R. P. Powers & Jetz, 2019). Conversely, these are among the most biodiverse regions in the world (Dirzo & Raven, 2003; Myers et al., 2000), and the impacts of anthropogenic activities on these ecosystems are disproportionately understudied compared to other regions (e.g., temperate; Gardner et al., 2009; Newbold et al., 2020). Furthermore, most of the research on land-use change in the tropics has been focused on the Neotropics, leaving tropical Africa poorly understood (Powers et al., 2011).

Land-use changes affect different aspects of biodiversity that reduce ecosystem resilience: decreased species richness (Newbold et al., 2015; Scales & Marsden, 2008), altered species abundance and composition (Harvey & González Villalobos, 2007; Newbold et al., 2015, 2016), changed ecological functions (Matuoka et al., 2020) and, ultimately, disrupted ecosystem services (Barnes et al., 2017). However, the responses of different biological groups to changes in land use may vary, and intrinsic species traits make some species more vulnerable than others (Newbold et al., 2014). For instance, Harvey & González Villalobos (2007) found birds to be more sensitive to change than bats, as their assemblages varied more across different land uses, from forests to monocultures. Likewise, Fulgence et al. (2021) observed stronger negative responses of amphibians to land-use change than those of reptiles, when comparing diversity across a gradient from primary forests to agroforests and rice paddies. Overall, an increasing body of evidence now supports that habitat specialists are typically more prone to local extinction than generalists (Devictor et al., 2008), and so are species with smaller geographic ranges compared to those with larger ones (Jones et al., 2003). Nonetheless, it remains less clear how certain understudied taxa respond to land-use change and how those responses vary geographically (Williams & Newbold, 2020).

Although biodiversity typically declines with increased agriculture coverage (Scales & Marsden, 2008), and agricultural land usually supports fewer species than native habitats (e.g., forests; Wurz et al., 2022), those areas plays very important role in food security (Godfray et al., 2010). In this context, we have to find a way to maximize biodiversity in those lands (Delabre et al., 2021; Perfecto & Vandermeer, 2010). Maintaining a heterogeneous landscape mosaic, including both agricultural and native habitats, can help keeping reasonable species diversity levels (Fahrig et al., 2011; Harvey & González Villalobos, 2007), and may even at times provide habitat for many, including some forest-dependent ones (Harvey & González Villalobos, 2007; Wurz et al., 2022). These systems, like heterogeneous habitat mosaics, may also improve the connectivity between formally protected areas and alleviate resource-use within them (Bhagwat et al., 2008; Kremen & Merenlender, 2018). The higher the complexity of the agricultural habitat and the similarity of its vegetation structure to that of the replaced native one, the higher the diversity the landscape withstands (Estrada-Carmona et al., 2022; Prevedello & Vieira, 2010). Still, there is generally a lack of empirical knowledge of the conservation value of such habitats (Arroyo-Rodríguez et al., 2020; but see e.g.,Wurz et al., 2022).

Even though it is one of the most biodiverse regions in the continent, West Africa has lost most of its primary vegetation (Myers et al., 2000), and that loss is expected to continue through this century (R. P. Powers & Jetz, 2019). Yet, the area has been subject to very few ecological studies compared to other biodiversity hotspots (Gardner et al., 2009; Gibson et al., 2011; Newbold et al., 2020). Furthermore, there is a decreasing pattern in the published literature as one moves westward (Luiselli et al., 2019), as is the case of Guinea-Bissau, on the westernmost tip of the continent. This country has historically been covered by a forest-savanna mosaic (Catarino et al., 2008), but its long history of agriculture has changed the landscape overtime (Temudo & Abrantes, 2013). Rice (*Oryza glaberrima*) has traditionally been cultivated for domestic use (Temudo & Abrantes, 2013) and, together with groundnuts, comprised the core of the agricultural land in the country until the 20th century (Catarino et al., 2015). After the 1940's, cashew trees (*Anacardium occidentale*) – native to Northeast Brazil – started to be systematically planted across the country, with higher prominence in the north (Temudo & Abrantes, 2014). This global agricultural commodity (Rege & Lee, 2023) has replaced most other forms of land use in Guinea-Bissau, especially since the 1980's (Temudo & Abrantes, 2013). Today, agriculture is still the main source of livelihood in the country and cashew nuts comprise the only cash crop for the economy of Guinea-Bissau, accounting for 90% of all exports (FAO, 2021; Temudo & Abrantes, 2013). Cashew

monocultures are typically dominated by smallholders (Rege & Lee, 2023) and even though this crop is quickly expanding throughout the tropics, the impacts of such conversion have received limited ecological research attention (Rege & Lee, 2023). Nevertheless, the highly complex bio-cultural landscapes in Guinea-Bissau comprising a forest-rice mosaic are known to withstand high biodiversity levels (Temudo et al., 2015), are now threatened by the quick expansion of cashew orchards, which are homogenizing the landscape (Catarino et al., 2015; Rege & Lee, 2023). Indeed, these monocultures have lower plant diversity and simpler vegetation structure when compared to forests (Rege & Lee, 2023; but see Sousa et al., 2015), and turn open habitats into closed-canopy ones when replacing rice paddies. So far, the little available literature regarding species responses to cashew expansion shows a decline of species richness and composition changes across different taxa compared to the corresponding reference habitats (Rege & Lee, 2023). Recently, Komanduri et al. (2023) reported shifts in composition of amphibians between cashew orchards and forests in India. Nonetheless, the true dimension of the impacts of cashew expansion on local biodiversity is not yet understood (Catarino et al., 2015; but see Rege & Lee, 2023).

Amphibians and reptiles are among the most threatened animals on Earth (Cordier et al., 2021; Dirzo & Raven, 2003), yet their responses to anthropogenic pressure are less studied than that of other taxa (e.g., invertebrates, birds; Newbold et al., 2014) and there is a strong geographical bias in the available literature, with efforts skewed toward temperate regions and the Neotropics (Cordier et al., 2021; Guedes et al., 2023). Although animals from both classes are ectothermic and thus vulnerable to environmental changes (Cordier et al., 2021; Newbold et al., 2014), the highly permeable skin of amphibians, together with their biphasic life cycle make them more sensitive to such changes than reptiles (Fulgence et al., 2021; Pendrill et al., 2022; Winter et al., 2016). Amphibians' breeding ecology often contributes to a high densities of amphibians in freshwater environments (Semlitsch et al., 2015). To better understand how amphibians and reptiles respond to changes in land use, I focused on forest-agriculture mosaics in northern Guinea-Bissau. I examined herptile species diversity in forest remnants, cashew orchards and rice paddies, considering their species richness, abundance and composition. I expected (1) amphibian and reptile species richness to be highest in forest fragments and lowest in cashew orchards; (2) amphibian abundance to be highest in rice paddies, and reptile in forest fragments; and (3) species composition to differ in forest remnants and cashew orchards from those of rice paddies for both classes.

2. METHODS

2.1. Master's thesis framing

I developed my thesis project within the frame of two major, multitaxa projects surveying the same study area in Guinea-Bissau, while based in Portuguese institutions: *Rice Guardians* (cE3c, Lisbon, Portugal; reference no. PTDC/ASP-AGR/0876/2020) and *TROPIBIO* (CIBIO, Vairão, Portugal; European Union's Horizon 2020 research and innovation programme under grant agreement No. 854248). The former aims at enhancing food security through assessing the role of birds and bats as pest control agents in west Africa; the latter promotes biodiversity conservation and sustainability in Portuguese-speaking African countries. Together, they have been addressing biodiversity patterns in multiple-use landscapes on different taxa – from invertebrates to medium-sized mammals – in the same area my work was carried. However, the projects were not considering herpetofauna. I was at the time looking for a project that would allow me to focus on the taxa I have passion for, and having familiarized with the recent work of Fulgence et. al (2021), I realized that the projects offered me the context to conduct a similar study in Guinea-Bissau, while, interestingly, other teams would be focusing on other taxa. My idea was welcomed by the project coordinators, and I proceeded with creating the protocol for the herpetofauna surveys together with my supervisors. The study design was conditioned to some extent by the work of the teams already on the ground. This meant that most of my study sites had already been established for surveying other taxa. This had been done according to the availability of each of the three three assessed habitat types at close proximity, with rice paddies being the limiting habitat for the selection of study sites. However, I adapted the sampling protocol for my focal taxa, also determining the sampling effort and period.

2.2. Study area

This study took place in northern Guinea-Bissau, Oio province, about 17 km south of Farim (12°19'49.82"N, 15°10'57.55"W; Figure 1). The once savanna-forest mosaic has given way to agricultural land over time (Catarino et al., 2008). The region now consists of scattered small *tabancas* (villages) surrounded by forest remnants and large areas of extensive agriculture. These make up mosaics of forest remnants, cashew orchards, and rice paddies in and around hydrographic basins. Within this region, cashew orchards are expanding, replacing mostly forest remnants, but also the rice paddies that do not gather much water, allowing the cashew

trees to grow. The area has a very smooth relief below 50 m altitude, and has defined wet –
from June to October – and dry – from October to June – seasons (Catarino et al., 2008). The
mean temperature throughout the country ranges between 25.9 and 27.1 ºC, and the annual
precipitation between 1200 mm in the northeast and 2600 mm in the southwest (Catarino et
al., 2008).

I surveyed amphibians and reptiles across three types of habitat – forest remnants,
cashew orchards and rice paddies. The surveys took place across 21 circular study sites of 25
m radius (Fulgence et al., 2021), seven of each habitat type nested into five locations (Figure
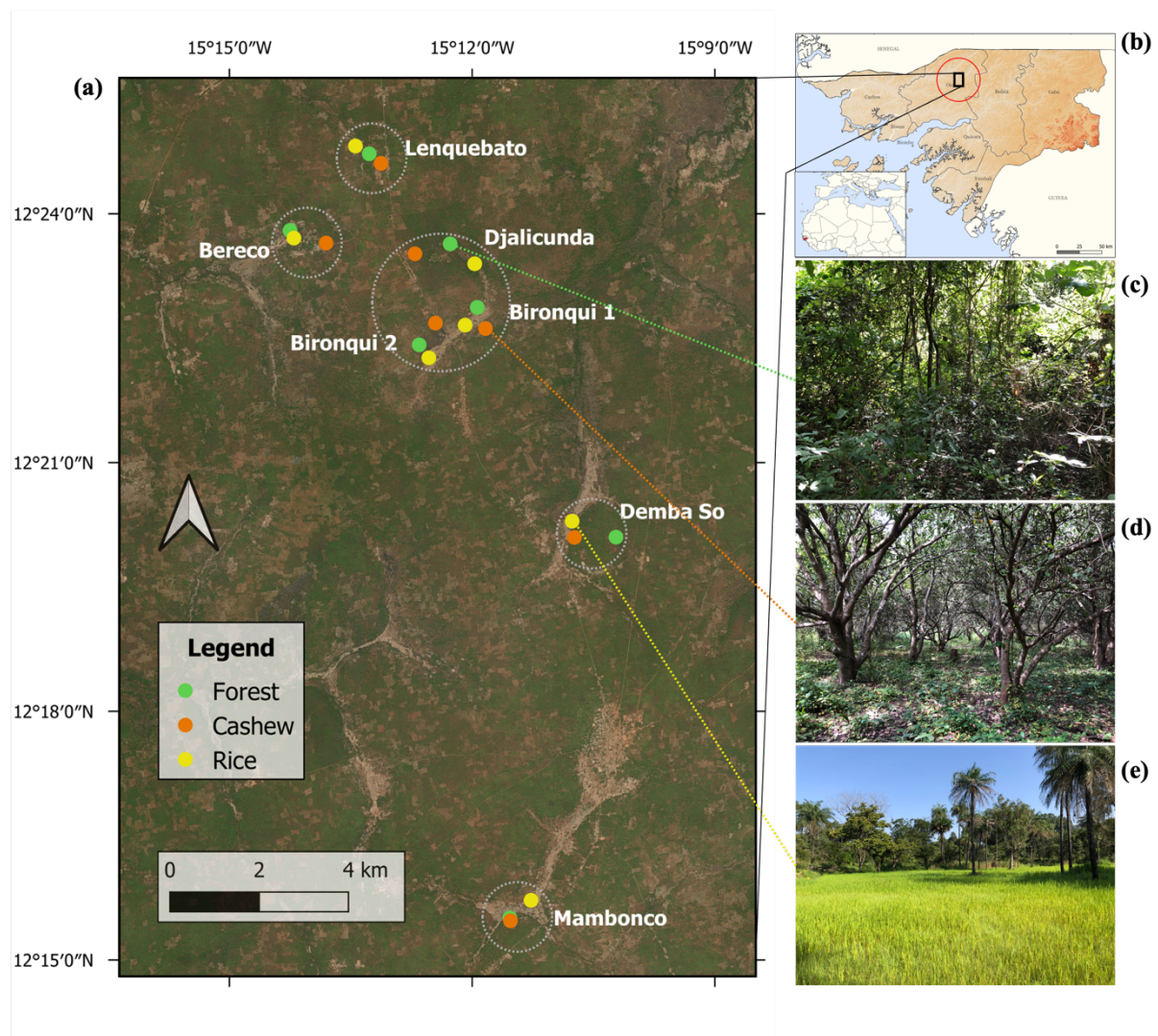1a; Appendix 1).

*Figure 1. (a) Study area in northern Guinea-Bissau highlighting the location of each of the
21 study sites (solid dots color-coded by habitat type), across seven* tabancas *(villages) in
northern Guinea-Bissau. Dashed grey circles represent the geographically nested structure
of the sampling sites; (b) Locations of Guinea-Bissau and of the study area. Each of the
sampled habitat types is further illustrated: (c) forest remnants, (d) cashew orchards and (e)
rice paddies (e). Map sources: qGIS (2023), GADM (2021) and geoBoundaries (2017).
Photos: Francisco Silva.*

2.3. Surveyed habitat types

To describe each study site and understand variation within, but especially between habitat types, I carried a visual characterization from the center of each site and estimated different metrics, after the rainy season. These included percentage of bare ground, leaf litter, percentage canopy cover, and the number of trees and stems for a five-meter radius, among others (Appendix 2). I then used the number of trees to extrapolate the density of trees per hectare for each study site, as shown below. These habitat metrics gave me a better idea of the structure of the different habitat types. However this data was only used in this context, not being included in subsequent analyses on this thesis. However, such data is expected to be used in the near future in combination with the larger scale metrics of habitat heterogeneity within and around each of the study sites (yet to be measured from the corresponding GIS together with the larger projects taking place in the study area; see *section 4.6.*). Below follows a description of each of the three surveyed habitat types.

Forest remnants in the region are classified as secondary growth because of the long history of human intervention in them (Catarino et al., 2008). The characteristics of these study sites vary among each other, particularly in terms of the amount of leaf litter covering the ground (ranging between 0 and 90%) and the number of stems (between 28 and 131). Still, the ground in forest remnants is rarely bare (between 0 and 10%, except Ber-F and Bir1-F with 40 and 50%, respectively), the canopy cover varies between 65 and 95%, and the density of trees between 892 and 1911 trees per ha (Appendix 2). Unlike cashew orchards and rice paddies, some forest remnants have many thin stems and lianas that increase the overall vertical complexity of the habitat. All the sampled forests are nearby local communities, and thus subject to human intervention, namely the extraction of forest products (e.g., fruit, bark, honey, game), without tree removal.

Cashew orchards share similar arboreal structure with forests, yet of lower height and without the presence of additional tree species. There is little to no bare ground (between 0 and 20%) throughout the cashew sites. Instead, there are short plants and leaf litter covering the ground. The density of cashew trees within surveyed sites varied between 1656 and 3949 trees per ha, and the canopy is relatively dense (≥80% in six out of the seven sites) (Appendix 2). These orchards are often crossed by narrow paths. Harvesting occurs between June and July, and the undergrowth is cut short just before flowering. Cashew orchards are biological, as no agro-chemicals nor irrigation are used in the cashew management (Catarino et al., 2015). All cashew orchard study sites appear to be replacing pre-existing forests. The exact

age of the orchards is unknown, but since all of them were already producing fruits, they are at least eight years old (Dendena & Corsi, 2014).

Rice paddies within the study area occupy the once open areas of the former savannah-forest mosaic. These areas flood naturally in the rainy season. They are crossed by banks that serve as dams and make up paths during the flooded period. There are spread out trees or small groups of trees throughout that may form small islands, but the tree density is low, ranging between 0 and 255 trees per ha. Therefore, there is little to no canopy cover (between 0 and 5%) in rice paddies. These retain water from the wet season until December. When flooded, the vegetation is made up mainly of rice (*Oryza glaberrima*), alongside a few other plants on the banks and islands. Once rice paddies dry, the ground is covered by low, sparse herbaceous vegetation, with patches of bare ground. Rice is planted in June/July and harvested in November/December, except when the paddy is left fallow. Rice paddies are among the few available bodies of water over the study area, besides man-made structures and road-side ditches.

2.4. Herpetofauna surveys

I conducted fieldwork over two four-week long campaigns in 2022. To account for seasonal differences in herptile activity, the first campaign was carried out at the end of the dry season/beginning of the wet season (June/July) and the second one at the end of the wet season (October/November). In each campaign, I surveyed all study sites three times during the day (between 09h15 and 12h30), and once at night (between 19h30 and 22h00), equaling eight surveys at each of the 21 sites.

I collected the data in time-standardized surveys (Fulgence et al., 2021). In every survey, I systematically surveyed each site for 45 minutes, amounting to a total of 126 sampling hours: 94.5 h during day time and 31.5 h at night time. In each survey, I thoroughly searched the sites in a zig-zag manner, and carefully checked for herptiles underneath by lifting any loose object (e.g., dead wood, bark, leaf litter) with the aid of protective equipment. I also used binoculars to assist with the search and identification. I noted the date, time and weather at the beginning of every survey. For each amphibian and reptile encounter, I registered the species (or the lowest possible taxonomic level), microhabitat (e.g., tree trunk, leaf litter and under log), age (i.e., adult or juvenile), photo ID (if available), and any other information (e.g., amphibian vocalizations, mating behavior, etc.).

2.5. Species identification

There is no one guide compiling the amphibians and reptiles of the study region. As such, I first prepared a potential species list for the study area. To do so, I obtained all the available shapefiles for all species of both classes from IUCN (IUCN, 2022), and intercepted them with the study area plus a 500 km buffer on ArcMap (ArcGIS Release 10.1, 2022). Out of the obtained species list, I gathered online photos of each species, highlighting their most relevant morphological traits, if any. I identified amphibians with the aid of AmphibiaWeb (AmphibiaWeb, 2022) and complimentary literature (e.g., Pickersgill, 2007). For reptile identification, I used the field guides Chippaux & Jackson (2019) for snakes, and Trape et al. (2012) for lizards, crocodiles and testudines. Before going to the field, I studied the species and their traits well, which, together with my already extensive experience with these taxa, prepared me for quickly identifying them in the field.

I identified each herpetofauna record down to the lowest possible taxonomic level based on morphological characters. When identification was inconclusive, I took a photo and asked Cristian Pizzigali – my co-supervisor and a herpethologist with extensive experience in the area – to confirm the ID. When no photo was available and collecting the specimen was possible, I extracted a tissue sample for DNA barcoding: toe tips from amphibians (Gonser & Collura, 1996) and tail tips from reptiles (Velo-Antón et al., 2022). Live specimens were released immediately after tissue collection on the same site I found them. Biological samples were stored in a polypropylene tube containing 96% ethanol (Velo-Antón et al., 2022) and transported to the Research Center in Biodiversity and Genetic Resources (CIBIO), in Portugal, for barcoding. Instituto da Biodiversidade e Areas Protegidas (IBAP), the Guinean institute in charge of emitting transport permissions of biological samples, issued the corresponding declaration. The still ongoing barcoding of 30 genetic samples will allow for a confirmation of some species' ID, as well as the identification of some specimens down to species level. For the 28 times (<3%) I could not identify the specimen to the genus level nor capture it, I disregarded the encounter (except one record from the Leptotyphlopidae family, see *section 2.7.*).

2.6. Research permits and ethics

This work, and the wider projects it is part of (*Rice Guardians* and *TROPIBIO*), was carried out in cooperation with KAFO, a local NGO that works in close contact with local communities. This organization established the connection between research teams and local

communities. The committee of each village was consulted in each field season and granted permission for the said work.

Herpetofauna surveys, handling and tissue sample collection was carried out following the appropriate guidelines (Gonser & Collura, 1996; Mulualem, 2016; Velo-Antón et al., 2022), and animal welfare was considered at all times.

2.7. Data analysis

I conducted all the analyses on R version 2023.03.0+386 (R Core Team, 2022), and used the "ggplot2" (Wickham, 2016) R-package for visualization. Amphibians were analyzed at the *taxa* level since five taxa were identified to species and four to genus level. Reptiles were assessed at species level, except for the family Leptotyphlopidae represented by one encounter. For simplification purposes, hereafter I will refer to *taxa diversity* as *species diversity*. Each study site includes the sum of all observations on all eight surveys conducted on that site, regardless of the season or time of survey. Because the functions used for rarefied species richness and composition analyses cannot handle zeros, I removed four sites that had no encounters from the subsequent analyses: two sites (Dem-R and Mom-R) from the amphibian, and two (Dem-F and Mom-F) from the reptile analyses.

2.7.1. Sampling sufficiency

To check sampling sufficiency, I made encounter-based species accumulation curves using the *rarecurve* function of "vegan" R-package (Oksasen et al. 2020). These were done for each study site, each habitat, and considering amphibians and reptiles separately. Even though the effort was the same throughout the 21 study sites, it was not enough to capture a representative sample of each study site, habitat or class (i.e., species accumulation curves had not yet reached the asymptote; Appendix 3).

2.7.2. Rarefied species richness

Due to this inadequate sampling sufficiency, I used Anne Chao's proposed method to estimate species richness at each study site – *Chao1* (Chao, 1987) –, which is often used in the assessment of richness in herpetological studies (Fulgence et al., 2021; Hutchens & DePerno, 2009). Rarefied species richness was estimated using the function *ChaoRichness* from the R package "iNEXT" (Chao et al., 2014). This function uses the formula: $SChao = Sobs + \frac{n1(n1-1)}{2(n2+1)}$, where: $SChao$ = estimated richness, $Sobs$ = observed number of species, $n1$

= number of species observed only once (i.e., "singletons"), *n2* = number of species observed twice (i.e., "doubletons"). As such, the number of observed singletons and doubletons make rarefied species richness higher than the observed.

2.7.3. Species abundance

Because I may have observed the same specimen at more than one occasion, the number of encounters does not necessarily correspond to the number of individuals and it was used as a proxy for species abundance (Fulgence et al., 2021).

2.7.4. Species composition

I assessed species composition in two dimensions using Non-Metric Multidimensional Scaling (NMDS; Kruskal, 1964) with Bray-Curtis abundance-based dissimilarities (Bray and Curtis, 1957), using the *metaMDS* function of the R-package "vegan" (Oksasen et al. 2020) (stress = 0.114 and 0.059 for amphibians and reptiles, respectively). Sites Bir1-R, Len-C and Len-R were characterized by only an exclusive species for either of the classes (Len-C had an exclusive amphibian species, and Bir1-R and Len-R exclusive reptile species), each being included in a preliminary NMDS analyses, which were then considered as outliers. When these outliers where considered, the scores of NMDS axis 1 and 2 were extremely discrepant (Len-C = 5320.9, <0.0; Bir1-R = 2867.5, -996.4; Len-R = 2353.3, 1189.0), precluding both showing them in the ordination diagram together with the remaining sites and fitting a data distribution to these response variables in subsequent modeling analysis. I then removed those outliers from subsequent analysis. The scores for the first and second axes of the NMDS were extracted and used as response variables in subsequent models.

2.7.5. Habitat type effect on species diversity

I used three different metrics – rarefied species richness, abundance and composition – to examine the effect of habitat type on amphibians and reptiles species diversity. I used Generalized Linear Mixed Models (GLMMs) or Linear Mixed Models (LMMs), depending on whether the normality criteria was met, to assess such effects. To account for any effect due to distance and natural variability of study sites, since these were nested within five locations (Figure 1a), the location identity was included as a random factor. I checked the distribution of the response variables and fitted appropriate models to the corresponding distributions. As such, I fitted a Poisson distribution (*log* link) for rarefied species richness, and a negative binomial for abundance, as the species abundance residuals were

overdispersed when a model with Poisson distribution (*log* link) was tested. I fitted LMMs with Gaussian distribution for composition. All models were computed using the "lme4" package of R (Bates et al*.,* 2015). There were further plans to include additional covariates in the models, such as day/night and season, but due to the small sampling size, these had to be discarded.

2.7.6. Species distribution per habitat type

To illustrate changes in species composition across the three habitat types, the proportion of each observed species per habitat type was also plotted. This included all encounters.

3. RESULTS

I recorded a total of 703 amphibian and 266 reptile encounters across the 21 sampling sites. The amphibians belonged to nine taxa (five species and four genera), from nine genera and six families; the reptiles to 14 species, from 13 genera and nine families. The most recorded amphibians were *Ptychadena* spp. (54.5%)*, Hyperolius spatzi* (25.0%) and *Leptopelis viridis* (13.8%), while three taxa were only recorded once (0.14%). Rice paddies had the highest mean rarefied amphibian richness ($N = 4.3$ +/- 1.6; Appendix 4), with 85% of all species being observed in that habitat. The lizards *Trachylepis affinis* (39.1%), *Lygodactylus gutturalis* (37.6%) and *Agama agama* (15.4%) made up most of the reptile records, whereas eight species were recorded only once (0.38%) or twice throughout the study (0.75%). Forest remnants had the highest rarefied reptile richness ($N = 5.1$+/- 3.6; Appendix 4), and over two thirds (67.3%) of the reptiles observations were in cashew plantations.

The common toad *Sclerophrys* sp. was not recorded during the surveys, even though it was occasionally observed nearby study sites. The frog *Kassina* sp. was heard multiple times, but was only observed once on surveys. Additional reptiles species are also common in the region, including *Bitis arietans, Causus maculatus, Python* sp*., Philothamnus semivariegatus, Chamaeleo gracillis* and *Tarentola senegalensis*, but were never observed during surveys.

3.1. Rarefied species richness across habitat types

Rarefying species richness reduced richness on habitat types that had study sites removed from the analysis, and inflated it on study sites that had most *singletons* and *doubletons* (see *section 2.7.2.*), when compared to observed species richness (Appendix 4a). Amphibian

rarefied species richness was similar across habitat types (Figure 2a). Reptile rarefied species richness, on the other hand, was lowest in rice paddies ($Z = -3.150$, $P = 0.002$; Table 1; Figure 2b).

3.2. Species abundance across habitat types

Amphibian abundance was higher in rice paddies ($Z = 4.642$, $P < 0.0001$; Table 1; Figure 2c) than in forest remnants. Reptile abundance was higher in cashew orchards ($Z = 4.143$, $P < 0.0001$) compared to forest remnants, yet it was lower in rice paddies ($Z = -4.7376$, $P < 0.0001$; Figure 2 (d); Table 1; Figure 2e).
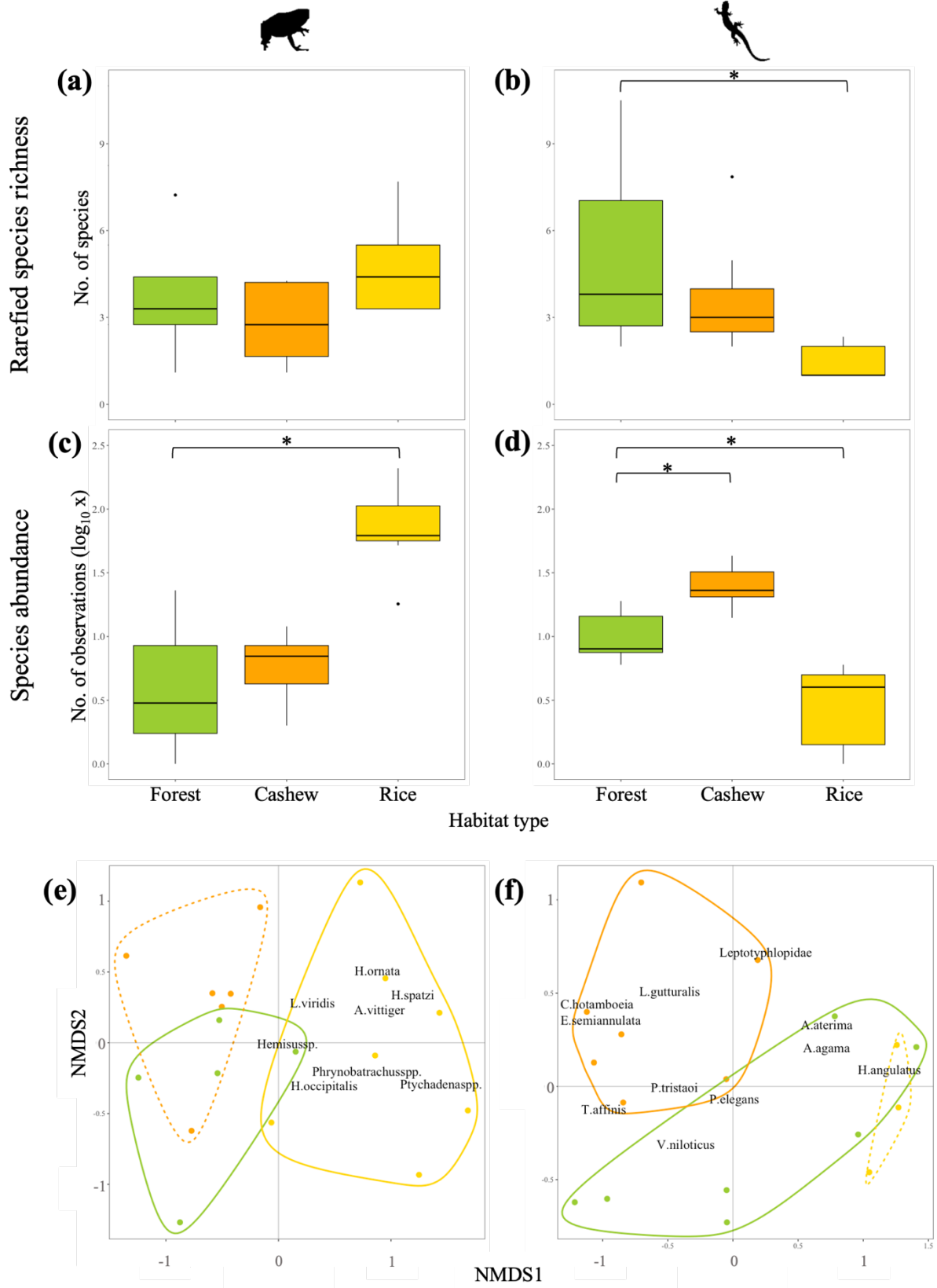
Figure 2. Plots of (a, b) rarefied species richness, (c, d) observed abundance (log$_{10}$) given by the number of encounters and (e, f) non-metric multidimensional scaling (NMDS) of species composition of amphibians (left column) and reptiles (right column) across forest remnants (green), cashew plantations (orange) and rice paddies (yellow) in northern Guinea-Bissau.

On the NMDS plots, points denote study sites and text species; the stress values are (e) 0.114 and (f) 0.059. Two study sites were discarded from amphibian and reptile rarefied richness and composition plots (two forest fragments and two rice paddies, respectively) due to the absence of records on those sites for each class; three other sites were further discarded from the composition analysis, as they were outliers – study sites which only species were exclusive to them ((e) one cashew orchard and (f) two rice paddies); the dashed lines indicate habitat types that had mentioned outliers.

3.3. Species composition and distribution across habitat types

The amphibian ordination diagram shows an overlap of forest remnant study sites with those of cashew orchards, but rice paddies' appear grouped towards higher values along NMDS axis 1. All amphibian species scores are in rice paddies. Reptile's diagram shows similarities between forest remnants and rice paddies, but cashew orchard's study sites form a distinct group. Most reptile species scores go within in cashew orchards, but several show in forest remnant. Amphibian composition differed between forest remnants and rice paddies (T = -7.948, P < 0.0001), as denoted from the first axis of the NMDS (Table 1), while that of cashew orchards were similar to forest remnants. Reptile assemblages in forest remnants differed from those of cashew plantations (NMDS1: T = -2.445, P < 0.015; NMDS2: T = 3.044, P < 0.01), as noted from the two NMDS axes (Table 1).

Rice paddies had the most exclusive amphibian species (*Afrixalus vittiger, Hoplobatrachus occipitalis* and *Hildebrandtia ornata*), while four taxa were recorded across all habitat types (*Phrynobatrachus* spp*., Leptopelis viridis, Ptychadena* spp*.* and *Hyperolius spatzi*; Figure 3 a). Forest remnants and cashew orchards had only one exclusive taxon each (*Hemisus* sp*.* and *Kassina* sp., respectively), both *singletons*. Two reptile species were recorded exclusively in forest remnants, three in cashew orchards, and three in rice plantations. Only two reptile species were found across the three land-uses (*Agama agama* and *Varanus niloticus*), while six in both forest remnants and cashew orchards (Figure 3b).

Table 1. Summary of Generalized Linear Mixed Models (GLMMs) and Linear Mixed Models (LMMs) explaining rarefied ('Chao1') species richness (GLMMs), observed ($log_{10}x$) abundance (GLMMs) and NMDS axes 1 and 2 (LMMs) for amphibians and reptiles across three habitat types from 21 study sites in northern Guinea-Bissau; t-values are shown for models fitted with a Gaussian distribution (NMDS axes 1 and 2) and z-values for models fitted with a Poisson (rarefied species richness) and negative binomial (species abundance). As an exception, the models for rarefied richness of both classes were based on 19 sites, as two sites for each class had no records. Significant p-values are denoted in bold.

Response variable	Class	Model parameters	Estimate	Std. error	t/z-value	p-value
Rarefied species richness	Amphibians	Forest (Intercept)	1.253	0.278	4.501	**<0.0001**
		Cashew	-0.274	0.332	-0.823	0.410
		Rice	0.183	0.302	0.607	0.544
	Reptiles	Forest (Intercept)	1.637	0.117	9.826	**<0.001**
		Cashew	-0.325	0.257	-1.264	0.206
		Rice	-1.301	0.413	-3.150	**0.002**
Species abundance ($log_{10}x$)	Amphibians	Forest (Intercept)	1.434	0.421	3.403	**<0.01**
		Cashew	0.084	0.445	0.188	0.851
		Rice	2.843	0.428	4.642	**<0.0001**
	Reptiles	Forest (Intercept)	2.303	0.173	13.287	**<0.0001**
		Cashew	0.939	0.227	4.143	**<0.0001**
		Rice	-1.415	0.323	-4.376	**<0.0001**
NMDS 1	Amphibians	Forest (Intercept)	-0.632	0.249	-2.236	**<0.05**
		Cashew	-0.105	0.204	-0.516	0.6060
		Rice	1.531	0.193	-7.948	**<0.0001**
	Reptiles	Forest (Intercept)	-0.001	0.310	-0.031	0.976
		Cashew	-0.761	0.311	-2.445	**0.015**
		Rice	0.800	0.417	1.921	0.055

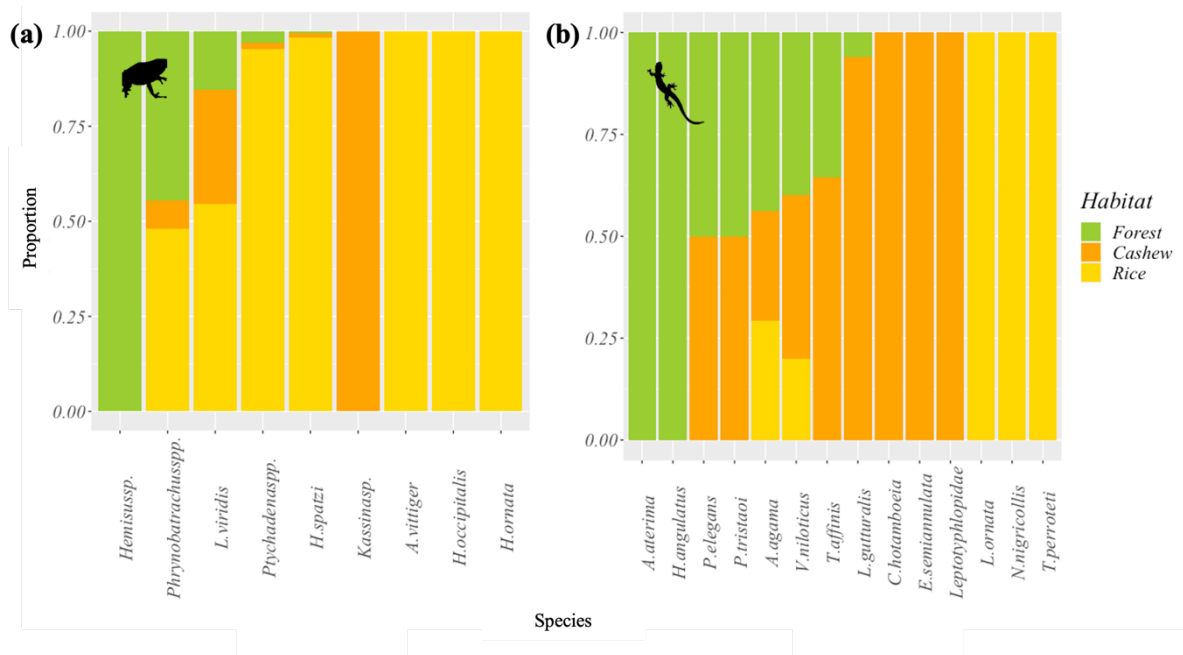| NMDS 2 | Amphibians | Forest (Intercept) | -0.327 | 0.272 | -1.201 | 0.230 |
		Cashew	0.643	0.368	-1.747	0.081
		Rice	0.289	0.356	0.811	0.416
	Reptiles	Forest (Intercept)	-3118	0.156	-1.994	**<0.05**
		Cashew	0.673	0.221	3.044	**<0.01**
		Rice	0.196	0.285	0.687	0.492

Figure 3. Proportions of (a) amphibian and (b) reptile species encounters across the three sampled habitat types in northern Guinea-Bissau. Data includes nine amphibian species out of 703 encounters and 14 reptile species out of 266 encounters.

4. DISCUSSION

In this study, I found that some diversity metrics of amphibians and reptiles vary across forest remnants, cashew orchards and rice paddies in northern Guinea-Bissau, and that the response to each habitat type is class-dependent, which met the initial expectations and agrees with Fulgence et al. (2021). Rarefied amphibian richness was similar across habitat types, but abundance was highest in rice paddies, and this habitat had a distinct composition. Rarefied reptile richness and abundance were lowest in rice paddies, and cashew orchards had the

highest abundance, as well as a different composition compared to that of forest remnants and rice paddies. Surprisingly, cashew orchards were similar to forest remnants across all diversity metrics for amphibians, and in rarefied species richness for reptiles. This is, to my knowledge, not only the first study evaluating the impacts of land use on herpetofauna in Guinea-Bissau, but also the first comprehensive overview for both classes in the study area, with day and night surveys performed across two distinct seasons and different types of habitat, even though herpetofauna has been surveyed in other regions of the country (Auliya et al., 2012; Cabuy, 2014).

The landscape diversity of 23 taxa that belong to at least 23 species (nine amphibians and 14 reptiles) turned out to be far lower than the obtained species list from IUCN distribution data within a 500 km buffer of the study area (120 species; see *section 2.5.*). Even though the used buffer was purposely conservative (i.e., too large), it may not have been realistic, as it includes species from distinct climates, that range from the semi-arid sahel (e.g., *Elapsoidea trapei*; Chippaux & Jackson, 2019) to tropical forests (e.g., *Hormonotus modestus;* Chippaux & Jackson, 2019). The number of observed taxa goes more in line with those of Auliya et al. (2012) and Cabuy (2014), in Guinea-Bissau, who found 13 and 22 species of amphibians, and 17 and 30 species of reptiles, respectively. Even though my number of observed taxa is still lower, this may be explained by the fact that I have two genus of amphibians that may belong to more than one species (*Ptychadena* spp. may belong to several), as well as by distinct methodologies: unlike in the other two works that used multiple sampling methods (e.g., pitfalls, collection of dead specimens), my surveys were time-based, did not include urban areas, and only used visual encounters. This also justifies some common species (e.g., the toad *Sclerophrys* spp., the chameleon *Chamaeleo gracillis*) not being encountered during my surveys, even if seen throughout the study area. As discussed below (see *section 4.4.*), the low sampling sufficiency also suggests that a higher sampling effort, would lead to more species being encountered. Nonetheless, my results serve their purpose, allowing for a comparison of different habitat types, as all sampling sites were subject to the same sampling effort. Overall, the herpetofauna diversity across the landscape can be divided into two groups: (1) forest remnants and cashew plantations, and (2) rice paddies; these may be seen as analogous to the forest-savanna mosaic that pre-existed in the region.

4.1. Resemblances of cashew orchards to forest fragments

Cashew orchards were similar to forest remnants across all diversity metrics for amphibians, and in rarefied species richness for reptiles. These similarities may be due to (1) the structural resemblances between the two habitats, (2) the heterogeneity of the landscape and (3) the low quality of forest remnants. Cashew monoculture leads to the homogenization of the habitat, typically leaving cashew as the only tree species, all of which are the same age, height, evenly spaced, and with lower clutter (i.e., vines, stems) than forests (Appendix 2). Nonetheless, cashew plantations share similarities with forest fragments: both are characterized by a dense canopy that filters sunlight and helps regulate the temperature within them (Komanduri et al., 2021). Furthermore, cashew orchards in Guinea-Bissau are subject to low management intensity: they are rainfed and no agro-chemicals are used (Catarino et al., 2015). Newbold et al. (2014) suggested human-modified habitats that retained vertical structure of the pre-existing native plant communities could be important for bird diversity in agricultural landscapes. Likewise, Osen et al. (2021) showed land-use history mattered for tree species diversity and composition. Since cashew orchards in this study derive from forests, this may hold true for herptiles here.

The habitat heterogeneity of the study area and the close proximity between habitats (Figure 1a) may also be contributing to the high diversity in cashew orchards, as heterogeneous landscapes have higher biodiversity levels (Estrada-Carmona et al., 2022). Bhagwat et al. (2008) also support finding, as they found species richness and composition to be similar between agricultural land and neighboring forests across many taxa, from fungi to mammals. Lastly, because the secondary forests that prevailed in the landscape are distributed in a low number of forest remnants of relatively small size, they may no longer withstand the species they once did, as habitat specialists may have gone extinct (Devictor et al., 2008; Palmeirim et al., 2017). Yet, due to lack of reference data, it is impossible to know the species these forests held in the past. In other words, it may not only be cashew orchards that withhold high herptile diversity levels, but also current forest remnants may withhold less diversity than they did before.

4.2. Amphibian diversity per habitat type

Amphibian diversity was similar between forest remnants and cashew orchards across all measured metrics (rarefied species richness, abundance and composition). In addition to the reasons mentioned above, these similarities may partly be attributed to the fact that the taxa

that made up most of the encounters in these habitats are generalists that are distributed throughout most of Sub-Saharan Africa (e.g., *Ptychadena* spp. and *Phrynobatrachus* spp.; AmphibiaWeb, 2022), that belong to families that are tolerant to habitat modifications (Ptychadenidae and Phrynobatrachtidae; Nowakowski et al., 2017). This result suggests that, even though cashew orchards are a monoculture of an exotic species, they still provide suitable alternative habitat for at least generalist amphibians. These findings partly agree with those observed by Komandori et al. (2023), who, despite having observed changes in species composition between cashew orchards and forests in the Western Ghats (India), found cashew orchards to have similar abundances to those of forests, and to withstand 67% of the amphibian species that occur in the region.

Rice paddies presented similar rarefied species richness as the other habitat types, but distinct abundance (Figure 2c) and composition (Figure 2e). The unique composition of the rice paddies may be attributed to the presence of three exclusive taxa, in addition to the overall much higher amphibian abundance. In fact, most recorded amphibian species (*Ptychadena* spp., *Hyperolius sptazi*, *Hildebrandtia ornata*, *Afrixalus vittiger*, *Phrynobatrachys* spp.) show a strong association with rice paddies on the composition diagram (Figure 2e), and only two of the nine taxa were absent in this habitat (Figure 3a). This may be a reflection of the breeding ecology of this class, as amphibians depend on water for reproduction (Fulgence et al., 2021; Ribeiro et al., 2019; Semlitsch et al., 2015), but is also related to the life traits of some species. For instance, three taxa exclusive from rice paddies – *Hoplobatrachus occipitalis*, *Afrixalus vittiger* and *Hildebrandtia ornata* – are savanna-adapted species (AmphibiaWeb, 2022), the habitat that rice paddies have replaced in the study area (Catarino et al., 2008). Even though *H. ornata* is a very inconspicuous frog which is rarely observed throughout its distribution range (Amphibia Web, 2022), I found it in rice paddies. This is, to my knowledge, the first time this species was documented in such a habitat. In sum, rice paddies appear to be a valuable habitat on the landscape, that may complement the different habitat requirements of amphibians throughout their life cycle (Ribeiro et al., 2019).

4.3. Reptile diversity per habitat type

Forest remnants had the same rarefied species richness as cashew orchards, but reptile abundance on the latter was higher (Figure 2d), and these showed distinct composition (Figure 2f). The high abundance in cashew orchards, and the presence of five exclusive

species in both that habitat (N = 3) and forest remnants (N = 2), may justify the differences in composition. The skink *Trachylepis affinis* and the gecko *Lygodactylus gutturalis* were the greatest contributors to the high species abundance in cashew orchards (90.0%). These are both common arboreal species that occur through most of west and central Africa (IUCN, 2022): the former is found on the lower part of three trunks and is common in degraded forests, while the latter relies on vertical structures, including walls and fences within villages (Trape et al., 2012). Both species were also present in forest remnants. This suggests what Vasconcelos et al. (2015) reported on butterflies, which found cashew orchards in Guinea-Bissau to be dominated by generalist species, may also be true for reptile assemblages. The same was observed by Newbold et al. (2014) in the tropics and subtropics across different taxa, including amphibians and reptiles: the abundance of species persisting in human-modified habitats (e.g., croplands, plantation forests) increased, and those had larger geographic ranges. Likewise, Palmeirim et al. (2017) showed that changes in composition in human-disturbed habitats is possibly due to replacements, suggesting similar richness in these habitats are due to specialists being replaced by generalist species.

Rice paddies had the lowest rarefied species richness and abundance. Rice paddies are dry and have nearly bare ground for part of the year, making it a harsh environment for reptiles with little to no available shade; during the rest of the year, these habitats flood, leaving little to no room for terrestrial reptile species. Yet, rice paddies had three exclusive species (Figure 3b): the cobra *Naja nigricollis*, a habitat generalist (Chippaux & Jackson, 2019); the skink *Trachylepis perotteti,* which basks in open areas (Trape et al., 2012); and the lizard *Latastia ornata*, a species known only from the type specimen observed in 1938 (Meiri et al., 2018; Monard, 1940). *Latastia ornata* shows Data Deficient (DD) on the IUCN Red List (IUCN, 2022), yet it may be highly thermophile like its congeneric *L. caudalis (Trape* et al*., 2012)*, as it was seen basking at different occasions in the hottest periods of the day (personal observations). This suggests that at least the latter two species exclusive to rice paddies depend on open areas. As for amphibians, rice paddies, analogous to the savannas they have replaced, may retain the open-habitat species of the landscape mosaic. As such, despite the lower richness and abundance of reptiles in this habitat, rice paddies have an important conservation value for this class.

Contrary to what was expected, and likely because of the exclusion of four rice paddy study sites (out of seven) from the composition analysis (see *section 2.7.*), assemblages in rice paddies appear as a subgroup of those from forest fragments (Figure 2f). This is due to the only two species found on the three rice paddies considered for the analysis (*Agama*

agama and *Varanus niloticus*), having also been recorded in forest remnants. In fact, these large-sized reptiles occur in a variety of habitats (Trape et al. 2012), and were observed across all sampled habitat types.

4.4. Sampling sufficiency

The sampling effort of this work was not perfect, as species accumulation curves illustrate (Appendix 3). In fact, while amphibian rice paddies and cashew plantations' accumulation curves were close to asymptote, those of forest remnants were still rising; in the case of the reptiles, the accumulation curves of all three habitat types were on the rise, but forest fragments appear to be the best sampled one, and rice paddies the worst. The overall sufficiency was better for amphibians than for reptiles. A higher sampling effort would have been better given (1) the high complexity of some study sites (e.g., Ber-F, Dja-F), and (2) the nature of the studied organisms (i.e., discrete and often small - e.g., the frog *Phrynobatrachus* sp. measures 20 mm when adult), which contribute to a low detection rate. Forest remnants, and cashew orchards to a certain extent, had a complex vertical structure with trees, canopy and vines, and often dense ground cover (Appendix 1 and 2), which may decrease detectability. Rice paddies, on the other hand, were structurally simpler, making detection easier, especially when dry. Even though the species accumulation curves for each class had not reached the asymptote (Appendix 3), amphibians were better sampled than reptiles at landscape level. The higher sampling sufficiency of this class is likely due to the high amphibian abundance in rice paddies, which were mostly juveniles (77.0%). Conversely, out of the 14 observed reptile species, eight were recorded only once or twice, contributing to the ascending tendency of the curve for this class. Many of the reptiles in the study area are diurnal and alert, and so may discretely flee when approached without being noticed. Furthermore, nocturnal reptiles within the study area (e.g., *Dasypeltis confusa*, *Prosymna meleagris*) may have been missed on the surveys because only one quarter of them were conducted at night.

4.5. Study site removal from rarefied species richness and composition analyses

To make species richness comparisons possible among study sites that, despite the same sampling effort had different sampling sufficiency, Chao's rarefied species richness was used. Because the rarefying function cannot handle zeros (see *section 2.7.2.*), two habitats were removed from the analyses of each class. The two sites (Dem-F and Mom-F) removed

from the amphibian analyses were forest remnants, and the two removed from the reptile analyses (Dem-R and Mom-R) were rice paddies. I considered the lack of encounters not to be an accurate representation of those sites' herptile assemblages, but instead a consequence of low sampling sufficiency (Appendix 3). The removal of these sites, together with rarifying species richness, caused the habitats that had study sites with low sampling sufficiency to increase in richness, when compared to observed values (Appendix 5a). This was the case with amphibian richness in forest remnants: removing the study sites that had no observations from the analysis artificially inflated richness in that habitat (as the zeros were excluded) and, because the remaining five forest remnant study sites had *singletons* and *doubletons*, rarefied richness increased further (see equation in *section 2.7.2.*). This has caused the differences in amphibian richness between forest fragments and rice paddies to be less pronounced than observed, since rice paddies were well-sampled for this class (Appendix 3), and so rarefied richness did not increase as much. Rarefying reptile richness also caused the forest remnants to show a greater variation when compared to observed, even though the median values remained similar (Figure 2b and Appendix 5b).

Besides the study sites removed from the estimated species richness analyses, one cashew orchard site from the amphibian (Len-C) and two rice paddy sites (Bir1-R and Len-R) from the reptile composition analyses were considered outliers and removed (see *section 2.7.4.*). This has made comparing reptile assemblages between habitats particularly difficult, since rice paddies on the composition plot (Figure 2f) are only represented by three study sites (out of seven).

4.6. Other study limitations

The initial plans included a comparison of the herpetofauna diversity across habitats before and after the rainy season, and between day and night surveys. However, these plans had to be discarded because of the low number of observations, particularly at the end of the dry season, as well as the reduced number of night surveys. The discrepancy between day (six) and night (two) surveys was due to logistic constraints, as it was difficult to have permissions, transportation and field assistance for night fieldwork.

Finding amphibians and reptiles is a very demanding task, because the encounter success is very low (Hutchens & DePerno, 2009) and so requires a large sampling effort to get meaningful samples of the assemblages. This could have been improved by increasing the number of observers, night surveys, and by combining different sampling methods, such as

pitfall traps or artificial refugia (Hutchens & DePerno, 2009; Watling & Braga, 2015). This would have provided an even better characterization of the landscape, and possibly allow for more detailed analyses in which each season could be looked at separately, as well as days *vs*. nights.

The close proximity between study sites, as well as the overall small scale of this work, may also prevent further conclusions. The total size of each habitat patch was also not taken into consideration, even though it may be playing an important role in the assemblages at each study site (Palmeirim et al., 2017; Prevedello & Vieira, 2010). This is why I will continue exploring my data further in the near future, and include additional covariates on my models, from data I have already collected and from data that are currently being collected in the field by the larger projects of which my thesis is part. These covariates include the total size of each habitat patch, topography, habitat metrics (e.g., no. of trees, stems), and the age of the cashew orchards, which plays a role in the biodiversity these habitats withhold (Rege & Lee, 2023).

4.7. Implications for conservation

The different responses of each of the classes to the habitat types emphasizes the importance of assessing each separately, as suggested by Cordier et al. (2021), and opposed to the classical approach of considering amphibians and reptiles as a single group. Yet, despite following a similar study design to that of Fulgence et al. (2021), my work does not support the premise that amphibians are more sensitive to land-use change than reptiles. In fact, while amphibian diversity only varied across habitats for two metrics (rarefied species richness and composition), reptiles showed variation in all three assessed diversity metrics. This work also highlights the importance of looking at multiple diversity metrics, as species richness alone may be misleading when assessing the biodiversity value of a habitat (Palmeirim et al., 2017).

It is important that the open-close-habitat mosaic we have today in northern Guinea-Bissau persists, as it is contributing to the rich diversity seen at landscape level. Studies like these are particularly relevant when land use is changing at unprecedented rates, quickly transforming the forest-rice mosaic into vast areas of cashew plantations, with ever decreasing forested and rice habitats (Temudo & Abrantes, 2014). The fact that forest remnants appear to have comparable diversity to an agricultural habitat must be looked at carefully, and the limitations of this study considered. What is clearer, however, is the

importance of rice paddies at landscape level: besides an important breeding place for amphibians, rice paddies seem to serve the role of the long gone open habitats and maintain important herptile species. From an ecosystem-service point of view, the presence of amphibians in high abundances in rice paddies may also be a relevant pest-control agent (Hocking & Babbitt, 2014). In face of the imminent habitat conversion, my thesis suggests that cashew cultivation, and the economical and societal benefits it entails (Dendena & Corsi, 2014), may be possible without the cost of herpetofauna, if habitats that resemble the natural history of the landscape are left present. Furthermore, my results highlight the importance of maintaining a heterogeneous landscape to minimize biodiversity loss. As cashew orchards expand to other regions (Powell et al., 2023), my results may be useful in informing managing practices in those regions. Still, extrapolations should be done carefully, as the assessed cashew orchards are biological, and the heterogeneity of the study landscape is very specific. Complementing similar studies on other taxa and other regions would help understand if the findings hold true for other groups and further grasp the ecological impacts of the expansion of this commodity.

5. ACKNOWLEDGEMENTS

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Appendix

UNIVERSITY OF HELSINKI

RESPONSES OF HERPETOFAUNAL ASSEMBLAGES TO DIFFERENT HABITATS IN WEST AFRICA

A CASE STUDY IN NORTHERN GUINEA-BISSAU

Master's Programme in Ecology and Evolutionary Biology

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Appendix 1. *Photo of the 21 study sites, three of each habitat type: forest fragments, cashew orchards and rice paddies across seven tabancas (villages) in northern Guinea-Bissau. Foto credits: Francisco Silva.*

	Forest (F)	Cashew (C)	Rice (R)
Lenquebate (LEN)			
Bereco (BER)			
Djalicunda (DJA)			
Bironqui-1 (BIR1)			
Bironqui-2 (BIR2)			

|	Dembaso (DEM)		

| | Mombonco (MOM) | | |

Appendix 2. Habitat characterization of the 21 sampling sites, seven of each habitat type - forest fragments, cashew orchards and rice paddies - after the rainy season in northern Guinea-Bissau.

Site	bareground (%)	leaf litter (%)	grass cover (%)	tall grass cover (%)	shrub cover (%)	mid-canopy cover (%)	upper-canopy cover (%)	clutter (0-3)	no. of trees DBH >10cm	Average height 5 highest tres	termite mounds (0-3)	wood piles/fallen trees (0-3)	water cover (%)	Habitat
Ber-C	5	0	85	5	5	85	0	1	16	6	2	1	0	C
Ber-F	40	10	5	5	40	95	5	2	7	25	1	2	0	F
Ber1-R	5	0	60	5	0	5	0	0	0	5	1	3	15	R
Bir1-C	5	45	45	5	0	100	0	1	14	6	1	1	0	C
Bir1-F	50	0	10	20	20	90	0	1	13	10	1	1	10	F
Bir-R	0	0	0	70	0	5	5	0	1	1	0	0	65	R
Bir2-C	20	20	50	10	0	90	0	1	20	6	0	2	0	C
Bir2-F	10	5	40	40	5	70	10	1	12	22	2	2	0	F
Bir2-R	5	0	5	60	0	0	0	0	0	9	1	1	45	R
Daj-C	0	25	65	10	0	90	0	1	13	13,6	2	0	0	C
Dem-C	10	5	60	20	5	65	0	1	24	22	1	2	0	C
Dem-F	0	90	5	5	0	95	5	3	11	20	2	1	0	F

Dem-R	0	0	0	80	5	0	0	0	0	15	1	0	85	R
Dja-F	5	5	30	20	40	70	15	2	15	25	1	1	0	F
Dja-R	5	0	0	30	0	0	0	0	0	8,4	1	1	65	R
Len-C	5	20	70	5	0	95	0	0	31	6	2	1	0	C
Len-F	25	20	30	15	10	90	5	2	12	21	1	1	0	F
Len-R	5	0	5	50	0	0	5	0	2	11,8	1	0	70	R
Man-C	0	5	50	30	15	90	0	1	15	6,4	1	1	0	C
Man-F	5	80	5	5	5	95	5	3	15	18	2	1	0	F
Man-R	0	0	85	5	0	5	0	0	0	4	1	0	90	R
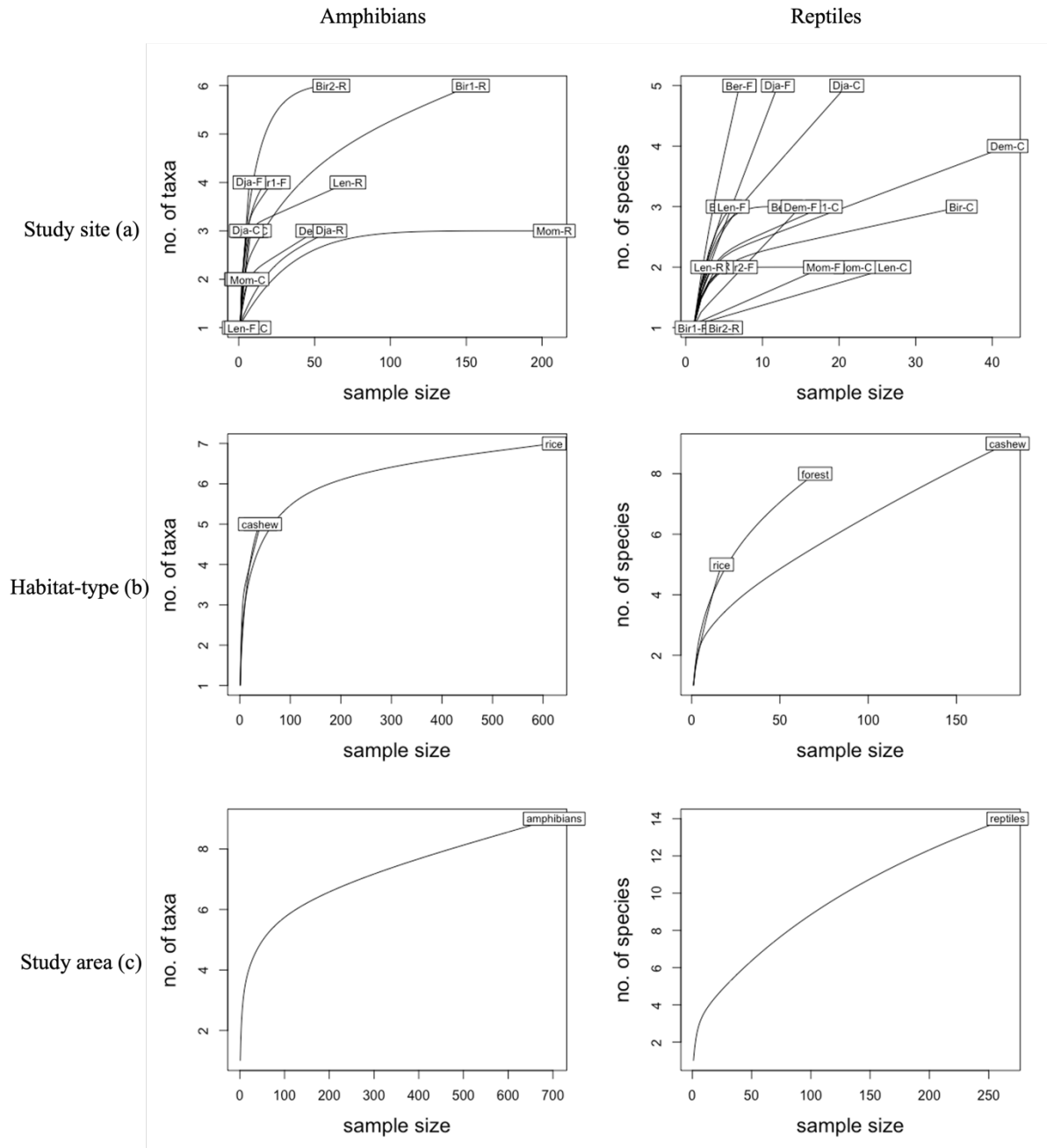
Appendix 3. Encounter-based species accumulation curves for amphibians and reptiles in north Guinea-Bissau across (a) sampling sites, (b) habitat type and (c) study area.

Appendix 4. Mean values across study sites for rarefied species richness ('Chao1') and abundance for each habitat type.

Taxa	Metric	Forest	Cashew	Rice
Amphibians	Estimated Chao richness	3.41	2.58	4.28
	Observed abundance	5.86	5.71	88.86
Reptiles	Estimated Chao richness	5.11	3.69	1.47
	Observed abundance	10.00	25.57	2.43
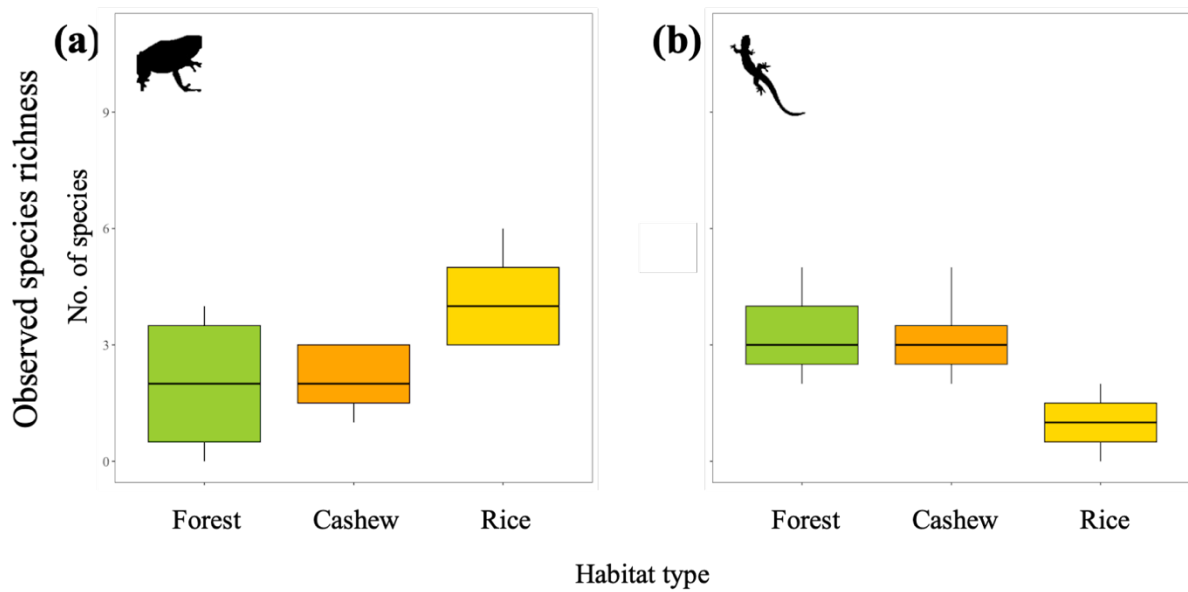
Appendix 5. Observed species richness of (a) amphibians and (b) reptiles across forest remnants, cashew orchards and rice paddies in northern Guinea-Bissau.