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Diversidade taxonômica de pequenos mamíferos e uso do espaço de *Rhipidomys mastacalis* e *Marmosa murina*

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Tese apresentada à Universidade Estadual de Santa Cruz, como parte das exigências para obter o título de doutora em Ecologia e Conservação da Biodiversidade.

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Sumário

Resumo

Diante da atual conjuntura onde o crescimento populacional impõe a demanda crescente por recursos naturais e por insumos agrícolas, o meio ambiente parece ficar em segundo plano. Conforme o agronegócio expande, as áreas de florestas naturais são substituídas por monoculturas e pasto, principalmente. Porém essa troca do uso do solo traz consequências, geralmente negativas, para a biodiversidade. Os pequenos mamíferos também sofrem com as alterações no ambiente, e mudanças em seus padrões podem nos mostrar, em um curto espaço de tempo, os efeitos. Com isso, o objetivo dessa tese foi investigar a ocorrência de pequenos mamíferos em áreas alteradas na Floresta Atlântica e a resposta das assembleias nos padrões de diversidade e movimento, em escala ampla (considerando toda o domínio da Floresta Atlântica), de paisagem (quantidade de floresta e agroflorestas) e local (bioclima, adensamento de árvores, sombreamento, complexidade estrutural). No primeiro capítulo foi realizada uma revisão biográfica dos pequenos mamíferos da Floresta Atlântica e quais fatores locais (bioclima) e da paisagem (quantidade de floresta e outros tipos de uso do solo) no padrão de diversidade deles. No segundo capítulo nós avaliamos o efeito da intensificação de manejo (adensamento de árvores, sombreamento e complexidade vertical) em pequenos mamíferos de agroflorestas de cacau no sul da Bahia. No terceiro capítulo, buscamos entender o padrão de movimento de duas espécies de pequenos mamíferos em agroflorestas de cacau no sul da Bahia, e quais influencias do sexo e peso corpóreo dos animais nesse padrão. Considerando amostras provenientes de toda a Floresta Atlântica, a quantidade de floresta foi o fator mais importante para determinar diversidade de pequenos mamíferos. No sul da Bahia, a quantidade de agrofloresta na paisagem é negativamente relacionada com riqueza de pequenos mamíferos. Além, a abundancia foi menor que a esperada possivelmente isso seja reflexo na intensificação do manejo. O padrão de movimento de pequenos mamíferos não mostrou nenhuma relação com sexo e tamanho dos animais, sem diferenças significativas do tamanho e intensidade de uso da área de vida diária. Essa tese enfatiza que as agroflorestas de cacau podem contribuir para a conservação da biodiversidade, porém só será eficiente se for aliada com a conservação de florestas naturais.

Palavras-chave: Rodentia, Didelphimorphia, Floresta Atlântica, Agrofloresta de cacau

Abstract

In face of the population growth that imposes a growing demand for natural resources and agricultural inputs, the environment seems to be in the background. While agribusiness expands, areas of natural forests are replaced by monocultures and pastures. This change in land use has consequences, usually negative, for biodiversity. Small mammals also are affected by changes in the environment. Their biodiversity patterns can change and show us, in a short time, the true effects. Thus, the objective of this thesis was to investigate the occurrence of small mammals in altered areas in the Atlantic Forest and their response to modification, on a broad scale (considering the entire domain of the Atlantic Forest), of landscape (amount of forest and agroforestry) and local (bioclimate, tree density, shading, structural complexity). In the first chapter, a biographical review of the small mammals of the Atlantic Forest was carried out, and what local factors (bioclimate) and landscape (amount of forest and other types of land use) in their diversity pattern were carried out. In the second chapter, we evaluated the effect of management intensification (tree density, shading, and vertical complexity) on small mammals from cocoa agroforests in southern Bahia. In the third chapter, we seek to understand the movement pattern of two species of small mammals in cocoa agroforests in southern Bahia, and what influences the sex and body weight of animals in this pattern. Considering samples from the entire Atlantic Forest, the amount of forest was the most important factor to determine the diversity of small mammals. In southern Bahia, the amount of agroforestry in the landscape is negatively related to the richness of small mammals. In addition, the abundance was lower than expected, possibly this is a reflection of the intensification of management. The movement pattern of small mammals showed no relationship with the sex and size of the animals, with no significant differences in the size and intensity of use of the daily life area. This thesis emphasizes that cocoa agroforestry can contribute to the conservation of biodiversity, but it will only be efficient if it is combined with the conservation of natural forests.

key-words: Rodentia, Didelphimorphia, Atlantic Forest, Cocoa Agroforest

Introdução geral

A era do antropoceno é marcada pelas alterações que o homem causou devido ao aumento no tamanho populacional e demanda por recursos naturais (Crutzen, 2006). Habitats naturais foram modificados principalmente para a expansão da agricultura (FAO, 2018). Em consequência, perdemos grandes extensão de ambientes naturais e as áreas naturais remanescentes são pequenas e estão isoladas (Ribeiro et al., 2009).

Os efeitos da perda de ambientes naturais e isolamentos dos remanescentes são considerados atualmente os principais problemas que leva a perda de biodiversidade (Cassano et al., 2014; Galetti et al., 2021; Pardini et al., 2017; Rios et al., 2021) e funções vitais prestados pelos animais são comprometidas (Maas et al., 2015). Além disso, os efeitos da perda e isolamento sobre a biodiversidade são moderados pelas características do ambiente no entorno das áreas naturais (Driscoll et al., 2013), bem como as características do grupo biológico estudado (Gascon et al., 1999). Com isso se faz cada vez mais necessário compreender como esses distúrbios podem atuar sobre as comunidades, sendo possível assim prever o futuro das espécies e ações eficazes de conservação.

As florestas tropicais foram particularmente afetadas pela expansão da agricultura (FAO, 2018). Como é o caso da Floresta Atlântica, uma das maiores do mundo - antes era um contínuo de floresta tropical úmida distribuída ao longo da costa brasileira, hoje é somente uma parcela de toda grandiosidade. Aproximadamente 88% da cobertura original da floresta Atlântica (Ribeiro et al., 2009) foi retirada para dar lugar aos centros urbanos e agricultura (Joly et al., 2014; Lapola et al., 2014; Ribeiro et al., 2009), e assim suprir as necessidades crescentes do consumo de recursos pelos humanos. Hoje restam apenas pequenos fragmentos menores que 50ha, distantes uns dos outros (Paula Koeler Lira et al., 2012; Ribeiro et al., 2009).

A Floresta Atlântica é um bioma chave para compreender como ações antrópicas podem alterar os padrões das comunidades. Mesmo restando apenas uma parcela da cobertura original, é considerado um bioma mega diverso e possui muitas espécies endêmicas (Mittermeier et al., 2011; Myers et al., 2000), como cerca de 2,7% das plantas e 2,1% do vertebrados do mundo (Myers et al., 2000).

A Floresta Atlântica do sul da Bahia merece um destaque pois experimenta um intenso e extenso histórico de degradação pela ocupação humana, restando aproximadamente 17% da vegetação original (Ribeiro et al., 2009). Ainda assim, a região é considerada um dos centros de endemismo e *hotpoint* da biodiversidade (Martini et al., 2007b).

A região merece um destaque, também, pela produção de cacau (*Theobroma cacao*) em sistema agroflorestal (Figura 1). O cacau começou a ser cultivado na região no século 19 e possui importância econômica, histórica e biológica (Tabarelli et al., 2005). Historicamente, a vegetação nativa não era completamente suprimida para a plantação do cacau no sul da Bahia. Os produtores removiam as árvores do sub-bosque e o cacau era plantado sob a sombra das árvores nativas (Gama-Rodrigues et al., 2021a), localmente conhecida como cabruca. As agroflorestas de cacau são heterogêneas quanto à quantidade de árvores e escolha nas árvores de sombra (Piasentin et al., 2014).

Figura 1. Agrofloresta de cacau no município de Belmonte sul da Bahia.

Entretanto, após a chegada de um fungo (*Moniliophthora perniciosa*) causador da “vassoura de bruxa” com consequente diminuição na produtividade do cacau, ocorreu a intensificação do manejo nas agroflorestas (Schroth & Harvey, 2007). A intensificação se dá pela retirada de árvores de sombra permitindo da entrada de luz nos pés de cacau, pelo maior adensamento de pés cacau e pelo aumento de insumos agrícolas (Schroth & Harvey, 2007). As árvores nativas foram substituídas por outras espécies arbóreas como *Spondias mombin* (cajazeira), *Artocarpus heterophyllus* (jaca), and *Erythrina* spp., que também servem como alimento e lenha (Piasentin et al., 2014).

As agroflorestas de cacau são ambientes naturais amigáveis à biodiversidade, e contribuem para a conservação na região. Elas podem contribuir para a manutenção de serviços ecossistêmicos (Schroth et al., 2015) ou padrões de diversidade biológica (Cassano et al., 2009). Essas áreas atuam mitigando os impactos negativos da perda de habitat, abrigando espécies ameaçadas de extinção (Cassano et al., 2011; Schroth et al., 2011), morcegos (Faria & Baumgarten, 2007), grandes mamíferos (Cassano et al., 2012; Ferreira et al., 2020) e pequenos mamíferos (Silva et al., 2019).

Os mamíferos constituem um grupo diverso, com suas espécies apresentando grandes variações físicas e ecológicas, com tamanho corporal variado, dieta diversificada, uso de diferentes habitats, com espécies utilizando o bosque e sub-bosque de uma mesma área (A. Paglia et al., 2012; Reis et al., 2006). Desempenham funções ecológicas, dentre elas, dispersão e predação de sementes, herbivoria, são hospedeiros de parasitas, e importantes nas cadeias tróficas, sendo fonte de alimento para carnívoros, aves e serpentes (Bueno et al., 2013; Mittelman et al., 2021; Wright & Duber, 2001).

Os pequenos mamíferos não voadores é incluem os pequenos roedores e marsupiais (Rodentia e Didelphimorphia), sendo o grupo mais diversos de mamíferos da Floresta Atlântica (Paglia et al., 2012) com 97 espécies descritas (Reis et al., 2006). Apresentam altas taxas reprodutivas, e rápida resposta a alterações no ambiente, sendo assim um bom modelo para avaliar a distribuição espacial e composição de espécies (Pardini et al., 2010; Vieira et al., 2003), bem como a resposta à modificações na paisagem em um curto período de tempo (Banks-Leite et al., 2014; Galetti et al., 2015; Pardini, 2004; Vieira & Monteiro-Filho, 2003).

O padrão de movimento dos pequenos mamíferos também pode ser informativo. Entendendo padrão do uso do espaço podemos entender mais sobre migração, dispersão, dinâmica populacional (Vieira & Monteiro-Filho, 2003). Também é possível fazer inferências sobre o padrão de movimentação e efeito de borda (Ascensão et al., 2017) e o efeito do clima (Ferreira et al., 2017; Loretto & Vieira, 2005; Loveridge et al., 2016).

Visando entender como atributos espaciais como, uso da terra, fatores bioclimáticos, composição e configuração da paisagem, assim como a intensificação do manejo, afetam a abundância e ocorrência das espécies de pequenos mamíferos da Floresta Atlântica brasileira e em agroflorestas de cacau do sul da Bahia, esta tese foi estruturada em três capítulos. No primeiro capítulo nós realizamos uma revisão bibliográfica e buscamos compreender quais fatores em escala local e de paisagem afetam a diversidade de pequenos mamíferos na Mata Atlântica. No segundo capítulo avaliamos o efeito da intensificação do manejo e a cobertura florestal na riqueza e abundância de pequenos mamíferos em agroflorestas de cacau no sul da Bahia. No capítulo três realizamos a descrição de uso do espaço de duas espécies de pequenos mamíferos (*Rhipidomuys mastacalis* e *Marmosa murina*) nas agroflorestas de cacau, e a relação da área de vida diárias dessas espécies de acordo com sexo, tamanho e peso.

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Capítulo 1

How land use and bioclimatic factors are shaping small mammal communities in the Atlantic Forest?

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Abstract

Understanding how mammals' diversity responds to anthropogenic disturbances on a local and landscape scale is an urgent task. The Atlantic Forest, with only 12% of its original forest cover still harbors great biodiversity of small mammals (Rodent and Didelphimorphia), a key group that responds fast to disturbances. Here, we aimed to evaluate what and how factors in local and landscape scales affect non-volant small mammal diversity. To do so we use 214 small mammals' assemblages across the Atlantic Forest domain. Our results show that forest amount, with positive relation, was the most important predictor for explaining the diversity of small mammals in the Atlantic Forest remnants. We also found that the bioclimatic (temperature and precipitation) variables can affect positive and/or negative small mammal biodiversity, depending on the region analyzed. This study reinforces the importance to analyze different scales to access diversity, once landscape scale (forest amount), and local scale (temperature and precipitation) was important to shaping the diversity of small mammal regardless of the biogeographic context.

Keywords: Rodent; Marsupials; Diversity; Fragmentation; Land use

Introduction

Community assembly at multiple spatial scales has been an essential topic in community ecology (Fukami & Morin, 2003). Assessments on how species diversity at local to landscape scales are distributed became relevant due to the provision of ecosystem services (Tscharntke et al., 2012; Whittaker et al., 2001). Ecologists have shown that changes in habitat amount and environmental variables can shape community composition (Dambros et al., 2015; Delciellos et al., 2016; Gaston, 2000; Melo et al., 2017), which are also expected with the occurrence of anthropogenic disturbances at multiple spatial and temporal scales (Chase et al., 2019). Most of the native tropical forest was removed and converted into urban areas, agriculture, and livestock due to human disturbances, including land-use change and overexploitation of natural resources (FAO, 2018). In this context, deforestation and habitat loss are the main drivers of the decline in biodiversity (Cassano et al., 2014; Galetti et al., 2021; Pardini et al., 2017; Rios et al., 2021).

The Brazilian Atlantic Forest (AF) covers 1.5 million km² along the Brazilian coast of northeastern Argentina and eastern Paraguay (Tabarelli et al., 2005). After hundreds of years of deforestation, the Atlantic Forest lost around 88% of its original vegetation cover (Ribeiro et al., 2009) due to anthropogenic disturbances (Joly et al., 2014; Lapola et al., 2014; Silva & Marques, 2017). Today, mostly remnant fragments surrounded by several different anthropogenic matrices can be found through the original Atlantic Forest extension (Lira et al., 2012). Even so, the Atlantic Forest hosts high biodiversity, including endemic species (Mittermeier et al., 2011), being a global hotspot of biodiversity (Myers et al., 2000). Within its rich biodiversity, the Atlantic Forest harbors a substantial diversity of mammals, comprising more than 41% of all Brazilian mammals

(Bovendorp et al., 2017), and most of the non-volant mammals belong to Rodentia and Didelphimorphia order (Paglia et al., 2012).

Rodents and Marsupials comprise more than 120 species (Abreu et al., 2021) within the Atlantic Forest. They occupy several strata (fossorial, terrestrial, and arboreal) and have different habitat requirements (Abreu & De Oliveira, 2014; Estavillo et al., 2013; Umetsu & Pardini, 2007). Compared to medium and large mammals, rodents and marsupials are less vulnerable to extinction from anthropogenic disturbances due to their size and rapid reproductive rates (Gardner, 2008; Keesing, 2000; Renata Pardini et al., 2010; Smith, 2001). However, many species are sensitive to fragmentation and loss of landscape connectivity (Banks-Leite et al., 2014; Renata Pardini et al., 2010), land use changes (Cassano et al., 2014; Ferreira et al., 2020; Silva et al., 2019; Vieira et al., 2009), variation in food availability (Taitt, 1981; Taitt & Krebs, 1981) and climate change (Loyola et al., 2012). Anthropogenic disturbances in natural habitats lead to defaunation (Bovendorp et al., 2019; Cardillo et al., 2008; Fritz et al., 2009; Galetti et al., 2015; Lira et al., 2012), and for those reasons, small mammals are ideal models for investigating how diversity is shaped at local to landscape scales through different land-cover landscapes across the Atlantic Forest.

The diversity of small mammals has been associated with the amount and distribution of the landscape elements (forest remnants and matrix) (Palmeirim et al., 2019; Pardini et al., 2010; Vieira et al., 2018). The amount of forest seems to be the most important factor, and highly forested landscapes tend to have greater small mammal richness, mainly for forest specialist species (Palmeirim et al., 2019; Pardini et al., 2010; Vieira et al., 2018). Besides, the matrix composition can positively or negatively influence small mammals' richness and abundance, hanging on the species' tolerance to the matrix composition (Brady et al., 2011; Paise et al., 2020). Highly fragmented landscapes with isolated forest patches tend to have low richness and abundance of forest specialist species (Vieira et al., 2018) although they positively influence the abundance of habitat generalist species (Palmeirim et al., 2019).

In addition, studies have shown that local factors, such as temperature and precipitation, can influence small mammal assembly (Bergallo and Magnusson, 1999; Dambros et al., 2015; Graipel et al., 2006; Ferreguetti et al., 2021). The spatial variation of climate can shape small mammals' assemblages' dispersion limits (Dambros et al., 2015). Precipitation can also shape small mammal assemblies due to the positive effects on primary productivity (i.e.: food availability) (Ferreguetti et al., 2021).

In this context, we aim to evaluate how local and landscape scale factors affect non-volant small mammal diversity through the Atlantic Forest remnants. Further, we aim to verify how the factors on local and landscape scales that affect the diversity of small mammals through the Atlantic Forest remnants differ among the three main Atlantic Forest regions (Northeast, Southeast, and South) because of the geographic barriers, biogeographic processes (Costa, 2003; Leite et al., 2016) and heterogeneous species pools (Costa et al., 2000; DaSilva et al., 2015; Müller 1973; Prance, 1982; Silva et al., 2012). We hypothesize that small mammals' diversity would be more affected by factors related to landscape scale than by local scale. Thus, we expect that small mammals' diversity will increase as the forest amount increases in the landscape, based on previous studies that demonstrate this relationship locally for mammals in the Atlantic Forest (Melo et al., 2017; Palmeirim et al., 2018; Pardini et al., 2005, 2010). Also, we hypothesize that factors that affect the diversity of small mammals in the whole Atlantic Forest will be different from ones that affect regional pools.

Materials and Methods

Small mammals' assemblages

We gathered information about small mammals (rodents and marsupials) available in the most recent and complete data papers published by (Bovendorp et al. (2017) and Figueiredo et al. (2017). We used only studies that provide appropriate geographic coordinates, richness, abundance, taxonomic identification, sampling year, and trapping effort (Figure 1). Because these data papers had repeated information, we deleted the duplicates.

We classified the data into three main region groups (Northeast, Southeast, and South) based on the assemblage's latitudinal distribution. To do so, we considered geographic barriers (rivers and high mountains), distinct biogeographic processes (Costa, 2003; Leite et al., 2016), and community composition along the Atlantic Forest once just a few species occur in all three regions, creating three heterogeneous pools (Costa et al., 2000; DaSilva et al., 2015; Müller 1973; Prance, 1982; Silva et al., 2012).

Landscape variables

To access the land cover through the Atlantic Forest, we use MapBiomas (https://mapbiomas.org/en), which contains historical time-series information about the land cover. We quantified, in percentage, the amount for each land cover around the sampling site within multiple spatial scales (100, 250, 500, 1000, 1500, 2000, 3000, 4000, and 5000m radius). The radius centers were the geographic coordinates in each paper, and the historical map information about the land cover was chosen based on the small mammals' sampling year. Forest formation, pasture, and agriculture were the predominant land cover in the sites. Pasture and agriculture refer to unnatural plantations that have production objectives, and for this reason, the amount of them was added into one land cover category (farming). The landscape variables (forest amount and farming amount) were used in percentage. We also found other land cover types such as urban infrastructure, rivers, lakes, oceans, mangroves, beaches, dunes, and mining, but due to the low frequency in our dataset, we did not use them in our analyses.

We only included assemblages with complete land cover use information for the largest radius (5km). This step was performed in the Diva-Gis program. Additionally, we tested the appropriate spatial scale with a ‘multifit’ package in R environmental, by AIC criteria (Huais, 2018).

Bioclimatic variables

The bioclimatic variables were obtained from Worldclim (www.worldclim.org). We used the 19 bioclimatic variables to perform a correlation test, using the package ‘*ENMwizard’* (Heming *et al*., 2018) we selected the variables that are less correlated and present statistical independence for our data. After that, we used six bioclimatic variables (Mean Diurnal Range, Isothermality, Max Temperature of Warmest Month, Annual Precipitation, Precipitation Seasonality, Precipitation of Wettest Quarter, and Precipitation of Coldest Quarter).

Data analysis

We calculated the Shannon index for each small mammal assemblage using the function ‘*diversity*’. Also, we performed a Mantel Correlation to verify if the assemblages are spatially and (or) temporally correlated using the Mantel Corr function. We performed both analyses using the package Vegan (Oksanen, 2017).

We performed an interpolation/extrapolation of the assemblies using the package '*iNEXT*' (Hsieh et al., 2016) to access the community completeness once several assemblages present different sampling efforts and species pools (Hsieh et al., 2016). We only included assemblages that had sample completeness higher than or equal to 80% in an observed methodology.

The relationship of the Shannon index with the predictor variables (forest amount, farming amount, mean diurnal range, isothermality, the max temperature of the warmest month, annual precipitation, precipitation seasonality, precipitation of wettest quarter, and precipitation of coldest quartet) was assessed fitting generalized linear models using 'glm' function. We used the *dredge* function to generate a model selection table and we limited the number of models (N = 56), by establishing the maximum number of terms (predictor variables) in single models (N = 2). We ranked the models using second-order AICc weights, with the *model.sel* function. As the final model, we built an averaged model (Anderson, 2008; Burnham & Anderson, 2002), based on the models' weight (>= 0.001) using the *model.avg* function. The 85% confidence interval of each variable in the averaged models was used to check for uninformative parameters (Arnold, 2010). For model building, comparison, and averaging, we used the R package "*MuMIn*" (Barton, 2022).

We split the complete dataset into three subsets representing the regions (South, Southeast, and Northeast). We used the average model for the subsets as well, under the same terms, to verify if the factors that affected the diversity of small mammals differ among the whole Atlantic Forest and the three regions.

The landscape variables (forest and farming amount) were used in linear and polynomial (quadratic) forms. The model was adjusted using a normal distribution. We also assessed the statistical evidence of the variables (variable importance) by summing the AICc weights (w) of the model in which the explanatory variables were present (Burnham & Anderson, 2002). All analyses were performed on the R platform (R Core Team 2019).

Results

We compiled information about 1228 assemblages and excluded 994 for lack of information about the assemblage or landscape and 20 more due to the inclusion criterion based on the results of the interpolation/extrapolation. Our data were composed, therefore, of 214 small mammal assemblages (Figure 1) with no spatial and (or) tetemporalorrelation. The assemblages have 45195 individuals from 104 species, and the average number of individuals per assemblage was 186. The most abundant species in these assemblages were *Akodon montensis* (n = 6401), *Oligoryzomys nigripes* (n = 4826), *Akodon cursor* (n = 3650), *Didelphis aurita* (n = 3582), and *Nectomys squamipes* (n = 2236).

The appropriate spatial scale for our data was a 5000m radius, and all landscape variables in the model selection analysis were performed within this size. The most informative variables were forest amount (linear, w = 0.55, estimate = 0.00004, $p < 0.05$ and polynomial, w = 0.40, estimate = 0.005, $p < 0.05$), and precipitation of wettest quarter (w = 0.24, estimate = 0.001, $p < 0.05$) with positive effect on diversity of small mammals (Tables 1 and 2, Figure 2). But max temperature of warmest month (w = 0.40, estimate = -0.004, $p < 0.05$) and precipitation of coldest quarter (w = 0.26, estimate = -0.001, $p < 0.05$) showed negative effect on diversity of small mammals (Tables 1 and 2).

Regionally, in the northeast region (n = 31) none of the variables had statistical significance. At southeast region (n = 139), precipitation of wettest quarter (w = 0.42, estimate = 0.001, $p < 0.05$), forest amount (linear, w = 0.19, w = 0.16 $p < 0.05$; estimate

= 0.005, polynomial, $p < 0.05$), and annual precipitation ($w = 0.08$, estimate = 0.001, $p < 0.05$) had positive effect on diversity of small mammals (Table 3). On the other hand, max temperature of warmest month ($w = 0.49$, estimate = -0.006, $p < 0.05$), farming amount (linear, $w = 0.23$, estimate = -0.005, $p < 0.05$; polynomial, $w = 0.29$, estimate = -0.00005, $p < 0.05$), mean diurnal range ($w = 0.09$, estimate = -0.009, $p < 0.05$), and isothermality ($w = 002$, estimate = -0.025, $p < 0.05$) had negative effect (Table 3). At the south region (n = 44), forest amount (linear, $w = 0.54$, estimate = 0.01, $p < 0.05$; polynomial, $w = 0.45$, estimate = 0.0001, $p < 0.05$), farming amount (linear, $w = 0.24$, estimate = 0.009, $p < 0.05$; polynomial, $w = 0.20$, estimate = 0.0001, $p < 0.05$) and mean diurnal range ($w = 0.16$, estimate = 0.008, $p < 0.05$) had positive effect on diversity of small mammals (Table 3).

Discussion

As we expected, landscape-scale variables strongly affected the diversity of Atlantic Forest small mammals. Our results showed that forest amount was the most important predictor for explaining the diversity of small mammals in the Atlantic Forest remnants. We also found that the bioclimatic variables (temperature and precipitation) affect small mammal biodiversity.

Forest amount in the landscape has a positive influence on small mammals' diversity (Figure 2), across all levels of analysis, per region or in the entire Atlantic Forest. Other studies observed the same positive relationship between small mammals and forest amount, in the Atlantic Forest (Palmeirim et al., 2019) and Brazilian Savana (Cerrado) (Melo et al., 2017).

Meantime, the small mammal diversity is also influenced by the configuration and composition of the elements in the landscape. For example, the size of the forest patch, in general, has a positive relation to the small mammal's diversity (Pardini et al., 2005) and the land use type in the same landscape can harbor different species of small mammal (Estavillo et al., 2013). However, species generally respond in different ways to habitat amount, patch size, and land use type.

The different responses to habitat characteristics and composition will depend on the habitat requirement of each species. The habitat specialist's species are more related to their habitat and are positively affected by high amounts and large patches in the landscape (Delciellos et al., 2016; Melo et al., 2017; Pardini et al., 2010). The habitat generalist species tend to benefit from the changes in the landscape and are positively affected by low amounts and small patches in the landscape (Bonecker et al., 2009; Hannibal et al., 2018; Pardini et al., 2010).

We also found that the bioclimatic variables (temperature and precipitation) can affect small mammal biodiversity. For our dataset, the max temperature of the warmest month and precipitation in the coldest quarter have a negative relationship with small mammal diversity, while for precipitation in the wettest quarter the relationship is positive (Tables 1 and 3). Other studies have tested the relationship of temperature and precipitation with the richness and abundance of small mammals and found a positive relationship between precipitation and abundance or richness (Barros-Battesti et al., 2000; Ferreguetti et al., 2021). The bioclimatic variables can indirectly influence the richness and abundance of small mammals through the increase in available food (Bergallo & Magnusson, 1999; Graipel et al., 2006; Passamani & Ribeiro, 2009) that increa in the reproduction rate (Barros, 2013; Bonecker et al., 2009; Graipel et al., 2006).

Looking for the three main regions of the Atlantic Forest, none of the variables used in this study was statistically significant for the northeast region. This region has a low variance in precipitation and temperature throughout the year, and that may explain the lack of effect in small mammal diversity. But considering the high degree of deforestation, the lowest number of fragments (Dalapicolla et al., 2021), which are also small (<50ha) and distant from each other (Ribeiro et al., 2009) in the northeast region is probably that most of the original mammal diversity has likely been extinct due to the lack of forest patches large enough to support their populations.

For the southeast region, the max temperature of the warmest month, mean diurnal range, isothermality, and farming amount negatively influences the small mammal's diversity, while precipitation of the wettest quarter, annual precipitation, and forest amount have a positive relationship. Despite historical disturbances by agriculture and urban areas (Joly et al., 2014), the southeast region has the largest fragments of Atlantic Forest (Ribeiro et al., 2009) that contribute to small mammal conservation and also to the relevance of forest amount in that group, besides is the most studied. In this region, the summer is usually hot and wet, and abundant rainfall and mild summer temperatures increase food availability, increasing small mammals' abundance (Corrêa et al., 2017), increasing the chances of capturing species rare, and thus increasing the observed richness.

For the south region, the landscape variables are the most relevant, and both, forest and farming amount have a positive relationship with small mammal diversity. The second and third largest Atlantic Forest fragments are in the southern region (Ribeiro et al., 2009), which contributes to small mammal conservation in the south of the Atlantic Forest. The unexpected results showing the positive relationship between small mammals' diversity and the farming amount may be due to the characteristics of the farming in the region which have greater complexity (vertical structures) such as Pinus and Eucalyptus (C. R.

Fonseca et al., 2009) and available microhabitats that, indirectly contribute to small mammal diversity (Dalmagro & Vieira, 2005; Lima et al., 2010; Melo et al., 2011). Besides, these farms were possibly established in regions originally rich, as indicated by the presence of areas with high endemism of small mammal (Dalapicolla et al., 2021).

Finally, our results demonstrated that forest amount in the landscape positively influences small mammal diversity across both levels of analysis (the regional subset and the entire Atlantic Forest dataset) and all regions (except for the northeast region). This result demonstrates the importance of the forest amount for the diversity of small mammals regardless of the biogeographic context (Ribeiro et al., 2009). Also, the results show that small mammal assemblages respond in different ways to variation in bioclimatic and landscape features, depending on the context of the region where they are inserted.

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Tables

Table 1. Variable, variable scale (Scale), type of relationship tested (Relation), Model averaged estimates (Estimate), standard errors (SE), and the p-value given for the Z-statistic (Pr(> | z|)) across the model-average linear mixed model (GLM) testing the variation of small mammal Shannon index with data from studies carried out in the Atlantic Forest.

Variables	**Scale**	**Relation**	**Estimate**	**SE**	**z value**	**Pr(> | z|)**
(Intercept)			1.637	0.761	2.150	0.032
Max temperature of the warmest month	Local	Linear	-0.004	0.001	2.858	0.004*
Forest amount quadratic	Landscape	Non-linear	0.00004	0.00002	2.814	0.005*
Precipitation of coldest quarter	Local	Linear	-0.001	0.0002	2.697	0.007*
Forest amount	Landscape	Linear	0.005	0.002	2.127	0.033*
Precipitation of wettest quarter	Local	Linear	0.001	0.0002	2.682	0.007*
Farming amount	Landscape	Linear	0.004	0.005	0.640	0.522
Isothermality	Local	Linear	0.012	0.006	1.766	0.077
Farming amount quadratic	Landscape	Non-linear	-0.00001	0.00004	0.233	0.816
Mean diurnal range	Local	Linear	-0.0004	0.003	0.161	0.872
Annual precipitation	Local	Linear	-0.00001	0.0001	0.078	0.938

Table 2. Variable, variable scale (Scale), type of relationship tested (Relation), and importance of each variable (W). The importance value was obtained by the sum of the weights of each variable in the global models.

Variables	Scale	Relation	W
Forest amount quadratic	Landscape	Non-linear	0.55
Forest amount	Landscape	Linear	0.40
Max temperature of the warmest month	Local	Linear	0.40
Precipitation of coldest quarter	Local	Linear	0.26
Precipitation of wettest quarter	Local	Linear	0.24
Farming amount	Landscape	Linear	0.05
Isothermality	Local	Linear	0.03
Farming amount quadratic	Landscape	Non-linear	0.03
Mean diurnal range	Local	Linear	0.01
Annual precipitation	Local	Linear	0.01

Table 3. Variable, variable scale (Scale), type of relationship tested (Relation), and importance of each variable (*W*) for each region. The importance value was obtained by the sum of the weights of each variable in the global models.

Variables	Scale	Relation	W Northeast	W Southeast	W South
Annual precipitation	Local	Linear	0.11	0.08	0.02
Isothermality	Local	Linear	0.42	0.02	0.14
Max temperature of the warmest month	Local	Linear	0.09	0.49	0.06
Mean diurnal range	Local	Linear	0.12	0.09	0.16
Precipitation of coldest quarter	Local	Linear	0.14	0.01	0.07
Precipitation of wettest quarter	Local	Linear	0.18	0.42	0.04
Farming amount	Landscape	Linear	0.13	0.23	0.24
Forestry amount	Landscape	Linear	0.13	0.16	0.54
Farming amount quadratic	Landscape	Non-linear	0.14	0.29	0.20
Forestry amount quadratic	Landscape	Non-linear	0.14	0.19	0.45

Table 4. Variable, variable scale (Scale), type of relationship tested (Relation), Model averaged estimates (Estimate), standard errors (SE), and the p-value given for the Z-statistic (Pr(> | z|)) across the model-average linear mixed model (GLM) testing the variation of small mammal Shannon index with data from studies carried out in the Atlantic Forest (for the southeast dataset).

Variable	Scale	Relation	Estimate	SE	z	Pr(> | z|)
Intercept			2.116	1.250	1.691	0.091
Max temperature of the warmest month	Local	Linear	-0.006	0.002	3.215	0.001*
Farming amount quadratic	Landscape	Non-linear	-0.00005	0.00002	3.127	0.002*
Precipitation of wettest quarter	Local	Linear	0.001	0.0004	2.681	0.007*
Farming amount	Landscape	Linear	-0.005	0.002	3.045	0.002*
Forest amount quadratic	Landscape	Non-linear	0.00004	0.00001	2.987	0.003*
Forest amount	Landscape	Linear	0.005	0.002	2.927	0.003*
Mean diurnal range	Local	Linear	-0.009	0.004	2.505	0.012*
Annual precipitation	Local	Linear	0.001	0.0002	2.533	0.011*
Isothermality	Local	Linear	-0.025	0.012	2.047	0.041*
Precipitation of coldest quarter	Local	Linear	0.001	0.001	0.914	0.361

Table 5. Variable, variable scale (Scale), type of relationship tested (Relation), Model averaged estimates (Estimate), standard errors (SE), and the p-value given for the Z-statistic (Pr(> | z|)) across the model-average linear mixed model (GLM) testing the variation of small mammal Shannon index with data from studies carried out in the Atlantic Forest (for the south dataset).

	Scale	Relation	Estimate	SE	z	Pr(> | z|)
(Intercept)			0.419	0.787	0.527	0.598
Farming amount quadratic	Landscape	Non-linear	0.0001	0.0001	2.024	0.043*
Forestry amount	Landscape	Linear	0.010	0.004	2.431	0.015*
Farming amount	Landscape	Linear	0.009	0.004	2.116	0.034*
Forestry amount quadratic	Landscape	Non-linear	0.0001	0.00003	2.447	0.014*
Mean diurnal range	Local	Linear	0.008	0.004	1.984	0.047*
Isothermality	Local	Linear	0.028	0.014	1.906	0.057
Precipitation of coldest quarter	Local	Linear	0.001	0.001	1.516	0.130
Max temperature of the warmest month	Local	Linear	-0.004	0.003	1.346	0.178
Precipitation of wettest quarter	Local	Linear	-0.001	0.001	1.102	0.270
Annual precipitation	Local	Linear	0	0.0003	0.008	0.994

Figure Captions

Figure 1. Geographic distribution of the 214 small mammal assemblages in the Atlantic Forest, Brazil. Gray shows the historical Atlantic Forest distribution, and green shows the remaining patches.

Figure 2. Graph showing the relationship between (a) small mammal diversity and forest amount and (b) small mammal diversity and max temperature of the warmest month.

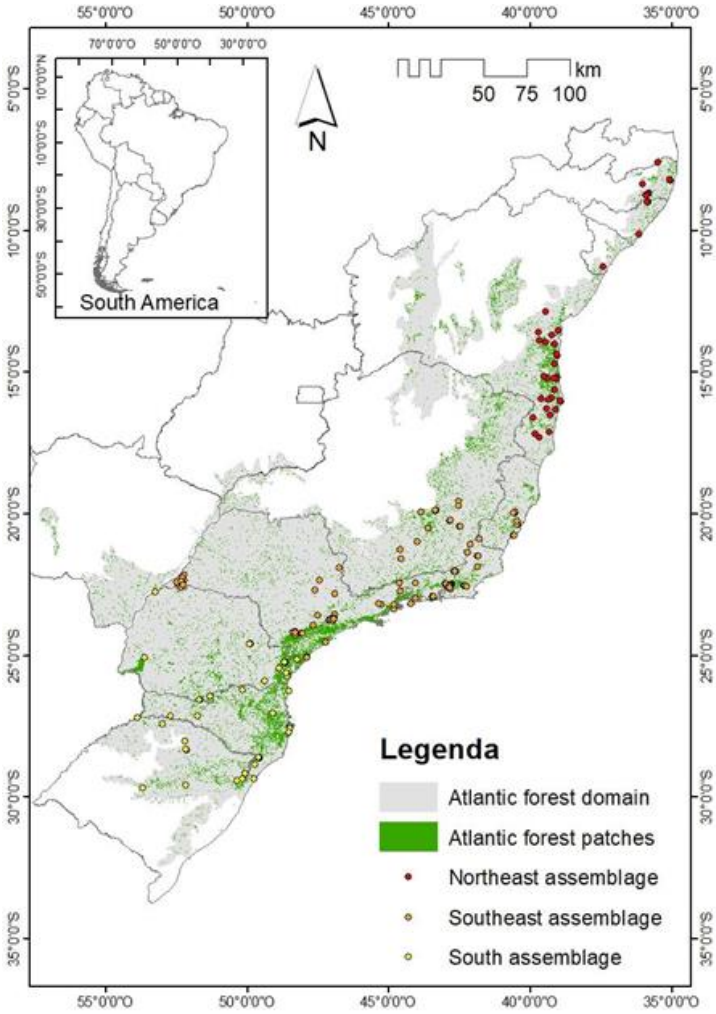

Figure 1. Geographic distribution of the 214 small mammal assemblages in the Atlantic Forest, Brazil. Gary shows the historical Atlantic Forest distribution, and green shows the remaining patches.

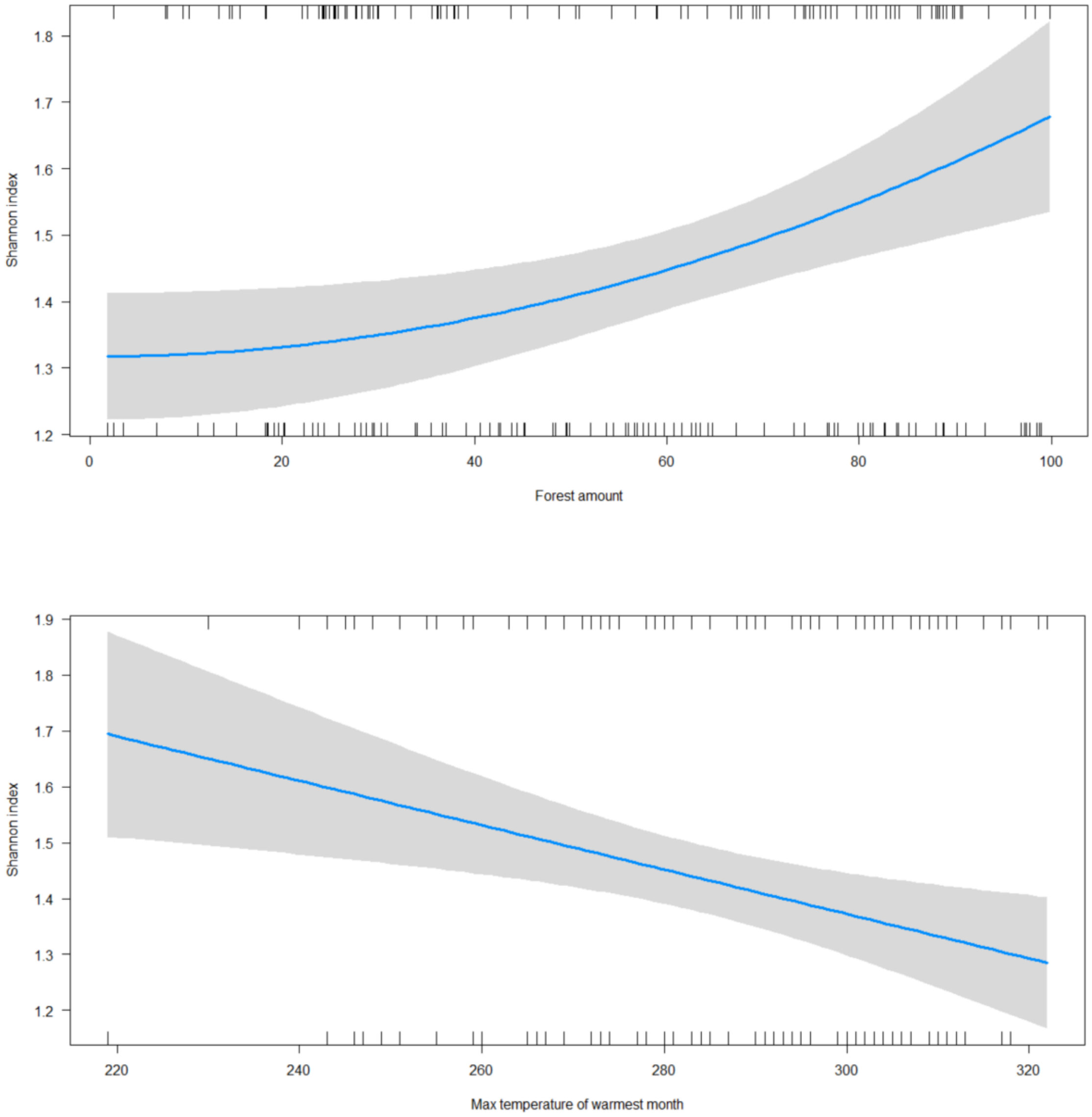

Figure 2. Graph showing the relationship between (a) small mammal diversity and forest amount and (b) small mammal diversity and max temperature of the warmest month, considering the entire data set.

Capítulo 2

Small mammals' assemblages in cocoa agroforest in southern Bahia, Brazil

Manuscrito formatado nas normas da revista Mammalian biology

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Abstract

The reduction of natural habitats, due to the expansion of agriculture, can lead to a decrease in biodiversity, as occurs in the Atlantic Forest. On the other hand, agroforestry systems contribute to the conservation of biodiversity due to the cultivation of several cultures together, creating structural complexity. However, the amount of remaining natural habitat around the agroforestry as well as the local characteristics are important for the biodiversity within the systems. The cocoa (*Theobroma cacao*) agroforestry in southern Bahia has been intensified, with greater cocoa density and lower density of trees for shade. Our objective was to unravel the effect of local characteristics (shading, number of trees, vertical structure) and landscape (forest cover and cocoa agroforestry) on patterns of richness and abundance of small mammals in cocoa agroforestry in southern Bahia. The study was carried out in 12 cocoa agroforests, for 17 days using pitfall traps, Sherman and Tomahawk. We obtained 96 captures of 15 species of small mammals. The most plausible model for richness and abundance shows that both are negatively affected by the amount of agroforestry in the landscape. Possibly, the landscapes of southern Bahia are already in an advanced stage of degradation, and the richness of small mammals has been compromised. We expected abundance to be positively related to the amount of cocoa agroforestry in the landscape. However, we found that this relationship was negative. Possibly these results are a reflection of the intensification of management in agroforestry, and the consequent increase in the use of pesticides in plantations.

Keywords: Rodentia; Didelphimorphia; cabrucas; agrosystems

Introduction

Natural habitats have been continuously modified, mainly by the expansion of agriculture (FAO, 2018). The modifications lead to the loss and isolation of natural habitat, which can lead to the loss of biodiversity (Cassano et al., 2014; Galetti et al., 2021; Pardini et al., 2017; Rios et al., 2021). As a result, the functions and services provided by different groups are also compromised, though, the functions, and services are vital for productive crops (Maas et al., 2015).

Tropical forests are particularly affected by the expansion of agriculture (FAO, 2018). The Atlantic forest had lost most of its original vegetation because of anthropogenic disturbances such as agriculture (Joly et al., 2014; Lapola et al., 2014; Ribeiro et al., 2009) and now have a few small fragments of original vegetation remain (Lira et al., 2012). Even so, the Atlantic Forest is a megadiverse, has many endemic species, and is a hotspot for biodiversity (Mittermeier et al., 2011; Myers et al., 2000).

Given the human change in the environment, the agroforestry system can contribute by integrating agriculture and biodiversity conservation (Schroth & Harvey, 2007). Agroforestry is an anthropic land use that associates trees and crops in the same space (Atangana et al., 2014). The structural complexity resulting from the culture of several plant species makes it a more human-friendly environment. In this way, this culture can minimize the damage caused to the environment by agricultural expansion, contributing to maintaining biodiversity even in anthropic landscapes (Bhagwat et al., 2008). However, the contribution of agroforestry to biodiversity depends on the surrounding landscape and local management in them (Bhagwat et al., 2008; Cassano et al., 2014; A. S. Ferreira et al., 2020).

The landscape composition around agroforestry can contribute to taxonomic diversity (Arroyo-Rodríguez et al., 2020). The amount of native vegetation can positively contribute to taxonomic diversity (Estavillo et al., 2013; Morante-Filho et al., 2015), to the abundance and richness of some groups of birds (Cabral et al., 2021), and the richness of bats (Faria et al., 2006, 2007).

Since the late XIX, southern Bahia is the core zone of cocoa production (Tabarelli et al., 2005). Generally, cocoa production is in an agroforestry system, usually in consortium with tree species that shaded the cocoa trees (Gama-Rodrigues et al., 2021b) and give extra income to farmers (Piasentin et al., 2014). Cocoa agroforestry is heterogeneous and has variations in the number of tree species (Sambuichi et al., 2012; Sambuichi & Haridasan, 2007), and the tree species choice (Piasentin et al., 2014). Some native trees were found in these plantations but were removed constantly because of the market value, such as *Cariniana legalis* (jequitibá), *Cedrela fissilis* (cedro), *Plathymenia foliolosa* (vinhatico) (Piasentin et al., 2014). Currently, the producers have used exotic trees, such as *Spondias mombin* (cajazeira), *Artocarpus heterophyllus* (jackfruit), and *Erythrina* spp., which also serve as food and firewood (Piasentin et al., 2014).

However, cocoa production in the region drops significantly after a fungal disease (witches' broom) introduction and producers have been encouraged to intensify management, increasing the density of cocoa plants, decreasing shading (i.e. the number of trees) (Cassano et al., 2009; Schroth & Harvey, 2007), and using agrochemicals (such as fertilizers, herbicides, and insecticides). However, it’s questionable whether management intensification can increase productivity. Although this is possible that such a widespread intensification will not deliver the expected increase in regional productivity, it can negatively affect regional levels of biodiversity. That way, intermediate shade can optimize the trade-off between productivity, and biodiversity conservation (Blaser et al., 2018).

Besides the economic contribution, cocoa agroforestry can contribute to carbon stock conservation in south Bahia (Schroth et al., 2015) and biodiversity conservation (Cassano et al., 2009). But, it will depend on their local characteristics (structure, composition), the surrounding landscape characteristics (Schroth & Harvey, 2007), besides the target biological group characteristics. Cocoa agroforestry can provide habitat or act as a corridor because of their high permeability for several species (Schroth et al., 2011), mitigating the negative impacts of habitat loss (Cassano et al., 2009). Among others, cocoa agroforestry can harbor endangered species (Cassano et al., 2011; Rocha et al., 2015; Schroth et al., 2011), bats (Faria & Baumgarten, 2007), large mammals (Cassano et al., 2012; Ferreira et al., 2020), and small mammals (Silva et al., 2019).

A non-fly small mammal is a polyphyletic group composed of Rodentia and Didelphimorphia (Reis et al., 2006). It is the most diverse group of mammals in the Atlantic Forest (Paglia et al., 2012) and has around 97 species (Reis et al., 2006). They are a good indicator of the quality of the environment (Pardini et al., 2010; Vieira et al., 2003). The composition, richness, and abundance of small mammals respond to modifications in the landscape in a brief period (Banks-Leite et al., 2014; Galetti et al., 2015; Pardini, 2004; Vieira & Monteiro-Filho, 2003).

We aim to unveil the effect of management intensification and the remaining forest cover at the landscape scale on ecological patterns of small mammal assemblages in cocoa (*Theobroma cacao*) agroforestry in southern Bahia, northeastern Brazil. We used small mammals captured in 12 cocoa agroforestry to test the role of local and landscape features in shaping the richness, abundance, and diversity of small mammals. Furthermore, we expected that: 1) small mammals' richness will be positively related to native vegetation amount in the landscape; 2) small mammals' abundance will be positively related to the shaded cocoa amount in the landscape; 3) small mammals' diversity will be positively related to agroforest vertical structure.

Methodology

Study region and sampled sites

We conducted this study in cocoa agroforestry systems in southern Bahia, Brazil (Figure 1a). The climate is hot and humid (AF in Koppen's classification), with 1200-1800 mm of annual rainfall (Mori et al., 1983). This region is inside the original Atlantic Forest domain, and it's a concern for biodiversity conservation. The reason is the biodiversity (Martini et al., 2007a) besides being an endemic center (Silva et al., 2004). However, the southern Bahia region was modified by humans' activities, and now the landscapes are composed mainly of urban centers, cattle pastures, rubber trees (*Hevea brasiliensis*), eucalyptus (*Eucalyptus* sp.), and cocoa (*Theobroma cacao*) plantations (Morante-Filho et al., 2016).

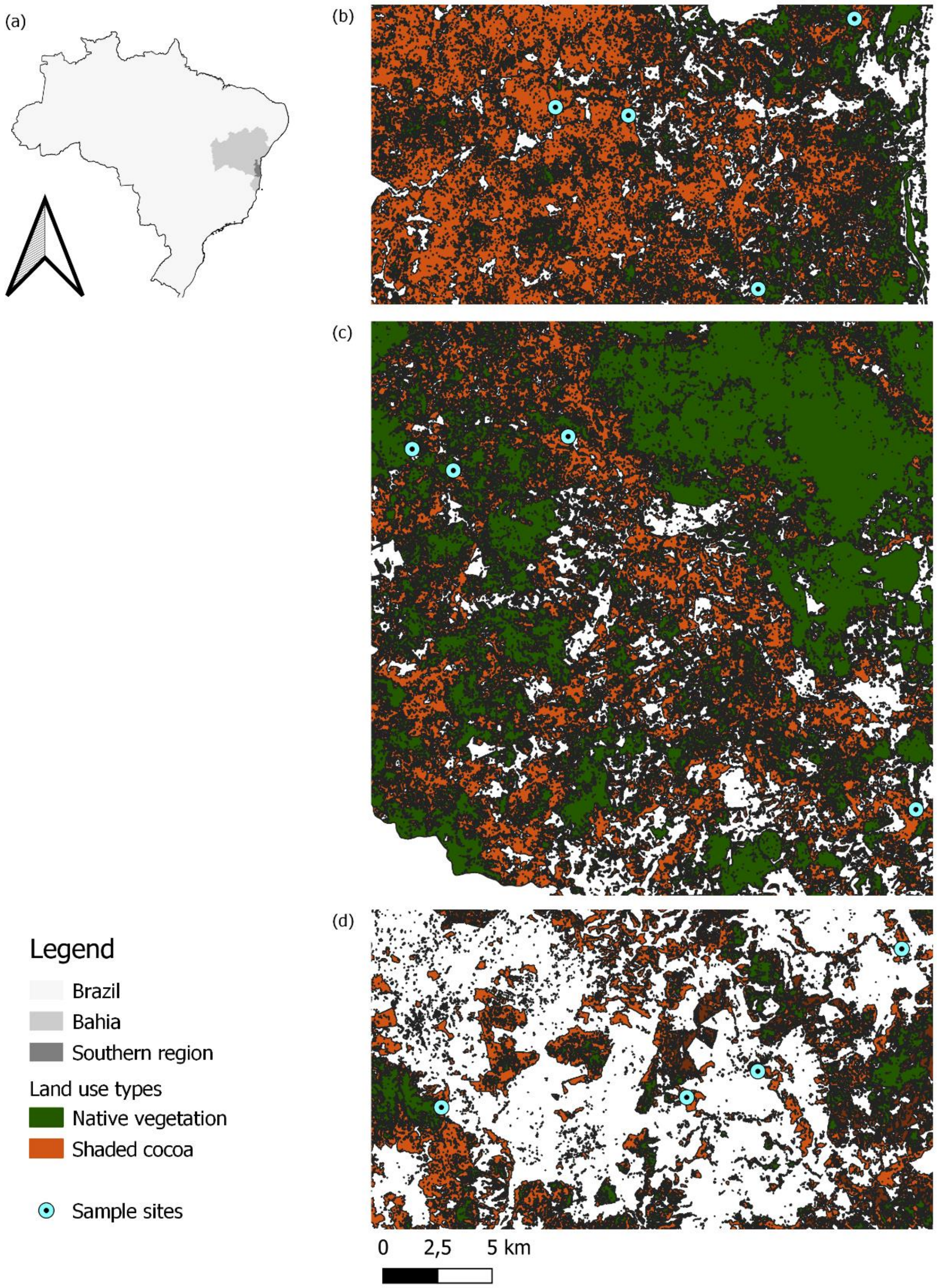

Figure 1. (a) Location of studies: southern region of Bahia state, Brazil; (b, c and d) the 12 sampled sites (colors points) and the maps are colored by types of land use (native vegetation and shaded cocoa).

This research was made in twelve (12) cocoa agroforestry (Figure 1b), equally distributed in 3 subregions (Belmonte, Una, and Ilhéus). All of our study areas involve small land-owners, that are key sponsors to achieving regional crop sustainability and biodiversity conservation.

Considering a circular landscape with a 1000 m radius, the three subregions differ in the amount of native vegetation, cocoa agroforestry, and other elements in the landscape. In the Ilhéus subregion, the landscapes are dominated by cocoa agroforestry. In the Una subregion, the landscape is primarily shared between native vegetation and shaded cocoa. At least, in the Belmonte subregion, the landscape is dominated by non-forested land use (Figure 1c).

Small mammals sampling

We carried out two sessions of small mammal capture study in 12 cocoa agroforestry between January 2020 and March 2021. The first sessions were conducted for 10 consecutive days from January to March and December 2020. The second session was conducted for 7 consecutive days from January to March 2021. We merged information from the two sessions for the analyses.

At each sample site, we established one grid (100x40 m) for small mammal capture. The grid was composed of three paralleled transect lines, 20 meters apart. Each transect has 10 capture stations 10 meters apart, totaling 30 capture stations at each site (510 traps-night per site). For the central transects' capture station, we buried 60l plastic buckets at ground level in a straight line, and we set up a 50 cm drift fence with wood and plastic sheeting between the buckets. The two extremity transects' capture stations were composted by live traps (5 Shermans [7,62x8,89x22,86 cm] and 5 Tomahawks [50x21,5x20 cm]), interleaved. We placed the live traps on the ground or understory, interleaved, and we baited them with a mix of peanut butter, banana, sardines, oatmeal, and cornmeal.

We used the combination of three different traps for a more efficient sampling of small mammals. Pitfall traps increase the estimate of the richness and abundance of small mammals in neotropical forests because of allowing the capture of more than one individual at a time, despite the manual labor required to bury the buckets and mount the fence (Bovendorp et al., 2017; McCleery et al., 2021). Sherman is more efficient for capturing small rodents and Tomahawk for capturing marsupials, and both are walk-in live traps with spring-loaded doors that close when triggered (McCleery et al., 2021).

We checked the traps every morning, and we put more bait if necessary. All small mammals captured for the first time were marked with a numbered ear tag, weighed, measured, and we observed the reproductive state, marsupial's dental development, and taxonomic identification. If the animal was recaptured, we just wrote down the tag number. Finally, we released the animals at the same capture station.

This work was approved by Brazilian Institute for the Environment and Renewable Natural Resources (in Portuguese: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis - IBAMA) process number 69688 and the Ethics Commission for Animals Use (in Portuguese: Comitê de ética no uso de animais - CEUA) from UESC process number 005/19. We followed the guidelines of the American Society of Mammologists (Sikes, 2016) and the field guide (Bonvicino et al., 2008) for helping in taxonomic identification. All animals that died in the traps were deposited in the mammal collection Alexandre Rodrigues Ferreira, at UESC.

Landscape variables

We downloaded a map, made with satellite images from 2019, by MapBiomas (Souza et al., 2020), which separates land use into seven classes: i) native vegetation: in different successional stages; ii) shaded cocoa: which includes cocoa agroforestry plantations, irrespective of the type of crop; iii) water; iv) urban areas; v) non-forested; vi) wetlands; vii) silviculture: forest plantation. However, for the analysis, we only used the native vegetation and shaded cocoa classes.

We quantified the amount of each land use around the grid center, using a multi-scale approach (250-, 500-, 750- and 1000-meters radius), this step was performed in the QGis (3.16.14) program (QGIS Development Team, 2021). Afterward, we calculate the percentage that each land use type occupies in the multi-scale landscapes.

We used the native vegetation amount in different scales to identify the radius size more appropriate for our response variables, and have a correct understanding of our finds (Huais, 2018). For that, we used the 'multifit' package (Huais, 2018) by AIC criteria, and built one model for each response variable.

Local variables

We established a plot of 100x25 m (0.25 ha) at each site for obtaining the local variables' descriptors. Within each plot, we collected information about the trees (native and exotic), vertical stratification, and shading.

Regarding the trees, we counted and identified all living trees with diameters at breast height (DBH) greater than 10 cm, and we counted the cocoa trees, regardless of the DBH.

Regarding vertical stratification, we made a visual estimate of how much the leaves occupy an imaginary vertical line in eight strata classes (0-1 m, 1-2 m, 2-3 m, 3-4 m, 4-5 m, 5-10 m, 10-15m, >15 m), we estimated the height with the help of a 5-meter pole. The estimate was made using a scale of 1-5, where 1 indicates that at least 20% of the strata class is covered with leaves and 5 indicates that from 81 to 100% of the strata class is covered with leaves. We repeated this estimate at five random points within the plot and we used the mean value to rank the sample sites in a Principal Component Analysis (PCA), and the second axis as the synthesis variable, which explains 22.8% of the vertical complexity of agroforestry.

Regarding shading, we estimate the percentage of shad at 1.5 meters from the ground by using the densitometer and canopy photographs. With the densitometer, we measured 20 times the shading by counting how much had been filled in with the foliage. With canopy photography, we get five images of the canopy and with the help of the GLMA app, we get the percentage of shade.

And finally, we use the local variables to perform a correlation test, using the package 'Multifit' by the AIC criterion (Huais, 2018). This step was carried out to reduce the number of variables used in the construction of the final model because we do not have enough replicas to test with all local variables. The models included the 1000-meter scale as the best for richness, 750-m for abundance, and 250-m for Shannon index.

Data analysis

We calculated the Shannon index for each site, gathering the two sections, using the 'diversity' function from the Vegan package (Oksanen, 2017). We used a model selection approach to evaluate the effect of local (stratification and shading) and landscape (native vegetation and shaded cocoa amount) variables on small mammals' richness, abundance, and diversity, plus the null model. Likewise, we fitted a generalized linear mixed model (GLMM) with zero-inflation and gamma distribution using the 'glmmTMB' function in the 'glmmTMB' package (M. Brooks et al., 2017). We used the 'dredge' function to create the model selection tables, ranking the models using second-order AICc with the 'model.sel' function, and we used as a criterion of the best model the lowest AICc value. We used the R package "MuMIn" for created and rank the model selection table. We built a model for each response variable and we used the R environment software to perform the analysis (CoreTeam, 2017).

Results

We recorded 96 captures of 15 small mammal species (Table 2) with a capture effort of 6120 traps/nights for all 12 sites and the mean trapping success was 1.57%. Ten species belong to Rodentia (*Akodon cursor, Guerlinguetus ingrami, Hylaeamys seuanezi, Nectomys squamipes, Oecomys catharinae, Oligoryzomys nigripes, Rattus rattus, Rhypidomys mastacalis,* and *Thaptomys nigrita*) and five to Didelphimorphia order (*Didelphis aurita, Marmosa murina, Marmosops incanus, Metachirus nudicaudatus,* and *Monodelphis americana*). The most frequently captured species were *Hylaeamys seuanezi* (19 captures in 7 sites), *M. murina* (17 captures in 9 sites), and *R. mastacalis* (16 captures in 4 sites). The rare species were *G. ingrami*, *M. nudicaudatus*, *M. americana*, *O. catherinae*, and *T. nigrita*; with only one capture of each. We only recorded one invasive species (*Rattus ratus*), on one site.

Table 1. The abundance of small mammal species was recorded in 12 cocoa agroforestry sites in southern Bahia.

	Belmonte	Ilhéus	Una	**Total**
Akodon cursor	2	1	3	**6**
Didelphis aurita	4		1	**5**
Guerlinguetus ingrami	1			**1**
No ID	2			**2**
Hylaeamys seuanezi	10		9	**19**
Marmosa murina	5	5	7	**17**
Marmosops incanus	4	3		**7**
Metachirus nudicaudatus			1	**1**
Monodelphis americana			1	**1**
Nectomys squamipes	10			**10**

Oecomys catherinae	1			**1**
Oligoryzomys nigripes	8			**8**
Rattus rattus		1		**1**
Rhipidomys mastacalis	13	1	2	**16**
Thaptomys nigrita			1	**1**

For richness, the most supported model included only cocoa agroforestry in a 1000 m radius landscape (estimate = -0.02, z value < 0.05). The model indicates that a landscape with a high amount of shaded cocoa has a smaller richness of small mammals (figure 2 and table 4).

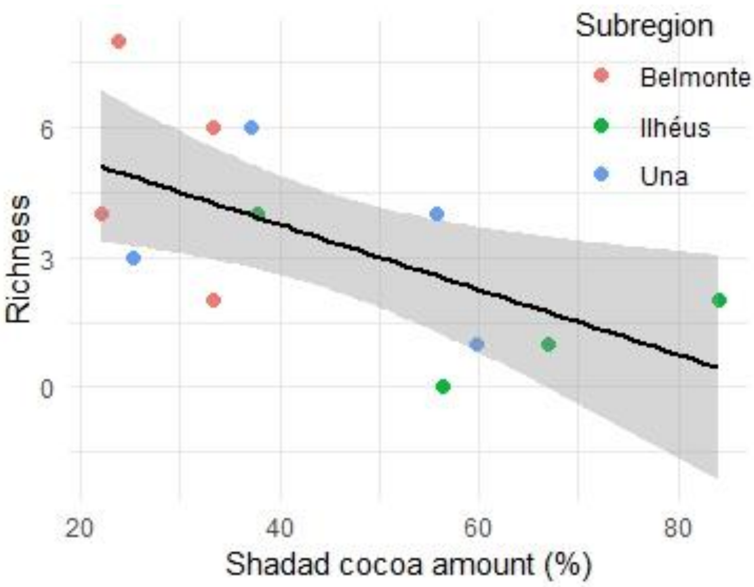

Figure 2. Relation between small mammal richness and shaded cocoa amount (in percentage) for 1000 m radius landscape. The gray areas represent the confidence interval.

Table 4. Model estimates (Estimate), unconditional standard errors (SE), and the z value of the fixed effects across all generalized linear mixed models (GLMM) with zero-inflation and gamma distribution testing the richness response. Fixed variables considered include vertical stratification, forest cover, and shaded cocoa cover (in a 1000 m radius).

	Estimate	SE	z value
(Intercept)	2.06	0.51	4.04

Vertical stratification	-0.04	0.08	-0.52
Forest amount	0.00	0.01	0.04
Shaded cocoa amount	-0.02	0.01	-2.36

For abundance, the model selected included only shading (estimate = 0.02, z value < 0.05). Shading has a positive relationship with the abundance of small mammals (figure 3 and table 5).

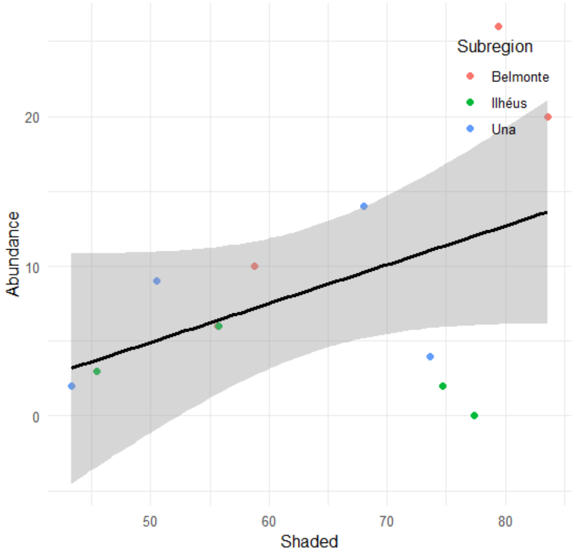

Figure 3. Relation between small mammal abundance and shading. The gray areas represent the confidence interval.

Table 5. Model estimates (Estimate), unconditional standard errors (SE), and the z value of the fixed effects across all generalized linear mixed models (GLMM) with zero-inflation and gamma distribution testing the abundance response. Fixed variables considered include shading, forest cover, and shaded cocoa cover (in a 750 m radius).

	Estimate	SE	z value
(Intercept)	1.870236	1.764742	1.059779
Shading	0.022201	0.01755	1.265036

Shaded cocoa amount	-0.02047	0.014229	-1.43856
Forest amount	-0.01038	0.009459	-1.09766

For diversity, the null model had the lowest AICc value. None of the local or landscape variables explained the variation in small mammal diversity between sites.

Discussion

The capture success was lower than recorded in other studies in cocoa agroforest (Silva et al., 2019) and forests remain in south Bahia (Pardini, 2004). This suggests the existence of small populations of small mammals in the cocoa agroforest. Although the number of small mammal species recorded is lower than recorded in previous studies in the regions (Pardini, 2004; Silva et al., 2019) it is relatively closer, representing a portion of the richness. Also, the small mammal's assemblage is dominated by generalist species such as *Rhipidomys mastacalis*, *Marmosa murina*, and *Nectomys squamipes* (Pardini, 2004; Silva et al., 2019).

Our data suggest that small mammals' richness was negatively related to the shaded cocoa amount. Small mammals' richness seems to be positively related to the native vegetation amount in the landscape (Palmeirim et al., 2019; Pardini et al., 2010; Vieira et al., 2018). So, because of the degradation in the three subregions of south Bahia Atlantic Forest (Dalapicolla et al., 2021; Passamani & Ribeiro, 2009), several species may have become extinct or are reclusive to some fragments with natural vegetation.

We expected that the abundance of small mammals in cocoa agroforestry would be positively related to the shaded cocoa amount because the generalist species could benefit from changes in the environment (Brady et al., 2011; Paise et al., 2020; Palmeirim et al., 2019). But our results showed the opposite and point out that cocoa agroforestry immersed in a landscape with a high shaded cocoa amount tends to have a lower abundance of small mammal. Our results may reflect the management intensification of these systems in south Bahia, and the increasing use of pesticides, herbicides, and fertilizers (Clough et al., 2009; Schroth et al., 2015).

In conclusion, our results demonstrated that shaded cocoa amount in the landscape negatively influences small mammal richness and abundance, in cocoa agroforestry in south Bahia, Brazil. Our results may be related to the intensification of management in these cultures. Small mammals are important as seed dispersers and arthropod predators (Paglia et al., 2012). The decrease of this group in agroforestry can lead to an increase in the abundance of uncontrolled arthropods, becoming a pest. As a result, farmers may be driven to use even more pesticides, further affecting diversity.

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Capítulo 3

Use of space by *Rhipidomys mastacalis* and *Marmosa murina* in cocoa agroforest in southern Bahia, Brazil

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Abstract

Understanding the animals' movements provide information about their life history, besides the inferences about the relations of the movement with the environment. But it's usually high cost due to the necessary equipment. Spool-and-line it's a cheap alternative to track animals' movement, which also does not cause injury or interferer with animal behavior, and can prover detailed information about movement and use of the environment. We used the spool and line technique to register the movement of *Rhipidomys mastacalis* and *Marmosa murina* in cocoa agroforestry systems in South Bahia. That way, we aimed to estimate the daily home range size and use intensity for both species, and estimate how the movements are related to sex and body mass. For to achieve that, we sampled small mammals in 12 cocoa agroforests in south Bahia for 17 non-consecutive days using pitfall and live traps. We track just four *Rhipidomys mastacalis* and nine *Marmosa murina*. Then we estimate the daily home range and use intensity using qgis. Finally, we build two models to test how both can be influenced by body size and sex. We found no evidence that predicts the relation between daily home range and use intensity of *R. mastacalis* and *M. murina* in cocoa agroforestry in southern Bahia with body size and sex. Other factors can influence the home range size of small mammals in cocoa agroforests like food availability and age. Also, the sample size of our trials may not have been sufficient, but informative and this methodology is important and can contribute to the knowledge of daily home range and use intensity.

Keywords: Rodentia, Didelphimorphia, Atlantic Forest

Introduction

Understanding the animals' use of space and movements helps to understand patterns of migration, dispersion, dynamic population, and community structure (Vieira & Monteiro-Filho, 2003; Vieira & Loretto, 2004). The size of the daily home range (DHR) (Almeida et al., 2008; Mendel & Vieira, 2003; Prevedello et al., 2010; Vieira & Loretto, 2004) and the estimation of the daily habitat use intensity (UI) in a daily home range (Loretto & Vieira, 2005) are usually measured in studies of space use and movement. However, these studies are usually financially limited due to the price of the equipment.

With the spool-and-line approach is possible to track the movement of small species and measure the daily home range and the intensity of use (Prevedello et al., 2008). Besides the low cost, this approach does not cause injury or interference in natural behavior (Steinwald et al., 2006) and it's not necessary to recapture the animal to remove the equipment, as it's attached to their fur that naturally falls off. As well, provides accurate trajectory on a small scale with high resolution (Prevedello et al., 2010; Wells et al., 2008), even in dense forests with low satellite signal (Kazimierski et al., 2021).

Spool studies in small mammals made it possible to locate nests (Boonstra & Craine, 1986), and calculate the daily home range and habitat use intensity (Almeida et al., 2008; Almeida et al., 2013; Delciellos et al., 2017). These parameters allow o make inferences about the effects of body mass, sex (Ferrando et al., 2019; Vieira & Cunha, 2008; Vieira et al., 2019), and climatic (Ferreira et al., 2017; Loretto & Vieira, 2005; Loveridge et al., 2016) on movement behavior. It also helps to test the edge permeability (Ascensão et al., 2017), identify patterns in microhabitat (Calazans & Bocchiglieri, 2019; Haby et al., 2013; Lees et al., 2022), and habitat selection (Prevedello et al., 2010).

The small mammals are represented by Didelphimorphia (marsupials), Rodentia (rodents) e Lagomorpha (rabbits) lighter than 3 kg (Fonseca et al., 1996; Paglia et al., 2012). This is a taxonomically diverse group (Fonseca et al., 1996; Reis et al., 2006), but almost all of them have nocturnal habits, and similar captures methodology, favoring the study of assemblages (Prevedello et al., 2008). Small mammals are commonly found in altered areas, insofar as some species benefit from changes in the environment due to their generalist habitat.

The small mammals *Rhipidomys mastacalis* (Rodentia) and *Marmosa murina* (Didelphimorphia) have generalist and arboreal life habits (Pardini, 2004). Meanwhile, these species differ in alimental habitat, since *R. mastacalis* is a frugivorous/seed predator while *M. murina* is an insectivore/omnivore (Paglia et al., 2012). We chose these species as a biological model because they are abundant in altered environments (Pardini, 2004), such as in cocoa agroforests in southern Bahia (Cassano et al., 2021; Silva et al., 2019). Besides, both are related to consuming the cocoa fruit (Cassano et al., 2021), which can lead to damage in the agroforestry and conflict for the farmers.

Agroforestry systems are an alternative to agricultural production with a less negative impact on the environment (Schroth & Harvey, 2007). Those systems associate several plantations (Atangana et al., 2014; Gama-Rodrigues et al., 2021a) which helps create complexity in the environment (Bhagwat et al., 2008). In south Bahia, the cocoa is usually planted in an agroforestry system (Tabarelli et al., 2005), under the shade of native or exotic trees (Piasentin et al., 2014; Sambuichi et al., 2012; Sambuichi & Haridasan, 2007) and can contribute to conservation (Cassano et al., 2011; Ferreira et al., 2020; Mittermeier et al., 2011; Myers et al., 2000; Schroth et al., 2011). The cocoa agroforestry in southern Bahia is in the Atlantic Forest’s original domains, however, the natural vegetation remains in just some small areas (Joly et al., 2014; Lira et al., 2012; Ribeiro et al., 2009).

We used the spool and line technique to register the movement of two small mammals' species (*R. mastacalis* and *M. murina*) in cocoa agroforestry systems in South Bahia. We aim a) to estimate the daily home range size for both species; b) to estimate the UI for both species; c) to estimate how the movements are related to sex and body size.

Methodology

Study region and sampled sites

We conducted this study in 12 cocoa agroforestry systems in southern Bahia (figure 1), in 3 cities (Belmonte, Una, and Ilhéus). This region is in the Atlantic Forest original domain, the climate is hot and humid (AF in Koppen's classification), with 1200-1800 mm of annual rainfall (Mori et al., 1983).

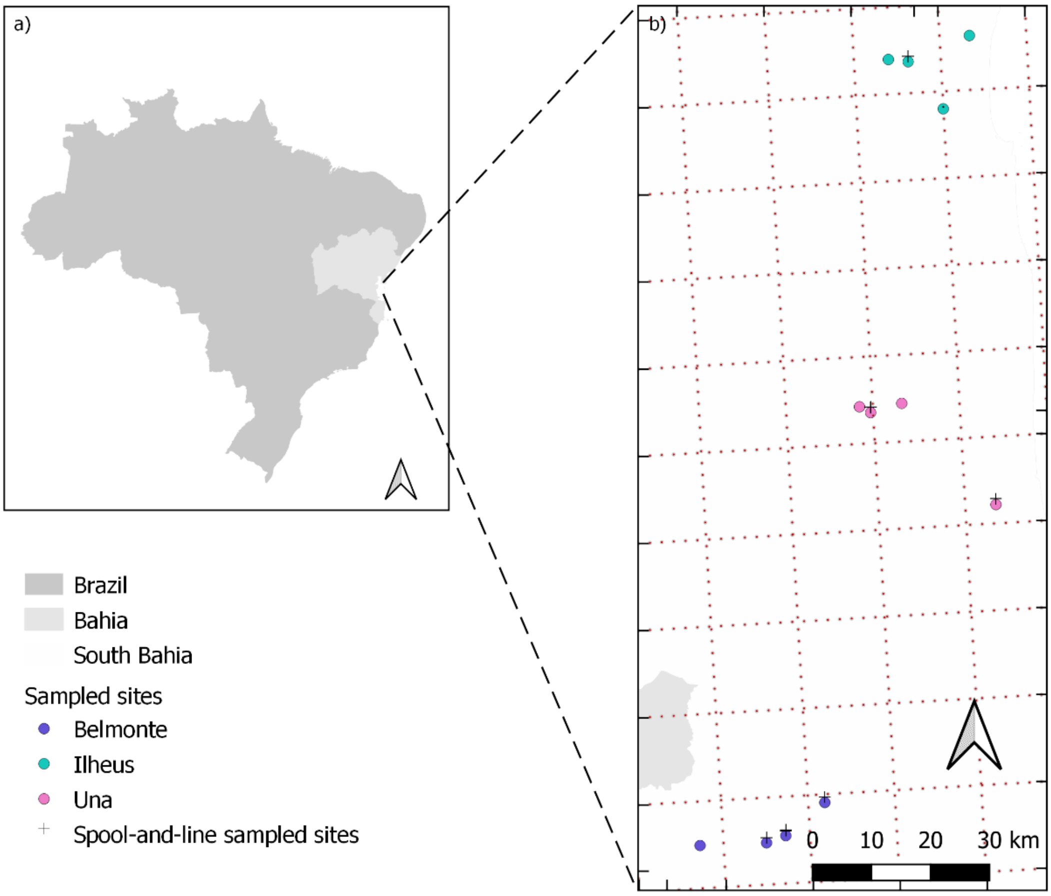

Figure 2. Study area and 12-cocoa agroforestry sample sites were life trap surveys on small mammals.

Small mammals sampling

We conducted two sampling sessions: the first during 10 consecutive days between January 2020 and March 2021, and the second during 7 consecutive days from January to March 2021. We merged information from the two sessions for the analyses.

At each sample site, we established one grid (100x40 m) for small mammal capture. The grid was composed of three paralleled transects lines, 20 meters apart. Each transect has 10 capture stations 10 meters apart, totaling 30 capture stations at each site (510 traps-night per site). For the central transects' capture station, we buried 60l plastic buckets at ground level in a straight line, and we set up a 50 cm drift fence with wood and plastic sheeting between the buckets. The two extremity transects' capture stations were composted by live traps (5 Shermans [7,62x8,89x22,86 cm] and 5 Tomahawks [50x21,5x20 cm]), interleaved. We placed the live traps on the ground or understory, interleaved, and we baited them with a mix of peanut butter, banana, sardines, oatmeal, and cornmeal. We checked the traps every morning, and we put more bait if necessary. We marked with a numbered ear tag, weighed, measured, and observed the reproductive state, taxonomic identification, and *M. murina* dental development.

Spool-and-line technique

We attached a spool-and-line device to track the movement of *Rhipidomys mastacalis* and *Marmosa murina*. The spool-and-line device is a bubbliness cocoon of nylon. Before fieldwork, we colored the ends of the lines, so we could know if the spool reached the final or if the line had broken. We also wrapped the spool-and-line device in a thin layer of a plastic film due to the high rainfall in the study region.

Two people always worked together for placing the spool-and-line device, so one person contained the animal in a safe way for both the team and the animal. The second person brushed the animals between shoulder fur, attach the device to the fur with superglue and use it to help fasten the device, we never attach the device to the skin. Then, we tied the line to a branch and released the animals at the same capture station (Mendel & Vieira, 2003; Vieira & Loretto, 2004). We tracked the animal paths the next day of release by using a hand-held GPS to record coordinates position along the line, whenever the line changed the angle. Finally, we removed the line from the environment to avoid confusion with subsequent lines.

Figure 3 Rodentia (a) and Didelphimorphia (b) individuals with the spool-and-line device.

We had 17 captured *M. murina* and 16 of *R. mastacalis* but we successfully track a small portion of the captured animals (table 1).

Table 1. A total number of the spool-and-line tracked in *Marmosa murina* and *Rhipidomys mastacalis* individuals for tracking their movement in 12 cocoa agroforestry sites (in three subregions: Belmonte, Ilhéus, and Una) in southern Bahia.

	Female	*Male*

Marmosa murina	4	5
Rhipidomys mastacalis	3	1

This work was approved by Brazilian Institute for the Environment and Renewable Natural Resources (in Portuguese: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis - IBAMA) and the Ethics Commission for Animals Use (in Portuguese: Comitê de ética no uso de animais - CEUA) from UESC. We followed the guidelines of the American Society of Mammologists (Sikes, 2016) and the field guide (Bonvicino et al., 2008) for helping in taxonomic identification. All animals that nature died in the traps were deposited in the mammal collection Alexandre Rodrigues Ferreira, at UESC.

Data analysis

We used the GPS coordinate to estimate the DHR , by 100% of the minimum convex polygon (MCP) (Nilsen et al., 2008; Vieira et al., 2019) using the QGis (3.16.14) program (QGIS Development Team, 2021). We add up the entire length of the line to get the total distance traveled, and divided the value by the square root of the daily home range to estimate the U (Loretto & Vieira, 2005).

Finally, we fitted generalized linear modes using the ‘glmmTMB’ function to test the influence of body size, sex, and specie on DHR and UI (separately). We created a model selection table with the ‘dredge’ function and we rank them by AICc value using the ‘model.sel’ function, the best model, using the glmmTMB (Brooks et al., 2017) and MuMin package (Barton, 2022).

Results

Seventeen *R. mastacalis* and 16 *M. murina* were captured during the study. However, spool-and-line movement estimators were measured in four *R. mastacalis* and nine *M. murina*. The daily home range data calculated by the minimum convex polygon (supplement information) shows that the average home range for *R. mastacalis* was 0.018 ± 0.03 ha, trekking means 39.27 ± 13 m and the UI estimation means 3.58 ± 1.33. For *M. murina,* the average home range was 0.036 ± 0.01 ha, tracking a mean of 93,62 ± 63.38 m and the UC estimation means 5.47 ± 3.91.

We found no evidence that predicts daily home range (DHR) size in small mammals, the model did not show significant relationships for any variable. We can observe that the females of *M. murina* had a greater amplitude of the size of the home range (Figure 1a), but were not significant. We observed that body weight negatively affects the daily home range size (estimate = -0.000, $p < 0.057$) when we look at the entire dataset (Table 2, Figure 2b). It was not possible to calculate the relationship between body weight and daily home range size for *R. mastacalis* because the sample size was insufficient; while the differences were not significant for *M. murina*.

Table 2. Variables, model estimate (Estimate), standard errors (SE), and the p-value given for the Z-statistic (Pr(> | z|) across the linear model (glm) selection testing the variation of *Rhipidomys mastacalis* and *Marmosa murina* daily home range.

	Estimate	*SE*	*Pr(>|t|)*
Intercept	0.058	0.014	0.002
Body weight	-0.000	0.000	0.057
Male	-0.000	0.009	9.504

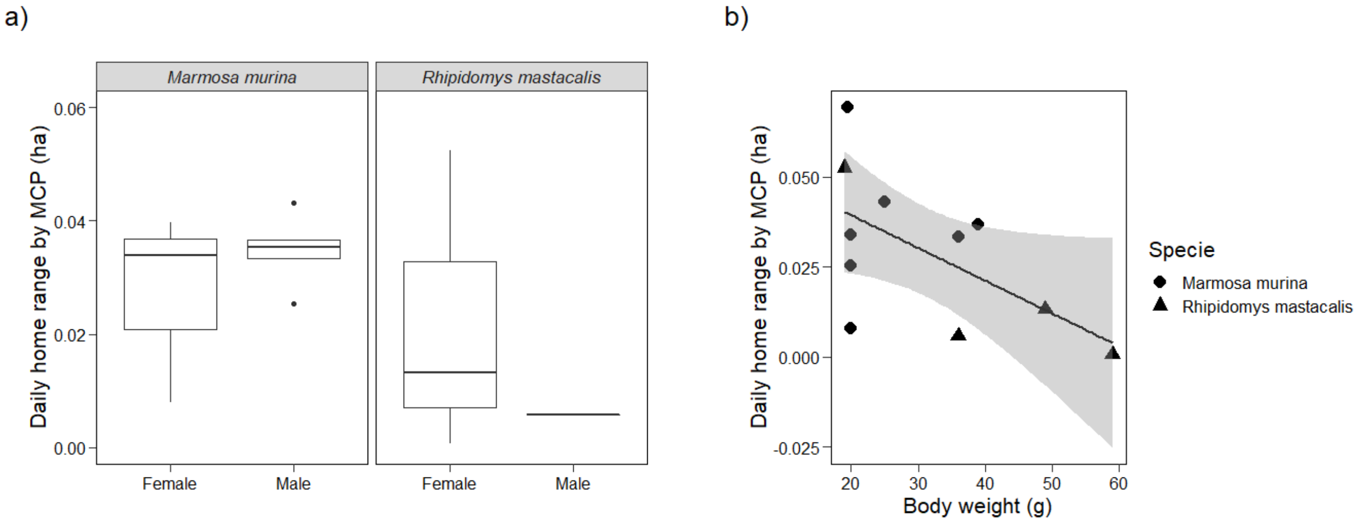

Figure 4. a) Boxplot of *Marmosa murina* and *Rhipidomys mastacalis* daily home range, across sex; b) Modelled relationship between daily home range (ha) and body weight (g) for both species. Black line is mean relationships and gray bands is 95% confidence interval.

We found no evidence that predicts the UI in a daily home range size for small mammals, the model did not show significant relationships for any variable. We can observe that *M. murina* had a greater amplitude of the size of the home range (Figure 3a), but that specie also had more sampled tracks. We observed that body weight does not affect the intensity of use (Table 3, Figure 3b).

Table 3. Variables, model estimate (Estimate), standard errors (SE), and the p-value given for the Z-statistic (Pr(> | z|) across the linear model (glm) selection testing the variation of *Rhipidomys mastacalis* and *Marmosa murina* intensity of use in a daily home range.

Variables	*Estimate*	*SE*	*Pr(>|t|)*

Intercept	5.352	2.692	0.046
Body mass	-0.014	0.075	0.850
Sexo (male)	0.961	1.982	0.627

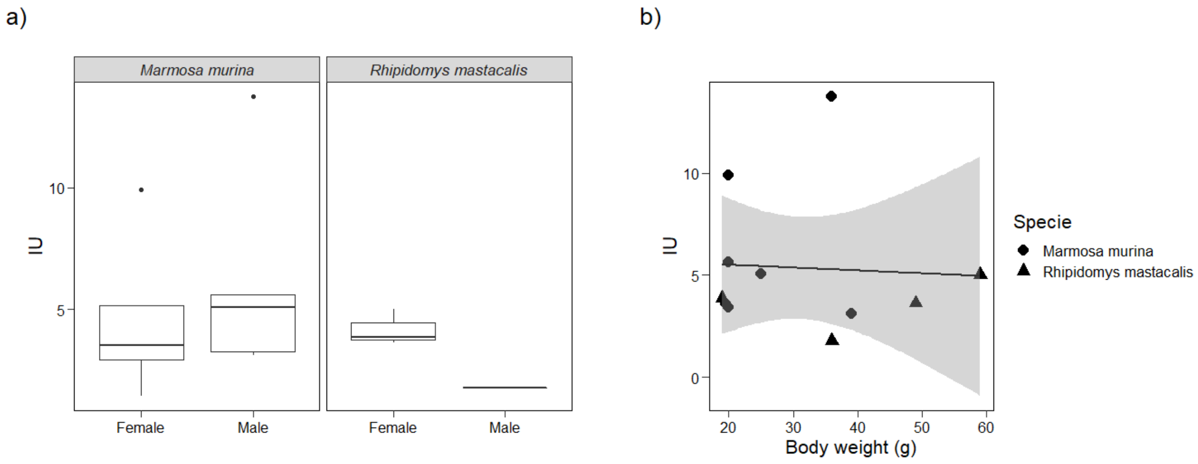

Figure 5 . a) Boxplot of *Marmosa murina* and *Rhipidomys mastacalis* daily home range, across sex; b) Modelled relationship between daily home range (ha) and body weight (g) for both species. Black line is mean relationships and gray bands is 95% confidence interval.

Discursion

The presence of *R. mastacalis* and *M. murina* in cocoa agroforests are related to habitat generalist aspects (Pardini, 2004). Both have already been found in agroforestry in the region and are usually dominant in assemblies (Cassano et al., 2021; Silva et al., 2019). Although only *R. mastacalis* is described as frugivorous (Paglia et al., 2012), both are also reported as consumers of cocoa (Cassano et al., 2021). Therefore, it is also important to know the movement pattern of these species and thus try to minimize the conflict in agroforestry.

The spool and line methodology has the disadvantage of not showing the time series of the movement and the high loss rate of the device in the field (Mendel & Vieira, 2003). And, more importantly, with this methodology, it is possible to answer several questions about the use of space on a small scale, with details on the use of elements in the environment (Kazimierski et al., 2021).

We found no evidence in our model selection that predicts the size of the DHR. For rodents, it has already been observed that the size of the daily home range can be related to sex, and males use to have a greater daily home range (Almeida et al., 2013). For marsupials, it has been observed that adults have higher DHR than sub-adults, which may be a reflex of the energetic requirement (Almeida et al., 2008).

There are other factors, in addition, to which we have studied, that can influence the home range size of small mammals in cocoa agroforests. Food availability can affect animal movement (Adler, 2011; Cáceres & Monteiro-Filho, 2001). In environments with high resource availability, animals do not need to travel long distances to obtain food. Agroforests have the availability of fruits, both cocoa, and other fruit trees planted to shade the cocoa and increase income (Gama-Rodrigues et al., 2021a; Piasentin et al., 2014).

The UI represents how the individual intensity of use and greater values indicate that the animal had a repetitive movement for a short distance while smaller values indicate straight movements for a long distance. The UI can be influenced by age, and adult animals tend to use the space more intensively or they maybe use the space more efficiently (Almeida et al., 2008). The combination of sex and reproductive period also affects the intensity of use, and it was seen that males in reproductive periods have lower UI values (Loretto & Vieira, 2005).

Despite the low number of samples we obtained, this methodology is important and can contribute to the knowledge of DHR and UI. Using the spool of thread technique, we were able to track thirteen individuals and with the coordinates obtained in the field, it was possible to calculate the DHR and UI for all. It’s important to rebound that these results should be read cautiously as our sample number was small. It is also important to emphasize that several factors can influence the movement and use of space and it is important to look for factors that are related to the conservation of biodiversity.

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Conclusão geral

Os resultados obtidos com a realização desse trabalho elucidam sobre os principais determinantes da riqueza de pequenos mamíferos em paisagens modificadas pelo homem ao longo da Floresta Atlântica brasileira, em fragmentos de floresta e agroflorestas inseridas nesse bioma.

A revisão da literatura mostrou que a quantidade de floresta na paisagem foi a característica mais importante como determinante da riqueza de pequenos mamíferos. A riqueza de pequenos mamíferos em fragmentos de Floresta Atlântica responde positivamente à quantidade altas e intermedias de floresta na paisagem. Esse resultado demostra a importância de conservar áreas de florestas natural, mesmo em paisagens muito modificadas.

Nossos resultados empíricos demonstraram que as agroflorestas de cacau no sul da Bahia ainda abrigam pequenos mamíferos, porém com intensificação do manejo a abundância total tende a diminuir. Para assembleias de pequenos mamíferos nesses ambientes, a quantidade de agroflorestas de cacau na paisagem exerce relação negativa com a riqueza e abundancia desse grupo de animais.

Também foi possível testar a eficiência do carretel-de-linha para mapear o uso do espaço utilizado por pequenos mamíferos. Com as informações de onde eles passaram, foi possível calcular o tamanho da área de uso diário e a intensidade de uso do ambiente. Com essa metodologia é possível descrever com detalhe espacial o movimento de pequenos animais, em curto período de tempo. O padrão de movimento desses animais não demostrou relação com o sexo ou com o peso corporal. Talvez pela alta disponibilidade de recurso nessas agroflorestas, o período reprodutivo pode ter relação com o movimento dos pequenos mamíferos.

Os resultados obtidos nessa tese demonstram a importância de ambientes de florestas em paisagens antropizadas. Bem como a importância de culturas mais amigáveis para mitigar os danos causados pela expansão da agricultura. Estudar esses ambientes contrastantes (florestas e agroflorestas) nos permite compreender melhor o efeito das perturbações e como diminuir o problema de agora em diante, visto que os danos já foram causados.