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EFEITOS DE BORDA E VARIÁVEIS AMBIENTAIS LOCAIS NAS ASSEMBLEIAS DE BESOUROS ROLA-BOSTA NA AMAZÔNIA CENTRAL

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Manaus-Amazonas
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Sinopse:

Estudamos o efeito de borda e a influência de fatores ambientais locais nas assembleias de besouros rola-bosta nas florestas ao longo da BR-319, rodovia que conecta Manaus a Humaitá, no estado do Amazonas, Brasil. Aspectos ecológicos como o tipo de guilda funcional, sítios de ocorrência, abundância, composição das assembleias foram avaliados para compreender os padrões de resposta das espécies em função das variações ambientais locais.

Palavras-chave: Scarabaeinae; efeito de borda; BR-319; variáveis ambientais; guildas funcionais.

“À minha família, pelo incentivo e aos meus amigos que me ajudaram nesta caminhada.”

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“A biodiversidade é a maior riqueza do planeta, mas também a mais ameaçada pela humanidade.”

Thomas Lovejoy

RESUMO

Os efeitos de borda, resultantes da fragmentação florestal, provocam mudanças nas condições bióticas e abióticas nas zonas de transição entre áreas florestadas e desmatadas, podendo alterar o microclima, a estrutura da vegetação e os processos ecológicos. Essas alterações influenciam diretamente a composição e a abundância de espécies, afetando a dinâmica ecológica dos fragmentos e contribuindo para a perda de biodiversidade em ecossistemas tropicais. Este estudo teve como objetivo investigar e analisar como a distância em relação a áreas desmatadas e variáveis ambientais locais, como o nível do lençol freático e a composição granulométrica do solo, influenciam a composição de espécies e a estrutura funcional das comunidades de Scarabaeinae ao longo da rodovia BR-319, na Amazônia Central. As coletas foram realizadas em quatro módulos de amostragem, distribuídos em 30 parcelas, por meio de armadilhas do tipo pitfall iscadas com fezes, em parcelas padronizadas. As espécies foram classificadas em três guildas funcionais: habitantes, escavadores e roladores. No total, foram coletados 21.246 indivíduos, pertencentes a 15 gêneros e 66 espécies. Os modelos multivariados ajustados com dados de presença-ausência para todas as espécies e para os grupos funcionais indicaram que a distância até a área desmatada foi o preditor mais forte da composição de espécies. Algumas espécies apresentaram associação positiva com as bordas da floresta, enquanto outras exibiram tendência oposta. Padrões semelhantes foram observados ao analisar separadamente os grupos funcionais e os dados de abundância. A composição da assembleia foi avaliada em função da distância à borda, e foi identificado um ponto de interrupção a 1,4 km, indicando uma mudança acentuada na composição da fauna próxima à borda. Embora as variáveis ambientais locais (argila, silte e nível do lençol freático) possam ser relevantes em determinados contextos, neste estudo elas apresentaram influência secundária sobre a composição das espécies. Esses resultados ressaltam a influência dominante dos efeitos de borda nos padrões de biodiversidade em florestas tropicais impactadas pelo desmatamento. As respostas das espécies aos efeitos de borda foram altamente variáveis, podendo ser positivas, negativas ou neutras. Compreender esse fator determinante nas mudanças da fauna é essencial para prever as respostas da biodiversidade às transformações no uso da terra.

ABSTRACT

Edge effects resulting from forest fragmentation cause changes in biotic and abiotic conditions in transition zones between forested and deforested areas, potentially altering the microclimate, vegetation structure, and ecological processes. These alterations directly influence species composition and abundance, affecting the ecological dynamics of forest fragments and contributing to biodiversity loss in tropical ecosystems. This study aimed to investigate how the distance from deforested areas and local environmental variables, such as groundwater level and soil texture, influence species composition and the functional structure of dung beetle (Scarabaeinae) communities along the BR-319 highway in Central Amazonia. Sampling was conducted across four modules, totaling 30 plots, using standardized pitfall traps baited with feces. Species were categorized into three functional guilds: dwellers, tunnelers, and rollers. A total of 21.246 individuals were collected, representing 15 genera and 66 species. Multivariate models based on presence–absence data, applied to all species and functional groups, indicated that distance to deforested areas was the strongest predictor of species composition. Some species were positively associated with forest edges, while others exhibited the opposite trend. Similar patterns were observed when analyzing each functional group separately and when using species abundance data. The distance at which assemblage composition was affected was also evaluated, revealing a significant breakpoint at 1.4 km from the forest edge, indicating a sharp shift in species composition near deforested zones. Although local environmental variables (clay, silt, and groundwater level) may be relevant in some contexts, they showed secondary influence in this study. These results highlight the dominant role of edge effects in shaping biodiversity patterns in deforested tropical forests. Species responses to edge effects were highly variable—ranging from positive to negative and neutral. Understanding this key driver of species turnover is essential for predicting biodiversity responses to land-use change.

Sumário

INTRODUÇÃO GERAL

Efeitos de borda são alterações ecológicas que ocorrem nas áreas de transição entre habitats diferentes, frequentemente como consequência da fragmentação do habitat (Harper et al., 2005; Murcia, 1995). Nas regiões iniciais do interior das florestas, após a borda, são observadas alterações nas condições bióticas e abióticas, as quais podem promover variações na diversidade e composição das espécies (Machado et al., 2017).

A fragmentação do habitat é um dos principais fatores que afetam negativamente a biodiversidade em regiões tropicais, pois modifica a estrutura e a composição da paisagem, comprometendo a conectividade entre os ecossistemas e, consequentemente, os processos ecológicos que sustentam a vida (Haddad et al., 2015). O desmatamento pode causar distúrbios na paisagem podendo levar a perdas significativas de biodiversidade, indicando que os efeitos de borda são um componente da perturbação da paisagem, que surge do desmatamento (Barlow et al., 2016).

Os efeitos de borda provocam mudanças significativas nas condições bióticas e abióticas nessas zonas de contato, influenciando o microclima, a vegetação e a fauna local (Laurance et al., 2002, 2011). Os efeitos de borda não são uniformes, eles podem variar com base na proximidade da borda e nas condições ambientais locais, como eventos climáticos (Laurance et al., 2007). Algumas espécies diminuem, enquanto outras se tornam mais abundantes, indicando uma mudança na dinâmica da comunidade (Laurance et al., 2002).

Os efeitos de borda podem levar à homogeneização das comunidades, favorecendo as espécies generalistas e reduzindo a diversidade das espécies do interior (Hurst et al., 2013). As bordas geralmente apresentam uma maior abundância de espécies generalistas em comparação com os interiores da floresta, o que pode levar a mudanças na composição da comunidade (Gasperini et al., 2022).

Os besouros rola-bosta, pertencentes à subfamília Scarabaeinae (Coleoptera: Scarabaeidae), conhecidos por suas importantes funções ecológicas nos ecossistemas, na decomposição da matéria orgânica, ciclagem de nutrientes, dispersão secundária de sementes e entre outras funções. (Nichols et al. 2008; Andresen & Urrea-Galeano, 2022; deCastro-Arrazola et al., 2023; Bang et al. 2005; Andresen, et al. 2002). Os fenômenos ambientais influenciam significativamente a estrutura da composição, riqueza e abundância de besouros Scarabaeinae e as funções ecológicas das comunidades (Nichols et al., 2008). A fragmentação do habitat parte dos fenômenos ambientais produz mudanças na qualidade do habitat de várias espécies, incluindo besouros de esterco (Filgueiras et al., 2011).

Nas regiões de borda, há frequentemente uma mistura de espécies típicas da floresta e de ambientes abertos, o que pode elevar a riqueza local, mas também alterar a estrutura funcional das comunidades (Ewers & Didham, 2008; Bitencourt et al., 2020; Costa et al. 2013).

A comunidade de besouros rola-bosta é afetada pelos fragmentos florestais tanto a sua composição quanto a estrutura funcional (Nichols et al., 2007). Estudos indicam que o uso intensivo da terra compromete diversas funções ecológicas desempenhadas pelos besouros rola-bosta, como remoções de esterco, escavação do solo e dispersão de sementes, indicando que à medida que os habitats se tornam mais perturbados, os papéis ecológicos dos besouros de esterco diminuem (Braga et al., 2013).

Os besouros rola-bosta são divididos em grupos funcionais dependendo das estratégias de nidificação e comportamento: os roladores (telecoprideos) que transportam o recurso para nidificação, os escavadores (paracoprídeos) enterram o recurso diretamente abaixo e os moradores (endecoprídeos) que utilizam o recurso no local (Halffter; Edmonds, 1982). As mudanças na paisagem, como efeitos de borda e conversão de habitat, impactam negativamente a abundância e a riqueza das comunidades, indicando que diferentes guildas de escaravelhos, têm diferentes abundâncias e distribuições, especialmente em certos habitats (Martello et al., 2016).

Estudo destacam também que não só há uma diminuição na riqueza de espécies, mas também um declínio na abundância e mudanças na composição das espécies, que são influenciadas pelo grau de transformação do habitat (Barragán et al., 2011). As comunidades de escaravelhos em áreas de matriz regenerada passaram a assemelhar-se mais às comunidades próximas às bordas florestais do que às de áreas degradadas (Barnes et al., 2014).

As assembleias de besouros rola-bosta em ambientes amazônicos demonstraram respostas significativas em termos de riqueza de espécies, abundância e tamanho corporal, evidenciando que a perda de cobertura florestal constitui o principal fator da paisagem responsável por impactos negativos (Mesquita et al., 2025). A intensidade dos efeitos de borda é influenciada pelo grau de fragmentação da paisagem, pelas características da matriz adjacente e pelo histórico de uso do solo (Ewers & Didham, 2006; Harper et al., 2005; Laurance et al., 2011).

A Amazônia é uma das regiões mais biodiversa do planeta (Malhi et al., 2008), entretanto, esse bioma tem sido severamente impactado pelas ações antrópicas, especialmente pelo avanço do desmatamento (Fearnside, 2009). O desmatamento na Amazônia brasileira destrói significativamente os serviços ambientais vitais (Fearnside, 2017). As principais rodovias são reconhecidas como principais causadoras do desmatamento, sendo que seu desenvolvimento por meio de áreas desmatadas pode fragmentar os ecossistemas, interrompendo os habitats da vida selvagem e levando à perda de biodiversidade (Barber et al., 2014). As chamadas bordas florestais ocorrem nas interfaces entre áreas naturais e zonas perturbadas, como estradas, pastagens ou clareiras, e são conhecidas por promover alterações microambientais profundas, incluindo mudanças na temperatura, umidade, estrutura da vegetação e na disponibilidade de recursos bióticos (Harper et al., 2005; Ewers & Didham, 2006). Esses efeitos, denominados efeitos de borda, podem afetar negativamente diversas comunidades biológicas, especialmente aquelas compostas por espécies sensíveis à alteração do habitat, como os besouros rola-bosta (Scarabaeinae) (Nichols et al., 2007).

São considerados bioindicadores eficientes de qualidade ambiental, uma vez que suas comunidades respondem rapidamente à alteração de habitat (Gardner et al., 2008; Nichols et al., 2007). Embora variáveis locais, como a composição do solo, o nível do lençol freático (Salomão et al., 2022), também possam influenciar a distribuição e abundância desses insetos, há evidências de que os efeitos de borda podem exercer uma influência mais determinante sobre as assembleias de besouros rola-bosta.

Nesse contexto, torna-se relevante investigar se a proximidade da borda afeta mais fortemente as assembleias dos besouros rola-bosta do que fatores ambientais locais ao longo da rodovia da BR-319.

OBJETIVOS

O presente estudo teve como objetivo geral investigar e analisar como a distância em relação às áreas desmatadas e variáveis ambientais locais (profundidade do lençol freático e granulometria do solo) influenciam a composição e a estrutura funcional das assembleias de besouros rola-bosta (Scarabaeinae) ao longo da rodovia BR-319, na Amazônia Central. Como Objetivos específicos buscou-se (i) Avaliar se a composição e a estrutura funcional das comunidades de besouros rola-bosta variam em função da distância até áreas desmatadas; (ii) Analisar os padrões de distribuição e abundância das diferentes guildas funcionais (habitantes, escavadores e roladores) de besouros rola-bosta; (iii) Identificar a distância a partir da qual ocorrem mudanças na composição de espécies em resposta a distancia do desmatamento.

Capitulo 1

FABA, A. S.; ROSA, C.A.; MAGNUSSON, W. E.; TAVARES, A. L.; QUERIDO, L. C.; SCHIETTI, J; MAIA, L. P.; SANTORELLI JUNIOR, S. High variability in dung-beetle responses to forest edges, within and between functional groups.

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High variability in dung-beetle responses to forest edges, within and between functional groups.

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Abstract

Edge effects resulting from forest fragmentation cause changes in biotic and abiotic conditions in transition zones between forested and deforested areas, potentially altering the microclimate, vegetation structure, and ecological processes. These alterations directly influence species composition and abundance, affecting the ecological dynamics of forest fragments and contributing to biodiversity loss in tropical ecosystems. This study aimed to investigate how the distance from deforested areas and local environmental variables, such as groundwater level and soil texture, influence species composition and the functional structure of dung beetle (Scarabaeinae) communities along the BR-319 highway in Central Amazonia. Multivariate models based on presence–absence data, applied to all species and functional groups, indicated that distance to deforested areas was the strongest predictor of species composition. Some species were positively associated with forest edges, while others exhibited the opposite trend. Similar patterns were observed when analyzing each functional group separately and when using species abundance data. The distance at which assemblage composition was affected was also evaluated, revealing a significant breakpoint at 1.4 km from the forest edge, indicating a sharp shift in species composition near deforested zones. Although local environmental variables may be relevant in some contexts, they showed secondary influence in this study. These results highlight the dominant role of edge effects in shaping biodiversity patterns in deforested tropical forests. Species responses to edge effects were highly variable, ranging from positive to negative and neutral. Understanding this key driver of species turnover is essential for predicting biodiversity responses to land-use change.

Keywords: dung beetles, functional groups; edge effects, environmental gradients, Amazon rainforest

1- Introduction

Transition zones between adjacent ecosystems with distinct vegetation structure or land-use types can occur naturally or be human-induced, resulting from habitat loss and fragmentation (Harper et al., 2005; Machado et al., 2017; Barlow et al., 2016). Edge effects refer to the biotic and abiotic changes that occur within these transition zones, particularly those associated with anthropogenic edges. These effects include alterations in microclimate, vegetation structure, and ecological processes, which can influence species composition and abundance in adjacent habitats (Laurance et al., 2002; 2011).

The intensity and direction of edge effects vary spatially and can significantly shape ecological dynamics within forest fragments, potentially contributing to biodiversity loss in tropical regions (Haddad et al., 2015; Laurance et al., 2007). Edge effects tend to reduce interior forest habitats for specialist species while promoting the proliferation of generalist species in disturbed habitats, such as forest edges (Hust et al., 2013), ultimately leading to changes in assemblage composition (Gasperini et al., 2022). Importantly, detecting edge effects depends on measuring changes in local environmental conditions. However, the spatial extent and magnitude of these changes vary with habitat type and context, and patterns attributed to edge effects can overlap with natural environmental gradients, making it difficult to disentangle the influence of distance to edge from other unmeasured local variables (Ries et al., 2004; Ewers & Didham, 2006). Therefore, assessing edge effects requires considering the scale at which spatial and local variables operate, rather than treating them as independent or mutually exclusive.

Dung beetles (Scarabaeinae) are particularly sensitive to both natural environmental gradients and anthropogenic edge effects (e.g., Salomão et al., 2023; Nichols et al., 2007). Their responses have been shown to vary according to the beetles´ functional traits (Rivera et al., 2021), and the ecological functions they provide, such as dung removal, soil aeration, and seed dispersal, are increasingly impaired as habitats degrade (Braga et al., 2013). Moreover, several studies highlight the role of local environmental variables, such as soil texture (e.g. silt and clay content) and groundwater level, in shaping dung beetle assemblages (Salomão et al., 2023, Silva et al., 2015). Thus, understanding how dung beetles respond to edge effects requires disentangling these responses from those driven by natural habitat heterogeneity. This is essential to accurately assess the impacts of habitat loss on species composition.

Here, we define edge effects on dung beetles as changes in species composition associated with proximity to forest edges, indicating a breakdown in assemblage structure compared to interior forest conditions. We aimed to identify the point at which composition diverges from interior conditions in Amazonian forest, while accounting for local environmental gradients known to influence these patterns.

To answer this question, we sampled dung beetles in forests along the BR-319 highway, a major infrastructure that contributes to ongoing deforestation in the Amazon (Barber et al., 2014). This highway and its associated agricultural activities lead to habitat loss and create artificial edges that may directly and indirectly impact biodiversity. Dung beetles are well-studied organisms because they frequently are used as indicators of environmental change (Nichols et al., 2007), due to the key ecological functions they perform (Nichols et al., 2008). However, in the Amazon, studies that simultaneously evaluate the effects of forest edges and the influence of local environmental variables on dung beetle communities remain scarce. Given the complex environmental heterogeneity of tropical forests and the multiple pathways through which habitat loss and fragmentation can affect biodiversity, it is essential to assess these factors jointly to better understand their complementary roles in shaping species assemblages.

Based on previous studies, we predicted that members of the functional group dwellers would be most sensitive to edge effects, and that species within the tunneller and roller functional groups would be more adaptable to the environmental changes related to distance from deforested areas.

2- Material & Methods

2.1- Study area

Our study was conducted along the western extreme of the BR-319 highway, located in the Purus-Madeira interfluve in the central Brazilian Amazon (Figure 1A). The region is characterized by a hot and humid equatorial climate, with a mean annual temperature of approximately 27 °C and consistently high relative humidity (RADAMBRASIL, 1978). Annual precipitation ranges from about 2,800 mm in the north-east to 2,100 mm in the south-west of the interfluve, reflecting climatic patterns typical of humid tropical forests (Alvares et al., 2013; Fick & Hijmans, 2017).

The vegetation in the region is highly diverse, encompassing a variety of forest physiognomies. These include Lowland Ombrophilous Forests (both dense and open types) as well as areas of regenerating secondary forests that occur on terrain not flooded by major rivers

(RADAMBRASIL, 1978). Toward the southern portion of the interfluve, the landscape gradually transitions into more open forest types, with an increasing dominance of palms (BRASIL, 1974).

The region features altitudinal variation ranging from 30 to 80 meters above sea level (Sombroek, 2000), accompanied by differences in groundwater depth, basal area of forest trees, and soil granulometry (Souza et al., 2020; Schietti et al., 2016; Ferreira et al., 2018). These environmental gradients are important drivers of biodiversity patterns and may influence species responses to habitat disturbance (Peixoto et. al., 2019).

2.2- Sampling design

We conducted our sampling in 30 plots distributed across four RAPELD modules along the BR-319 highway (Figure 1B–E). Each module consists of two 5-km trails connected by 1-km trails on the extremities. Each 5-km trail contains five sampling plots established along contour lines, spaced 1 km apart from 500 m to 4500 m along the trail (see Figure 1B-E), with each plot measuring 250 m in length (Magnusson et al., 2005).

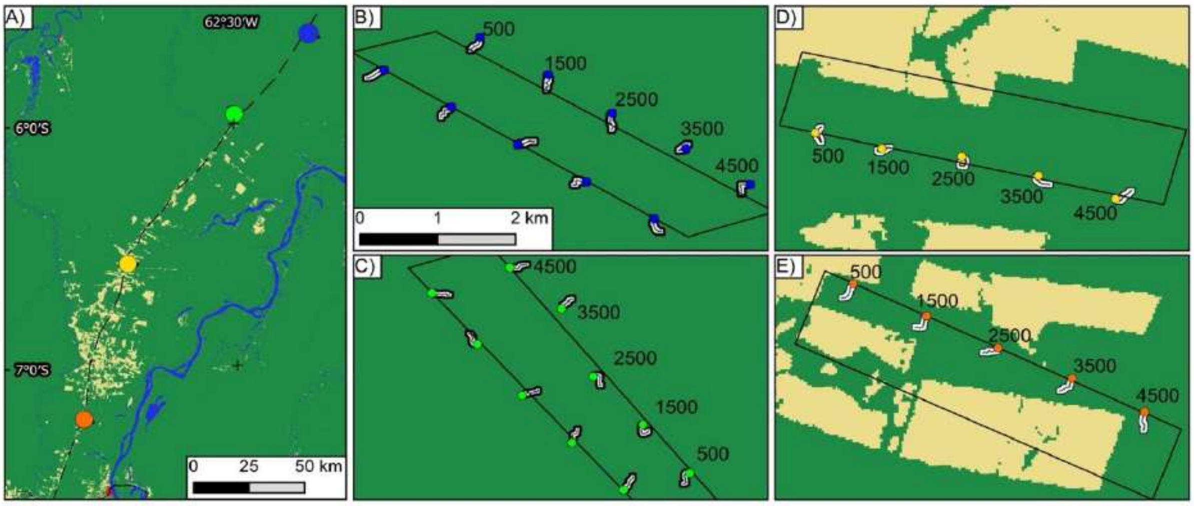

Figure 1. Sampling locations along the south-western portion of the BR-319 highway. Panel A shows the distribution of RAPELD modules along the highway, with each color representing a different module. Panels B–E provide detailed views of the trails and sampling plots within each module. In Panels D and E, deforested areas are highlighted in yellow. Deforested areas are about 2 km distant from the areas shown in panels B and C. Sampling sites (colored dots in panels B to E) are spaced 1 km apart. The black line in panel A represents the BR-319 highway; while in panels B to E, it represents the 5 km trail connecting the plots.

2.3- Dung-Beetle Sampling

We sampled dung beetles during November and December 2023. In each of the 30 plots, we installed six pitfall traps at 50 m intervals – starting from 0m to 250m along the center line of the plot. Traps were buried flush with the ground and partially filled with a solution of water, detergent, and salt. We used approximately 20 g of fresh human feces as bait in each trap. Traps remained in the field for 48 hours, after which we collected the invertebrates and preserved them in 70% ethanol.

For species identification, we sorted beetles into morphospecies after drying at 42 °C for 48 hours. Species were identifed at the Scarabaeidology Laboratory of the Federal University of Mato Grosso (UFMT), using taxonomic keys (Vaz-De-Mello, 2011; Carvalho et al., 2024), with final confirmation by Dr. Fernando Zagury Vaz-de-Mello, a specialist in the group. We classified species into three functional guilds based on their resource removal strategies: rollers, tunnelers, and dwellers (Halffter & Edmonds, 1982).

2.4- Environmental Variables

To represent soil-water availability, we used groundwater-level data obtained from piezometers installed according to PPBio protocols (https://ppbio.inpa.gov.br/manuais, Freitas & Schietti, 2015). Each piezometer consisted of a 6 cm diameter, 7.5-m long PVC tube, installed vertically to about 7 m depth. The lower end was perforated and covered with fine mesh to allow water entry while preventing sediment blockage; the upper end extended 0.5 m above the surface and was sealed with a PVC cap. We obtained measurements taken manually in 2011, 2012, and 2013 from the PPBio repository (https://ppbiodata.inpa.gov.br/metacatui/). For each sampling site, we calculated the mean of eight measurements, which we used as a proxy for local groundwater level.

Soil samples were collected following PPBio protocols (https://ppbio.inpa.gov.br/manuais, Moulatlet & Emilio, 2011). In each plot, samples were taken using a Dutch auger at six points along the 250 m transect (0, 50, 100, 150, 200, and 250 m). For our analyses, we used only the uppermost soil layer (0–10 cm depth). Soil texture analysis (silt, sand and clay contents) followed the methods of Donagema et al. (2011), and we used the data from the public PPBio repository (https://ppbiodata.inpa.gov.br/metacatui/) for the same sampling points.

To calculate the distance from plots in the forest to the nearest deforested area, we used land-use and land-cover classification data from the MapBiomas project (2023). We imported MapBiomas classes into QGIS, and identified anthropogenic areas based on class 15 (pasture), commonly associated with deforestation in the region. We calculated the shortest distance between ten subplots within each 250-plot and the nearest deforested area. We used the average distance per plot as a proxy for distance from the forest edge.

2.5- Data analysis

To describe the distance from the forest edge at which dung-beetle species composition shifts, we used Non-metric Multidimensional Scaling (NMDS) ordinations, which captures the major variation in community composition, for both presence-absence and abundance data. We then used the NMDS axes as the response variables in a segmented linear model to identify the breakpoint distance from the edge at which dung beetle assemblage composition changes. Only distance to the deforested area will be included in this analysis, as it was the strongest predictor of dung-beetle assemblage composition in the MVAbund models.

To assess how distance from forest edge and local environmental variables influence the structure of dung-beetle assemblages, we employed two complementary modeling approaches.

First, we fitted multivariate models using presence-absence data for dung-beetle species, assuming a binomial response distribution. We applied the "cloglog" link function to relate predictor variables (distance to deforested areas, soil clay and silt contents, and groundwater level) to species occurrence. Second, we applied the same modeling framework to species abundance data, assuming a negative binomial distribution and using the "log" link function.

To increase model robustness, we excluded species that occurred in fewer than four sampling plots. Additionally, we included "module" as a fixed factor in all models to account for spatial autocorrelation. This was necessary because MVABUND does not support random effects. Summary statistics of the community data, including species richness, total abundance, and distribution patterns across plots are provided in Table S1 (Supplementary Material).

We carried out all analyses in R version 4.4.2 (R Core Team, 2024) using the packages mvabund (version 4.2.1, Wang et al., 2012), vegan (Version 2.6-4, Oksanen et al., 2020) and segmented (Version 2.1-4, Muggeo, 2008).

3- Results

Environmental conditions varied substantially across the study area. Groundwater depth ranged from 5.13 m to 7.11 m. Topsoil (0–10 cm) silt content ranged from 22.79% to 69.85%, while clay content varied between 9.75% and 27.75%, reflecting pronounced differences in soil texture. The distance from forest plots to the nearest deforested area also varied widely—from approximately 157 m to over 6,100 m—capturing a marked edge-to-interior gradient across the sampling sites (see Supplementary Material, Table S2).

Dung-beetle sampling yielded 21,246 individuals distributed across 66 species and three main functional guilds. The assemblages were numerically dominated by Tunnelers (paracoprid) species, particularly Ateuchus murrayi (2,642 individuals) and Ateuchus substriatus (770 individuals), both of which were present in nearly all plots. Other abundant species included Onthophagus aff. acuminatus (N = 1,893), Onthophagus aff. osculatii (N = 1,588), and Onthophagus aff. rubrescens (N = 1,400), which together contributed substantially to total abundance. Paracoprids accounted for the majority of records (57%), while rollers 26% (telecoprids) and dwellers 17% (endocoprids) were less abundant in terms of total number of individuals and species richness (see Supplementary Table S1).

The segmented linear model, used to assess the distance from the forest edge at which dung beetle species composition shifts, revealed a significant compositional breakpoint at 1.4 km from the nearest deforested area (Figure 2). This indicates that dung-beetle assemblages experience a marked shift in species composition at this distance of forest edge, with changes becoming considerably less further into the forest, but the decrease continuing up to the furthest distance we measured (~6 km). A similar pattern was observed when using species abundance data (Figure S1), reinforcing the existence of a strong edge-interior gradient in dung beetle assemblage structure.

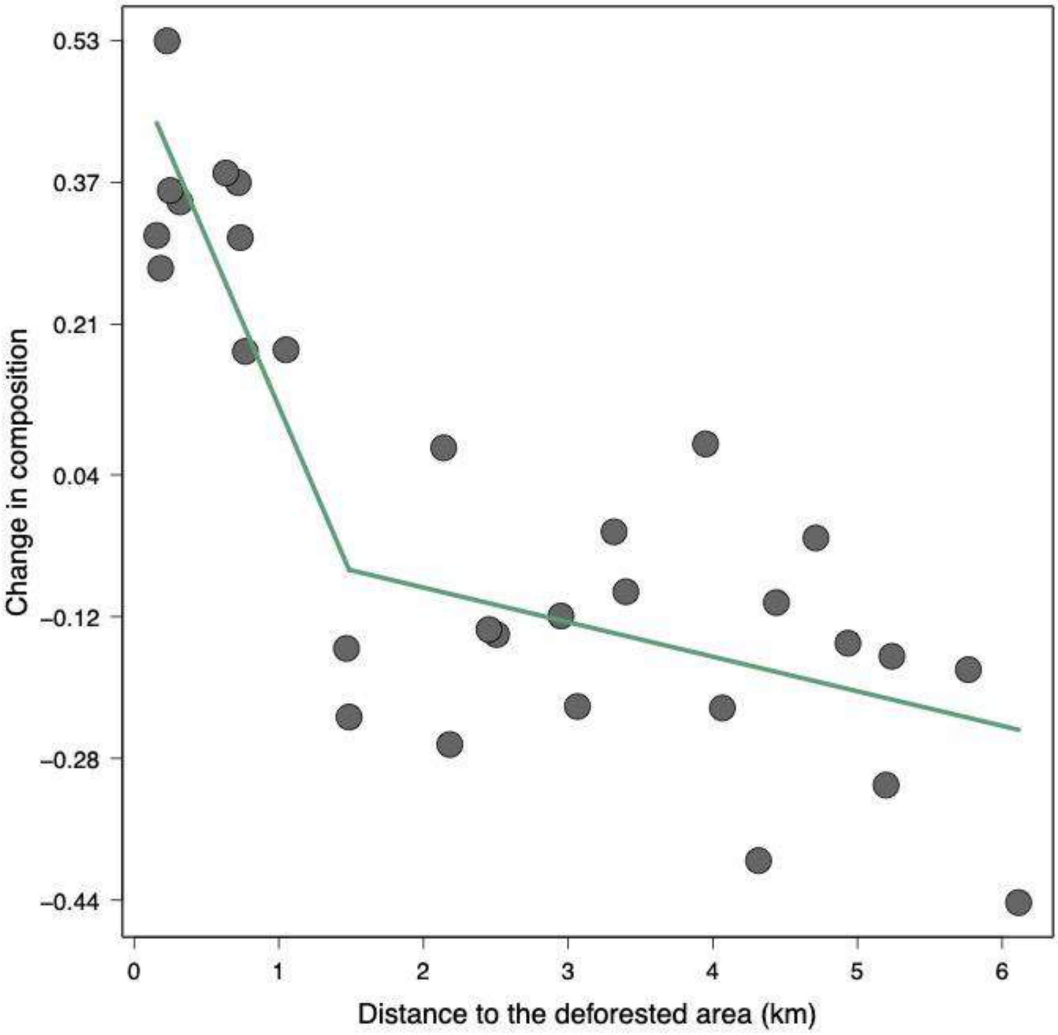

Figure 2. Change in dung beetle composition based on presence-absence data along the gradient from the deforested edge. The green line shows the segmented linear trend, and the breakpoint at 1.4 km indicates a marked shift in assemblage composition at this distance.

The multivariate models fitted using presence-absence and abundance data for dung-beetle species, including all species and functional groups (dwellers, rollers and tunnellers), indicated that distance to deforested area was the strongest predictor of species composition (Table 1). Some species showed a positive association with forest edges, while others exhibited the opposite trend, with decreased frequency of occurrence and abundance (Figures 3-4 and Figures S2-S3). Additionally, several species showed no clear association, exhibiting relatively stable occurrence and abundance across the gradient (Figures 3-4 and Figures S2-S3). The non-significant ($P > 0.05$) predictors for presence-absence and abundance data are shown in Figures S4-S8. We observed similar patterns when analyzing the presence-absence and abundance data for the functional groups individually (note the color patterns in Figures 3-4). In these abundance-based models, clay content also emerged as an important predictor alongside the distance to deforested area (Table 1 and Figure S9).

Table 1. Multivariate models were fitted using presence–absence data of dung beetle species, including all species and functional groups (dwellers, rollers and tunnellers). Bold values indicate statistically significant ($P < 0.05$) results.

Dung beetle	**Predictors**	**Dev.**	**P_{value}**
PRESENCE-ABSENCE DATA			
All species	Clay content	46.9	0.349
	Silt content	47.8	0.429
	Groundwater level	48.6	0.616
	Distance to deforested area	**232.3**	**0.001**
	Module**	328.9	0.002
Tunnelers	Clay content	27.9	0.236
	Silt content	35.4	0.139
	Groundwater level	29.4	0.402
	Distance to deforested area	**81.4**	**0.001**
	Module**	151.0	0.001
Rollers	Clay content	14.7	0.344
	Silt content	4.9	0.957
	Groundwater level	8.0	0.878
	Distance to deforested area	**131.2**	**0.001**
	Module**	100.6	0.001
Dwellers	Clay content	4.2	0.730
	Silt content	7.3	0.495
	Groundwater level	11.15	0.235
	Distance to deforested area	**19.64**	**0.054**
	Module**	77.17	0.001
ABUNDANCE DATA			
All species	**Clay content**	**119.1**	**0.018**

	Silt content	71.0	0.193
	Groundwater level	53.6	0.461
	Distance to deforested area	**259.3**	**0.002**
	Module**	910.8	0.001
Tunnelers	**Clay content**	**79.08**	**0.013**
	Silt content	50.6	0.079
	Groundwater level	35.0	0.363
	Distance to deforested area	**136.1**	**0.001**
	Module**	437.8	0.001
Rollers	Clay content	22.2	0.095
	Silt content	12.3	0.477
	Groundwater level	7.7	0.827
	Distance to deforested area	**104.7**	**0.005**
	Module**	235.3	0.001
Dwellers	Clay content	17.1	0.081
	Silt content	8.0	0.466
	Groundwater level	10.8	0.311
	Distance to deforested area	**18.4**	**0.097**
	Module**	237.6	0.001

**Since the function does not support random effects, ‘module’ was included as a fixed effect to account for potential autocorrelation among sampling sites.

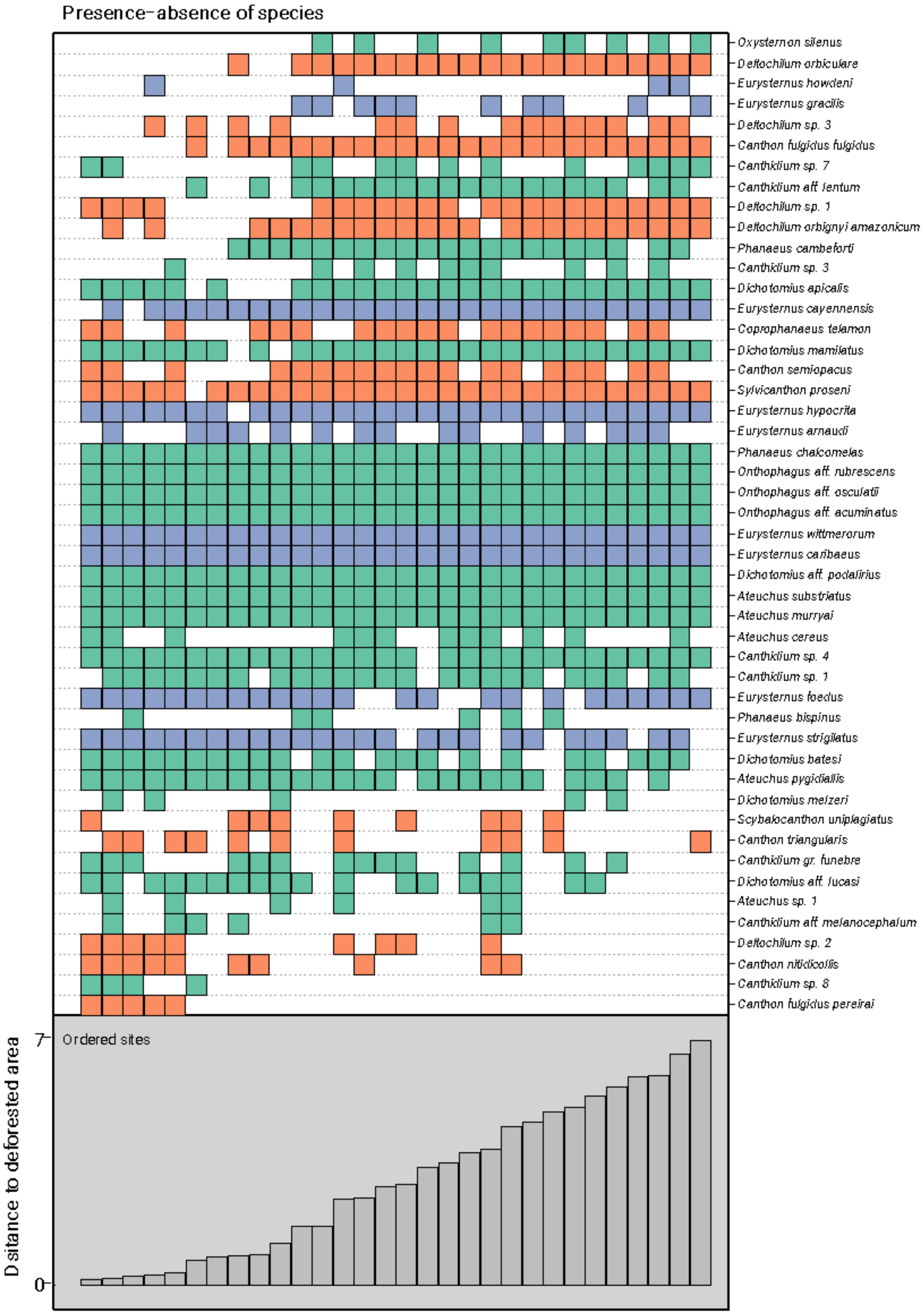

Figure 3. Presence-absence of dung beetle across sites ordered by distance from the deforested area. Each row corresponds to a species, and each column to a sampling site. The colors green, orange and purple represent the functional groups tunnelers, rollers and dwellers, respectively. The bottom panel shows the gradient of distance to the deforested area, scaled in kilometers.

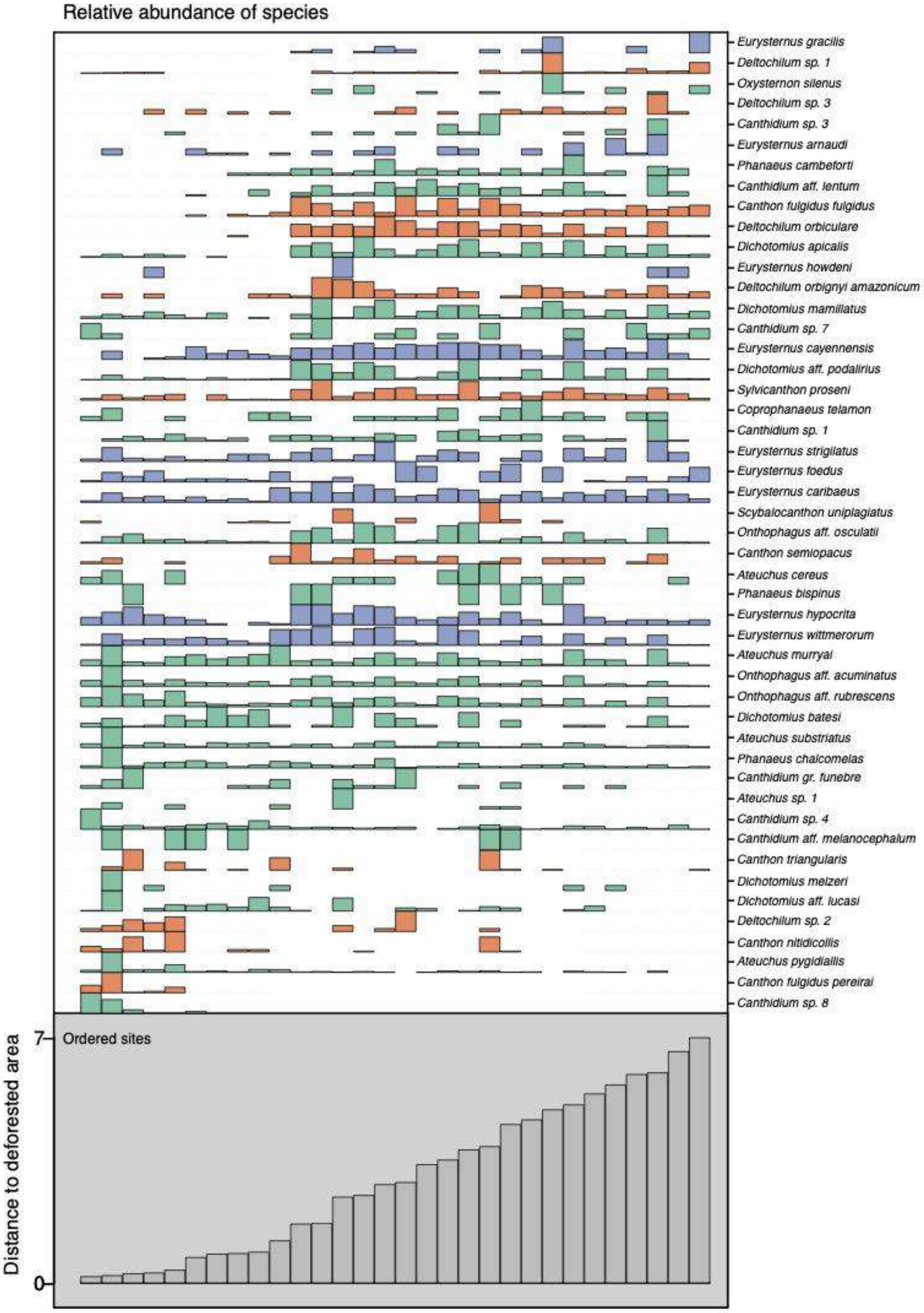

Figure 4. Relative abundance of dung beetles across sites ordered by distance from the deforested area. Each row corresponds to a species, and each column to a sampling site. The colors green, orange and purple represent the functional groups tunnelers, rollers and dwellers, respectively. The bottom panel shows the gradient of distance to the deforested area, scaled in

kilometers. The relative abundance was calculated by dividing each value by the maximum value for that species.

4- Discussion

Our results revealed a strong edge effect extending up to 1,4 km into the forest, indicating a profound restructuring of dung beetle communities near deforested areas. Distance to deforested edges emerged as the strongest predictor of species composition, both in terms of presence-absence and abundance, highlighting the dominant role of spatial processes associated with habitat loss. However, local environmental variables, particularly soil clay content, also influenced assemblage patterns, especially when associated with species abundance, suggesting that edge effects interact with underlying environmental heterogeneity to shape community patterns. Although secondary in explanatory power, these environmental factors likely mediate or amplify edge responses, supporting the idea that edge effects and local gradients are complementary rather than independent forces influencing biodiversity in tropical landscapes that experience habitat loss. This integrated perspective reinforces recent ecological frameworks that advocate for multi-scalar analyses to understand species turnover in human-modified environments (Levin, 2000; Fahrig, 2003).

Species-specific responses to edge effects were highly variable, ranging from positive (increased frequency of occurrence and abundance), to negative (decreased frequency of occurrence and abundance) and neutral (no significant change in frequency or abundance). This variability reflects a reorganization of species assemblages, rather than a uniform loss or gain, which has important implications for predicting ecological outcomes of forest fragmentation. Understanding how these drivers jointly affect species turnover is essential to anticipate biodiversity responses to ongoing land-use change in the Amazon.

The distance at which edge effects strongly influenced dung beetle composition in our study (1.4 km) is considerably larger than what has been reported in most previous studies, which typically detect edge influence within 300–500 m (e.g., Laurance et al., 2002; Ewers & Didham, 2006), and more subtle effects extend to at least 6 km. Few studies have documented such long-distance edge effects (Ewers & Didham, 2008; Costa et al., 2022). The continued variation in species composition beyond 1 km reinforces the need to evaluate edge effects at broader spatial scales, which may have direct applications in conservation planning—especially in defining effective buffer zones and the minimum size of intact forest patches.

Species that responded negatively to edge proximity presumably perceive edge habitats as unsuitable or even physiologically stressful environments (Willmer et al., 2022). These patterns have been reported in many studies and are typically associated with changes in microclimate conditions and resource quality near edges (Filgueiras et al., 2011; Barragán et al., 2011; Murcia, 1995; Didham & Lawton, 1999). These species may be physiologically or behaviorally adapted to microhabitats with high canopy cover, lower temperatures, and reduced light and wind exposure (Nichols et al., 2008; Barretto et al., 2019). Such conditions are disrupted near edges, where increased solar exposure and drier soils reduce resource quality and nesting viability (Didham & Ewers, 2014; Filgueiras et al., 2011). In this context, the edge habitat can be unsuitable or even harmful for species adapted to the more stable and humid microclimates found in forest interiors.

Functional groups responded to edge effects consistently with the overall assemblage. Some species within each group exhibited negative or positive responses, suggesting that abiotic factors may also influence species compositions within functional groups. For example, dweller species - which lay their eggs directly on dung - are thought to be especially sensitive to desiccation and microclimate shifts, making them less tolerant to edge habitats (Halffter & Edmonds, 1982). In forest interiors, moisture retention by the canopy and reduced exposure to direct sunlight keep the dung moist for longer periods, which is thought to favor these species (Horgan et al., 2005). However, we did not detect statistically significant effects of distance from edge for dwellers, and most of the species that occurred consistently at all distances from the edge were dwellers.

Other species, such as tunnellers, require adequate soil moisture, which facilitates excavation and larval development, which may be negatively affected by compacted or dry soils common near disturbed areas (Halffter & Edmonds, 1982). However, despite showing turnover in species composition, some species of tunnellers were more common at edges, and others more abundant in interior plots, indicating that membership in this functional group is not a good predictor of vulnerability to edge effects.

Rollers, which move dung balls across open ground, may suffer greater predation near edges or rely on resources less stable over time, especially when open areas are exposed or frequently disturbed (de Castro-Arrazola et al., 2023; Halffter & Edmonds, 1982). However, like rollers, there were species within this functional group more abundant near edges and others more common in interior sites.

These results indicate that patterns seen in some areas should not be generalized to the whole Amazon biome, and these functional groups do not capture the full range of potential behavioral responses to natural and human-induced environmental changes.

Conversely, some species appeared to be favored by edge conditions, although the mechanism behind these positive responses remain unclear. One possible explanation is the mass effect mechanism (Leboucher et al., 2020), where individuals from populations in adjacent open areas disperse into edge habitats. Some dung beetle species are known to be restricted to open areas (Costa et al., 2013), and their presence in the edge may thus result from migration and passive overflow from nearby suitable environments. In this scenario, edge habitats may act as spillover zones, receiving individuals even if these areas are suboptimal for long-term persistence. Additionally, cattle dung in nearby pastures may create ephemeral but nutrient-rich resource patches, attracting dung beetles to forest edges (Martello et al., 2016). This resource enrichment could enhance beetle activity in edge zones, increasing the detectability of certain species. However, it remains unclear whether these species are establishing viable populations or simply using edge areas temporarily. Furthermore, interactions between edge-favored species and interior species—such as competition—may also shape assemblage composition, and deserve attention in future research.

Despite the strong influence of edge proximity, our models also identified a role for soil clay content, particularly in abundance-based models. As edge conditions, soil texture can affect dung moisture retention, compaction, and nesting success, making it an important environmental filter for dung beetles (Silva et al., 2015; Salomão et al., 2022). The interaction between soil texture and edge-induced microclimatic changes could further shape species-specific nesting success and larval development. On the other hand, silt content and groundwater level had no significant effect, possibly due to the coarser temporal resolution of these datasets or their weaker influence in the specific context of our study area. Still, their inclusion highlights the importance of testing multiple environmental gradients in ecological studies, even when effects are not statistically significant.

In conclusion, our results show that forest edges exert a dominant influence on dung beetle assemblages in the southwestern Amazon in areas that experienced habitat loss, but this effect interacts with local environmental gradients to shape community structure in complex ways. Agricultural expansion along highways like BR-319 continues to deforested Amazonian forests and intensify edge creation. Recognizing the long spatial reach of edge effects is crucial for improving conservation strategies, including the delineation of buffer zones and core areas in protected landscapes. Integrated approaches—combining spatial metrics, species traits, and environmental gradients—are essential to accurately assess biodiversity responses to habitat change, and dung beetles offer a valuable model for such investigations. Future research should expand this framework across different biotic groups and spatial scales, enabling more robust predictions of ecological change in the face of continued forest loss.

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Supplementary Material

Table S1. Summary statistics of the community data. M08 to M11 are the modules (see Material and Methods) where dung beetle species (Scarabaeinae) were captured. “NC” in the collum “Resource removal strategy” means “not classified”. “N-total” refers to the total number of indviduals of each species captured.

Species	Resource removal strategy	Number of individuals				N-total	Number of registered plots
		M08	M09	M10	M11		
Ateuchus cereus (Harold, 1868)	Tunneller	5	9	0	5	19	12
Ateuchus murrayi (Harold, 1868)	Tunneller	400	1.100	664	478	2.642	30
Ateuchus pygidialis (Harold, 1868)	Tunneller	17	51	55	234	357	25
Ateuchus sp. 1	Tunneller	12	0	2	5	19	6
Ateuchus sp. 2	Tunneller	0	1	0	2	3	3
Ateuchus sp. 3	Tunneller	0	1	0	1	2	2
Ateuchus substriatus (Harold, 1868)	Tunneller	80	299	124	267	770	30
Bdelyrus sp. 1	NC	0	1	0	0	1	1
Canthidium aff. *lentum*	Tunneller	55	85	7	0	147	20
Canthidium aff. *melanocephalum*	Tunneller	2	0	2	2	6	6
Canthidium gr. *funebre*	Tunneller	12	5	5	11	33	14
Canthidium sp. 1	Tunneller	30	104	16	21	171	24
Canthidium sp. 2	Tunneller	1	6	0	0	7	3
Canthidium sp. 3	Tunneller	9	16	0	1	26	10
Canthidium sp. 4	Tunneller	168	115	201	261	745	29
Canthidium sp. 5	Tunneller	0	0	2	0	2	2
Canthidium sp. 6	Tunneller	1	0	0	0	1	1

Species	Resource removal strategy	Number of individuals				N-total	Number of registered plots
		M08	M09	M10	M11		
Canthidium sp. 7	Tunneller	11	10	0	4	25	13
Canthidium sp. 8	Tunneller	0	0	1	22	23	4
Canthidium sp. 9	Tunneller	0	0	1	0	1	1
Canthon fulgidus fulgidus Redtenbacher, 1868	Roller	716	675	53	0	1.444	24
Canthon fulgidus pereirai Nunes & Vaz-de-Mello, 2018	Roller	0	0	0	71	71	5
Canthon nitidicollis Lucas, 1859	Roller	20	1	6	58	85	10
Canthon quadrimaculatus Schmidt, 1922	Roller	0	2	0	0	2	2
Canthon semiopacus Harold, 1868	Roller	19	34	4	5	62	19
Canthon sp. 1	Roller	0	0	0	1	1	1
Canthon triangularis (Drury, 1770)	Roller	36	0	21	48	105	11
Coprophanaeus telamon (Erichson, 1847)	Tunneller	10	15	4	5	34	19
Deltochilum orbiculare Lansberge, 1874	Roller	57	115	1	0	173	21
Deltochilum orbignyi amazonicum Bates, 1887	Roller	27	50	4	4	85	23
Deltochilum sp. 1	Roller	164	39	0	9	212	22
Deltochilum sp. 2	Roller	10	1	0	15	26	9
Deltochilum sp. 3	Roller	10	16	4	2	32	15
Dichotomius aff. *lucasi*	Tunneller	50	4	54	48	156	18
Dichotomius aff. *podalirius*	Tunneller	124	799	22	45	990	30

Species	Resource removal strategy	Number of individuals				N-total	Number of registered plots
		M08	M09	M10	M11		
Dichotomius apicalis (Luederwaldt, 1931)	Tunneller	62	243	1	15	321	26
Dichotomius batesi (Harold, 1869)	Tunneller	43	44	60	28	175	22
Dichotomius gandinii Rossini & Vaz-de-Mello, 2020	Tunneller	0	2	0	0	2	2
Dichotomius mamillatus (Felsche, 1901)	Tunneller	81	207	12	31	331	28
Dichotomius melzeri (Luederwaldt, 1922)	Tunneller	0	2	1	5	8	5
Dichotomius nimuendaju Luederwaldt, 1925	Tunneller	0	1	1	0	2	2
Dichotomius robustus (Luederwaldt, 1935)	Tunneller	0	2	0	0	2	2
Dichotomius worontzowi (Pereira, 1942)	Tunneller	0	0	0	1	1	1
Eurysternus arnaudi (Génier, 2009)	Dowller	1	42	6	3	52	15
Eurysternus caribaeus (Herbst, 1789)	Dowller	367	779	157	141	1.444	30
Eurysternus cayennensis Castelnau, 1840	Dowller	284	420	105	35	844	28
Eurysternus foedus Guérin-Méneville, 1844	Dowller	240	4	45	65	354	24
Eurysternus gracilis Génier, 2009	Dowller	31	10	0	0	41	10
Eurysternus hamaticollis Balthasar, 1939	Dowller	0	0	0	1	1	1
Eurysternus howdeni Génier, 2009	Dowller	3	1	0	1	5	4
Eurysternus hypocrita Balthasar, 1939	Dowller	52	104	8	44	208	29
Eurysternus strigilatus Génier, 2009	Dowller	29	154	24	33	240	25

Species	Resource removal strategy	Number of individuals				N-total	Number of registered plots
		M08	M09	M10	M11		
Eurysternus ventricosus Gill, 1990	Dowller	0	0	2	0	2	2
Eurysternus wittmerorum Martinez, 1988	Dowller	37	251	66	54	408	30
Onthophagus aff. *acuminatus*	Tunneller	272	891	201	529	1.893	30
Onthophagus aff. *osculatii*	Tunneller	179	1.146	65	198	1.588	30
Onthophagus aff. *rubrescens*	Tunneller	164	629	118	489	1.400	30
Ontophagus aff. clypeatus	Tunneller	0	1	0	0	1	1
Oxysternon silenus Castelnau, 1840	Tunneller	16	11	0	0	27	9
Phanaeus bispinus Bates, 1868	Tunneller	2	3	0	1	6	6
Phanaeus cambeforti Arnaud, 1982	Tunneller	17	36	3	0	56	21
Phanaeus chalcomelas (Perty, 1830)	Tunneller	22	52	32	49	155	30
Scybalocanthon uniplagiatus (Schmidt, 1922)	Roller	58	0	4	2	64	9
Sylvicanthon mayri Cupello & Vaz-de-Mello, 2018	Roller	0	3	0	0	3	3
Sylvicanthon proseni (Martinez, 1948)	Roller	959	1.741	118	313	3.131	29
Uroxys sp. 1	Tunneller	1	0	1	1	3	3
Total number of individuals by module	All species	4.966	10.333	2.283	3.664	21.246	
	Dowller	1.044	1.765	413	377	3.599	
	Tunneller	1.846	5.890	1.655	2.759	12.150	
	Roller	2.076	2.677	215	528	5.496	

Species	Resource removal strategy	Number of individuals				N-total	Number of registered plots
		M08	M09	M10	M11		
Total number of species by module	All species	48	52	43	48	66	
	Dowller	9	9	8	9	11	
	Tunneller	28	31	26	28	38	
	Roller	11	11	9	11	16	

Table S2: Sampling of environmental data obtained at different collection points between Modules M08-M11, including water table depth, soil composition and distance to the nearest deforestation.

Module	plot_id	Groundwater level	Silt content	Clay content	Distance to deforested area
M08	M08_TN_0500	5.13	44.01	22.00	2505,25691
M08	M08_TN_1500	6.82	48.99	20.50	3398,881737
M08	M08_TN_2500	6.95	50.02	15.50	4315,713506
M08	M08_TN_3500	5.50	60.20	9.75	5197,596965
M08	M08_TN_4500	6.65	62.45	16.50	6113,831122
M08	M08_TS_0500	6.88	43.87	19.25	2139,567556
M08	M08_TS_1500	7.03	57.02	14.25	2950,385905
M08	M08_TS_2500	6.45	67.14	19.00	3949,90557
M08	M08_TS_3500	7.04	49.54	10.75	4712,706199
M08	M08_TS_4500	7.11	68.63	13.75	5766,53096
M09	M09_TN_0500	6.94	57.19	15.50	1467,413002
M09	M09_TN_1500	6.86	54.20	17.00	2181,882178
M09	M09_TN_2500	6.96	64.14	20.00	3063,729564
M09	M09_TN_3500	6.99	51.91	14.25	4066,012816
M09	M09_TN_4500	6.82	31.12	21.75	4934,058498
M09	M09_TS_0500	7.05	67.15	16.00	1485,588814
M09	M09_TS_1500	6.70	47.81	21.25	2452,509249
M09	M09_TS_2500	7.01	55.00	19.00	3317,082144
M09	M09_TS_3500	7.05	36.63	11.50	4439,587233
M09	M09_TS_4500	5.60	51.70	26.00	5237,852464
M10	M10_TS_0500	7.00	39.08	13.50	719,3971324
M10	M10_TS_1500	7.04	46.61	12.50	768,5456658
M10	M10_TS_2500	6.88	50.06	14.00	733,5910373
M10	M10_TS_3500	7.07	45.33	11.75	634,163217
M10	M10_TS_4500	7.06	34.93	22.75	1050,024456
M11	M11_TN_0500	6.92	40.21	12.50	156,6030688
M11	M11_TN_1500	6.56	22.79	27.75	182,892333
M11	M11_TN_2500	6.53	62.46	16.25	316,8703847
M11	M11_TN_3500	6.64	69.85	16.50	227,9215722
M11	M11_TN_4500	6.76	62.35	19.25	249,2239831

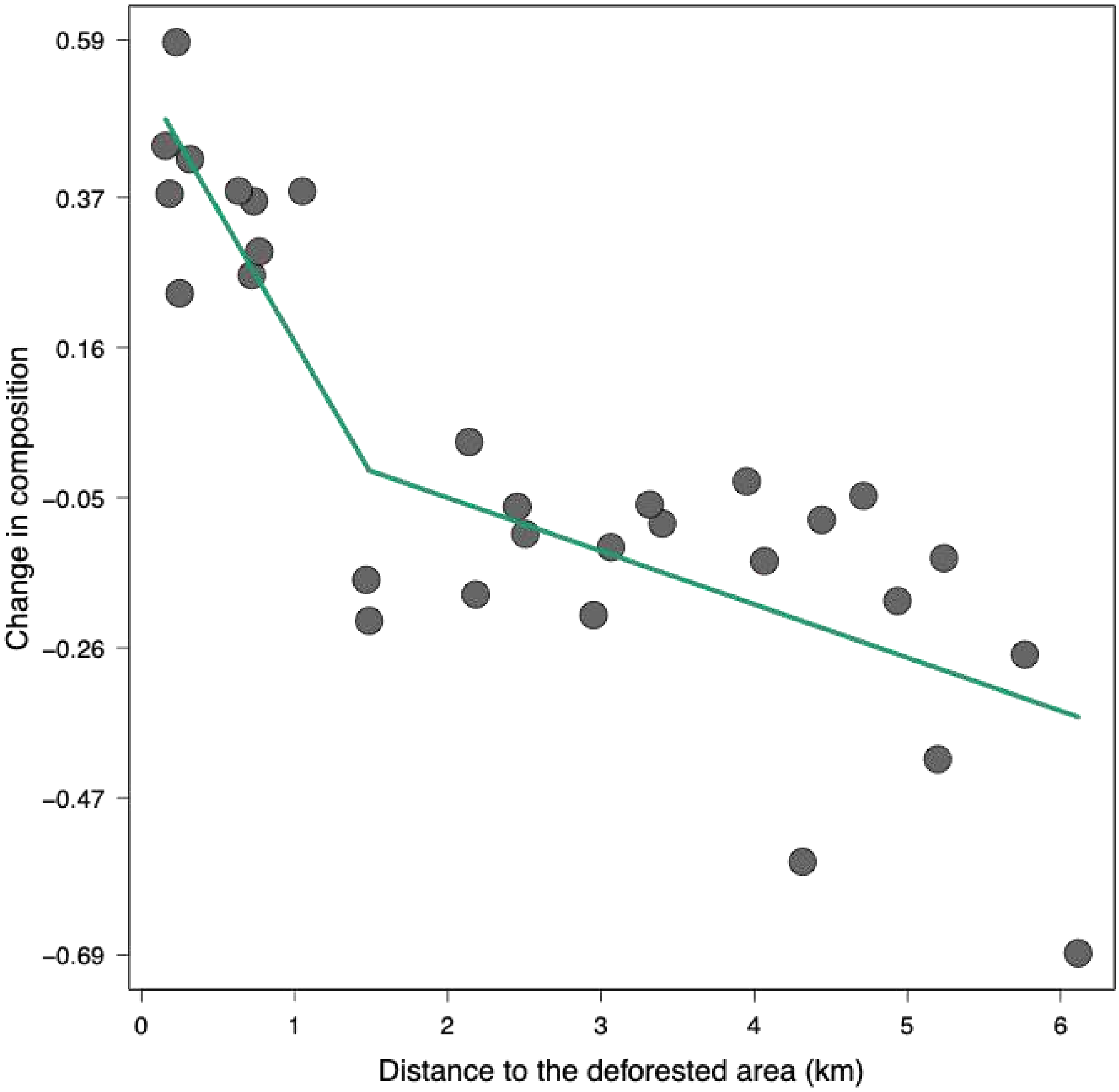

Figure S1 - Change in dung beetle composition based on abundance data along the gradient from the deforested edge. The green line shows the segmented linear trend, and the breakpoint at 1.4 km indicates a marked shift in assemblage composition near the edge.

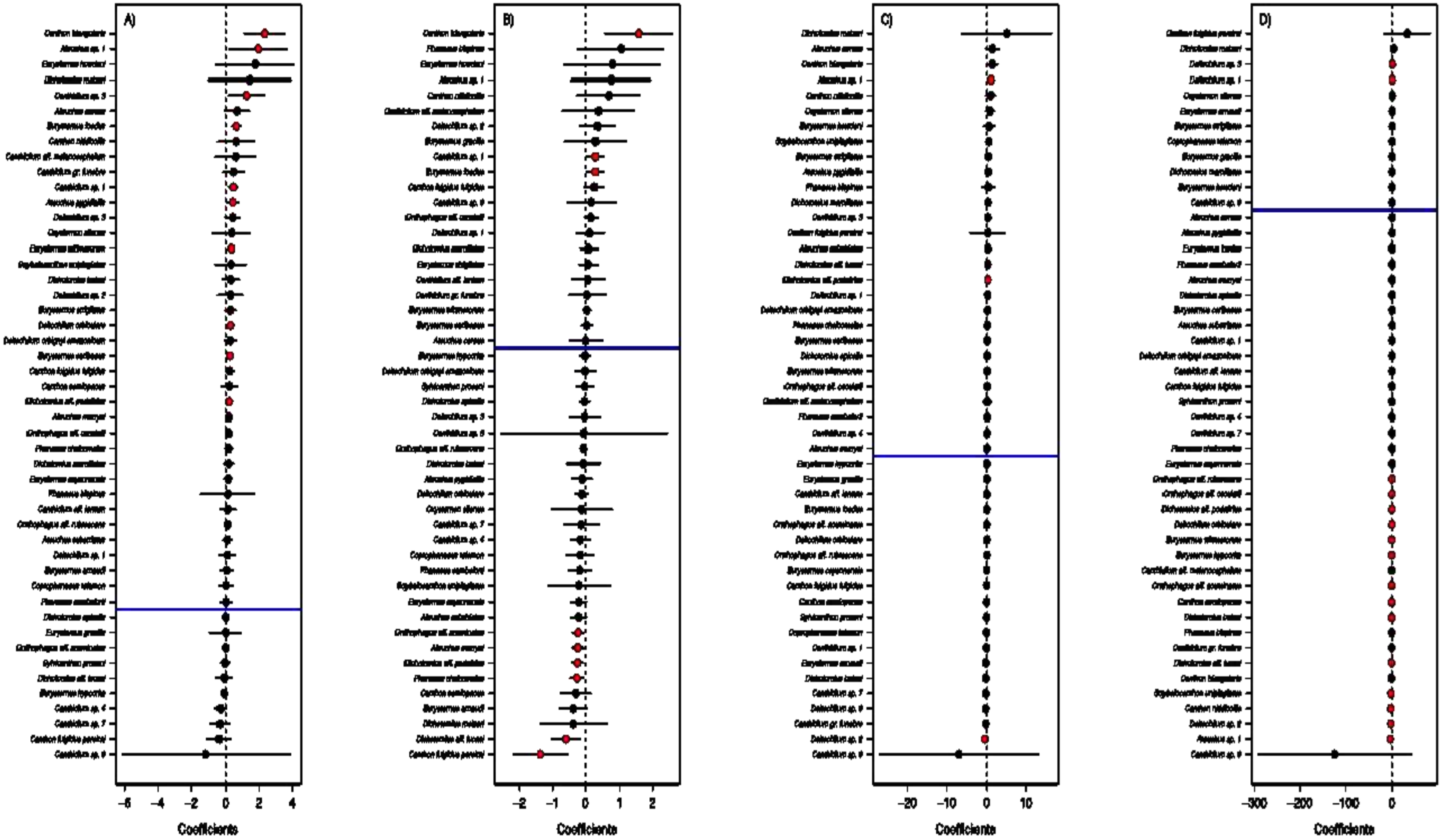

Figure S2 – Coefficients (black dots) and confidence intervals (black horizontal lines) estimated from multivariate models, showing the effect of each predictor on the abundance of dung beetle species. Letters A to D correspond to clay content, silt content, groundwater level, and distance to deforested area, respectively. Red dots indicate statistically significant effects. Blue horizontal lines were added to help interpret the sign of the coefficients: dots below the line indicate negative effects, while those above indicate positive effects.

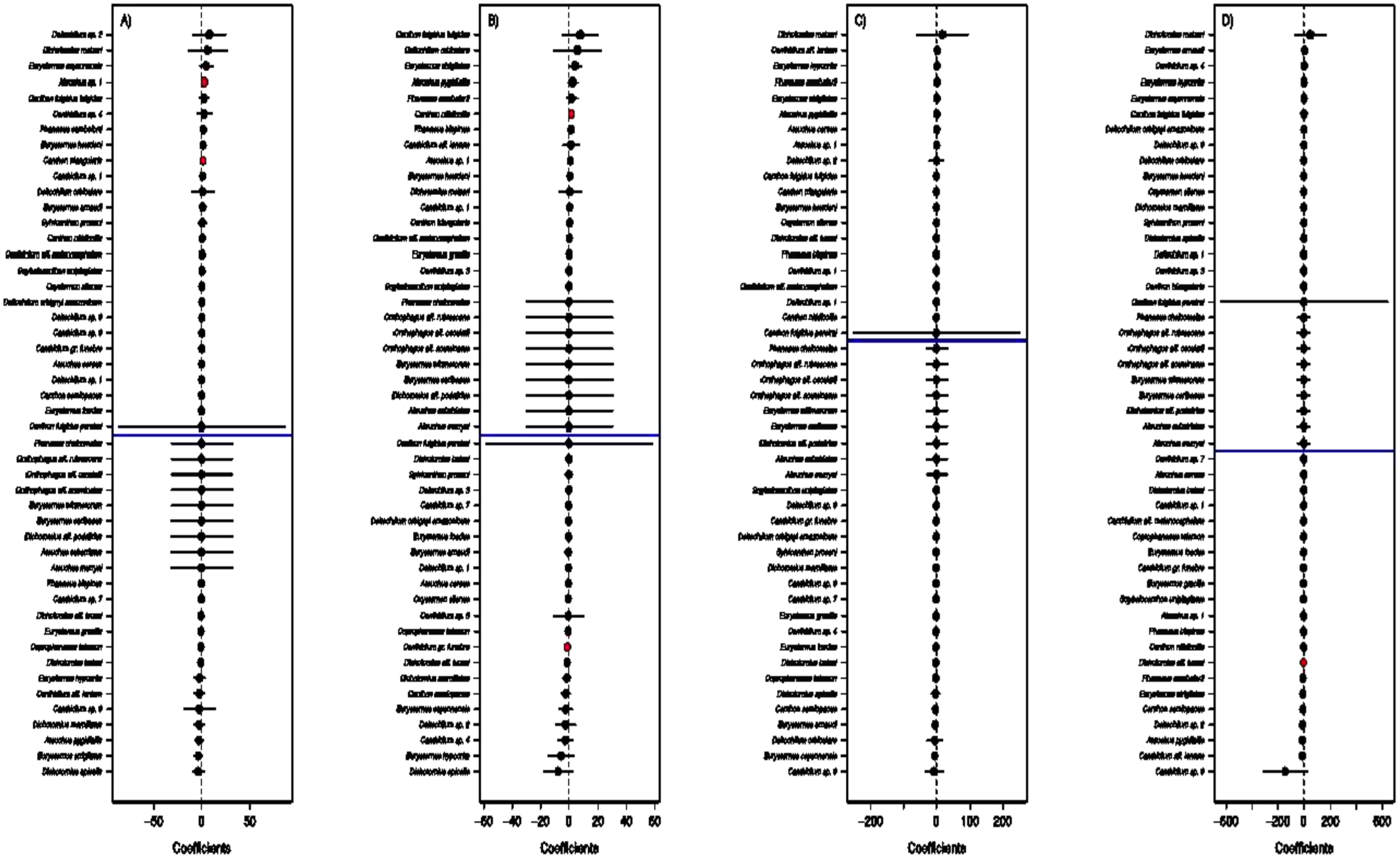

Figure S3 – Coefficients (black dots) and confidence intervals (black horizontal lines) estimated from multivariate models, showing the effect of each predictor on the presence-absence of dung beetle species. Letters A to D correspond to clay content, silt content, groundwater level, and distance to deforested area, respectively. Red dots indicate statistically significant effects. Blue horizontal lines were added to help interpret the sign of the coefficients: dots below the line indicate negative effects, while those above indicate positive effect.

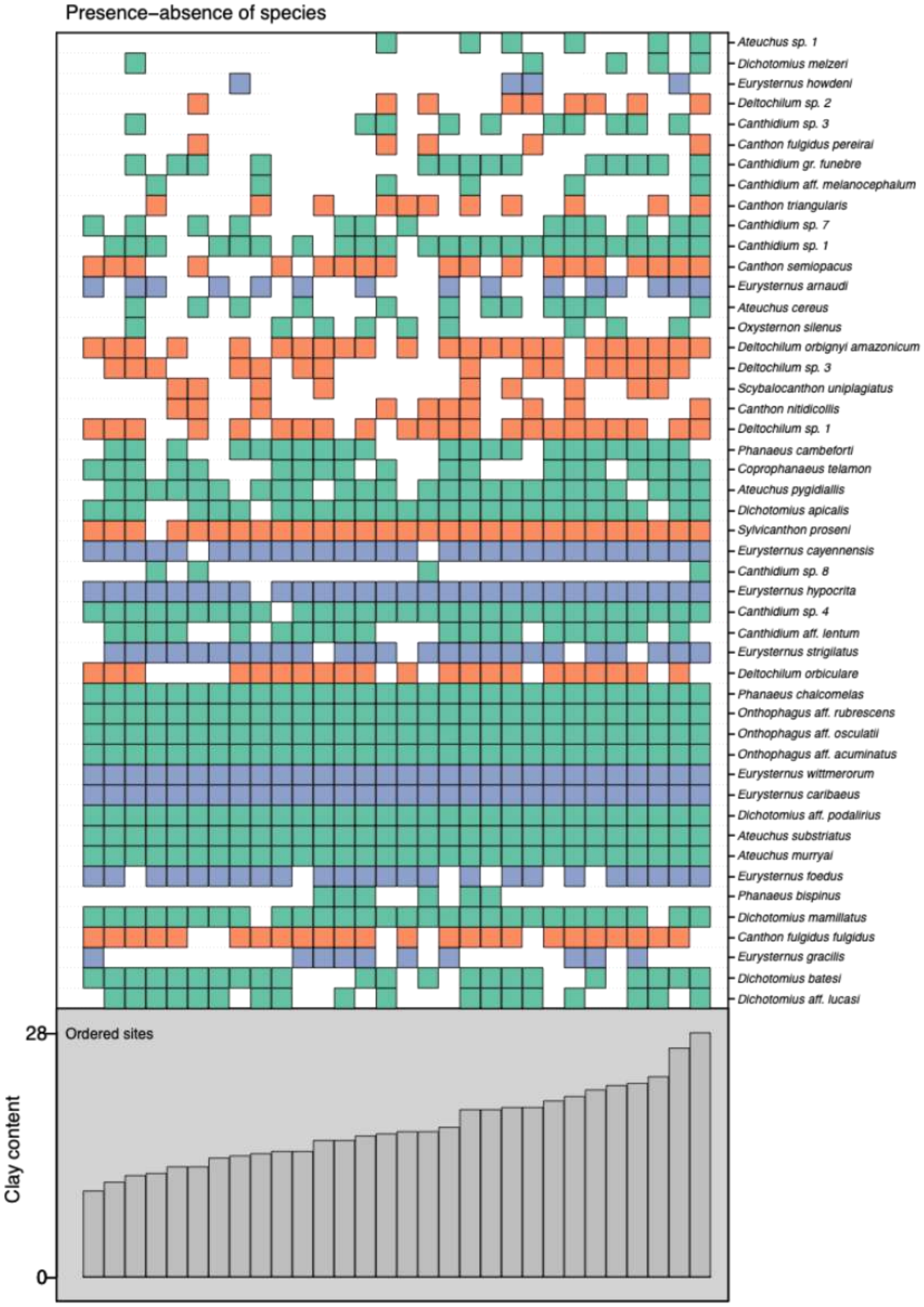

Figure S4 – Presence-absence of dung beetle across sites ordered by clay content. Each row corresponds to a species, and each column to a sampling site. The colors green, orange and purple represent the functional groups tunnelers, rollers and dwellers, respectively. The bottom panel shows the gradient of clay content, scaled in percentage.

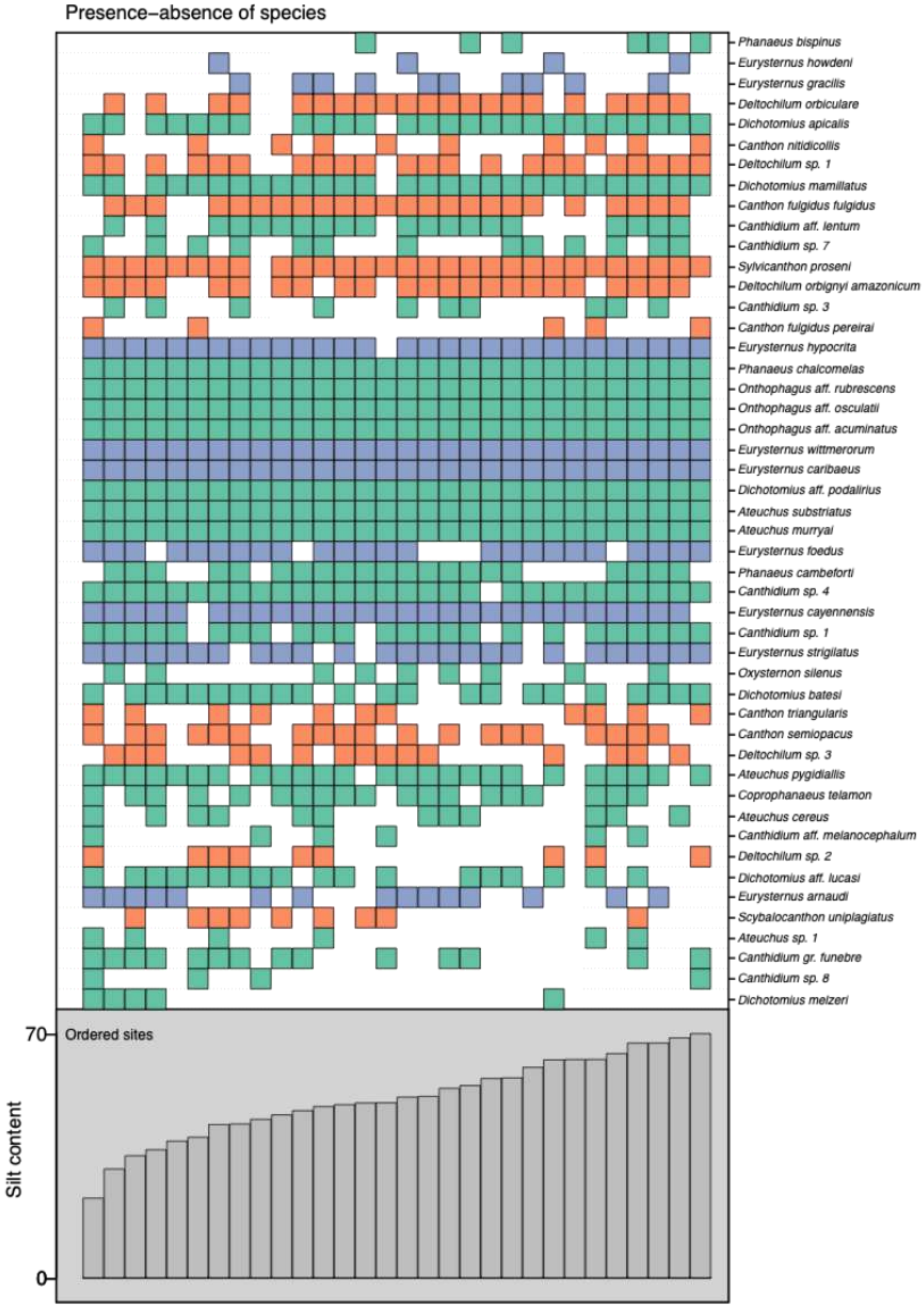

Figure S5 – Presence-absence of dung beetle across sites ordered by silt content. Each row corresponds to a species, and each column to a sampling site. The colors green, orange and purple represent the functional groups tunnelers, rollers and dwellers, respectively. The bottom panel shows the gradient of silt content, scaled in percentage.

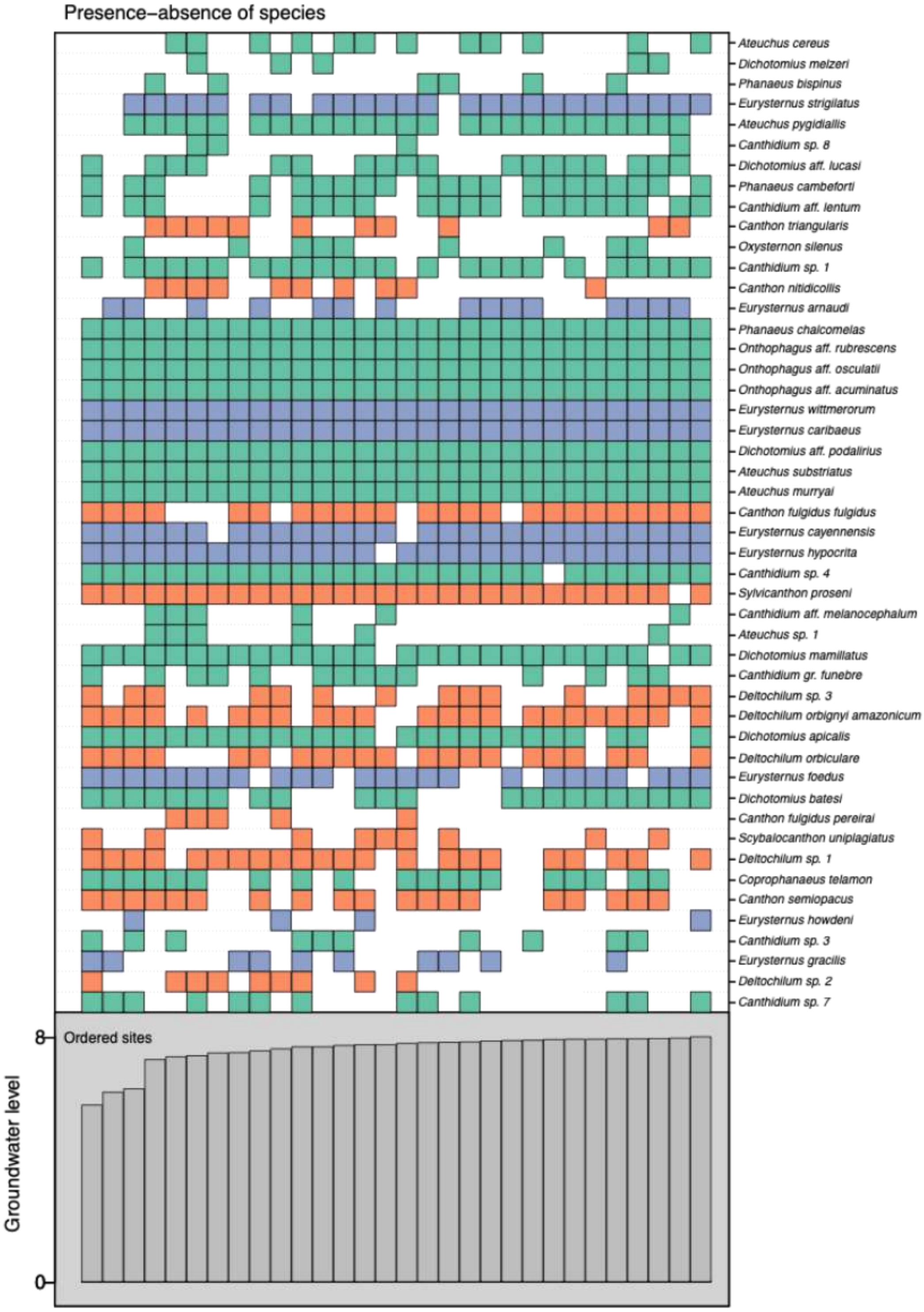

Figure S6 – Presence-absence of dung beetle across sites ordered by groundwater level. Each row corresponds to a species, and each column to a sampling site. The colors green, orange and purple represent the functional groups tunnelers, rollers and dwellers, respectively. The bottom panel shows the gradient of groundwater level, scaled meters.

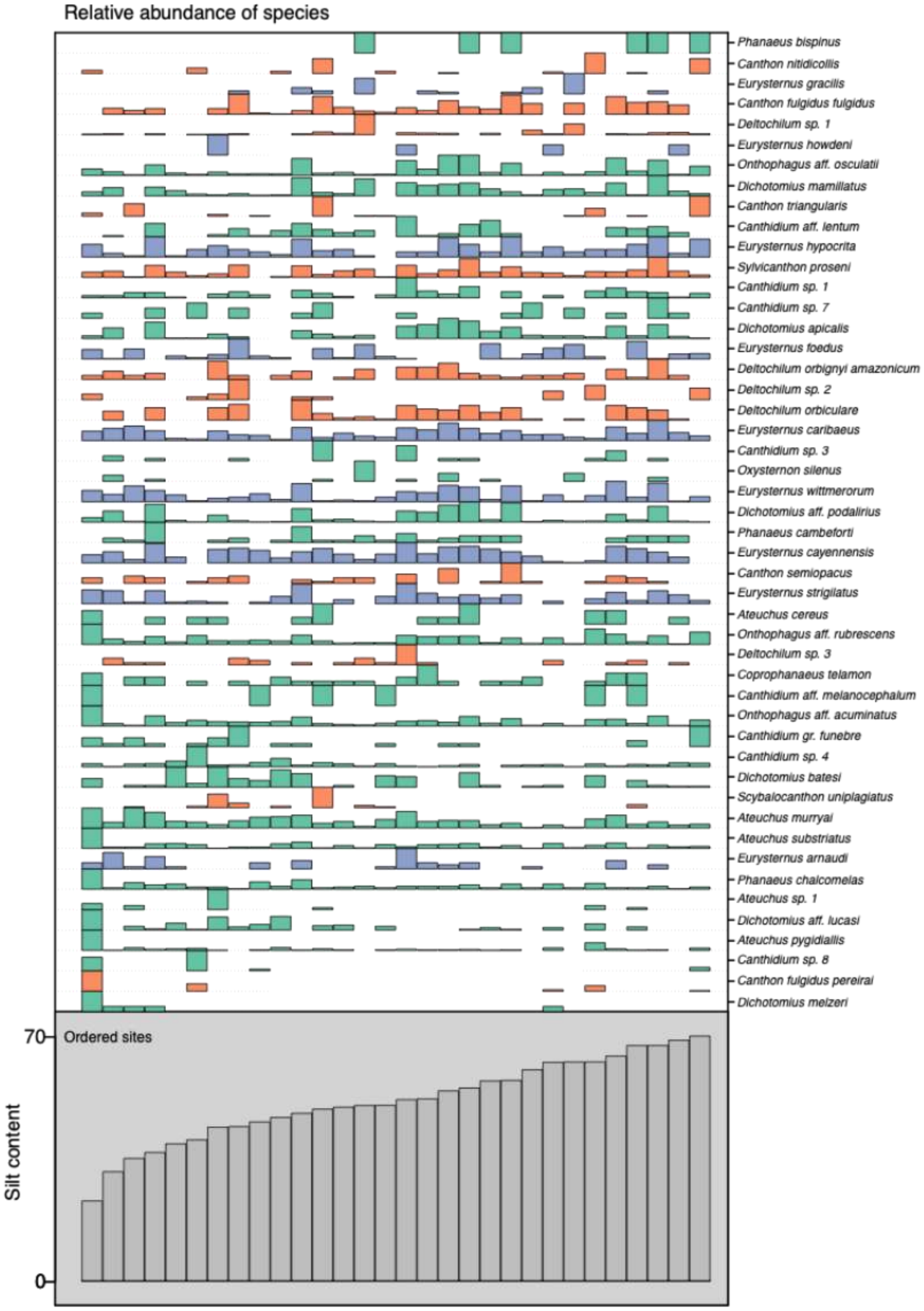

Figure S7 - Abundance of dung beetle across sites ordered by silt content. Each row corresponds to a species, and each column to a sampling site. The colors green, orange and purple represent the functional groups tunnelers, rollers and dwellers, respectively. The bottom panel shows the gradient of silt content, scaled in percentage.

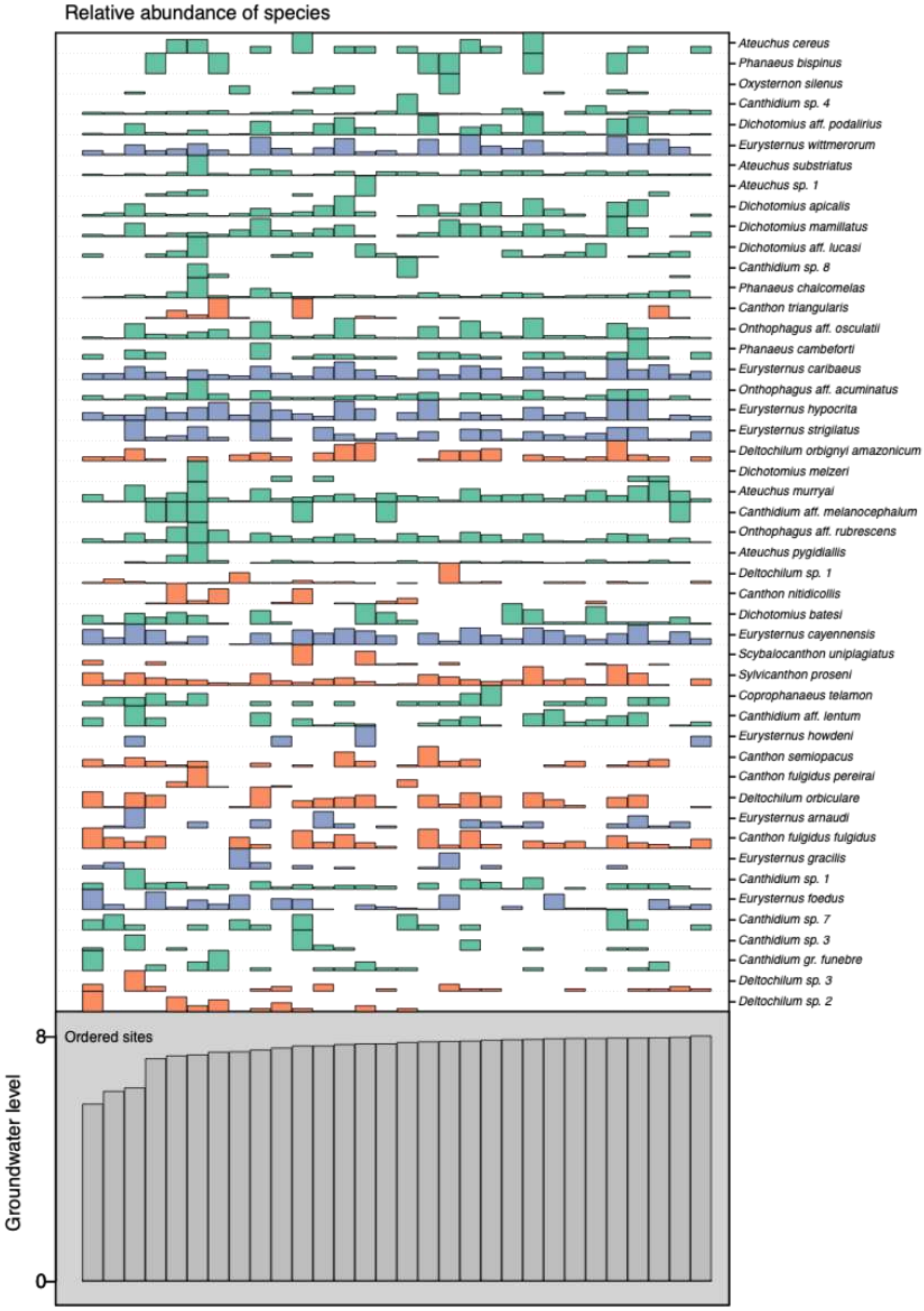

Figure S8 - Abundance of dung beetle across sites ordered by groundwater lever. Each row corresponds to a species, and each column to a sampling site. The colors green, orange and purple represent the functional groups tunnelers, rollers and dwellers, respectively. The bottom panel shows the gradient of groundwater level, scaled in meters.

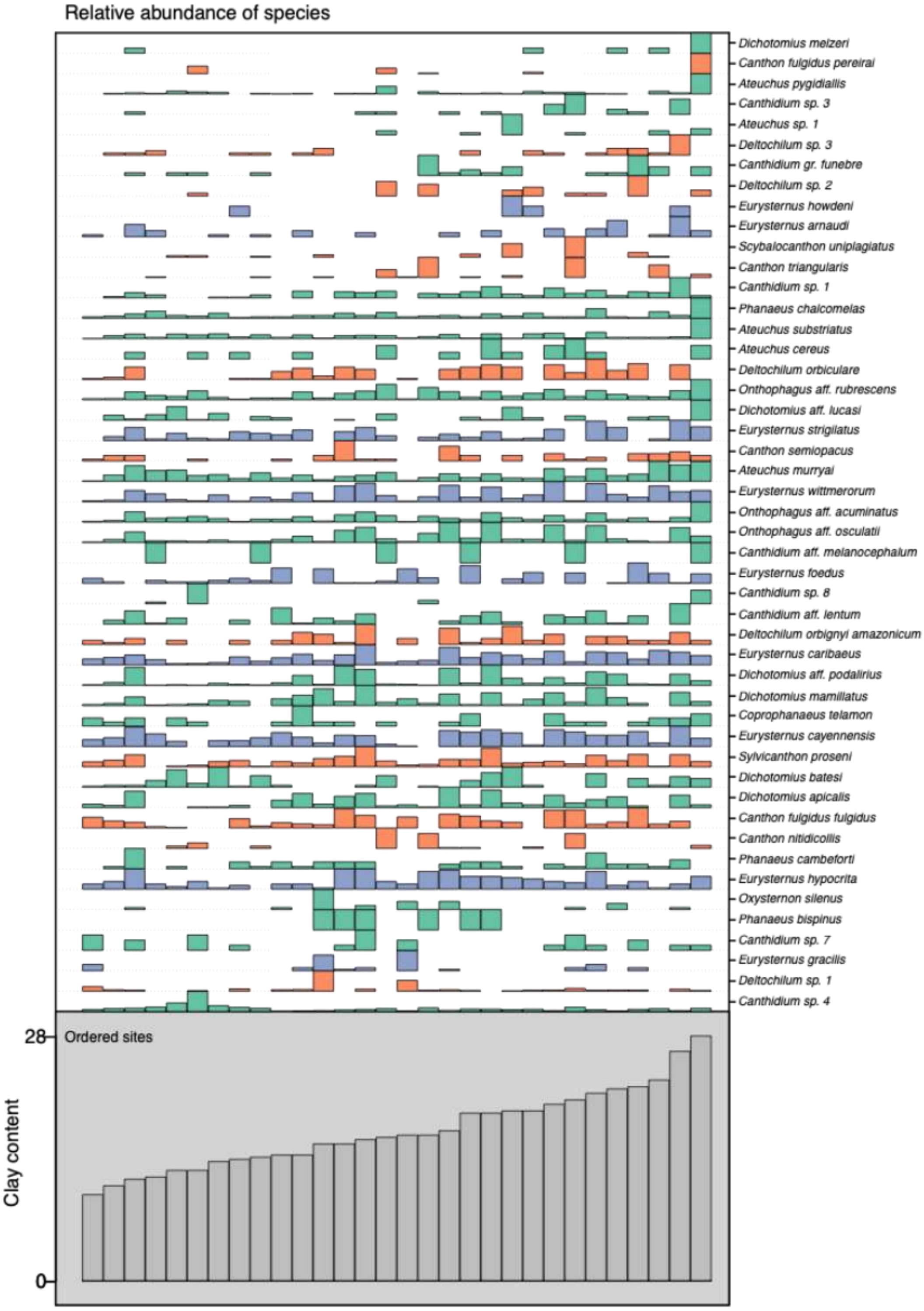

Figure S9 - Abundance of dung beetle across sites ordered by clay content. Each row corresponds to a species, and each column to a sampling site. The colors green, orange and purple represent the functional groups tunnelers, rollers and dwellers, respectively. The bottom panel shows the gradient of clay content, scaled in percentage.

CONCLUSÃO

Em conclusão, nossos resultados mostram que as bordas florestais exercem uma influência dominante sobre as assembleias de besouros rola-bostas no sudoeste da Amazônia em áreas que sofreram perda de habitat, mas esse efeito interage com gradientes ambientais locais para moldar a estrutura da comunidade de maneiras complexas. A expansão agrícola ao longo de rodovias como a BR-319 continua a desmatar as florestas amazônicas e intensificar a criação de bordas. Reconhecer o longo alcance espacial dos efeitos de borda é crucial para aprimorar as estratégias de conservação, incluindo a delimitação de zonas de amortecimento e áreas núcleo em paisagens protegidas. Abordagens integradas — combinando métricas espaciais, características das espécies e gradientes ambientais — são essenciais para avaliar com precisão as respostas da biodiversidade às mudanças de habitat, e os besouros rola-bostas oferecem um modelo valioso para tais investigações. Pesquisas futuras devem expandir essa estrutura para diferentes grupos bióticos e escalas espaciais, permitindo previsões mais robustas de mudanças ecológicas diante da perda contínua de florestas. Além de alcançar os objetivos propostos, este trabalho fornece evidências empíricas consistentes sobre o uso dos besouros rola-bosta como bioindicadores ecológicos. Destaca-se, ainda, que compreender a dinâmica das bordas é essencial para a formulação de estratégias de conservação na Amazônia, especialmente diante da expansão das atividades antrópicas.

CONCLUSION

In conclusion, our results show that forest edges exert a dominant influence on dung beetle assemblages in the southwestern Amazon in areas that experienced habitat loss, but this effect interacts with local environmental gradients to shape community structure in complex ways. Agricultural expansion along highways like BR-319 continues to deforested Amazonian forests and intensify edge creation. Recognizing the long spatial reach of edge effects is crucial for improving conservation strategies, including the delineation of buffer zones and core areas in protected landscapes. Integrated approaches—combining spatial metrics, species traits, and environmental gradients—are essential to accurately assess biodiversity responses to habitat change, and dung beetles offer a valuable model for such investigations. Future research should expand this framework across different biotic groups and spatial scales, enabling more robust predictions of ecological change in the face of continued forest loss. In addition to achieving its proposed objectives, this work provides consistent empirical evidence on the use of dung beetles as ecological bioindicators. It also highlights that understanding edge dynamics is essential for formulating conservation strategies in the Amazon, especially in light of the expansion of human activities.