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Mammalian response to FSC forest certification in production plantations

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ABSTRACT

The expansion of intensive forestry practices, targeting both native forests and exotic plantations, has led to a growing need for the implementation of sustainable forest management practices. Therefore, forest certification schemes, such as the Forest Stewardship Council (FSC), have been developed with the objective of promoting environmentally responsible forest management. Despite its widespread adoption, a substantial knowledge gap persists regarding the effectiveness of FSC environmental criteria in safeguarding biodiversity, especially for mammals. In this study, we utilized FSC-certified *Eucalyptus* plantations in Central Portugal, as a model system to assess the efficacy of FSC environmental criteria, and the subsequent sustainable management actions on mammal communities. We deployed camera traps in three plantations to evaluate the influence of FSC requirements, such as the protection of native vegetation, the promotion of vegetation productivity, and the designation of conservation zones, on the mammal spatial use in plantations. Our findings indicate that the retention of native vegetation and the promotion of vegetation productivity within plantations are associated with increased mammal occurrence. Conversely, we found that designated conservation zones, and harvesting operations along with the resulting fragmentation, had neutral and negative effects on species occurrence, respectively. This suggests that FSC criteria relating to these practices may be insufficiently implemented to promote the presence of mammals. These findings underscore the necessity for refinement in FSC certification standards to more effectively align with biodiversity goals. This study contributes significantly to the ongoing debate on forest certification by assessing the strengths and limitations of the FSC framework in managing biodiversity in production plantations.

1. Introduction

The depreciation of biodiversity has been a consequence of cumulative human activities (Storch et al., 2022). However, the recent extensive anthropogenic changes in land use have precipitated the current biodiversity crisis (Caro et al., 2022). Presently, 293 million ha of land are designated forest plantations, representing 3 % of the total forested area worldwide (FAO, 2020). Additionally, approximately 40 % of forests are affected by commercial logging, resulting in forest degradation, a loss of carbon stock, and increased human access to such forested areas (Laurance et al., 2014). The management practices of forestry operations vary significantly worldwide (Tobler et al., 2018), which together with the regional environmental context, may result in disparate biodiversity impacts and conservation outcomes (Gullison, 2003). This underscores the challenges associated with the implementation of landscape-level sustainable forest management policies. To overcome these challenges, forest management certification emerged in the 1990s and has received interest from ecologists and economists involved in enhancing management practices in production plantations, aiming for forestry sustainability.

One of the most recognized forest certifications worldwide is the Forest Stewardship Council (FSC). FSC was established in 1993 as an impartial third-party certification scheme for responsible forest management, with rigorous and well-defined standards and guidelines. The FSC is rooted in ten equally important principles and 57 criteria, which collectively encompass the environmental, social, and economic

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characteristics of forest management. The objective of this framework is to encourage the implementation of suitable management practices by incorporating all management dimensions (Cubbage et al., 2010). An FSC certificate is valid for a period of five years for each management unit (i.e., an area where forest management activities are carried out under a single management plan, complying with FSC certification requirements). During this period, forestry companies are required to undergo annual third-party assessments to verify compliance with the relevant standards. The FSC has two principles – principles six and nine - that are directly related to environmental management practices. Principle six states that the organization shall: (i) maintain, conserve and/or restore ecosystem services and environmental values of the management unit, and avoid, repair, or mitigate negative environmental impacts; and (ii) protect rare and threatened species and their habitats in the management unit through conservation zones, protection areas, connectivity and/or (where necessary) other direct measures for their survival and viability. Principle nine states that the organization shall: (i) identify and protect representative sample areas of native ecosystems and/or restore them to more natural conditions; and (ii) develop effective strategies that maintain and/or enhance the identified High Conservation Values, through engagement with affected stakeholders, interested stakeholders, and experts (FSC-STD-01–001 V5–3 EN). Hence, the implementation of FSC criteria shall correspond to specific on-site management practices that should be measurable through environmental indicators.

Since its implementation, several studies have addressed the success of the FSC certification in promoting biodiversity. These studies employed a quasi-experimental design, which includes both FSC-certified and non-FSC areas and compares biodiversity values in both (Medjibe et al., 2013; Kalonga et al., 2016; Blumroeder et al., 2019). However, there is no common pattern worldwide regarding FSC effectiveness as a conservation tool for biodiversity (see Matias et al., 2024 for a review). For instance, FSC has been shown to exert a positive effect on large mammal presence relative to non-FSC areas in Gaboon (Zwerts et al., 2024). Whereas in Germany, Blumroeder et al., (2019) found a similarity in several flora measures (e.g., species abundance and diversity) between FSC and non-FSC sites. These results underscore that the forestry practices implemented under FSC schemes may vary considerably (Dröge et al., 2025), together with the geographical and environmental contexts, and therefore so do the biodiversity outcomes (Burivalova et al., 2017). This presents a significant challenge to the rigorous assessment of the efficiency of the FSC certification.

Although many studies have focused on assessing the efficacy of FSC as a tool for wildlife conservation, there is a paucity of evidence regarding the real effect of FSC management practices on wildlife, especially in temperate regions (Matias et al., 2024). The majority of studies did not account for environmental indicators linked to FSC criteria implementation in management practices (e.g., harvest and conservation zones, remnants of native vegetation), but solely tested more general ecological criteria (e.g., distance to water, and herbaceous vegetation; Sollmann et al., 2017; Bahaa-el-din et al., 2016) as drivers of biodiversity variations between distinct sites. To determine the effectiveness of the FSC implementation on biodiversity preservation, it is paramount to measure the actual impact of on-site management practices with appropriate indicators.

Furthermore, most studies targeting the efficacy of FSC were focused on a single site or a limited number of species (Bahaa-el-din et al., 2016; Polisar et al., 2017). The inclusion of a diverse range of study areas and species is crucial to gaining a comprehensive understanding of this certification scheme's efficacy. Indeed, the heterogeneity in forest management practices across regions (Halalisan et al., 2016) stresses the necessity for comprehensive comparative analyses to identify the factors influencing the effectiveness of certification. The assessment of FSC efficacy is even more robust when it is feasible to ascertain the impact of environmental management practices on multiple species, for example, at the community level, thereby demonstrating that the management criteria yield a uniform outcome across species.

Wildlife occurrence is often limited by multiple factors, including resource availability, landscape structure (e.g., barriers or unsuitable habitats), and anthropogenic disturbances (Boulangeat et al., 2012). In forestry areas, this conceptual framework provides a basis for assessing how these drivers interact with management actions to shape species occurrence (Soberón, 2007). In managed plantations, the spatial homogeneity and temporal heterogeneity present unique challenges for species occurrence. The dominance of monocultures with synchronized growth cycles, characterized by same-age trees and regular understory control, limits food and refuge availability (Timo et al., 2014). Moreover, the fast grow-cut-replant cycle induces drastic temporal shifts in biomass (Stape et al., 2004), further constraining habitat suitability and, ultimately, species occurrence (Campos et al., 2018). The process of landscape fragmentation, consequent to forestry activities, results in the loss of native habitats, its fragmentation into smaller, more isolated patches, and an intensification of edge effects. These phenomena alter abiotic conditions and act as ecological filters, thereby restricting species' occurrence (Fahrig, 2003). In forestry landscapes, clear-cutting activities enhance fragmented habitats and edge density, which may act as barriers to movement, discouraging species from occupying heavily altered environments (Carvalho et al., 2021). Human-induced alterations (e.g., habitat fragmentation, clear-cutting, removal of understory vegetation) disrupt ecological networks, impacting food resources (Fontúrbel et al., 2015), exacerbating fragmentation (Coelho et al., 2020), and modifying local abiotic conditions (Jucker et al., 2020). In intensively managed plantations, these drivers may dictate both spatial and temporal habitat dynamics, ultimately influencing species' persistence. The integration of these ecological processes into species occurrence models (e.g., occupancy models) facilitates the accurate prediction of species responses to forest management.

To assess FSC efficacy to ensure mammals' use of forestry plantations, we used camera traps to (i) investigate the mammal community structure in three Portuguese FSC-certified *Eucalyptus* plantations and to (ii) ascertain how mammals respond to environmental management practices related to FSC environmental criteria. These plantations were selected for analysis as *Eucalyptus* is the most important tree genus in Europe for the pulp and paper industries (Tomé et al., 2021). Alongside, *Eucalyptus* spp. represents the primary FSC-certified species in Portugal (48.2 %; FSC Portugal, 2023). We assessed (i) species-specific occupancy patterns within certified areas, and (ii) species-specific response to environmental indicators related to certification management practices. To this end, we identified a set of environmental covariates that could be directly linked to the implementation of FSC criteria and the corresponding management practices (Appendix A, Tables A1–1). Then, we expressed how the variation of these covariates (i.e., indicators) may affect mammal species occupancy under three main hypotheses: dependence of species on resource availability (H 1), and their avoidance for human disturbance due to forestry activities (H2), and consequent forest fragmentation (H3; see Table 1). Namely, we predicted that species occupancy would be higher in areas with higher food availability (e.g., higher gains in productivity – NDVI; Santos et al., 2016; Cruz et al., 2015), and with lower forestry disturbance (higher native vegetation and near conservation zone; Mexia et al., 2022), whereas occupancy would be lower in harvested areas, and in highly fragmented areas (e.g., higher edge density; Carvalho et al., 2021, see Table 1 for hypotheses reasoning and specific predictions linked to covariates).

2. Methods

2.1. Study area

The study area comprises three *Eucalyptus* plantations (hereafter plantations), located in central Portugal (SW Europe), managed under the FSC forest certification scheme since 2006 (Ferreiras, Penha, and Arrepiado; Fig. 1) by the country's two largest forestry companies. Each

Table 1
Candidate covariates' expected effect ((+) for positive, and (-) for negative) on mammal occupancy in FSC-managed plantations, according to the resource availability, forestry disturbance, and fragmentation hypotheses. Corresponding predictions (P) and reasoning (R) are separately expressed for clarity for the two main mammal groups addressed by the camera trapping assessment, herbivores and carnivores. Herbivores: Iberian hare, wild boar, red deer, and roe deer. Carnivores: European badger, common genet, stone marten, Egyptian mongoose, and red fox.

Hypotheses	Prediction (P) & Reasoning (R)		Covariates (Effect on occupancy)
	Herbivores	Carnivores	
H1 – resource availability	(P) Herbivore's occupancy will be higher in areas with higher vegetation productivity and gains. (R) Greater vegetation productivity enhances forage availability and quality for herbivores, supporting their resource needs (Borowik et al., 2013a; Ares-Pereira et al., 2022), ensuring better habitat conditions.	(P) Carnivore's occupancy will increase in sites with higher vegetation productivity and gains. (R) Higher vegetation productivity and higher productivity gains create favorable conditions for carnivores' prey (e.g., small mammals; Santos et al., 2016), increasing their abundances (Carrilho et al., 2017).	NDVI (+) MDVG (+)
H2 – Forestry disturbance	(P) Herbivore's occupancy will be higher near Conservation Zones. (R) These sites are exposed to less human disturbance, thus they may provide refuge and better-quality habitats within the plantations for herbivores (Dias et al., 2016). (P) Additionally, herbivores' occupancy will be higher in sites with higher native vegetation cover. (R) These areas are less impacted by forestry activities and more plant-rich areas (Cruz et al., 2015).	(P) Carnivore's occupancy will increase near Conservation Zones. (R) These sites are less exposed to human pressure and remain in a more natural state. Therefore, these areas provide natural refuge from disturbance and are valued by carnivores, facilitating movement and access to prey (Dias et al., 2016). (P) Moreover, carnivores' occupancy will increase with higher native vegetation cover. (R) Native patches in plantations provide vital refuges for carnivores, offering richer, more stable habitats, less affected by forestry activities (Cruz et al., 2015).	D_CZ (-) NAT (+)
	(P) Herbivore's occupancy will be lower near harvested sites. (R) Although vegetation regrowth after harvesting can provide a food source for herbivores, the disturbance caused by human activity outweighs this resource opportunity, leading to avoidance (Carvalho et al., 2021).	(P) Carnivore's occupancy will decrease near harvested sites. (R) These areas present higher human presence and machinery activity, which cause disturbances and disrupt hunting opportunities (Carvalho et al., 2021).	D_HARVEST (+)
H3 - Fragmentation	(P) Herbivore's occupancy will be lower with the increase of edge density, thus fragmentation. (R) The fragmentation may disrupt habitat continuity, potentially disrupting connectivity between needed resources, and alter microclimate conditions (Ares-Pereira et al., 2022).	(P) Carnivore's occupancy will decrease with higher edge density, i. e., higher habitat fragmentation. (R) The associated fragmentation may negatively impact carnivores by restricting movement, reducing core habitat availability, and increasing competition (Garmendia et al., 2013).	EDGE (-)

study site is typically composed of a matrix of a monoculture of *Eucalyptus globulus*, with small patches of native shrubs (e.g., *Cytisus* spp., *Cistus* spp.), which represent a minor proportion of the landscape, averaging 5.8 % ± 1.2 % across the three sites. Despite the overall low representation of native vegetation, the cover proportion differs between study areas (Appendix A, Figs. A1–1), likely due to variations in management intensity and landscape history across the plantations. The three plantations also differ in other landscape characteristics, namely the mean Normalized Difference Vegetation Index (NDVI) during the study period, and the proportion of *Eucalyptus* (i.e., indicating a more or less homogeneous matrix), with higher homogeneity in Arrepiado (Appendix A, Figs. A1–1). Human activities occur in all three plantations, including forestry operations (e.g., fertilizing, planting, timber transportation; see also Appendix A, Figs. A1–2) and hunting (October-February; Law-Decree n. ° 202/2004—Official Journal (Diário da República) n.°194/2004, Series I-A de 2004–08–18). Although hunting may have a detrimental effect on mammal occurrence (Benitez-Lopez et al., 2017), we were unable to include it in our analyses, as no hunting signs were detected on camera traps during the study period. During the study period, the plantations in all study sites were harvested, with a mean proportion of harvested area of 20.02 % ± 6.99 (ranging from 10.17 % in Arrepiado to 25.61 % in Penha; see Appendix A, Figs. A1–2).

2.2. Mammal community survey

We deployed 20 unbaited camera-traps in each area, set in a grid format (1 km cell size, 12 km^2 / site *ca*), operating for 60 consecutive days, per two sampling periods: Nov–Feb of 2022/23 and May–Aug of 2023/24. The average intercamera distance was 874 m ± 108 m (range: 679 – 1216 m). Cameras were placed in trees, 50 cm above ground, and in locations assuring a higher detection probability for the mammal community surveyed (e.g., facing animal trails, open areas). We programmed cameras to take bursts of three photos (< 1 s apart) with 20 s intervals. We used the R package *camtrapR* (Niedballa et al., 2016; R Core Team, 2024) to process manually image sorting. Species-specific detection histories were generated on four-day sampling occasions when cameras were operational. We considered independent detection records whenever the timing between consecutive detections of the same species in the same camera was > 30 min (Rich et al., 2017).

2.3. Detection and occupancy covariates

We aimed to identify environmental covariates that would be directly and indirectly linked to the implementation of FSC criteria (Appendix A, Tables A1–1), and consequently with related on-site forestry management actions, while also being relevant to mammal occupancy in accordance with the resource availability, forestry disturbance, and landscape fragmentation hypotheses (Table 1). Accordingly, we selected six covariates: i) Monthly Difference in Vegetation Greenness during the study period (MDVG); ii) Mean NDVI during the study period (NDVI); iii) Native vegetation cover (NAT; Portuguese Land Use Raster, 10 m resolution); iv) distance to the nearest conservation zone (D_CZ); v) distance to nearest harvested area (D_HARV), and vi) edge density on the camera-site level (EDGE). MDVG and NDVI were extracted from the Portuguese Vegetation State Intra-annual raster with 10 m resolution (https://dados.gov.pt/). This product is based on Sentinel-2 imagery and provides monthly continuous values of the vegetation state (Costa et al., 2023). MDVG represents the difference in vegetation greenness compared to the previous month; thus, a positive value indicates an increase in vegetation greenness. MDVG and NDVI were used as a proxy for primary productivity and forestry activities, such as deforestation and understory removal (H 1, Table 1; see also Appendix A, Figs. A1–2). Native vegetation cover and the distance to the nearest conservation zone are proxies of the mandatory conservation impositions of FSC principles (six and nine), and the distance to the nearest harvested area aims to test the effect of the harvest-associated disturbance (H 2, Table 1; see also Appendix A, Tables A1–1). Finally, edge density is a measure of the resulting fragmentation due to forestry activities (H 3, Table 1). EDGE was measured as the total edge density within the 500 m radius camera buffer, calculated using the *spatialEco* R

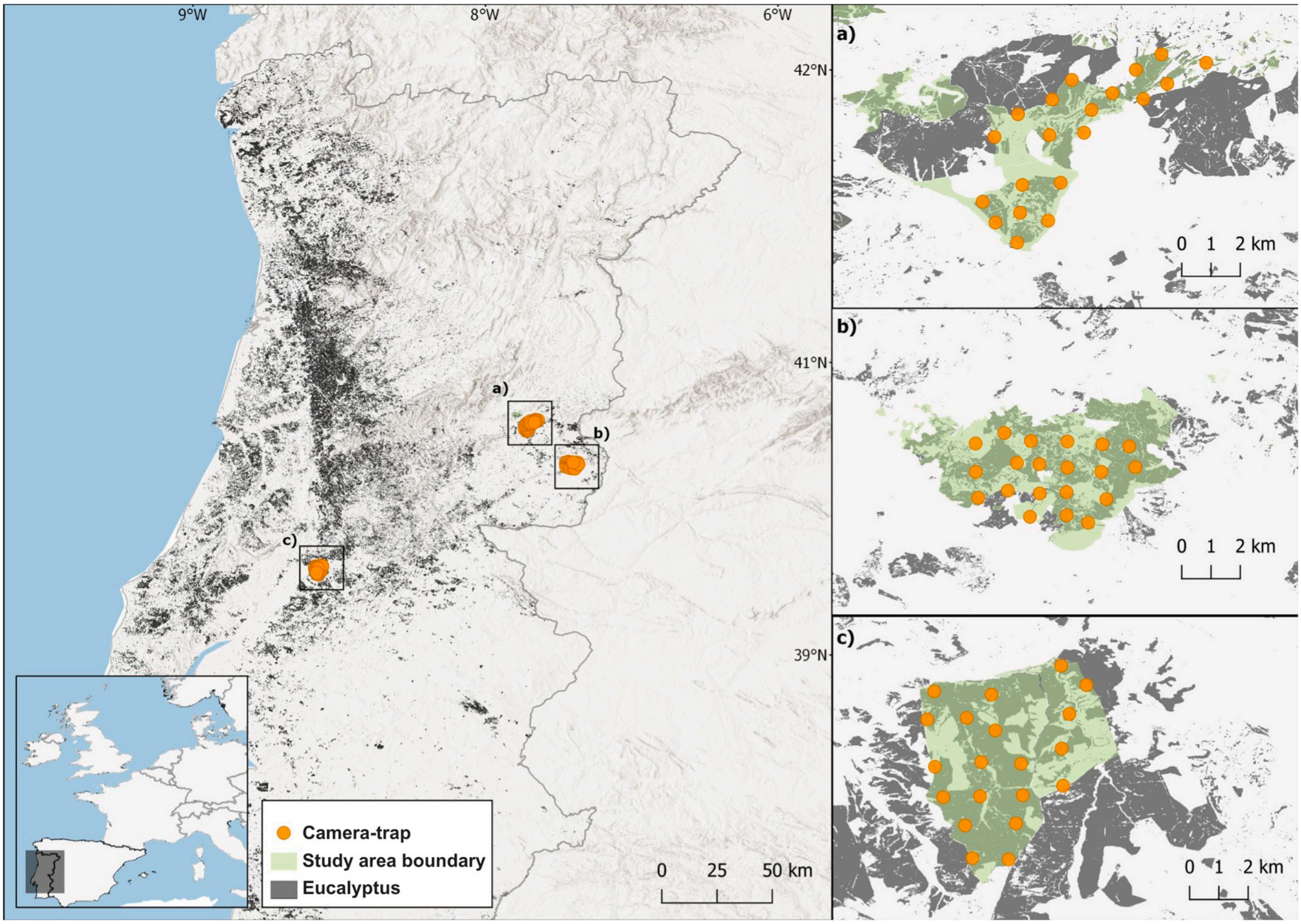

Fig. 1. Camera-trapping study conducted across three sites with FSC *Eucalyptus* plantations highlighted in light green (a– Ferreiras, b– Penha, and c– Arrepiado), in central Portugal. The study area location is shown on the left image, with background hill shade. The *Eucalyptus* cover is shown in dark grey, with the overlapping camera-trap 1 km grids represented by orange dots.

package (Evans et al., 2021).

The NDVI, MDVG, and NAT were quantified as average values within a 500 m radius buffer around each camera (see Appendix B). Prior to the analysis, all covariates were standardized with z-scores, to have a mean centered on 0 and a standard deviation of 1, apart from camera placement (on or off animal/human trail), which was tested as a detection driver, since revealed to influence species' detectability patterns in this dataset (see Matias et al., 2026).

2.4. Data analysis

We fitted multi-species occupancy models to estimate the probability of occupancy for the species composing the mammal community in our study sites, and determine the influence of the variables associated with FSC management on this metric (Dorazio and Royle, 2005). In this framework, the occupancy of a species i at a site j, z_{ij}, is modeled as a Bernoulli random variable governed by occupancy probability Ψ_{ij}. The detection probability p_{ijk}, where k is the active days of camera-trap, is conditional on the latent true occupancy z_{ij}. These two parameters were modelled as a logit-linear function of site covariates, specifically: NDVI, MDVG, D_CZ, NAT, D_HARVEST, and EDGE for occupancy (See Table 1); and camera placement (TRAIL; on or off animal/human trail), as a binary covariate for the detection parameter, specified as:

$$zij \sim Bernoulli(\Psi ij)$$

$$\text{logit}(\Psi ij) = \beta 0, i, area[j] + \beta 1, iNDVI[j] + \beta 2, iMDVG[j] + \beta 3, iD\_CZ[j] + \beta 4, iNAT[j] \quad + \beta 5, iD\_HARVEST[j] \quad + \beta 6, iEDGE[j]$$

$$logit(pijk) = \theta 0, \mathrm{i} + \theta 1, \mathrm{i}\ \mathrm{TRAIL}$$

To determine differences in baseline occupancy across areas among species, we estimated species-specific occupancy probabilities as a random effect with area-specific intercept ($\beta_{0,i,\text{area}[j]}$). Species-specific parameters $\beta 1{:}6,i$ *and* $\theta 1,i$ were treated as random effects from a community-level distribution:

$$\alpha \sim Normal(\mu, \sigma\alpha)$$

The community-level distribution specifies the mean community occupancy response and variation among species to each covariate. This improves parameter estimates for species with sparse data (Kéry and Royle, 2015).

We estimated model parameters using a Bayesian Markov Chain Monte Carlo (MCMC) simulation in JAGS (version 3.4.0), using *R2Jags* package (Su and Yajima, 2015). We sampled three chains of 150,000 iterations with a thinning rate of 10, with the first 30,000 iterations used as burn-in. We assessed model convergence using the Gelman-Rubin statistic, trace plots, and posterior density plots (Gelman and Rubin, 1992). We considered the 85 % threshold (i.e., > 85 % posterior probability – PD – that did not overlap 0) a well-supported effect to capture species-specific association with the covariates, to include species with limited sample sizes and/or high variation in the community response

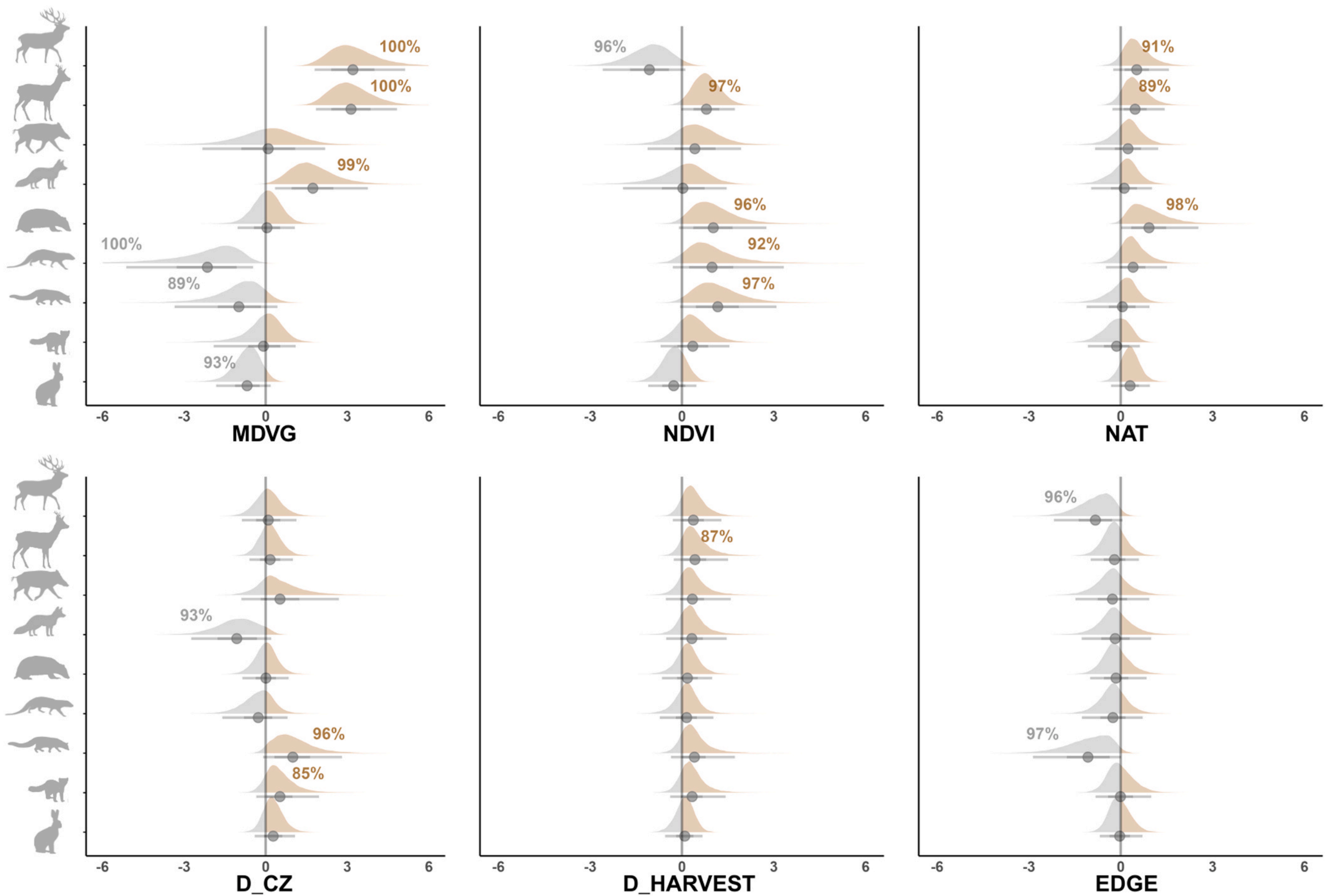

Fig. 2. Effect size of site-scale covariates (X-axis) on species-specific occupancy probabilities (Y-axis). Listed percentage is equal to the posterior probability of a positive (brown) or negative (grey) response. Only > 85 % posterior density greater than or less than 0 are detailed. Points are posterior distribution means, and error bars represent 95 % Bayesian credible intervals (BCIs). MDVG: Monthly Difference in Vegetation Greenness; NDVI: Normalized Difference Vegetation Index; NAT: Native vegetation cover; D_CZ: distance to the nearest conservation zone; D_HARVEST: distance to nearest harvested area; and EDGE: total edge density. Species symbols represent, from the top to the bottom: red deer, roe deer, wild boar, red fox, European badger, Egyptian mongoose, common genet, stone marten, and Iberian hare.

(Suraci et al., 2021; Matias et al., 2022).

3. Results

Across the three areas, we detected 10 native wild mammal species over 12,980 effective trap days, with a total of 2910 detections (Appendix A, Table A1–2). The most commonly detected species were the wild boar (*Sus scrofa*, n = 845), red fox (*Vulpes vulpes*, n = 646), and red deer (*Cervus elaphus*, n = 478), detected at 98.3 %, 86.7 %, and 58.3 % of camera sites, respectively. Smaller mesocarnivores (e.g., Egyptian mongoose, *Herpestes ichneumon*; European badger, *Meles meles*, and Common genet, *Genetta genetta)* were among the least frequently detected species in the study areas (Appendix A, Table A1–2). However, the European rabbit (*Oryctolagus cuniculus*) exhibited an even lower detection rate (n = 6) and was therefore excluded from further analysis due to insufficient data (Appendix A, Table A1–2). Additionally, roe deer (*Capreolus capreolus*) and red deer were absent from the southern study area (Arrepiado), due to their natural distribution range.

The average species-specific occupancy rates across the study areas were relatively similar. Arrepiado exhibited the highest mean occupancy at 0.78 (95 % Bayesian credible interval [BCI]: 0.53 – 0.96), followed by Ferreiras at 0.66 (0.49 – 0.82), and Penha = 0.65 (0.50 – 0.80). Overall, ungulates (i.e., deer species and wild boar) present higher occupancy (mean = 0.89, 95 % BCI: 0.77 – 0.96), followed by lagomorphs (i.e., Iberian hare; 0.74, 0.55 – 0.88), and carnivores (e.g., stone marten, genet, and badger; 0.59, 0.37 – 0.79).

3.1. *Mammal occupancy responses to FSC-related covariates*

Large herbivores were strongly associated with natural features that exhibited increased vegetation gains (i.e., MDVG; Fig. 2). However, NDVI had opposing effects on the two deer species, being favorable for roe deer ($\beta_{\text{roe deer}} = 0.80 \pm 0.45$, −0.02 – 1.73) and exerting a negative influence on red deer occupancy ($\beta_{\text{red deer}} = -1.06 \pm 0.69$, −2.59 – 0.12). Alongside, the harvested areas appear to be avoided by these species since their occupancy is higher in regions far from clear-cutting areas (D_HARVEST; $\beta_{\text{red deer}} = 0.37 \pm 0.40$, −0.30 – 1.29; $\beta_{\text{roe deer}} = 0.43 \pm 0.44$, −0.27 – 1.51). In addition, red deer occupancy increases in more homogenous landscapes (i.e., lower edge densities; $\beta_{\text{red deer}} = -0.83 \pm 0.59$, −2.18 – 0.07). The Iberian hare occupancy was positively associated with regions with losses of vegetation productivity (MDVG; $\beta = -0.68 \pm 0.51$, −1.82 – 0.18; Fig. 2). However, despite the posterior probability lower than 85 %, hare appears to also prefer natural patches inside the plantations (PD = 83 %, Appendix A, Table A1–3). The wild boar occupancy did not seem to be affected by any of the tested drivers (85 % posterior distribution crosses 0; Fig. 2).

A common pattern among the carnivores was the preference for more productive areas (i.e., higher NDVI, Fig. 2). The common genet and mongoose exhibited a negative relationship with MDVG, meaning their occupancy decreased with greater vegetation gain ($\beta_{\text{genet}} = -1.00$

$\pm$ 0.96, −3.37 – 0.43; $\beta_{mongoose}$ = −2.25 $\pm$ 1.39, −5.84 – −0.47). Conversely, foxes showed a positive response to areas characterized by greater vegetation gain (β = 1.74 $\pm$ 0.88, 0.34 – 3.78), but negative to the distance from the conservation zones (β = −1.06 $\pm$ 0.76, −2.74 – 0.21). Whereas the two forest-dwelling species (i.e., stone marten and genet) exhibited higher occupancy values at greater distances from the conservation zones (β_{marten} = 0.52 $\pm$ 0.58, −0.34 – 1.96; β_{genet} = 1.00 $\pm$ 0.75, −0.09 – 2.81). Genet occupancy was also found to be higher in more homogeneous sites (i.e., lower edge densities; β = −1.07 $\pm$ 0.55, −2.87 – 0.01), and far from harvested areas (β = 0.41 $\pm$ 0.53, −0.36 – 1.73). As for large herbivores, the badger demonstrated a favorable response to areas characterized by a higher proportion of natural vegetation (β_{badger} = 0.93 $\pm$ 0.66, 0.02 – 2.54).

Overall, species had higher detection probabilities in sites located on human/animal trails ($\beta_{community}$= 0.36 $\pm$ 0.13, 0.12 – 0.63). Detailed model outputs, including posterior means, standard deviations, and 95 % Bayesian credible intervals (BCIs) for all species and covariates, are provided in Appendix A, Table A1–4.

4. Discussion

This study constitutes the first comprehensive evaluation of the effectiveness of the management actions linked to the implementation of FSC certification for *Eucalyptus* plantations in supporting the mammal community. The FSC's stated objectives are to promote forest management that is environmentally responsible, socially beneficial, and economically viable. The results suggest that certain FSC-compliant management practices, such as preserving native vegetation and maintaining its primary productivity, benefit the mammal community in these disturbed plantation landscapes. Conversely, other practices, such as the designated conservation zones and the harvesting activities, may have a neutral or negative effect on different mammalian species in the study sites. Allover, our findings suggest a need to refine some FSC guidelines to better align certification requirements with biodiversity conservation goals, ensuring that forest management practices support the preservation of a wider range of native species inhabiting plantations.

4.1. Mammal responses to forest certification

4.1.1. Resource availability

The strong correlation between large herbivores, such as red and roe deer, and areas exhibiting higher vegetation gains, and thus higher food availability, supports the hypothesis that resource availability is a key determinant of their presence within plantations, even though some vegetation gains may not constitute edible forage. Studies at local scales consistently found that the movements and habitat selection of deer were driven by plant phenology (Dupke et al., 2017; Mysterud et al., 2017), with some species targeting higher forage quantity (i.e., higher NDVI areas), and others higher forage quality (i.e. gains in NDVI) (Shamon et al., 2022). In our study, roe deer demonstrated a positive response to areas exhibiting higher vegetation productivity (i.e., NDVI), while red deer exhibited a negative association. Several studies have showed the red deer's preference for quantity over quality (Rempfler et al., 2024; Sigrist et al., 2022). However, in forested systems like *Eucalyptus* plantations, the relationship between NDVI and understory biomass can vary throughout the year, as fully developed canopies at certain times can obscure ground vegetation (Borowik et al., 2013b). Furthermore, a negative relationship was detected between the extent of *Eucalyptus* cover and the amount of vegetation gain, thus indicating that higher *Eucalyptus* cover corresponds to higher levels of native understory vegetation loss (Appendix A, Figs. A1–2b). The observed preference for sites with higher vegetation gains by large herbivores might therefore be linked to plantation avoidance, a pattern already detected in a previous study in the same areas (Ares-Pereira et al., 2022). The resource availability hypothesis was not corroborated for habitat generalist herbivores such as the hare, since its occupancy was negatively related to vegetation gains. However, in Spain, radio-marked hares revealed that shoots of *Eucalyptus* trees and pine were the major food sources in a disturbed landscape (Jaramillo-Fayad et al., 2015). This result may indicate that for hares, the loss of vegetation can lead to an increase in shoots, which in turn can result in high food availability.

Overall, carnivores have been shown to demonstrate a preference for more productive sites within plantations (i.e., NDVI). Vegetation productivity is indicative of the quality of resources, a factor which is recognized as a significant driver for these species' occurrence, given their frequent utilization of fruits as a food source (Rosalino and Santos-Reis, 2009). Furthermore, areas with higher NDVI (i.e., higher plant productivity) can serve as a proxy for the abundance of rodents, which are a common prey item for carnivores (Valerio et al., 2020; Afonso et al., 2021), corroborating our initial hypothesis. Additionally, a species-specific effect on vegetation gain was detected. Foxes demonstrated a preference for sites exhibiting vegetation gains, while genets and mongooses exhibited an opposite trend, avoiding areas with significant vegetation recovery. This contrast may reflect differences in foraging strategies and prey detection mechanisms. Genets and mongooses primarily consume small mammals and, in the case of mongooses, also lagomorphs (Barros et al., 2024). Denser vegetation may reduce hunting efficiency by offering more cover and escape opportunities for prey, potentially explaining their preference for areas with lower vegetation gains. In contrast, foxes are recognized for their more extensive trophic ecology (Soe et al., 2017). In Portugal, at a local scale, foxes have been observed to consume fruits and insects almost exclusively (Barros et al., 2024). Consequently, the increased vegetation availability in these areas might be advantageous for foxes, as it provides them with fruits and shelter for their insect prey.

4.1.2. Forestry disturbance

Our study demonstrates that in temperate and exotic plantations, harvesting had a negative impact on the entire mammal community. Our results support our second hypothesis, as forestry disturbances, particularly clear-cutting, exerted a negative influence on the occupancy of mammals (i.e., occupancy is higher further away from harvested sites). The deleterious consequences of logging disturbances in tropical mammalian communities have been extensively documented (Brodie et al., 2015b; Jamhuri et al., 2018). In addition, studies conducted in North America and Australia revealed that fishers (*Pekania pennanti*) and koalas (*Phascolarctos cinereus*), respectively, avoided harvested areas by moving to adjacent habitats and more complex stands (Moriarty et al., 2016; Hynes et al., 2021). Although harvesting provides some short-term resources (e.g., shoots) that can be consumed by herbivores, such as deer species and small mammals (Michał and Rafał, 2014), our results showed that the mammal community avoid areas that have been recently harvested. This finding suggests that the disturbance associated with the harvesting process, such as pre-harvest deforestation, tree felling, and timber transport, may drive mammals to avoid these areas (Michał and Rafał, 2014). Supporting this hypothesis, native vegetation patches had a positive effect on mammal occurrence, indicating that these remnants may serve as important refuges or alternative habitats during and after disturbance.

As outlined in FSC criterion 6.5, the organization is obligated to protect representative samples of native ecosystems and/or restore them to more natural conditions. This study demonstrates that areas with higher native vegetation cover within the plantations have a positive effect on mammals' occupancy, corroborating our forestry disturbance hypothesis (i.e., areas with higher native vegetation will be less disturbed and positively influence mammal occupancy). The wildlife preference for using native patches within *Eucalyptus* plantations has been demonstrated in several studies (Cruz et al., 2015; Castro et al., 2022), often linked to the increased food availability and refuge they offer. This finding underscores the notion that the preservation of native vegetation within plantations dominated landscapes is advantageous for the broader mammal community and validates the conservation relevance of the application FSC 6.5 criterion.

Overall, the importance of conservation zones (linked to FSC criterion 6.4) for mammals, within the forestry disturbance hypothesis framework, was not supported by our data. This is evidenced by the decrease in mammal occupancy in proximity to these zones, except for the red fox. FSC certification requires that a minimum of 10 % of the management unit must be dedicated to biodiversity conservation (i.e., conservation zones; Tollefson et al., 2009). Several studies recognized that these areas promote tree regeneration, vegetation diversity, and habitat heterogeneity when compared to non-conservation zones (Dias et al., 2016; Mexia et al., 2022). In contrast, our study demonstrates that the presence of conservation zones within our study areas is not effectively promoting the mammal community occurrence, with the notable exception of the fox. This outcome may be ascribed to the comparatively diminutive size, narrow configuration, and spatial aggregation of these areas within the landscape (Appendix A, Fig. A1–3). These characteristics may exert a detrimental effect on the mammal community, with the size of the conservation zones potentially being inadequate for them to function as a refuge from the continuous disturbance regimes in these landscapes. However, red foxes appear able to utilize these areas by integrating multiple conservation patches across the plantation matrix. This broader spatial use may give foxes a competitive advantage, potentially discouraging other species from occupying these zones. In addition, within the study areas, other patches of native vegetation that are not designated as conservation zones in the management plans can remain undisturbed and thus mask the effect of the designated zone. This suggests the possibility that certain species, which do not utilize conservation zones (e.g., stone martens and mongooses), may be using other native patches within the plantation (as evidenced by the general positive effect of native vegetation on mammal occupancy). Their role in maintaining biodiversity within plantations highlights the need to consider not only designated conservation zones but also the broader network of interconnected native vegetation areas within plantations when developing conservation strategies.

4.1.3. *Forest fragmentation*

The observed overall negative effect of edge density (i.e., an indicator of habitat fragmentation) on the entire mammal community highlights that fragmentation derived from forestry activities may compromise the habitat integrity and connectivity for mammals in these landscapes, corroborating our third hypothesis. Several studies exposed a negative effect of edge density and habitat fragmentation on mammals worldwide (Garmendia et al., 2013; Brodie et al., 2015a; Rios et al., 2021). For instance, a study in a forestry concession in Borneo demonstrated a decrease in the habitat use of several mammals due to significant microclimatic changes posed by forest edges (Brodie et al., 2015a). Larger-bodied species, such as red deer, tend to be more affected by fragmentation due to their larger home range requirements (Broekman et al., 2022), and the higher forest area losses and disturbance linked to higher edge densities. Furthermore, the disruption of trophic interactions within ecosystems can be caused by habitat fragmentation resulting from forestry activities. Research in the Argentine Chaco has demonstrated that habitat fragmentation can limit the occupancy of dispersal-limited prey species, consequently reducing the presence of top predators (Semper-Pascual et al., 2021). This disruption underscores the cascading effects fragmentation may have across trophic levels, which can also indirectly affect predators, which may explain the overall negative effect of fragmentation on the entire mesocarnivore community.

The adverse effect of edge density observed in the present study emphasizes the vulnerability of mammal communities to habitat fragmentation, particularly regarding habitat integrity and connectivity. However, the contrasting findings of Pereira et al. (2024), who detected a positive effect of edge density on mesocarnivore occupancy in *Eucalyptus* plantations, suggest that the impact of fragmentation is context dependent. The observed differences in results may be attributed to variations in landscape structure and management practices. In their study area, the increased edge density may provide more foraging opportunities and shelter for certain generalist mesocarnivores, whereas in our study, fragmentation is likely to exacerbate habitat loss and isolation, disproportionately affecting species with larger home ranges and higher sensitivity to landscape changes. This underscores the importance of incorporating site-specific ecological and management contexts when evaluating the impacts of habitat fragmentation on wildlife communities.

4.2. *Implications for forest certification management*

Our findings have significant implications for the management of forest certification, particularly within the context of Mediterranean FSC-certified *Eucalyptus* plantations. FSC environmental criteria 5, 6, and 9 (FSC-STD-01–001) are designed to ensure sustainable forestry activities by maintaining ecosystem services, minimizing environmental impacts, and safeguarding conservation zones, and ultimately wildlife. However, our study suggests that certain aspects of forestry management under FSC certification may require adjustments to better support mammal biodiversity and thus fulfil its objectives. To enhance the ecological sustainability of certified plantations, we identify key areas for improvement in forest certification management.

A pivotal finding of our study is the positive effect of high vegetation productivity and native vegetation patches within *Eucalyptus* plantations on mammal occupancy patterns. This underscores the importance of preserving and expanding native vegetation cover within certified plantations. Current FSC criteria require the protection of representative samples of native ecosystems (Criterion 6.5). By increasing the proportion of native vegetation and integrating it more effectively within plantation landscapes, forest managers can create a mosaic of interconnected habitats that not only serve as refuges, but also provide other essential resources (e.g., food), ultimately fostering a more diverse, stable and functional mammal community.

The negative impact of harvesting activities, particularly clearcutting, on mammal communities underscores the need for refining sustainable harvesting practices within FSC-certified plantations. FSC currently does not specify a limit on the area or volume of timber that can be harvested within certified stands (Matias et al., 2024). Therefore, we suggest that the FSC adopt a legal harvesting volume/area limit, which should be set at a fixed proportion of the total management unit. Besides, implementing longer rotation periods and stands at different production stages ensures that undisturbed or less-disturbed areas are consistently available for wildlife, reducing the risk of synchronized large-scale habitat disruption (Brockerhoff et al., 2017). Additionally, FSC certification should encourage measures that minimize the impact of timber extraction, such as maintaining unharvested buffer zones and ensuring post-harvest habitat restoration. The observed negative effects of habitat fragmentation on the mammal community reinforce the need to incorporate landscape-scale planning into forest certification criteria. Current FSC standards do not explicitly address the issue of habitat connectivity within managed plantations. Incorporating guidelines that promote native habitat corridors and reduce edge density could significantly improve landscape permeability for wildlife. Furthermore, ensuring that plantation expansion does not exacerbate fragmentation is crucial for maintaining functional ecosystems within certified areas.

The requirement that at least 10 % of the management unit is designated for biodiversity conservation (i.e., conservation zones; FSC Principle 6) is a commendable effort. However, our study found that overall, these conservation zones are not effectively promoting mammal occupancy. This may be due to their small size, narrow configuration, and spatial aggregation, which limit their functionality as wildlife habitats. To address this, certification bodies should consider revising guidelines to ensure that conservation zones are not only larger and more interconnected but also strategically distributed across the landscape to maximize their ecological value. Moreover, the integration of adaptive management approaches, such as incorporating periodic monitoring and flexible adjustments based on species' responses to changing conditions, could significantly improve the effectiveness of conservation zones, allowing them to better support biodiversity in the long term.

Finally, given the variability in species responses to FSC certification and management interventions (see also Matias et al., 2026), a more robust and adaptive monitoring framework is needed. Certification bodies should require regular multi-taxa biodiversity assessments that track the effectiveness of conservation measures over time. By integrating scientific research into certification processes, FSC can refine its standards to better reflect the local/regional ecological realities. Additionally, engaging with stakeholders, including researchers, local communities, and conservation organizations, can help inform adaptive management strategies that support both production and biodiversity goals.

CRediT authorship contribution statement

Luís Miguel Rosalino: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Gonçalo Matias:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesca Cagnacci:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Beatriz Monteiro:** Writing – review & editing, Data curation. **Maxime Sobral:** Writing – review & editing, Data curation. **Beatriz C. Afonso:** Writing – review & editing, Visualization, Data curation. **Vasco Valdez:** Writing – review & editing, Data curation.

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Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.123360.

Data availability

Data will be made available on request.

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