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Limited effectiveness of FSC certification in conserving mammals in exotic plantations

Gonçalo Matias [a,*], Francesca Cagnacci [b,c], Beatriz C. Afonso [a,d], Vasco Valdez [a], Beatriz Monteiro [a], Maxime Sobral [a], Luís Miguel Rosalino [a]

[a] cE3c–Centre for Ecology, Evolution and Environmental Changes and CHANGE–Global Change and Sustainability Institute, Campo Grande, 1749-016, Lisbon, Portugal
[b] Animal Ecology Unit, Research and Innovation Centre, Fondazione Edmund Mach, Via E. Mach 1, 38010, San Michele all'Adige, Italy
[c] National Biodiversity Future Centre (NBFC), Palermo, Italy
[d] Department of Biology and CESAM, University of Aveiro, Campus Universitário de Santiago, 3810-192, Aveiro, Portugal

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ABSTRACT

Deforestation remains a critical global challenge, with forestry activities often contributing to forest loss or simplification. Certification schemes, such as the Forest Stewardship Council (FSC), aim to promote sustainable forest management and support biodiversity conservation. FSC effectiveness regarding biodiversity preservation has been discontinuously assessed across regions, taxonomic groups and types of targeted forests. Exotic plantations, in particular, pose a threat to local biodiversity by establishing heavily managed non-native habitats, yet little is known about how communities respond to the establishment of FSC criteria in these managed landscapes. To address this gap, we used camera trapping to evaluate mammalian occupancy and community composition across three distinct forest management contexts in Portugal: FSC-certified Eucalyptus plantations, non-FSC Eucalyptus plantations, and native reference forests. The findings indicate that the mean occupancy rate of mammals was similar in FSC-certified and non-FSC plantations and slightly higher in native forests. Carnivore and deer species occupancy were similar between FSC-certified and non-FSC sites. Moreover, native forests exhibited higher species-specific occupancy rates relative to FSC-certified and non-FSC plantations, with management status being a stronger driver than fine-scale habitat characteristics (e.g., NDVI, habitat heterogeneity). These results indicate that FSC has limited influence on advancing mammal conservation within exotic plantations. This study underscores the need to strengthen the FSC environmental criteria to ensure they align more effectively with biodiversity conservation. By refining FSC standards, there is significant potential to enhance conservation outcomes for mammal communities, particularly in forestry-dominated landscapes where sustainable management is a key goal.

1. Introduction

Humans have modified landscapes for millennia (Steffen et al., 2015), and wilderness loss continues worldwide (Watson et al., 2016). Between 2010 and 2020, net forest loss averaged 4.7 million ha per year (FAO, 2020), with forestry activities accounting for 26 % of global forest loss (Curtis et al., 2018). Forest plantations, characterized by native or exotic planted forests, usually one or two species, and managed for timber or fiber production (Jones et al., 2024), have expanded by 123 million ha over the past three decades, now covering 293 million ha globally. The creation of large monocultures continues to raise significant conservation and sustainability concerns among researchers, stakeholders, and practitioners (Baral et al., 2016), particularly regarding the negative effect on biodiversity of habitat simplification and heavy management (Brockerhoff et al., 2008; Liao et al., 2012). Among these, plantations of exotic species, which account for 45 % of all plantations, are of particular concern, as they pose a double threat by establishing non-native, heavily simplified habitats (Wang et al., 2022).

The increase in deforestation and timber extraction from natural forests, coupled with the expansion of plantations, highlighted the necessity for a mechanism that could guarantee to consumers that forest commercial exploitation was conducted in an environmentally and socially responsible manner. Forest certification emerged as a potential solution to this challenge. In this context, the Forest Stewardship

* Corresponding author.
E-mail address: gfmatias@fc.ul.pt (G. Matias).

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Council (FSC) was established in 1993 to promote responsible conservation and management of forestry systems (Auld et al., 2008). FSC uses a labeling system based on 10 principles and 57 criteria involving ecological, economic, and social forestry dimensions to foster the sustainable and responsible use of the forest (Cubbage et al., 2010). Relevant criteria for biodiversity and forest integrity include the maintenance and protection of rare, threatened, or endangered species and their habitats (Criterion 6.4), the avoidance of conversion of natural forests (Criterion 6.5), the exclusion of genetically modified organisms (Criterion 6.6), and the conservation of representative ecosystems (Criterion 6.7; FSC, 2015). Currently, FSC forests are becoming an important type of landscape worldwide, covering 161 million hectares (5 % of the world's forest), in 89 countries (https://connect.fsc.org/). While FSC-certified forests are increasingly widespread globally, studies on the efficacy of FSC certification in conserving biodiversity rarely address animal communities (Burivalova et al., 2017). Among vertebrates, FSC certification has been shown to exert an overall positive effect on mammals worldwide in managed forests (Matias et al., 2024). However, there is considerable variation in its efficacy across species with distinct ecological traits, and a lack of information concerning those inhabiting European exotic plantations (see Matias et al., 2024), such as *Eucalyptus* plantations.

Furthermore, other limitations of studies that assess FSC effectiveness in preserving biodiversity include the lack of replicate sites and unlogged reference areas, which are essential for controlling environmental variability and establishing reliable baselines. The absence of these controls can lead to confounding results, making it challenging to accurately determine the impact of FSC certification on biodiversity (Matias et al., 2024; Burivalova et al., 2017). This is of paramount importance when FSC certification is assigned to exotic plantations, that represent per se a threat to biodiversity by establishing non-native habitats (Wang et al., 2022).

Eucalyptus plantations are among the most profitable forestry sectors, at the basis of the paper industry, yet exotic in most areas, as this group of plants is native to Oceania (Wingfield et al., 2015). Outside the native range, these exotic monocultures are established in regions where native forests have been cleared (Wingfield et al., 2015). Typically, they operate on short rotation cycles, with harvesting every five to nine years, followed by ploughing and replanting. As a result, *Eucalyptus* stands rarely reach maturity and generally lack a developed understory (Iglesias-Carrasco et al., 2025). This creates a simplified habitat structure, which can significantly alter local biodiversity. For mammal communities in particular, the low structural heterogeneity, absence of native plant species, and frequent disturbance may lead to reduced species richness and altered community composition (Almeida-Maués et al., 2022).

In Europe, nearly 80 % of *Eucalyptus* plantations occur in the Iberian Peninsula (Tomé et al., 2021), in particular accounting for 26 % of Portugal's forested area (ICNF, 2019). Studies conducted in this region have shown that *Eucalyptus* plantations limit mammals' distribution, as well as reduce vertebrate diversity and abundance, mostly by limiting food and shelter (Teixeira et al., 2023; Afonso et al., 2023; Pereira et al., 2024). It is of pivotal importance to maintain functional mammal communities in these productive systems, as they constitute vital elements of the ecosystem, playing an essential role in landscape structure and resilience (Velamazán et al., 2020), by acting as prey and vegetation controllers, and seed dispersers (Rosalino et al., 2010; Williams et al., 2018). In this context, certification might be a mitigatory tool in achieving this goal, yet no study worldwide has investigated how mammal communities respond to sustainable forest management of *Eucalyptus* plantations under the FSC scheme. Furthermore, a recent review of research gaps on Iberian carnivores identified a dearth of studies examining how species utilize anthropogenic environments (e.g., *Eucalyptus*-dominated landscapes; Rosalino et al., 2023), highlighting the urgent need for more accurate information on this subject.

To address this critical knowledge gap and given that no previous study has directly assessed how mammal communities respond to FSC-certified plantations in Europe, we investigated the effects of FSC management on mammals inhabiting Eucalyptus landscapes. We used a multi-region, multi-species occupancy model to document mammal responses across three forest management contexts: FSC-certified plantations, non-FSC plantations, and reference sites composed of native forests (hereafter native forests). Specifically, we evaluated (i) how species occupancy and site-level richness vary among the three management contexts, (ii) how occupancy rates of functional groups (lagomorphs, carnivores, artiodactyls) vary across these contexts, and (iii) how site-level habitat characteristics (productivity – NDVI, diversity – Shannon-Wiener index, and shrubland cover) influence species occupancy probabilities.

We hypothesized that: 1) overall mammal occupancy would be highest in native forests, reflecting higher resource availability and lower disturbance compared with production forests, consistent with previous studies highlighting biodiversity benefits of undisturbed habitats (Jones et al., 2024); 2) habitat generalist species (e.g., red fox, *Vulpes vulpes*; wild boar, *Sus scrofa*) would show similar occupancy in FSC-certified and non-FSC plantations (i.e., no FSC effect), as their behavioral plasticity allows them to exploit resources in managed landscapes (Jones et al., 2024; Teixeira et al., 2020); and 3) differences in species occupancy among management contexts would be primarily driven by habitat characteristics, namely higher primary productivity and structural heterogeneity, which increase resource availability (Santos et al., 2016), and greater shrub cover, providing refuge opportunities (Suárez-Tangil and Rodríguez, 2023).

By testing these hypotheses, our study provides the first direct assessment of mammal community responses to FSC certification in European plantations, thereby offering novel and critical evidence to the ongoing debate about the extent to which FSC fulfills its promise as a biodiversity conservation tool in production forests.

2. Methods

2.1. Study area

Our study was carried out in seven study sites, grouped into three forest management contexts – FSC-certified *Eucalyptus* dominated plantations ($n = 3$), non-FSC *Eucalyptus* dominated plantations (n = 3), and native forests ($n = 2$) – located in central Portugal (Fig. 1). Each study site comprised an area of ca. 16 km^2 located at least 10 km apart from any of the other sites. Three study sites were located within FSC-certified *Eucalyptus* plantations dominated landscapes (Arrepiado, Penha Garcia, and Ferreiras), managed by the two largest Portuguese forestry companies. These areas also comprised Mediterranean native woodland, dominated by *Quercus robur* but also sparsely including other Mediterranean tree and shrub species, e.g., *Quercus suber* and *Arbutus unedo*. However, the native patches accounted for only a small proportion of the landscape (5.80 % ± 1.20 %). The two non-FSC *Eucalyptus* plantation areas (Carvalhal and Góis) were characterized by small patches of *Eucalyptus*, with an average of 8.70 ha ± 5.70 ha each. The Carvalhal area was surrounded by FSC-certified *Eucalyptus* plantations and comprises larger non-FSC areas (11.90 ha ± 4.80 ha), whereas Góis had a higher proportion of non-FSC areas, although with a smaller size (5.70 ha ± 4.70 ha) (example of non-FSC area in Supplementary information Fig. S1). These two study sites were managed by multiple landowners, with heterogeneity between patches in relation to the *Eucalyptus* production phase, forestry interventions, and understory vegetation. We selected two control study sites, located in the Serra da Estrela Natural Park, and in the Serra da Malcata Nature Reserve. Both control areas are dominated by native vegetation, including native woodland forests of *Q. robur*, *Q. rotundifolia*, *Q. pyrenaica*, and conifer trees (*Pinus pinea*, *P. nigra* and *P. pinaster*). In Serra da Malcata, the vegetation was dominated by Mediterranean shrubland (*Cytisus* spp., *Erica* spp., *Cistus* spp., and *Arbutus unedo*), with few patches of conifer

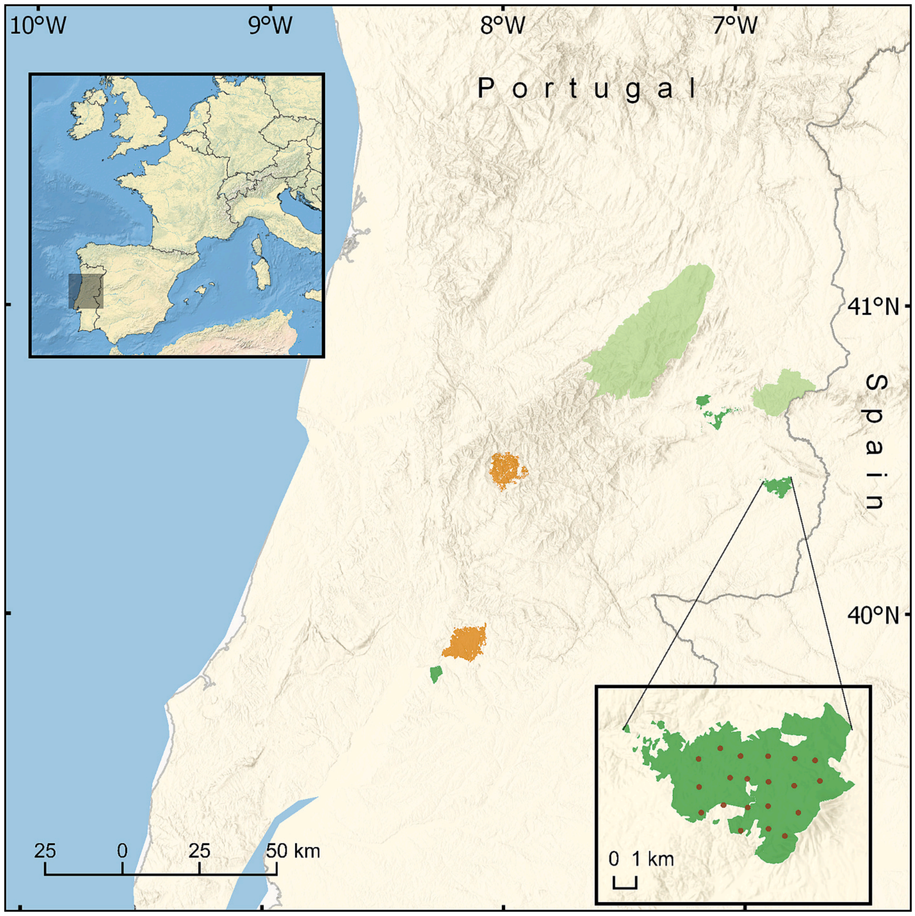

Fig. 1. Study sites in central Portugal where the camera-trap surveys were conducted. Control areas with native forests are represented in light green, FSC-certified *Eucalyptus* plantations in dark green, and non-FSC *Eucalyptus* plantations in orange. Brown dots in the subset symbolize the 1 km camera-trap grid that was deployed in all areas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

trees. Moreover, Serra da Malcata was characterized by the absence of villages and human settlements within its limits. In Serra da Estrela the conifer and woodland forests were dominant in the landscape, which also included agro-silvo-pastoral practices, which led to the replacement of these forests by stands of *Erica* spp., *Genista* spp., and meadows.

2.2. Mammal community survey design and covariates data collection

The study areas were sampled using a fixed camera-trap grid design. Cameras were placed regularly at an intercamera distance of 872 m ± 142 m (range: 540 m – 1, 420 m) and stayed active for 60 consecutive days, per sampling period. Due to the limited number of cameras, the seven areas were surveyed sequentially: cameras were deployed in four areas for the first 60 days and, upon completion, in the remaining three areas for another 60-day period. We deployed 20 unbaited cameras (Cuddeback H1453 and Browning Strike Force Pro DCL) at each study area, 50 cm above ground, attached to trees, and programmed to take three photos per trigger with a 20 s minimum delay between detections. We considered a detection record as independent if a record of the same species in the same camera had a minimum interval of 30 min (Rich et al., 2017). Cameras were placed in sites that provided the least obstructed field of view to achieve a higher detection probability of a wide range of species. We conducted surveys during four sampling periods, covering both wet and dry seasons: November 2022–February 2023 and November 2023–February 2024 (wet season), and May–August 2023 and May–August 2024 (dry season). Species were identified manually. The camera-trap data were processed and managed using the R package *camtrapR* (Niedballa et al., 2016), including image sorting, metadata extraction, and preparation for subsequent analysis. Species were manually identified from the images based on visual characteristics.

We selected environmental covariates that may be driving the possible detected effect of the management contexts on site-level occupancy. Namely, we expressed spatial variation in the level of habitat structure as: i) mean shrubland cover (SHRUB), retrieved from the Portuguese Land Cover 2022 raster (10 m resolution; https://snig.dgterritorio.gov.pt/); ii) Shannon-Wiener diversity index (SWI), representing habitat diversity within each camera-trap buffer (see below), calculated from the Land Cover 2022 raster land-use data using the R package *vegan* (Oksanen et al., 2017); and iii) Mean Normalized Difference Vegetation Index (NDVI) was calculated for each camera-trap site using the monthly NDVI values corresponding to the specific survey month, making the measure season-specific. Data were retrieved from the Portuguese Intra-Annual Maps of Vegetation Status (10 m resolution raster, https://dados.gov.pt/pt/). Covariate values were extracted as averages within a 500 m buffer around each camera trap. This buffer was selected to both minimize overlap between sites and approximate the core-area sizes of key target species (e.g., red fox, Eurasian badger; Cavallini and Lovari, 1994; Rosalino et al., 2004) ensuring that the spatial scale reflects typical species space use. We also included whether cameras were placed on animal/human trails as a binary covariate for the detection probability, as this variable has been demonstrated to be important even for elusive and rare species (Matias et al., 2021).

2.3. Multi-region community occupancy modelR

We adopted a Bayesian hierarchical multi-region community occupancy model to compare community composition (i.e., species-specific occupancy and site-level richness) between the three forest management contexts (Native, FSC-certified and, non-FSC, c = 3), while accounting for both imperfect detection and management context heterogeneity in species occupancy (Tenan et al., 2017). Species detection histories were generated using one-day sampling occasions, a common approach in camera-trapping studies. We acknowledge that this may introduce temporal autocorrelation between successive days (i.e., non-independence of detection events), but such effects are generally considered acceptable given the assumptions of occupancy models and the practical need to define consistent sampling intervals (MacKenzie et al., 2017). We organized the multispecies encounter frequency data from the three management contexts in a 3-dimensional array *Y*, with elements Y_{kjc} where $k = 1, \ldots, n_c$ being the species sampled at sites *j* and management context *c*. $Y_{jc} \geq 1$ indicates that species *k* was detected at site *j*. Missing observations due to cameras malfunction were implicitly handled: $Y_{kjc} \geq 1$ indicates detection of species *k* at site *j*, and sites with fewer active days contributed proportionally less to the likelihood.

Occupancy of species *k* at site *j* in management context *c* is represented by the latent variable z_{kjc}, defined as:

$$z_{kjc} \sim Bernoulli\ (\Psi_{kjc}\ \omega_{kc})$$

Here, Ψ_{kjc} is the probability that species *k* occupies site *j* in management context *c*, and ω_{kc} denotes whether species *k* is present in community *c* (see Tenan et al., 2017). For species that were observed in a management context the community membership ω_{kc} was fixed to 1, thus, estimates of species richness are conditional on the observed species set and do not account for undetected species (MacKenzie et al., 2017). Occupancy probabilities were modeled as logit-linear functions of site-level covariates SHRUB, SWI and NDVI:

$$\text{logit}\ (\Psi_{kjc}) = \beta_{0,k,c[j]} + \beta_{1,k}\text{SHRUB}_{[j]} + \beta_{2,k}SWI_{[j]} + \beta_{3,k}NDVI_{[j]}$$

We estimated species–specific occupancy probabilities as random effects with management context-specific intercepts ($\beta_{0,k,c[j]}$). This allowed us to specifically estimate differences in baseline occupancy across management contexts and among species.

The observation process was modeled as:

$$y_{kjic} \sim Bernoulli\left(z_{kjc}\ p_{kji}\right)$$

where p_{jki} denotes species detection probability, where *i* indexes sampling occasions (days), conditional on true occupancy z_{kjc} and modeled as a logit-linear function of site covariate TRAIL (i.e., on or off animal/human trail):

$$logit\left(p_{kji}\right) = \gamma_{0,k} + \gamma_{1,k}\text{TRAIL}_{[j]}$$

The species-specific regression coefficients $\beta_{1:3,k}$ and $\gamma_{1,k}$ (say θ) were treated as species-specific random effects from a community-level distribution, that we assumed to be constant across management contexts, in line with our focus on comparing community structure rather than context-specific covariate effects:

$$\theta_k \sim Normal\ (\mu_\theta \sigma_\theta)$$

Within the model, we determined species-specific comparisons between forest management contexts by subtracting the mean occupancy estimates for each species across all pairwise combinations of management contexts.

We implemented the model using Markov Chain Monte Carlo (MCMC) simulation in JAGS (version 3.4.0), called from R using the *R2Jags* package (Su and Yajima, 2015). We generated three parallel chains of 150,000 iterations each, with a burn-in of 30,000, and thinned by 10. To assess model convergence, we visually inspected the trace plots and used the Gelman-Rubin statistics (values ≤1.1 indicate convergence; Gelman et al., 1995). To evaluate the model fit we estimated the discrepancy between the deviance residuals of the observed and simulated data from the fitted model (Broms et al., 2016). We evaluated covariate effects by considering the 95 % Bayesian credible intervals (BCIs), i.e., 2.5 % and 97.5 % percentiles. Full convergence diagnostics for all monitored parameters are provided in Table S1.

3. Results

Across the three forest management contexts, we detected 15 wild mammal species. We removed five species with limited detections (< 5 in each area type) from the analysis: Iberian wolf, *Canis lupus signatus*; Fallow deer, *Dama dama*; European wildcat, *Felis silvestris*; European hedgehog, *Erinaceus europaeus*; and Red squirrel, *Sciurus vulgaris*. From 32,148 effective trap-nights (i.e., camera traps were fully operational without malfunctions; 95.68 %), we gathered 8409 independent records from the 10 target species (Table S2). Wild boar was observed most frequently ($n = 2574$), followed by red fox ($n = 1879$) and red deer (*Cervus elaphus*; $n = 1292$), while the lowest represented species with $n \geq 5$ were the Egyptian mongoose (*Herpestes ichneumon*; $n = 63$) and the European badger (*Meles meles*; $n = 110$).

The mean species occupancy among areas followed a gradient from native forests (0.58, range: 0.44–0.71), to FSC-certified (0.53, 0.42–0.64) and non-FSC plantations (0.44, 0.31–0.58; Fig. 2a). Using the posterior distribution of differences in mean occupancy (Δ), with 95 % Bayesian credible intervals and the posterior probability that occupancy in one management context exceeded another [Pr(Δ > 0)], FSC-certified plantations had slightly higher mean species occupancy than non-FSC plantations ($\Delta_{\text{FSC–Non-FSC}} = 0.09$, 95 % BCI: 0.03–0.15, Pr(Δ > 0) = 1.00), and slightly lower occupancy than native forests ($\Delta_{\text{FSC–Native}} = -0.05$, 95 % BCI: −0.11–0.01, Pr(Δ > 0) = 0.04), and non-FSC plantations had considerably lower occupancy than native forests ($\Delta_{\text{Non-FSC–Native}} = -0.14$, 95 % BCI: −0.20 to −0.08, Pr(Δ > 0) = 0.00).

At the community level, hyperparameter estimates showed similar trends in occupancy estimates, although with greater uncertainty: $\Delta_{\text{FSC–Non-FSC}} = 0.75$, 95 % BCI: −1.03–2.56, Pr(Δ > 0) = 0.80; $\Delta_{\text{FSC–Native}} = -0.46$, 95 % BCI: −2.35–1.40, Pr(Δ > 0) = 0.31; and $\Delta_{\text{Non-FSC–Native}} = -1.21$, 95 % BCI: −3.11–0.61, Pr(Δ > 0) = 0.09.

The observed mean species richness at site-level (i.e., the number of species directly detected at each site) followed a similar gradient (native forests: 5.80, range: 3–9 species; FSC-certified plantations: 5.28, 2–9 species; non-FSC plantations: 4.36, 0–8 species; Fig. 2b). FSC-certified plantations had higher mean observed species richness than non-FSC plantations ($\Delta_{\text{FSC–Non-FSC}} = 0.93$, 95 % BCI: 0.67–1.20, Pr(Δ > 0) = 1.00), and slightly lower richness than native forests ($\Delta_{\text{FSC–Native}} = -0.52$, 95 % BCI: −0.82 to −0.24, Pr(Δ > 0) = 0.00). Non-FSC plantations had markedly lower richness than native forests ($\Delta_{\text{Non-FSC–Native}} = -1.45$, 95 % BCI: −1.75 to −1.18, Pr(Δ > 0) = 0.00).

Despite the three forest management contexts did not strongly differ for overall species occupancy, comparing species-specific occupancy among contexts revealed that occupancy probability tended to be highest in the native areas for most species (Fig. 3c, e; Table S3). Four species – roe deer (*Capreolus capreolus*), stone marten (*Martes foina*), European rabbit (*Oryctolagus cuniculus*), and red fox – revealed higher occupancy (i.e., 95 % BCIs not overlapping zero) in native areas than FSC *Eucalyptus* plantations (Fig. 3d), and three species – Iberian hare (*Lepus granatensis*), stone marten and red fox – relative to non-FSC plantations (Fig. 3f; Tables S3–4). Only one species – Iberian hare – displayed a significantly higher occupancy in FSC plantations than in native areas (Fig. 3d). Species-specific mean occupancy was similar between the FSC and non-FSC plantations, except for the Iberian hare and the wild boar, which were more widespread in the FSC plantations, and the European rabbit (*Oryctolagus cuniculus*), which was more common in the non-FSC areas (Fig. 3a–b; Tables S3–4).

Few species demonstrated strong association with the site-level

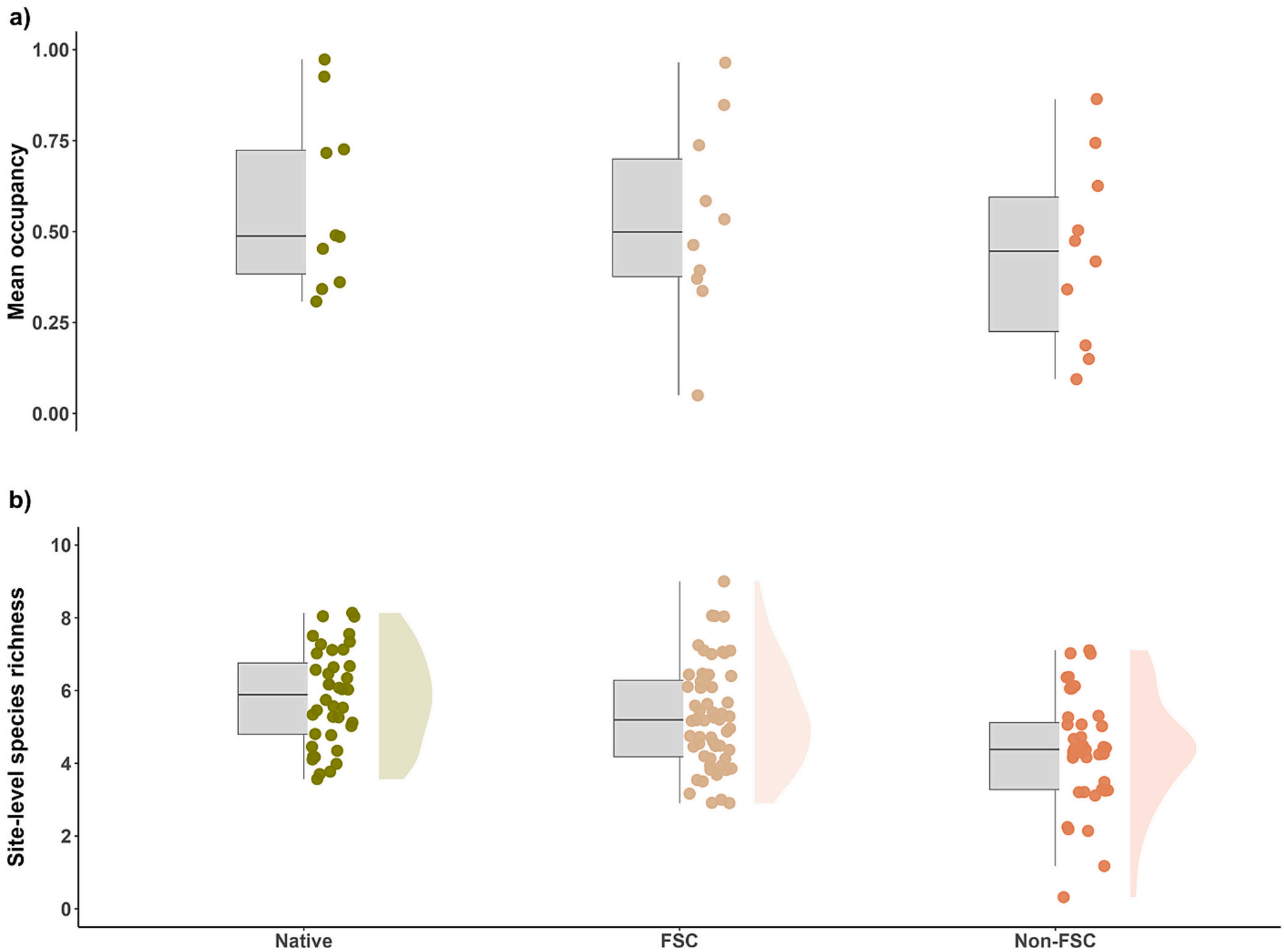

Fig. 2. (a) Mean species-specific occupancy and (b) observed species richness per camera trap site and management context (Native, FSC-certified, and non-FSC). Points are the posterior distribution means of species occupancy (a), and observed site-level richness (b). Error bars (95 % Bayesian credible intervals) are omitted from the figure for visual clarity. Species-specific occupancy estimates with standard deviations and 95 % Bayesian credible intervals are provided in Table S3.

covariates, with direction and strength of responses varying among species (Table S5; 95 % BCIs not overlapping zero). Among these, the European rabbit occupancy was positively related to shrub cover ($\beta = 1.04 \pm 0.43$, 0.22–1.93). A more complex habitat structure (i.e., higher Shannon index) had a positive effect on the occupancy of red fox ($\beta = 0.53 \pm 0.29$, 0.01–1.13) and roe deer ($\beta = 0.50 \pm 0.21$, 0.11–0.94). Moreover, higher values of NDVI increase the occupancy of the artiodactyl species ($\beta_{\text{red deer}} = 0.42 \pm 0.20$, 0.04–0.84; $\beta_{\text{roe deer}} = 0.83 \pm 0.24$, 0.38–1.33; $\beta_{\text{wild boar}} = 0.92 \pm 0.35$, 0.28–1.66). Overall, species had higher detection probabilities along human/animal trails (Table S5).

4. Discussion

The evaluation of the effectiveness of forest certification as a tool for mitigation of forestry impacts on wild mammal communities is scarce, especially in Europe, with an urgent need to improve forest management standards (Matias et al., 2024). Our research raises questions about the effectiveness of FSC certification on wild mammal conservation in *Eucalyptus* exotic plantations, in the Mediterranean region. Using a large-scale, case-control study design based in Portugal, we found no evidence that mammal site richness and community occupancy differed between FSC-certified relative to non-FSC forest management, while values were slightly higher in native areas. At the species level, however, we found evidence of higher occupancy in native areas for most species, consistent with our first hypothesis that mammals preferentially use unharvested native forests due to their higher resource availability and lower disturbance levels. In contrast, we found no evidence for our second hypothesis that habitat generalists such as red fox and wild boar would show similar occupancy across FSC-certified and non-FSC sites. Only a few opportunistic species (e.g., wild boar and Iberian hare) showed evidence of higher occupancy in FSC-certified plantations. Moreover, we found that environmental drivers played a key role in shaping species-specific occupancy patterns across management contexts, generally consistent with our third hypothesis. Specifically, higher vegetation productivity was linked to greater occupancy by ungulates, increased shrub cover benefited European rabbits, and habitat heterogeneity was important for roe deer and red foxes.

4.1. Patterns in wild mammal occupancy across management contexts

Despite the anticipated outcome of environmental-oriented FSC management being the maintenance or enhancement of biodiversity values (Miteva et al., 2015; Tritsch et al., 2020), the results obtained demonstrated an absence of evidence for most wild mammals inhabiting *Eucalyptus* exotic plantations. Overall mammal occupancy was similar across the FSC-certified and non-FSC plantations. This finding contradicts previous research reporting higher richness and/or populations abundance in FSC areas relative to non-FSC areas, albeit for different forest types and climates (e.g., tropical forest) and richer mammal communities than the Mediterranean one (Zwerts et al., 2024). This

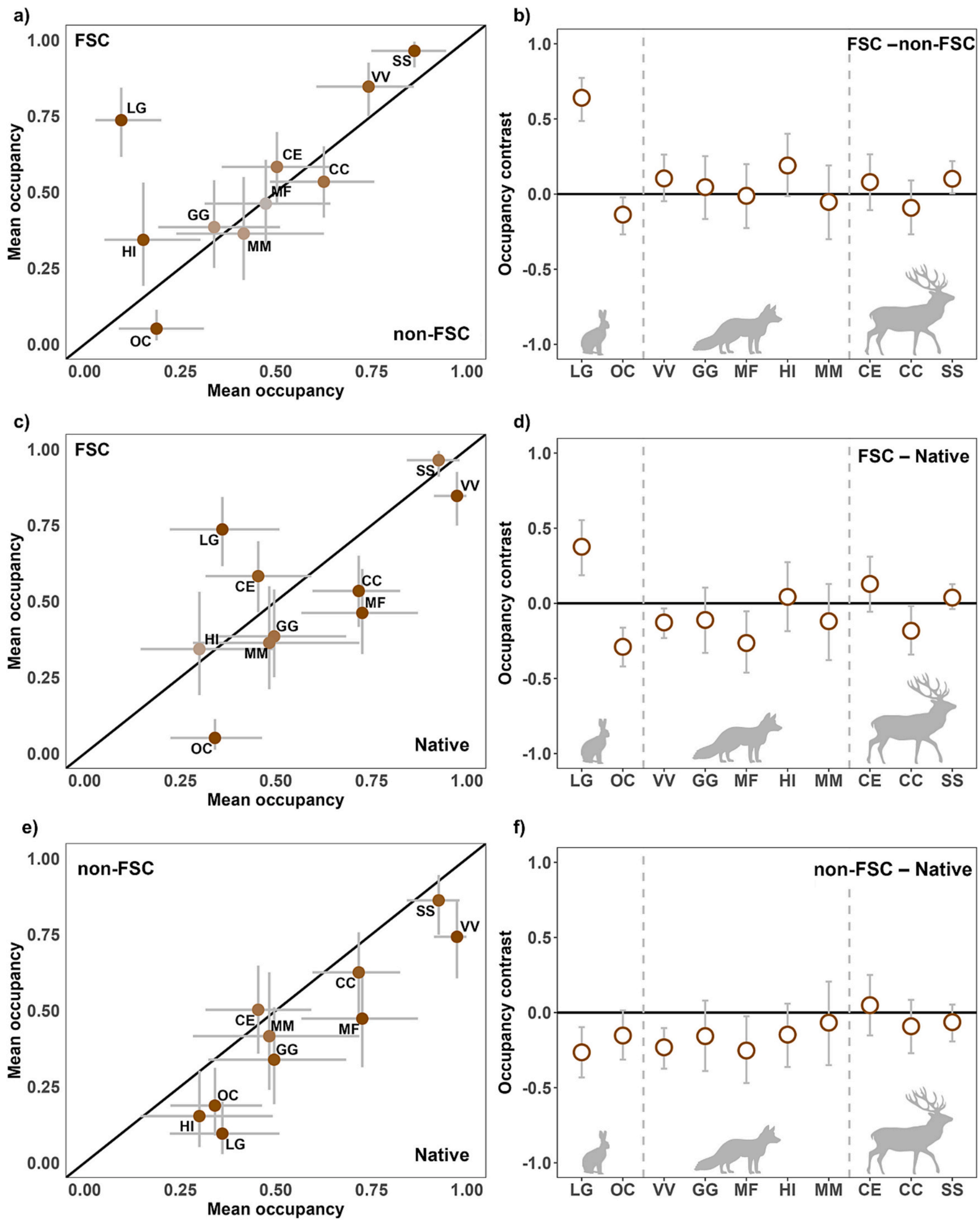

Fig. 3. a, c, e – Species-specific mean occupancy estimates between forest management contexts (Native, FSC plantations, and non-FSC plantations). Points above the diagonal line indicate higher occupancy in the *y*-axis area, whereas points below the diagonal line imply higher occupancy in the *x*-axis area. Error bars represent 95 % Bayesian credible intervals. b, d, f – Species-specific occupancy contrasts between forest management contexts. Vertical dashed lines indicate taxonomic groups, identified by reference species symbols: lagomorphs (LG – *L. granatensis*, OC – *O. cuniculus*), carnivores (VV – *V. vulpes*, GG – *G. genetta*, MF – *M. foina*, HI – *H. ichneumon*, MM – *M. meles*), artiodactyls (CE – *C. elaphus*, CC – *C. capreolus*, SS – *S. scrofa*).

discrepancy highlights the idea that different scenarios can lead to notable differences in the effectiveness of FSC at the regional level, modulating its overall impact on biodiversity (Panlasigui et al., 2018).

Our findings are consistent with the results of a global review on the impact of FSC on biodiversity, which indicates that carnivores and medium-large sized species appear to be more prevalent or have similar abundances in non-FSC areas (Matias et al., 2024). In our case, most species, including carnivores and artiodactyls, showed a similarity in occupancy between the two typologies, which contradicts the findings of some studies that suggest that FSC can benefit carnivores (Tobler et al., 2018; Zwerts et al., 2024). This may indicate two scenarios: i) the applied FSC management measures in our study areas do not promote mammal species occupancy and, ultimately, their safeguarding; ii) the non-FSC areas may be comparable to FSC management schemes and provide equal resources for mammals, thereby offering comparable conditions for mammal persistence. In any case, mammal species were found less frequently in both FSC-certified and non-FSC plantations compared to native forests (see below).

In designated FSC-certified areas, there is an obligation to promote the presence of native ecosystems (e.g., native patches composed of shrubs, which promote higher habitat heterogeneity), in accordance with FSC criterion 6.5. However, in the study areas under consideration, the FSC-certified areas exhibited the lowest levels of shrub cover, vegetation productivity and habitat heterogeneity (i.e., edge density; Fig. S2). This finding may indicate that the measures implemented are not promoting the presence and restoration of native ecosystems. We found evidence that certain species were more likely to respond positively to the presence of shrubs, higher vegetation productivity, and increased habitat heterogeneity (Table S5), with posterior estimates supporting our third hypothesis. Consequently, the ineffectiveness of implementing measures that promote these characteristics within FSC-certified areas may lead to the observed similarity in species occupancy values for most species. However, three species revealed higher occupancy in FSC-certified plantations (Iberian hare, wild boar, and Egyptian mongoose), supporting the effectiveness of certification schemes. This pattern may reflect species-specific factors, including natural population distributions and local abundances (Table S2), as well as site management-related habitat features such as shelter opportunities (e.g., dense shrubs cover). Previous studies indicate that these species tend to prefer areas with denser shrub cover, which provide refuge and foraging opportunities (Palomares and Delibes, 1993; Tapia et al., 2010; Laguna et al., 2021). However, our landscape analysis revealed that FSC sites exhibited significantly lower shrub cover compared to non-FSC areas. This apparent discrepancy suggests that the presence of finer-scale habitat features (e.g., small dense vegetation patches) not captured by our landscape metrics, or broader landscape context effects (e.g., connectivity to adjacent native habitats), may drive the observed patterns. These observations suggest that, while FSC management measures may not broadly enhance mammal occupancy in exotic *Eucalyptus* plantations, certain species can benefit from localized habitat features provided by certified landscapes.

Additionally, forestry impacts, including the rate of deforestation, may contribute to the observed patterns. Previous studies in Europe indicate minimal differences between FSC-certified and non-certified areas regarding ecologically responsible harvesting practices (Blumroeder et al., 2018, 2019). FSC Principle 6 mandates that forest management prevents or mitigate negative environmental impacts; however, the framework does not specify a quantitative threshold for permissible forest loss (FSC, 2015). The absence of such an explicit limit may result in forestry impacts in certified areas occasionally equaling or exceeding those in non-certified forests (Blumroeder et al., 2019), potentially explaining the observed similarities in mammal occupancy. These results highlight the importance of further investigating the effectiveness of FSC environmental criteria, particularly those aimed at enhancing structural complexity and biodiversity within certified plantations. Such evaluations are essential to ensure that certification schemes truly meet their conservation objectives and guide adaptive management strategies.

Another reason that may also influence our findings is the structure of our non-FSC areas. These areas are distinguished by their diminutive size (8.70 ha $\pm$ 5.70 ha) and multiple stakeholder management, which may lead to less intense forestry operations (e.g., reduced clear-cut areas, and thus higher shrub cover; Fig. S2). In contrast, the FSC-certified plantations are characterized by the management of large-scale properties (ca. 1200 ha) with substantial and wide scales of forestry activities (e.g., timber extraction). Notably, the absence of a stipulated rate of forest loss within the FSC framework enables the potential for the impact of this activity to occasionally equal or exceed that observed in non-FSC areas (Blumroeder et al., 2019), leading to the more similar mammal occupancy patterns detected.

Non-FSC areas exhibited better habitat conditions than FSC-certified areas, including higher shrub cover, vegetation productivity, and structural heterogeneity (Fig. S2). Despite this, generalist species such as fox and wild boar, associated with heterogeneous and productive habitats, respectively (Table S5), exhibited higher occupancy in FSC-certified areas. This pattern therefore provided little evidence for our second hypothesis. A likely explanation relates to spatial context: non-FSC patches are small and embedded within FSC-certified landscapes (Fig. S1), enabling animals to use resources in adjacent FSC areas, as the small non-FSC patches alone may not provide sufficient habitat.

Few studies have evaluated the effect of FSC on mammals relative to reference 'control' sites (e.g., primary forests or protected areas; Bahaa-el-din et al., 2016; Polisar et al., 2017; Matias et al., 2024). Although mean observed site-level species richness and average occupancy were similar between native forests and FSC-certified plantations, reliance on these aggregate metrics can obscure important species-specific patterns (Matias et al., 2024). Indeed, most mammal species exhibited higher occupancy in native forests, consistent with our first hypothesis. These native areas provide higher availability of suitable resources for mammals, through the presence of refuge sites (e.g., a higher proportion of understory vegetation; Fig. S2), an important driver for the European rabbit in our study (Table S5), and food resources (i.e., higher vegetation productivity; R.F.B. da Silva et al., 2019; L.P. da Silva et al., 2019), especially for the artiodactyl group (Table S5). Additionally, one area – Malcata Nature Reserve – is characterized by the absence of residents inside it, and our study site was within a hunting refuge area, thus with a reduced human pressure. Furthermore, native forests present a more heterogeneous landscape structure, characterized by a higher diversity of habitats and increased edge density. This structural complexity was associated with higher occupancy rates for species that preferentially use such environments (e.g., red fox and roe deer; Table S5; Ares-Pereira et al., 2022; Pereira et al., 2024).

Although it has been previously reported that logging plantations reduce biodiversity with respect to primary forests (Gómez-González et al., 2020), other studies have revealed a similarity in biodiversity metrics between FSC and reference sites (e.g., birds and bats abundance, flora richness and diversity, and mammal richness; Bicknell et al., 2015; Blumroeder et al., 2019; Lhoest et al., 2020), and even positive effects (e.g., bird richness; Campos-Cerqueira et al., 2020). These studies used community measures that may mask the individual species effects (Dornelas et al., 2011), as evidenced by our findings (see Figs. 2a and 3). Given that mammal species use forest differently and consequently shall respond differently to forestry and forest management (Carvalho et al., 2021; Tobler et al., 2018), the effectiveness of forest certifications should not be assessed at the community level only, as this approach may overlook detrimental effects at the species level, especially those that are already threatened.

4.2. Conservation implications

The findings of this study indicate the alleged ineffectiveness of FSC certification practices in *Eucalyptus* plantations, especially for some species. It is widely acknowledged that *Eucalyptus* spp. may have several impacts on the environment, such as i) decline of soil nutrient content (Merino et al., 2005), ii) reduction in water yield reduction (Rodriguez Suarez et al., 2014), and iii) loss of biodiversity and threat to mammal fitness (Teixeira et al., 2019; Afonso et al., 2023). These effects and the extensive global coverage of *Eucalyptus* plantations (20 million ha; Wingfield et al., 2015), induce an urgent need to evaluate certified plantations' effects to gain a broader overview of the effectiveness of the current application of FSC criteria in these plantations.

In Portugal, the national FSC standards and guidelines were defined to be applied to both native forests and exotic plantations, which may jeopardize the effective sustainable management of plantations and consequently, the biodiversity they contain. In the context of our study, where mammalian communities exhibited limited response to FSC certification in exotic *Eucalyptus* plantations, this absence of plantation-specific criteria may partly explain the modest conservation outcomes observed. The uniform application of standards designed for both native forests and plantations may overlook the distinct ecological realities of plantation systems, including reduced structural complexity, altered trophic dynamics, and intensive management regimes, which require tailored strategies to effectively support biodiversity.

For instance, Brazil has developed plantation-specific FSC standards and guidelines (FSC-STD-BRA-1.1-2025 Plantations), which indicate a more targeted and effective management approach for plantations, ultimately benefiting the biodiversity present (Verdade et al., 2012; Timo et al., 2014). These differ from those for natural forests (FSC-STD-BRA-02-2025) by allowing silvicultural practices tailored to plantation cycles (e.g., shorter rotations, uniform planting), while still requiring biodiversity conservation strategies like habitat mosaics and ecological corridors. Such adaptation to plantation realities enhances implementation feasibility and may help achieve FSC biodiversity goals more accurately.

The detected ambiguity surrounding the effectiveness of the FSC worldwide may indicate that the one-size-fits-all approach (i.e., international FSC standards, and national standards covering native and plantation forests) may not be achieving the desired positive results for biodiversity. However, the metrics used to assess the impact of FSC vary considerably between studies (e.g., biodiversity metrics, different methodological approaches, etc., see Matias et al., 2024). Consequently, the establishment of a precise protocol for comparing biodiversity patterns between FSC-certified, non-FSC, and reference sites is imperative (Elbakidze et al., 2011), as FSC Principle 8 states that certified concessions shall demonstrate the achievement of management objectives through a monitoring program. Such protocol should not be restricted to the overall biodiversity but consider the evaluation of specific species (e.g., threatened species occurring in the areas), since our study shows that the effect of FSC might be species-specific.

4.3. The demand to strengthen certification and future research

We present a clear, evidence-based message regarding the limited effect of FSC certification on mammals inhabiting *Eucalyptus* plantations, which are likely to be applicable to other *Eucalyptus* plantations worldwide. Nevertheless, we also recognize that certain characteristics, such as the volume of timber harvested, the size of the concession, the density of roads, etc., may affect the impact of FSC-certified forest management on mammals (Burivalova et al., 2014), so this conclusion should be drawn with caution. In addition to local management characteristics, broader landscape configuration, including connectivity with source habitats (e.g., native patches), can strongly influence mammal richness (Dorph et al., 2021), highlighting the importance of landscape planning for understanding biodiversity outcomes in production forests.

This study calls for immediate action, reinforcing previous studies suggestions that FSC environmental criteria must be improved (Blumroeder et al., 2018; Matias et al., 2024). The environmental criteria - 6 and 9 - are mainly associated with management goals directly related to the condition of the vegetation (e.g., restoration of natural riparian areas, conservation and/or restoration of rare and threatened habitats, and landscape connectivity). There is a lack of management measures or indicators related to faunal communities (e.g., species richness/abundance). Mammals provide broader benefits to forests by playing a central role in ecological processes such as seed dispersal, browsing, and nutrient cycling (Lacher et al., 2019), or prey regulation. It may therefore be beneficial to include in FSC criteria management goals that target the mammal community, to assess whether the effect of management measures allows them to thrive and maintain/improve the ecological services they provide in these areas.

However, the efficacy of the FSC as a tool in biodiversity conservation may not be fully determined by community richness/abundance metrics alone. Habitat use patterns may serve as a complementary metric for monitoring programs, given its presumable correlation with FSC management actions. Furthermore, the implementation of fine-scale habitat use i.e., telemetry data, could serve as a highly effective method for determining the use patterns of plantations by wildlife and thus assess the environmental effectiveness of actions implemented to comply with FSC environmental criteria (e.g., conservation areas, retention of vegetation after harvesting events, landscape connectivity, etc.). Consequently, future research should concentrate on the fine-scale spatial ecology of mammals in certified areas, with the objective of ascertaining whether the compliance with current environmental criteria is conducive to the preservation of biodiversity in FSC areas that are subject to logging activities.

Finally, while we suggest that FSC criteria and milestones should include wildlife populations, it is also imperative that the standards and indicators of FSC certification should be adapted to the different types of certified forests: exotic plantations or native, as those already implemented in Brazil.

CRediT authorship contribution statement

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

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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. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2025.111579.

Data availability

Data will be made available on request.

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