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Review

FSC forest certification effects on biodiversity: A global review and meta-analysis

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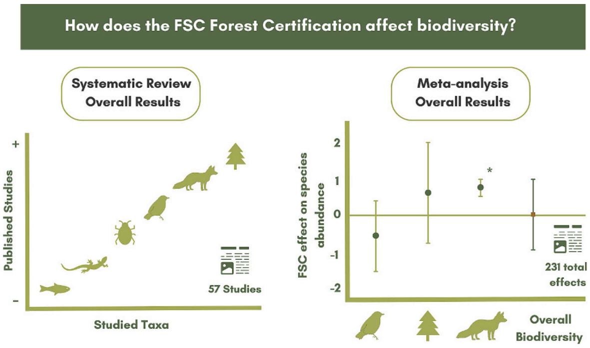
HIGHLIGHTS

- Overall, FSC certification has a neutral effect on taxa abundance.
- FSC effect on biodiversity varies across space and taxonomic groups.
- FSC-certified areas presented higher flora richness.
- Mammal responses to FSC certification depends on their ecological traits.

GRAPHICAL ABSTRACT



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ABSTRACT

FSC is a worldwide recognized forest certification scheme, that aims to promote the environmentally responsible management and conservation of the world's forests. Despite its broad application, there is little evidence of its effect on biodiversity. To address this important knowledge gap, here we conducted a systematic review and a hierarchical meta-analysis of the effects of FSC on biodiversity worldwide. Our review yielded 57 studies spanning 2004–2022. Most studies were in the Americas and Europe (31 % and 28 %, respectively), and largely focused on vascular plants (41 %). Half (51 %) of the studies aimed to determine the effect of FSC certification on biodiversity. There were 15 studies with sufficient information for meta-analysis, resulting in 231 effect sizes for mammal, bird, and vascular plant abundance and 10 for vascular plant richness. Overall, there is a neutral effect of certification on taxa abundance, with only a positive effect on mammal assemblages. Responses varied considerably between mammals' traits. Threatened species, individuals with reduced body weight, and omnivorous species benefit from management under the FSC scheme. Vascular plant richness exhibited significantly higher values in FSC-certified areas. Moreover, the abundance of vascular plants also differs among traits, with shrubs and adult trees benefiting from FSC certification. Our systematic review and meta-analysis revealed strong variation in biodiversity responses to FSC, and major geographic and taxonomic knowledge gaps. The overall neutral effect and the divergent responses of taxa and species traits suggest that taxa/species-specific management and improvement of FSC criteria are required.

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1. Introduction

The world has been losing biodiversity at a significant rate, regardless of conservation efforts (Butchart et al., 2010; Johnson et al., 2017). Human activities such as agricultural expansion (Foley et al., 2011; Tilman et al., 2017, 2011), and the transformation of natural habitats into planted and intensively managed forests (Payn et al., 2015) are the major drivers that promote this crisis. As a result of this pressure, the world's native forest area was reduced on average by 4.7 million hectares per year between 2010 and 2020 (FAO and UNEP, 2020). One of the most common conservation and management strategies to respond to these changing events has been the establishment of protected areas (Pringle, 2017). However, in recent years many protected areas have experienced degazetting and downscaling processes, being currently insufficient to prevent biodiversity loss (Jenkins and Joppa, 2009). Within this context, regulations implemented also outside protected areas have been seen as complementary tools to conservation efforts (De Alban et al., 2021). The increase of resource demand and consumption by the human population will add pressure on biodiversity conservation, hence it is essential to find suitable measures to integrate economically viable production outside protected areas and biodiversity conservation values (Gavin et al., 2018; Miller et al., 2011).

As a complement to protected areas, the management of private and public lands (e.g., planted and agricultural lands), which incorporates conservation values and or minimizes production impacts on biodiversity (Miralles-Wilhelm, 2021) has become an increasingly recognized strategy to reduce biodiversity losses (Bingham et al., 2017; Kamal et al., 2015). Planted forests with competent conservation management can still support some biodiversity (Hartley, 2002; Norris, 2008; Teixeira et al., 2020). But simply stating the adoption of reliable practices in production systems is not enough. The evaluation of the effective use of such options, and their impacts on the preservation of natural values is a pivotal issue to assure that biodiversity is still protected. Forest certification (FC) has been the most prominent private initiative to address responsible conservation management targeting forestry systems (Tollefson et al., 2009). FC is based on third-party auditing, considered a non-state market regulation developed by several governmental actors through public processes, that assesses the quality of forest management according to environmental, social, and economic standards (Marx and Cuypers, 2010). Within the context of forest management, several types of certification initiatives were developed, including the Forest Stewardship Council (FSC), the Lembaga Ekolabel Indonesia (LEI), the US Sustainable Forest Initiative (SFI), and the Programme for the Endorsement of Forest Certification Schemes (PEFC). However, the FSC is considered the only multistakeholder third-party certification scheme since the others utilize a form of self-regulation (Abbott and Snidal, 2009). Forest Stewardship Council was established in 1993, to promote "environmentally appropriate, socially beneficial, and economically viable management of the world's forests" (Auld et al., 2008), and individual/company participation was voluntary. FSC is based on 10 equal important principles and 57 criteria covering environmental, social, and economic characteristics of forest management. The standards (principles and criteria) certify responsible forest products that aim to promote high-quality management practices (Cubbage et al., 2010). Additionally, FSC monitors illegal and controls legal logging, thus contributing to halting deforestation and forest degradation. The standards used by FSC certification are considered some of the major and pioneering improvements in current environmental conservation (Agrawal et al., 2008). The area under FSC certification has increased worldwide in the last decades and to date covers about 160 million ha of forests, in 89 countries (https://connect.fsc.org/), representing 5 % of the world's forested area (FAO and UNEP, 2020). Despite FSC has been active for almost 30 years, the assessment of its effectiveness as a tool to assure the preservation of biodiversity in productive areas has been mostly carried out in tropical forests (Arbainsyah et al., 2014; Campos-Cerqueira et al., 2020; Romero et al., 2017), and especially targeting flora responses to the implemented management (Kalonga et al., 2016; Medjibe et al., 2013), with few studies implemented in temperate regions and using vertebrates as models (but see Dias et al., 2013; Oliveira et al., 2016). Forestry outcomes, auditing, and implementation practices diverge widely under FSC schemes (Burivalova et al., 2017; Nebel et al., 2005), which challenge the rigorous assessment of FSC impacts on biodiversity. Despite these constraints, several studies highlighted that compliance with FSC schemes reduces some environmental management impacts on biodiversity (Gullison, 2003; Johansson and Lidestav, 2011; Villalobos et al., 2018). By reducing environmental impacts, FSC can benefit the species richness and abundance of mammalian and plant communities, but the specific way that these species respond to FSC differs with species traits (e.g., morphological traits, trophic level; Lõhmus and Kraut, 2010; Sollmann et al., 2017).

In the context of global human pressure on forests, forest certification, particularly FSC certification, may represent an important tool for future forest sustainable management, and thus biodiversity conservation. However, to overcome some criticisms (e.g., Gullison, 2003) and distrust in the effectiveness of the process, it is pivotal to assess if the application of FCS principles can generate globally (geographically and taxonomically) positive impacts on biodiversity values. Studies that assess FSC certification outcomes often use conservation thresholds linked to natural and pristine areas (and not to uncertified production areas) and therefore tend to conclude that it falls short as a tool for assuring the maintenance of biodiversity values (Elbakidze et al., 2011). This suggests that the standard against which FSC outcomes are evaluated may affect the scale of the detected impacts. Moreover, the variation in scale and diversity of contexts of FSC-certified areas creates a significant challenge to adequately assess its effectiveness as a tool for biodiversity conservation (Panlasigui et al., 2018), and no general pattern has been assessed until now.

Therefore, we present here a global review and a hierarchical meta-analysis to evaluate how the FSC certification scheme affects biodiversity values. The specific objectives of this study were to (1) synthesize the published literature targeting the impact of FSC certification on biodiversity on a global scale, (2) highlight the major geographical and taxonomic knowledge gaps regarding the effect of FSC certification on biodiversity, (3) determine the overall effect of FSC on richness and abundance of different taxa, and (4) evaluate how the response to FSC certification varies across the detected species' traits.

2. Methodological approaches

2.1. Literature search

We conduct a detailed literature search aimed at identifying all the published articles that assess commonly used biodiversity metrics (e.g., species richness/abundance) in areas certified by the Forest Stewardship Council (FSC) across the world. To accomplish this, we used a combination of the following keywords that correlate the FSC certification scheme with biodiversity: "FSC" OR "Forest Stewardship council" AND "Forest* certifi*" OR "Forest* manage*" OR "certfi*" OR "manage*" AND "Biodivers* Conserv*" OR "Biodiv* Protec*" OR "Conserv*" OR "Protect*" OR "Effecti*" OR "Affect*" OR "Effic*" OR "Animal* protec*" OR "Animal* conserv*" OR "Species conserv*" OR "Species protec*". This query is associated with the research topic, broadly used, as well as accurate, however not overly specific to ensure a complete relevant literature. The search was performed using the Web of Science, and Scopus search engines, and included all the articles in English, between 1993 (establishment of FSC; Auld et al., 2008) and July 2022. We supplemented our literature search with publications used in previous reviews with similar topics to those targeted by our research (Burivalova et al., 2017; Romero et al., 2017). After title and abstract screening using the Revtolls R package (Westgate, 2019), our review yielded 131 studies. This number was reduced to 57 studies after the full-text screening (supplementary information Fig. S1), considering exclusion criteria, i.e., articles mentioning the FSC, although not focused on biodiversity metrics.

We recorded the following information from all the articles in the final database: date of the study, country, and continent, target taxa, and biodiversity metric (abundance, richness). We also retained whether the effect of the FSC certification was determined, the baseline against which FSC is evaluated (i.e., uncertified or protected/pristine forest), and if the effect was explicitly tested or inferred by the authors from their experience and knowledge.

2.2. *Meta-analysis*

To conduct the meta-analysis, we retained studies that measured biodiversity responses between FSC areas and uncertified areas. We used two measures commonly used as effective measures of biodiversity: i) species richness, and ii) species and/or assemblage abundances (Maurer and McGill, 2011). Species richness included observed/estimated richness, and genera richness. Species and/or assemblage abundances denote indices of abundance sensu *lato* (e.g., density, capture frequency, occupancy), for a single species and/or across species assemblages, both in FSC and uncertified areas (data available in the supplementary material). These conditions were only verified in studies targeting mammals, birds, and vascular plants, hence our meta-analysis only comprises these taxa. Most of the reviewed studies included mean, standard deviation of the metric, and sample sizes. Sample sizes were typically the number of sites sampled in each category, or plots/fixes used in data analysis. For studies with standard deviation omitted, we calculated it from confidence intervals/standard error using assertion methods (Higgins and Green, 2008). When data were presented only in figures, we retrieved those statistics using the metaDigite package in R (Pick et al., 2019). For each study, we measure the effect size Hedge's *d* (Koricheva et al., 2013), which is an estimate of the standardized mean difference (i.e., the effect size) between control (uncertified) and treatment (FSC areas). This metric has the advantage of being not biased by small sample size, since it adjusts for variation with the study effort i.e., sample size (Gurevitch et al., 2001). A negative response to FSC is indicated by a negative effect size (e.g., reduction in species abundance/richness in FSC areas). We carried out a hierarchical meta-analysis, which allow us to consider the multiple effect sizes gathered from the same study (Stevens and Taylor, 2009). Hence, we include a random effect comprising the publication level (i.e., study identification) as a nesting factor to incorporate the hierarchical dependence, as some studies presented various datasets. The effects of FSC certification were considered significant if the 95 % confidence intervals (CIs) of the effect sizes did not overlap zero (Koricheva et al., 2013). First, we analyzed the data with random effects model to determine the overall mean effect size of FSC on mammal, vascular plants, and bird species richness and abundance data, separately. Second, we considered mammal and vascular plant traits in the analysis, since species with different ecological traits may respond differently to forest certification (Lõhmus and Kraut, 2010; Sollmann et al., 2017). For mammals, we retrieved the body mass and converted it into three classes: i) small body mass (i.e., lower than 5 kg), ii) medium (i.e., between 5 and 100 kg), and iii) large (i.e., higher than 100 kg) (Hoffmann et al., 2010). Additionally, we collected information on the IUCN Red List threat category, trophic guild (herbivore, omnivore and carnivore), and locomotion mode (fossorial, and arboreal) for each mentioned species. Mammal information was obtained from the Pantheria database (Jones et al., 2009). Vascular plant traits were allocated into three main categories: seedlings, shrubs/herbs, and adult trees. Vascular plant information was retrieved from the article's information (i.e., the article stated one of these categories).

2.3. *Publication bias and study heterogeneity*

We explore the potential publication bias in our full dataset using two different methods. First, we performed Kendall's rank correlation on the full model dataset to test if the Hedge's *d* effect sizes are correlated, thus indicating publication bias (Jennions et al., 2013). Second, we computed Rosenthal's fail-safe number, which calculates the number of non-significant studies that would need to be added to the given set of observed outcomes to change the overall results. A fail-safe number is considered robust if it is larger than $5n + 10$, where n is the original number of studies included in the review (Jennions et al., 2013). Study heterogeneity among effect sizes was evaluated with a Q statistics heterogeneity test (I^2), which are weighted sum of squares tested compared to differences among categories, i.e., fixed effect sizes such as taxa, continent, mammal, and vascular plant traits in the model. Higher I^2 values indicate that a greater proportion of variation between effect sizes is due to variation between studies, rather than chance (Higgins and Green, 2008).

All the analyses were conducted in R Studio© version 1.1.463, and R version 3.5.3 (R Development Core Team, 2017), using the 'metafor' package (Viechtbauer, 2010).

3. Results

3.1. *Systematic review*

Our systematic review exhibited an increasing trend from 2015 onwards. Although FSC started in 1993, we only found studies that meet our criteria from 2004 onwards, nearly 10 years after FSC standards started to be implemented (Fig. 1). The continents for which we detected a greater number of published studies are the Americas (31.5 %), followed by Europe (28.1 %), Asia (22.8 %), and Africa (17.6 %). However, studies on the Americas are predominantly from South America (68 %), and only 16 % of the studies were from North and Central America. Studies retrieved in our literature search were mostly country-specific, with only a few encompassing more than one country (*ca.* 5 %).

The taxa more often targeted in our reviewed studies were vascular plants (40.8 %), followed by mammals (26.8 %), and the least studied groups were invertebrates (8.5 %), herptiles (i.e., reptiles and amphibians; 7 %), and fishes (1.4 %; Fig. 1). Overall, the majority of the studies included only one taxon, with a limited number of studies incorporating more than one taxon (5.6 % focusing on two taxa and 7 % on three taxa).

In total, 31 studies attempted to determine the effect of FSC certification on biodiversity values. Of those, 10 aimed to determine the effect of FSC in comparison to reference sites (i.e., protected areas, pristine forests), and 29 to uncertified sites (Fig. 2). Only 8 undertook the assessment of FSC biodiversity values and used both reference and uncertified sites for comparisons.

Overall, the impact more often associated with FSC effectiveness was positive (ca. 47 %), with 83 % of this being quantified (Fig. 2). The negative impact of FSC when compared to uncertified sites was less often detected, with only three studies stating this pattern. Concerning the effect of FSC when compared to reference sites, half of the studies had a neutral impact, 40 % had a negative effect, and only one study refers that FSC had a positive effect on biodiversity when compared to a reference site (Fig. 2).

3.2. *Meta-analysis*

From the original database with 57 studies, 15 of them met the criteria to be included in our meta-analysis, i.e., the difference in biodiversity values between FSC and uncertified sites was quantified. Several studies provided several observations; therefore, we obtained 243 observations (i.e., effect sizes). However, due to a reduced number of effect sizes comprehending herptiles ($n = 2$), we considered only 241 effects, 231 for abundance measures, and 10 related to species richness. The geographical coverage of this meta-analysis comprises 12 countries, from four continents. However, most research is from Asia and Europe, encompassing more than half of the effect sizes (68.8 %).

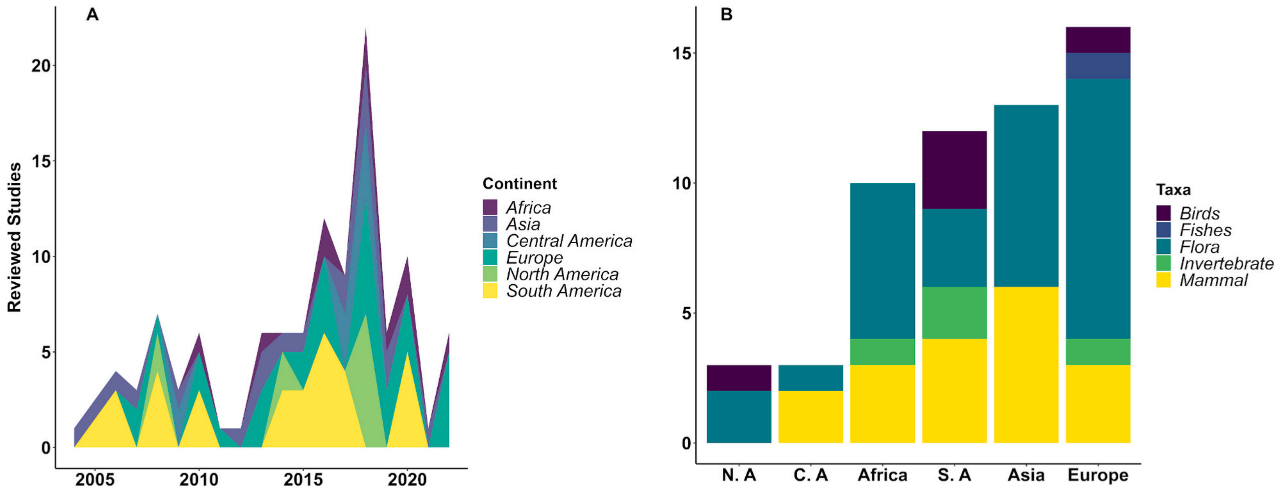

Fig. 1. Number of reviewed studies (total 57) per continent per year (a) and per continent per taxa (b). N. A (North America), C. A (Central America), S. A (South America).

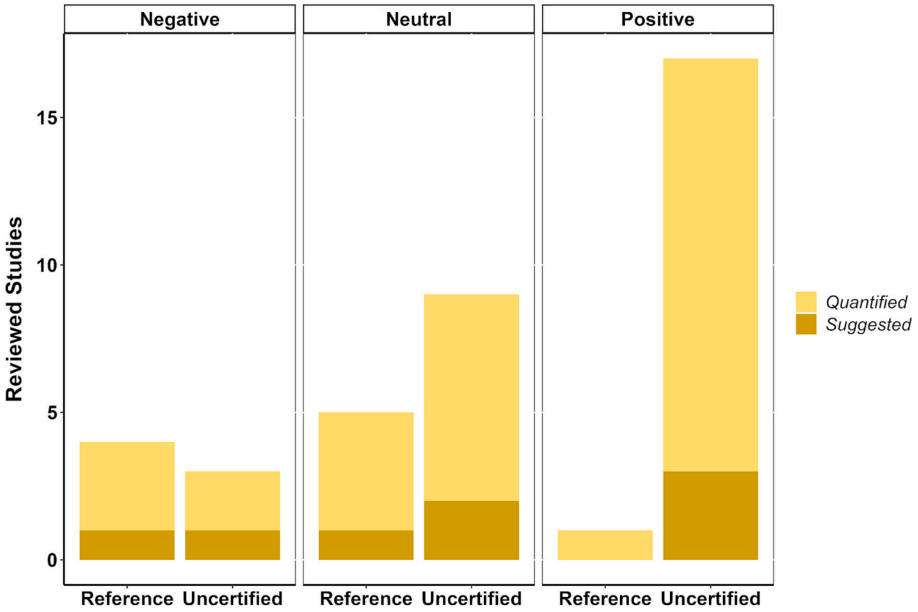

Fig. 2. Number of reviewed studies that incorporate the impact of FSC certification on biodiversity values when compared to reference and uncertified areas, and whether the impact was quantified or suggested by the authors (i.e., the authors' view, explicit in the study, concerning the FSC certification effect on biodiversity or possible effect).

We identified six studies that resulted in only 10 effect sizes covering species richness ($N_{\text{V. plants}} = 8$ effect sizes, $N_{\text{birds}} = 1$, and $N_{\text{mammals}} = 1$); therefore we were not able to implement a taxa-based study. Nevertheless, the heterogeneity was relatively high across those studies (QM = 70.8, $P < 0.001$, $I^2 = 85$ %), and the overall effect of FSC certification on species richness was positive ($\beta = 0.79 \pm 0.28$; CI_{95} 0.24 / 1.34), indicating that in FSC certified regions species richness is higher when compared to uncertified sites.

The overall effect of FSC certification on biodiversity abundance, when compared to uncertified sites, was neutral, since the effect was close to zero ($\beta = 0.03 \pm 0.33$), and the 95 % Confidence Intervals overlap zero (Fig. 3). We found significant heterogeneity of effects among taxa (QM = 39.9, $P < 0.001$, $I^2 = 97$ %) indicating that FSC affects differently taxa abundance. The most important pattern was the detected positive effect on mammals' abundance ($\beta = 0.74 \pm 0.12$; CI_{95} 0.51 / 0.97; Fig. 3). The effect of certification on the abundance of different taxonomic groups had no significant difference across continents (Fig. 3), as observed from the non-significant heterogeneity between studies of each continent (QM = 1.6, $P = 0.9$).

3.2.1. *Vascular plants*

Vascular plant traits database included 97 effect sizes with a relatively high heterogeneity across the studies (QM = 1890.01, $P < 0.001$, $I^2 = 97$ %). Despite the overall effect of FSC on vascular plant abundance was not significant, the certification exhibited a positive effect on shrubs and adult trees abundance (Fig. 4). The seedlings' abundance seems to be lower in certified areas, however the effect sizes had confidence intervals that overlapped zero and hence provided little additional insight.

3.2.2. *Mammals*

The mammal trait dataset had 118 effect sizes, from 48 different species. Heterogeneity tests revealed variation between studies for all mammalian traits (supplementary information Table S1). The FSC has a positive impact on the abundance of small mammals (body mass ≤ 5 kg),

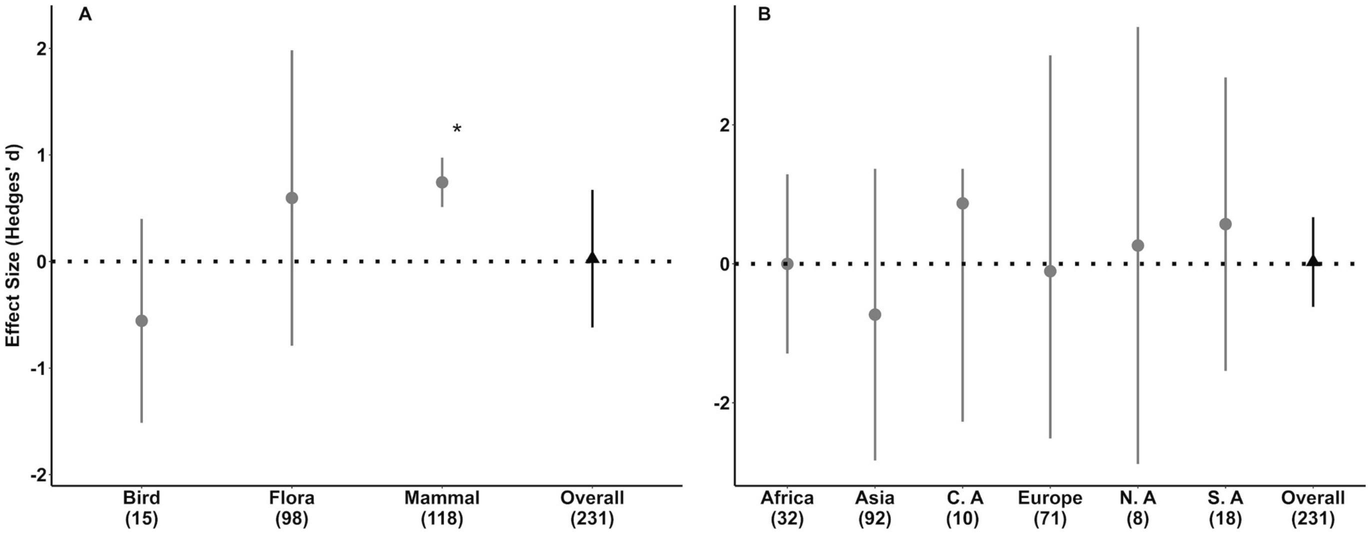

Fig. 3. Overall weighted-mean effect sizes and 95 % bias-corrected confidence intervals of FSC certification effects on (a) taxa abundance and (b) biodiversity abundance per Continent. The dashed horizontal line shows Hedge's d = 0. (*) Indicates significant Hedge's d values (i.e., values that did not overlap zero).

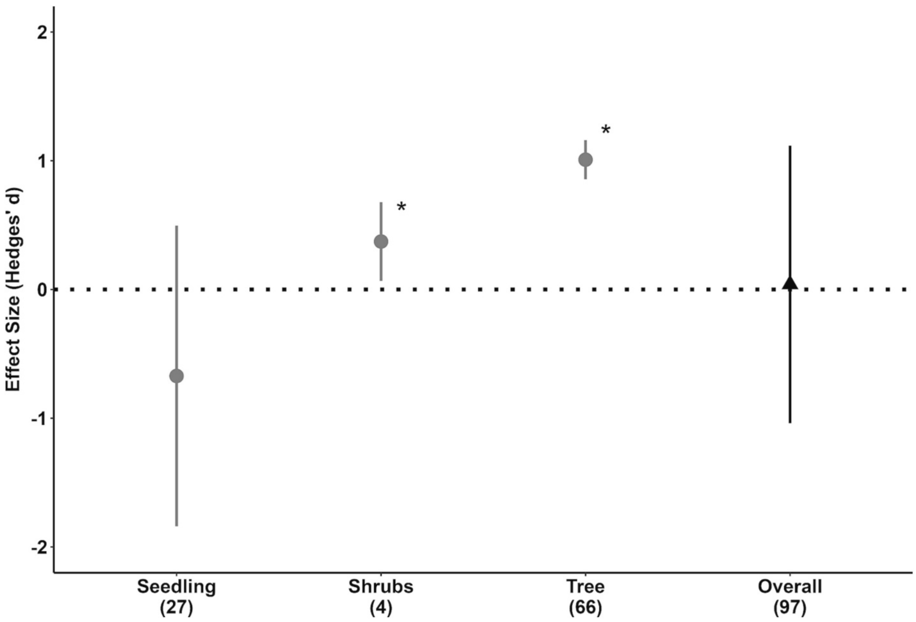

Fig. 4. Overall weighted-mean effect sizes and 95 % bias-corrected confidence intervals of FSC certification effects on vascular plant type abundance. The dashed horizontal line shows Hedge's d = 0. (*) Indicates significant Hedge's d values (i.e., values that did not overlap zero).

but also of species classified as least concern, vulnerable and endangered in the IUCN Red List, and of omnivores, when compared to populations inhabiting uncertified regions (Fig. 5). Contrariwise, the abundance of mammals with a carnivorous diet, and arboreal locomotion were negatively influenced by FSC (Fig. 5).

3.3. *Publication bias and study heterogeneity*

We did not detect evidences of publication bias, neither in our general abundance (Kendall's tau $= -0.04$, $P = 0.35$) and richness datasets (Kendall's tau $= 0.41$, $P = 0.10$), nor in the mammal and vascular plant traits datasets (Kendall's tau $= 0.07$, $P = 0.30$; Kendall's tau $= -0.10$, $P = 0.17$, respectively). Also, the Rosenthal's fail-safe number was higher than $5n + 10$, implying that the overall results achieved in our analysis are robust ($14{,}470 > 85$, $P < 0.001$). Altogether, our meta-analysis is not influenced by publication bias, indicating that our results efficiently describe the effect of FSC certification scheme on the targeted taxa in the studied geographical regions.

4. Discussion

Forest certification, namely FSC, is a pioneering scheme of a multi-stakeholder governance system that gives equal weight to the economic, environmental, and social dimensions of production, being the world's most trusted forest certification system (FSC consumer insights global report 2021; https://fsc.org/en/consumer-awareness). Despite its existence of about 30 years, our systematic review found several shortcomings: 1) the reduced number of studies on its effect on biodiversity, 2) geographic bias, with limited knowledge regarding the African and Central/North American continents systems, and 3) a bias in the studied taxa, with a lack of studies targeting bird, invertebrate and fish community. Moreover, most of the detected studies did not include

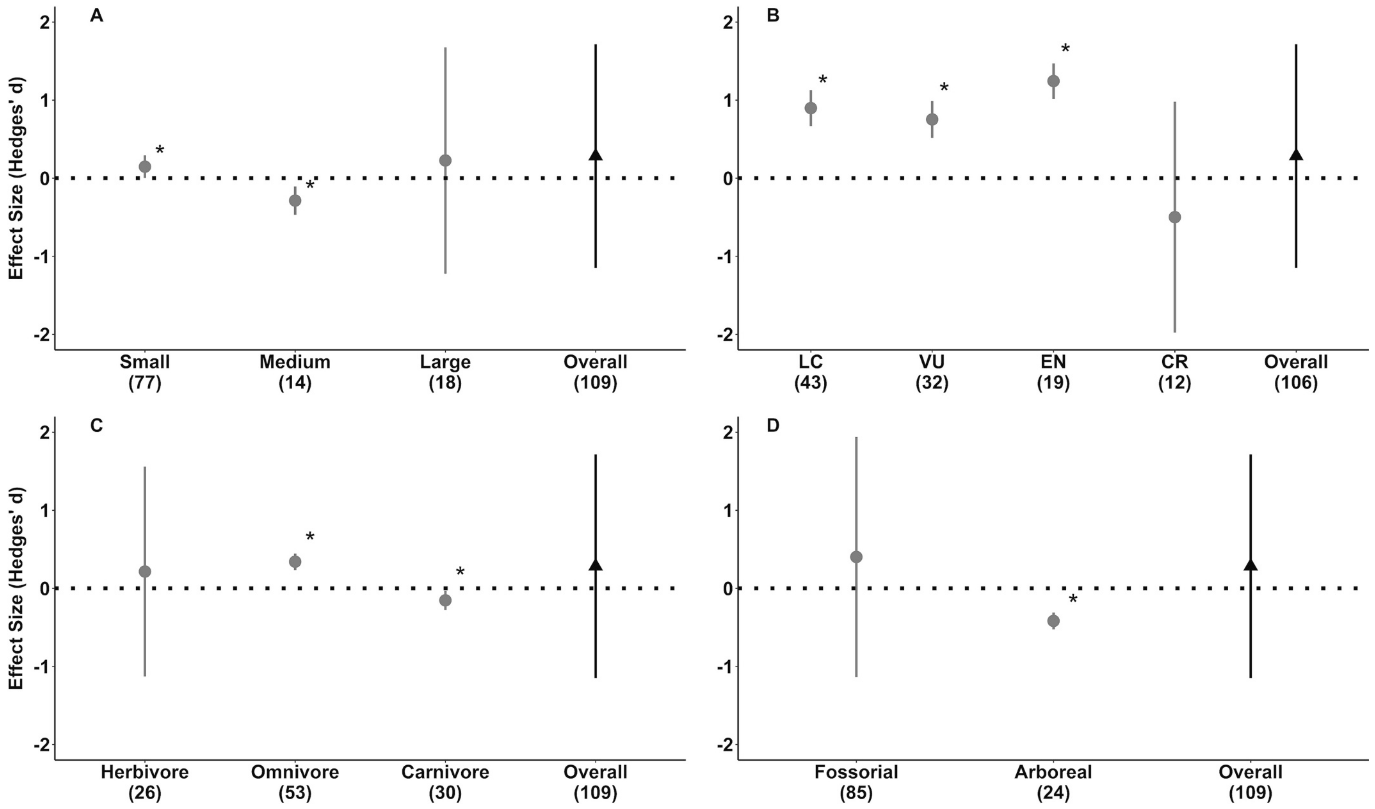

Fig. 5. Overall weighted-mean effect sizes and 95 % bias-corrected confidence intervals of FSC certification effects on mammals abundance: (a) body weight (small ≤5 Kg; medium >5 Kg and ≤100 Kg; large ≥100 Kg); (b) IUCN Red List categories (https://www.iucnredlist.org/); (c) trophic guild; and (d) locomotion mode (fossorial dwelling, arboreal dwelling). The dashed horizontal line shows Hedge's d = 0. (*) Indicates significant Hedge's d values (i.e., values that did not overlap zero).

measurements of the volume, and area of harvesting. This information can have an important impact on species abundance, and therefore should be included in the research description to allow the reader to better understand the mechanistic processes shaping the presented patterns (FSC, 2015; Gómez-González et al., 2020). Alongside, the majority of the studies reported biodiversity outcomes are related to flora measures (e.g., deforestation, forest cover). This may be linked to the fact that there is an assumption that native forest cover is a useful surrogate for biodiversity, although such an assumption is not always true (Burivalova et al., 2019). Moreover, forest cover and deforestation can be consistently estimated from satellite imagery (Hansen et al., 2013), which facilitates data acquisition even for more remote areas, while species richness/abundance/densities metrics are more expensive and logistically challenging to estimate (Ganivet and Bloomberg, 2019).

Our review suggested that the most frequently associated impact of FSC certification on biodiversity was positive, with most of these studies quantifying the impact. Such patterns on species richness were confirmed by our meta-analysis; however, it also revealed that the overall effect of FSC on the abundance of the studied taxa was neutral. This mismatch may be linked to the isolated or interaction effect of two factors: the variation in environmental contexts of FSC areas, and the wide divergence of FSC implementation practices, as showed by Keskitalo et al. (2009), which illustrates that the national infrastructure and market characteristics, results in significant differences in the impact of FSC at the local level. Such variation can make the generalization of FSC effects on the biodiversity patterns a challenging task (Panlasigui et al., 2018). In general, most studies included in our review quantified the FSC impact using a community measure (e.g., average species abundance), whereas in the meta-analysis we used the metrics for each species, which may influence the FSC effectiveness pattern, since species may respond differently to the forestry scheme (Lõhmus and Kraut, 2010), and estimating community metrics may mask species individual effects.

This overall neutral effect on abundance may indicate that the FSC-certified areas and the management measures applied do not promote the overall species abundance when compared to non-certified areas. Even in certified concessions, forest loss and anthropogenic disturbance are inevitable due to road construction, logging, and logging camps (Burivalova et al., 2017). Furthermore, as far as we know, there is no indication of the permitted rate of forest loss for an FSC-certified concession, thus, it may be possible that in some regions the intensity, volume, and area of logging are similar in certified and non-certified areas (Blumroeder et al., 2019; Medjibe et al., 2013). Thus, the possible absence of differences in these forestry metrics may influence the abundance of the studied taxa in our meta-analysis.

4.1. Vascular plant responses to forest certification

The abundance and vascular plant species richness, in areas certified with the FSC schemes, tend to be higher when compared to uncertified areas, despite the high variability in our data. The FSC scheme imposes a management of forests, either natural and production forests, guided by well-defined criteria concerning the vegetation dimension of management. For example, criteria 6.8 highlights that management units must be regulated to maintain and/or restore a varying mosaic of species, sizes, ages, spatial scales, and regeneration cycles appropriate for the landscape values in that region; and criteria 10.2 determines that concessions shall use native species and local genotypes for regeneration. Thus, by complying with these criteria, managers assure that plantations aligned with FCS criteria are having a positive effect on native vascular plant communities, by contributing to greater abundances and species richness in FSC areas when compared to non-certified forestry areas.

Furthermore, different types of vegetation, e.g., seedlings, shrubs, and trees, respond differently to FSC certification management. Shrubs and trees benefit from the management of forest certification and present higher abundances in FSC concessions. These results may be linked to the fact that areas managed competently through the FSC scheme must maintain and/or restore mosaics of different species/sizes for enhancing environmental and economic resilience (criterion 6.4 FSC; FSC, 2015). The same pattern was detected in several studies, where the abundance and richness of adult trees of different sizes were positively influenced by certification (Kalonga et al., 2016; Schaaf et al., 2020). Seedling's abundance effect sizes had variances that overlapped zero, suggesting FSC had no effect on this initial phase of plant's life cycle, or it was highly variable and uncertain. Concession deprived of sustainable use of forest resources under FSC scheme present also lower species richness (Blumroeder et al., 2019). We believe that the detected patterns are linked to the production forest commercial objective. The priority of the concession is timber exploration, and therefore, optimize profit. In such context, and without a sustainability perspective introduced into management by FSC it is expected that managers will prioritize within productions species that enhance profit (e.g., through timber extraction), and remove most of those that may compete for resources (e.g., space, light, nutrients, water), thus lowering species richness and abundances.

4.2. Mammals' responses to forest certification

Our findings revealed that the abundance of mammals is higher in FSC-certified concessions when compared to uncertified stands. Mammals have different ecological traits, which may imply different responses to forestry activities and therefore, forest management (Carvalho et al., 2021; Tobler et al., 2018). We observed that small mammals (i.e., body mass $\leq$ 5 kg), omnivores, and species included in least concern, vulnerable and endangered IUCN Red List categories reached higher abundances in certified forests when compared to populations inhabiting uncertified areas.

FSC certification requires that at least 10 % of the management unit is predominantly managed for biodiversity conservation (hereafter conservation zones; Tollefson et al., 2009). According to criterion 6.4, the conservation zones within the management unit shall protect rare and threatened species and their habitats (FSC, 2015). Conservation zones promote tree regeneration and shrubs diversity (Dias et al., 2016), which are crucial covariates for supporting functional small mammal communities (Afonso et al., 2021; Gonçalves et al., 2012), as well as threatened species (Penton et al., 2021). Thus, these conservation zones within FSC management units may provide sufficient habitat (including food and refuge resources) to increase the areas' carrying capacity in regions governed by logging activities, thus playing an important role in small mammals' well-supported communities (i.e., least concern species), and for threatened species. Moreover, FSC fosters habitat heterogeneity, especially inside conservation zones (Mexia et al., 2022). This heterogeneity might increase the food resources (Stein et al., 2014) and opportunities for omnivore species to achieve greater abundances (Denny et al., 2018) in FSC-certified concessions compared to uncertified regions. These results seem to confirm that criterion 6.4 is being fulfilled, leastways for the mammalian species inhabiting the study areas included in our meta-analysis.

This meta-analysis also indicated that mammals with a carnivorous diet and arboreal locomotion has lower abundances in certified areas when compared to non-certified areas. This result contradicts some studies that demonstrated that certification and competent management can beneficiate carnivores (e.g., jaguar, Tobler et al., 2018). We believe that this mismatch may be associated with the studies' methodological design. Our study includes 11 carnivore species, mostly over 10 kg (e.g., Leopard, African golden cat, Clouded leopard; Table S2). These species have greater home ranges and dispersal distances (Ofstad et al., 2016; Sutherland et al., 2000), and are often resilient to highly disturbed forests (Gardner et al., 2010). Most studies sampling designs did not assure spatial independence of the study areas, and therefore the FSC certified/non-certified areas are often contiguous in space. In such a spatial context is legitim to consider that these species individuals manage to use more than one area within the study period. In addition, some studies were located nearby natural areas (e.g., Natural Parks, and Nature Reserves) that surrounded the logging concessions, making it possible for medium-sized mammals to use undisturbed areas more regularly. Therefore, these results need to be interpreted with caution, as these species could have been more detected in non-certified areas due to the study design and spatial ecology of the species (i.e., home range size, dispersal distance) and the landscape spatial structure. The negative effect of certification on the abundance of species with arboreal locomotion might be related to the lack of difference in harvesting disturbance between the two contexts. For most studies no difference was found between the harvested area and volume intensity of the FSC-certified and uncertified areas (Imai et al., 2009; Sollmann et al., 2017). This absence of differences in disturbance scale does not imply that the FSC areas are not implementing their environmental management properly. It might indicate that the uncertified areas used in these studies have management schemes comparable to the FSC-certified areas. Hence, uncertified areas may provide equally suitable resources for arboreal species to thrive in logging concessions not using FSC certification.

4.3. Study limitations

Our literature study exhibited a taxa and species trait-specific effect of FSC certification. This pattern may be linked to the fact that ecological communities encompass a wide variety of populations, with very different ecological adaptations. Thus, researchers use community metrics that allow easier comparison between communities (e.g., species richness and/or relative abundance), but that may do not entirely address the complex nature of communities (Dornelas et al., 2011). Species presence and abundance may say little about how populations persist (i.e., survive and produce viable offspring) and to which extent they are affected by forestry activities and certification. High dispersal rates may generate a mismatch between species occurrence/abundance patterns and the ecological importance of the habitat (i.e. source-sink dynamics; Guisan and Thuiller, 2005). Additionally, specialist species with narrower niches, living in low abundances and usually across a limited distribution range, remain often undetected, or underestimated by the biodiversity indexes used in this meta-analysis. As specialist species tend to be more prone to changes and disturbances in the landscape (Sverdrup-Thygeson et al., 2017), missing their contribution to biodiversity indexes might underestimate the actual impact of disturbance. Thus, species presence/abundance in concessions should not be viewed as a sole surrogate of a suitable management regime, and factors such as habitat/resource use patterns and fitness could be valuable complementary monitoring metrics (Martínez-Abraín et al., 2010; Teixeira et al., 2019).

Furthermore, these metrics may be affected by temporal phenomena (e.g., reproduction, dispersion), as most studies included in our meta-analysis sampled communities over a short period of time. For example, it has been described that before a population collapse, the abundance and species richness may experience an increase (Pálinkás and Hufnagel, 2021), which may lead to an incorrect evaluation of their biodiversity status. Since human forestry activities in concessions that can have a negative effect on species abundance and richness (Chaudhary et al., 2016), have also a seasonal/yearly character linked to the production cycle (tree thinning/ harvesting; Elkin et al., 2015; Timo et al., 2014), future studies must incorporate a multi-season approach to encompass these phenomena in the assessment of biodiversity indexes.

4.4. FSC limitations & recommendations

The FSC's limited effectiveness in safeguarding and promoting biodiversity was highlighted throughout our work, as in other studies worldwide (Burivalova et al., 2019; Blumroeder et al., 2018, 2019). This inadequacy may result in a loss of biodiversity in several ecosystems around the world, with detrimental effects on the ecosystem functionality (Blumroeder et al., 2019).

The way FSC's environmental criteria are defined, quantified, and especially complied, is often poorly formulated, which may lead to inaccurate interpretation (Blumroeder et al., 2018). According to the FSC principle 8, FSC concessions are required to demonstrate that progress toward achieving the management objectives, the impacts of management activities, and the condition of the management unit, are monitored and evaluated proportionate to the scale, intensity, and risk of management activities, in order to implement adaptive management. However, to determine whether the management is FSC-efficient, is pivotal to define a precise and unambiguous evaluation metric that should be compared to the patterns estimated for uncertified concessions as well as a non-managed system (e.g. native habitat), as proposed by (Elbakidze et al., 2011). Accordingly, we suggest that the creation of a standard evaluation protocol, which allows quantifying the effectiveness of FSC applying measures such as abundance and species richness, using uncertified and non-managed regions as a comparison method, would be extremely vital for reliable insight into FSC certification worldwide. Nevertheless, our review showed that very few studies have adopted this approach.

The disagreement over the conservational value of tree plantations is in part related to the reference ecosystem considered, such as primary forests (Wang et al., 2022). It has been reported that tree plantations imply a decrease in biodiversity when the reference ecosystems are primary forests (Gómez-González et al., 2020). However, it has also been stated that FSC-certified concessions revealed greater bird richness when compared to noncertified and reference sites (primary forests with no logging history) (Campos-Cerqueira et al., 2020). Hence, accurate casual-comparative design to evaluate the effects of the FSC scheme on biodiversity should require an evaluation across multitrophic levels and appropriate reference ecosystems (i.e., non-FSC concessions and unmanaged systems).

It is critical that FSC certification scheme enhance the criteria related to: 1) the monitoring plan - it is essential to include uncertified areas as a control to determine the real effect of the management actions, and 2) volume/area harvesting limit - to our knowledge, FSC does not indicate a limit to the harvesting area/volume within certified stands, as the scale of harvesting will induce different impacts on wildlife. Thus, we suggest that FSC should create a legal harvesting volume/area limit (lower than the national harvesting limit for timber extraction) equivalent to a fixed proportion of the concession's size. These criteria, if correctly applied, may play an important role in biodiversity conservation, especially in areas where logging is the main activity.

5. Conclusion

FSC certification scheme was accepted as a system for achieving at least 11 goals within the agenda of the Sustainable Development Goals (FSC, 2016), thus it is assumed to be effective and reliable regarding biodiversity conservation and human wellbeing. However, our results suggest that there is no clear difference between the abundance of most taxa in FSC concessions compared to concessions deprived of ecologically responsible harvesting, i.e., uncertified stands. Our findings also highlight that further research is still needed. There are taxa that were not represented in our meta-analyses and that provide important ecosystem services and play crucial functional roles in ecosystems, such as invertebrates and aquatic fauna, evidencing gaps in knowledge. Moreover, given the divergent responses between taxa and species highlighted in our study, our meta-analysis emphasizes that prescribing a one-size-fits-all approach to managing biodiversity conservation could potentially have negative biodiversity outcomes. Finally, our results support the need to adapt some of the FSC criteria that mitigate forest activities and improve biodiversity conservation, to enhance the efficacy of this certification scheme for all taxa, at an international level. Without a full evidence base proving scientifically solid data of the benefits of FSC for biodiversity, decision-makers may be still reluctant to adopt and encourage advances in forestry practice toward environmentally sustainable production. Knowing that responsible management is likely to be fundamental to the long-term sustainability of production forests (Bicknell et al., 2015), our results clearly show that more research is needed to improve forestry practices and the assessment of biodiversity conservation management actions.

CRediT authorship contribution statement

Gonçalo Matias: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Francesca Cagnacci:** Conceptualization, Writing – review & editing, Supervision. **Luís Miguel Rosalino:** Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition.

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.

Data availability

The data used in this article is available on figshare (https://doi.org/10.6084/m9.figshare.23635815)

Data for Matias et al. "FSC forest certification effects on biodiversity: a global review and meta-analysis" (Original data)

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Appendix A. Supplementary data

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