Bridging the Gap: Exploring the Landscape Effects of Plantation Forestry on Biodiversity Conservation

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2025 IMEP

Advisor: Binbin Li

<u>Executive summary</u>

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In response to rising global demand for wood and fiber products, tree plantations have rapidly expanded over the past few decades. Compared to native forests, plantations generally support lower levels of biodiversity, particularly in monoculture systems with low structural complexity. However, outcomes vary widely depending on species composition, plantation age, and landscape context. Recent research highlights the importance of landscape-level factors, such as the proportion of surrounding natural forest, patch size, habitat connectivity, and matrix heterogeneity, in shaping biodiversity outcomes within plantation ecosystems. Primary forests, for instance, support more diverse and specialized species communities than secondary or plantation forests, while structurally diverse and well-connected landscapes can mitigate some of the biodiversity losses associated with plantations. This study aims to address persistent knowledge gaps by examining how plantation forests interact with landscape composition to influence biodiversity. Through meta-analysis and meta regression, it investigates how factors like plantation area, natural forest proportion, and patch configuration affect biodiversity within plantation-dominated landscapes, providing insights to inform sustainable forestry and conservation planning.

Data were systematically extracted from 92 peer-reviewed studies published up to May 2024, following a rigorous screening process from an initial pool of 5,897 articles retrieved via the Web of Science. Biodiversity metrics, forest types, plantation attributes, and geospatial information were compiled and standardized across studies. Effect sizes were calculated using Hedge’s g and analyzed through random-effects models to account for high heterogeneity across global datasets. Subgroup analyses were conducted by forest type, plantation age, taxonomic group, and biodiversity indicators. Landscape characteristics surrounding each study site were quantified using ArcGIS Pro and Fragstats based on a 10 km buffer, integrating multiple spatial datasets to derive metrics such as patch size, shape index, and interspersion index. Furthermore, multilevel meta-regression models were used to assess the influence of landscape metrics, forest composition, and climate variables on biodiversity outcomes. To minimize multicollinearity, only ecologically meaningful and low-correlation predictors were retained. This combined analytical framework provides a robust assessment of how plantation structure and landscape context affect biodiversity at multiple scales.

Key Findings

1. **Tree plantations exhibit an overall negative impact on biodiversity.** The meta-analysis revealed a significant overall reduction in biodiversity within tree plantations compared to natural forests. Both abundance and richness were significantly lower in plantations, whereas the Shannon–Wiener index showed no significant difference.
2. **Biodiversity responses vary across taxonomic groups, plantation characteristics, and landscape context.** Plants and vertebrates experienced the strongest biodiversity loss, while fungi and invertebrates showed more variable responses. Young and mid-aged plantations had significantly more negative effects on biodiversity than older plantations. Single-species plantations performed significantly worse than mixed-species systems, and plantations embedded in landscapes with <50% plantation cover suffered greater biodiversity losses.
3. **Landscape configuration and climatic variables influence biodiversity in plantations.** Meta-regression results identified log-transformed plantation area and plantation age as key positive predictors of biodiversity. Annual precipitation was also positively associated with biodiversity, whereas annual temperature showed no significant effect. Metrics such as shape index, interspersion and juxtaposition index (IJI), and the percentage of surrounding natural forest were not statistically significant.

Key Takeaways

1. **Plantation forests often support lower biodiversity than natural forests, but management strategies matter.** Single-species and exotic plantations generally exhibit reduced biodiversity, whereas native and mixed-species plantations can better mimic natural habitats and support richer faunal communities.
2. **Well-designed plantations can contribute to ecological restoration.** When established on degraded lands, plantations with diverse species compositions can aid in forest succession by improving microclimates, deterring invasive species, and facilitating seed dispersal.
3. **Future conservation-oriented forestry must adopt a nuanced, landscape-level approach.** Effective plantation management should integrate native and non-native species based on ecological context, promote habitat connectivity, and balance production with biodiversity goals to enhance ecosystem resilience under global change.

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Abstract

The interplay between ecological balance and anthropogenic alterations in the modern, ever-changing natural and human landscapes has resulted in significant impacts on biodiversity, while revealing a series of pressing research gaps. While existing studies have revealed some direct effects of tree plantations on biodiversity, in-depth analyses of how plantations indirectly affect biodiversity through the configuration and complexity of surrounding landscapes are insufficient. Specifically, there are still significant gaps in understanding how the size and connectivity of forest fragments, the presence of natural vegetation corridors, the percentage of surrounding natural or secondary forests, and the overall landscape mosaic combine to affect species richness and abundance in plantation ecosystems. In addition, interactions between plantations and neighboring ecosystems, whether they facilitate species migration or create barriers are poorly understood. These research gaps limit our ability to comprehensively assess the ecological impacts of plantations and optimize their contribution to biodiversity conservation.

This study aims to fill these gaps by exploring how plantations contribute to biodiversity restoration and what role landscape complexity plays in this process. Specifically, this study investigated whether plantation forests can restore biodiversity to near-natural forest levels, and how factors such as habitat connectivity, forest fragment size, and landscape heterogeneity influence the success of this restoration through meta-analysis . By focusing on landscape-level impacts, the research will provide valuable insights into how plantation management can be designed to support biodiversity restoration, not just within plantations, but across the landscape. This approach will contribute to the development of conservation practices that integrate biodiversity restoration with sustainable plantation forestry, ultimately promoting greater ecosystem resilience.

Key words: Plantation, Landscape effect, Natural Forests

Introduction

Over the past few decades, tree plantations have rapidly expanded to satisfy the rising global demand for wood and fiber products, while also alleviating pressure on natural forests. Since the 1960s, the area of plantation forests has increased significantly, reaching 291 million hectares by 2015(McEwan et al., 2020), with the most rapid growth observed in South America, Asia, and parts of Africa(*Global Forest Resources Assessment 2020*, 2020). These growth have been fueled by a combination of both market demand and government policies, including afforestation incentives and environmental restoration programs(McEwan et al., 2020). Plantation forests have been favored due to faster tree growth rates and shorter rotation lengths. For instance, eucalyptus and Acacia species are widely favored in plantation forestry due to their rapid growth rates, particularly in tropical climates where favorable temperature and precipitation conditions enable accelerated biomass accumulation(Santos et al., 2017). Countries such as China, Brazil, and India have led plantation expansion, with China alone increasing forest cover by 2.5 million hectares annually between 1990 and 2005 through programs like the Sloping Land Conversion Program(McEwan et al., 2020). In addition to their conventional function in timber production, plantation forests are increasingly recognized for their capacity to deliver a suite of ecosystem services, including carbon sequestration, biodiversity support, and the provision of renewable energy through bioenergy production(Pirard et al., 2016).This diversification of plantation roles is reshaping the design and management of forest landscapes. Industrial plantations are now being tailored not only for timber production but also for broader social and environmental outcomes(D'Amato et al., 2017). As a result, plantation forestry is transitioning into a multifunctional system that contributes to the emerging bio-economy and global climate goals.

Tree plantations can have both protective and detrimental effects on biodiversity and ecosystem integrity, with outcomes largely shaped by species composition, structural complexity, and management practices(Brockerhoff et al., 2017). On the positive side, increasing tree species diversity in plantations has been shown to enhance resistance to insect pests through mechanisms such as host dilution, associational resistance, and the support of natural enemies(Jactel et al., 2018). These processes stabilize ecosystem functioning, reduce pest outbreaks, and contribute to the long-term resilience of forest systems. In this sense, diversified plantations may offer partial biodiversity benefits and support certain ecological functions.

However, the ecological trade-offs associated with plantation forests can be significant. A global meta-analysis conducted by Hua et al. (2022) revealed that, relative to native forests, plantations characterized by low species richness and younger stand age consistently showed reduced performance across multiple ecosystem indicators. These included reductions of 29.3% in species-specific abundance, 32.8% in aboveground biomass, 60.6% in soil erosion control, and 13.4% in water yield. Even when compared to restored native forests of similar age, plantations were found to support lower biodiversity and offer weaker environmental services, particularly in dry regions(Hua et al., 2022). While plantations contribute substantially to timber and biomass production,their limited ecological performance highlights the need for reform in how these systems are designed and implemented. Enhancing the ecological role of plantations through mixed-species planting, structural diversification, and integration into heterogeneous landscapes is therefore essential(Uhl et al., 2024). As plantations continue to expand and play a central role in afforestation, reforestation, and carbon offsetting strategies, their transformation into multifunctional systems is critical for aligning production goals with environmental and conservation objectives.

Habitat fragmentation subdivides continuous forest landscapes into isolated patches, thereby decreasing the overall availability of suitable habitat and elevating the risk of both local and regional species extinctions. However, relevant studies have shown that certain types of landscape matrices can help mitigate the negative effects of habitat fragmentation(Kupfer et al., 2006). The matrix inside the landscapes can play several crucial roles, for example, it can provide additional habitats or resources for species, and can facilitate species dispersal between isolated patches, moreover, its properties or configuration can buffer against disturbance, such as reducing adverse edge effects(Driscoll et al., 2013; Ruffell et al., 2017). Plantation forests can significantly enhance matrix quality when embedded within landscapes containing native forest remnants(Felton et al., 2010, Fischer, 2007, Brockerhoff, et al. 2008). In New Zealand, Ruffell et al.(2017) found that landscapes with higher proportions of exotic pine plantations in the matrix experienced a much weaker decline in bird species richness as native forest cover decreased. Specifically, when native forest cover declined from 90% to 1%, species richness dropped by 60% in landscapes without plantations, but by only 15%(Ruffell et al., 2017) when 99% of the matrix was composed of plantation forest. Similarly, Brockerhoff et al.(2008) reported that plantation forests can support a variety of native forest species, including threatened taxa such as the brown kiwi (*Apteryx mantelli*) in New Zealand and the hoopoe (*Upupa epops*) in French pine plantations. These plantations can act as supplementary habitat, enhance connectivity among native forest patches, and buffer edge effects, thereby increasing overall matrix permeability and conservation value.

Global meta-analyses have consistently shown that tree plantations generally support lower biodiversity compared to primary forests(Wang et al., 2022) in terms of species richness and abundance. While biodiversity in plantations may sometimes approach levels found in secondary forests, particularly during natural succession, reforestation strategies that involve planting mixed native species have been shown to yield significantly greater biodiversity benefits(X. Wang et al., 2019). These results highlight the importance of plantation composition in shaping ecological outcomes.

Beyond plantation species composition, existing studies highlight the crucial role of landscape configuration and forest structure in shaping biodiversity outcomes. Barlow et al. (2007), in a comprehensive study involving 15 taxonomic groups in the Brazilian Amazon, demonstrated that biodiversity responses vary substantially across taxa, with primary forests consistently supporting higher levels of species uniqueness and distinct community composition than secondary or plantation forests. Landscape features such as patch size and spatial isolation were found to significantly affect species turnover, especially for less mobile organisms, as demonstrated in experimental landscapes designed to simulate habitat fragmentation (Spiesman et al., 2018).

In managed landscapes dominated by agriculture and plantations, landscape heterogeneity has been identified as a key determinant of ecological resilience. Powell et al(2015). found that landscapes maintaining a mosaic of land uses—including remnant native vegetation patches, diverse cropping systems, and agroforestry—were more likely to support higher levels of biodiversity and provide broader ecosystem services, such as nutritional diversity for local communities, compared to more homogeneous landscapes dominated by monoculture or single land-use types(Peters et al., 2023).

Looking more closely at taxon-specific responses to different forest types, patterns of biodiversity vary substantially. Bird assemblages generally show strong positive associations with primary forests, neutral responses to plantations, and slightly negative or mixed patterns in secondary or mixed forests ((Barlow et al., 2007, Amit & Klok, 2022). Large vertebrates, such as carnivores, piscivores, and herbivores, often display more idiosyncratic or neutral responses, with Barlow et al. (2007) noting comparable species richness of large mammals in both primary and secondary forests. In contrast, insects, particularly carabid beetles and dung beetles, are more sensitive to plantation expansion. For instance, Meng, (Meng, 2012) found that converting tropical forests to rubber plantations in southern Yunnan, China, led to a marked decline in native carabid beetle diversity.

Although research on plantations and biodiversity has grown, most studies remain focused on local-scale comparisons, such as the evaluation of biodiversity within plantations relative to adjacent primary or secondary forests (e.g. Gibson et al., 2011). However, there remains a substantial knowledge gap regarding the landscape-scale influences of plantations. Specifically, few studies have investigated how the spatial composition and configuration of the broader landscape affect biodiversity outcomes within plantation-dominated systems. For instance, how do factors such as the size and shape of forest patches, the percentage of the surrounding natural or secondary forest, the percentage of plantation forests in the total landscape, and the overall landscape mosaic impact species richness and abundance in plantation ecosystems? These gaps in knowledge limits our ability to assess the full ecological impact of plantations and develop strategies to optimize their contribution to biodiversity conservation.

This study aims to address these gaps by exploring how planted forests can contribute to biodiversity restoration and what role landscape complexity plays in this process. Specifically, it will investigate whether planted forests can restore biodiversity to levels comparable to natural forests and how factors like habitat connectivity, forest fragment size, and landscape heterogeneity influence the success of this restoration. By focusing on the landscape-level effects, this research will provide valuable insights into how plantation management can be designed to support biodiversity recovery, not just within the plantations themselves but across entire landscapes. This approach will help inform conservation practices that integrate biodiversity restoration with sustainable plantation forestry, ultimately contributing to more resilient ecosystems.

Planted forests are increasingly promoted as tools for ecological restoration, yet mounting evidence suggests they often support lower biodiversity than natural forests, particularly with regard to native species richness and ecosystem complexity (Stephens & Wagner, 2007). The biodiversity outcomes of plantation forests are influenced not only by stand characteristics, but also by broader landscape and environmental variables including temperature, precipitation, and surrounding forest types. For instance, mixed-species plantations tend to support higher biodiversity than monocultures, though their effectiveness varies by region and species selection (Liu et al., 2018). Moreover, landscapes with greater proportions of primary forest typically harbor more diverse communities than those dominated by secondary growth(Barlow et al., 2007). These findings underscore the importance of integrating plantation design with landscape context and ecological goals to enhance biodiversity outcomes.

To better understand the influence of landscape structure on biodiversity within plantation forests, this study proposes a series of hypotheses. The first is, landscape with larger area would have negative impact on biodiversity. The second is landscape with larger shape index would benefit the biodiversity(Estrada-Carmona et.al., 2022), and the third is, the percentage of plantation and natural forest inside the landscape can also affect the biodiversity. Several patches typically contain more species than a single large patch(Barlow et al., 2007), which means that the larger the total plantation patch area inside a landscape would negatively impact the biodiversity level. Additionally, the proportion of natural forests in the landscape surrounding planted forests has a positive impact on the biodiversity of planted forests, as natural forests can improve habitat coneectivity in facilitating species movement and genetic changes(Brockerhoff et al., 2013) and buffer plantation forests against distrubances such as pests and diseases(Hedwall et al., 2019; Viljur et al., 2022) thus enhacing the stability and resilience of plantation forests.

Method

2.1 Data preparation

To explore and compare the impacts of planted and natural forests on ecological diversity, this study employed meta-analysis and meta regression by integrating data from previous relevant research to derive more comprehensive research conclusions. Meta-analysis, a statistical technique for comparing and synthesizing results from prior studies on a shared scientific query, is central to drawing conclusions on the subject under study(Ahn & Kang, 2018). Its salient features include: 1. Integration beyond the scope of a single study. 2. Exploration of congruence and disparities in evidence across diverse studies. 3. Enhanced accuracy, objectivity, and generalizability(Noyes et al., 2019). Thus, the integrated and quantitative attributes of meta-analysis align well with the research focus on the contentious ecological impact of planted versus natural forests—a subject of ongoing debate among anthropologists. However, in the traditional meta-analysis, the observed effect in each study is an estimate, with some imprecisions, of the true effect in that study, and statistical heterogeneity refers to the true effects in each study may not being identical(Thompson & Higgins, 2002). Meta regression can utilize to relate the size of effect to one or more characteristics of the studies involved(Mathur, M. B., & VanderWeele, T. J. (2021)). In this way, by utilizing meta-analysis and meta regression, this study aspires to present a more comprehensive conclusion.
The search terms used, represented by the query TS=((“planting” OR “tree plant*” OR “plantation*” OR “afforestation” OR “reforestation” OR "production forest")

AND ("old-growth forest*" OR "old growth forest*" OR "primary forest*" OR "undisturbed forest*" OR "virgin forest*" OR ”secondary forest*" OR "secondary growth*" OR "naturally regenerat*" OR "natural regeneration" OR "natural regrowth" OR "natural forest*" OR "native forest*" OR "logged forest*" OR "environmental planting* OR "native planting*)AND ("biodiversity" OR “diversity” OR “richness” OR “abundanc*” OR "biomass" OR "basal area" OR "community" OR “densit*”)). The search was conducted on the Web of Science Core Collection without applying any filters on publication year, so as to include all relevant peer-reviewed studies available in the database at the time of the search. This comprehensive approach ensured the inclusion of both early foundational research and the most recent developments in the field. The final search was completed in May 2024. The finalized criteria of deciding if an article can be used are listed as follow:

1 it's a comparative research between natural forests & tree plantations
1.1 primary forests & tree plantations
1.2 secondary forests & tree plantations
2 it includes information on study location
2.1 specific lat. and lon.
2.2 map of study sites that can be identified through other tools
3 it includes extractable information on biodiversity as outcome variables
4 it includes study period

5 it should be a published in a peer-reviewed journal and have access to an English version

5897 academic articles included in the search result of the terms from Web of Science were reviewed and data were extracted. Among these papers, 107 of them do not have an open access. After contacting the authors of the papers and requested for PDF versions. By 9/23/2024, 26 responses have been received and articles were reviewed. In the rest of these articles, 1659 articles are excluded by criteria 1, 472 articles are excluded by criteria 2, 3012 articles are excluded by criteria 3, 2 articles are excluded by criteria 4, and 21 articles are excluded by criteria 6. Until now, 92 articles are eligible and used in the research.

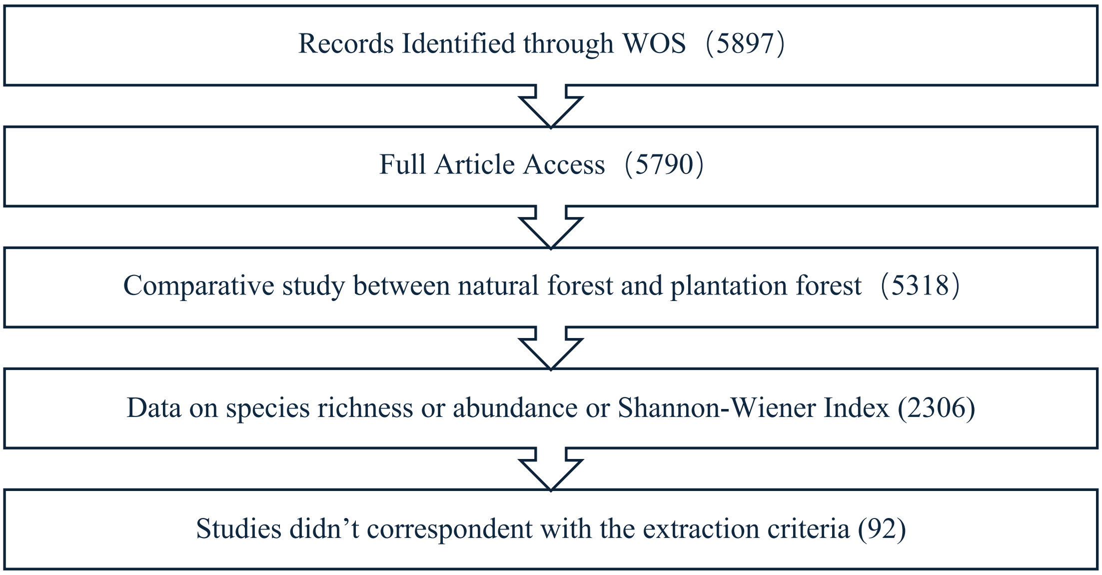

Figure 1. Data Extraction Form

After collecting the location, sample size, mean and standard deviation of different biodiversity indicators from the treatment group (plantation) and control group (natural forest), there are other data were collected such as the plantation type, the plantation age, the biodiversity indicators (for example, the abundance or the richness of the collected species). After turning each location to latitude and longitude and put into ArcGIS Pro, a buffer with 10km radius was created to determine the extent of the surrounding planation area to further identified the landscape metrics and characteristics of the surrounding natural forest or surrounding landcover type using Fragstats. Plantation forests data were compiled from multiple soueces, each with a spatical resolution of 30 meters. The primary dataset was the global-scale A global map of planting years of plantations (Du et al., 2022). However, to address spatial gaps and underrepresentation in certain regions, we supplemented this with two region-specific datasets: Pantropical tree plantation expansion (2000–2012) (Fagan et al., 2022), and a national-level dataset on plantation forests in Canada (Wulder et al., 2024).These additional datasets were included because several known plantation areas were either absent or incompletely mapped in the global dataset. The integration of these complementary sources enhances the spatial completeness and thematic accuracy of the plantation layer, thereby improving the reliability of subsequent spatial analyses at both regional and global scales.

To characterize natural forest cover and distinguish it from non-forested or plantation areas, we used tree canopy cover data from the Global Forest Change dataset (Hansen et al., 2013). Tree cover was reclassified based on canopy cover thresholds, with pixels showing above 30% canopy cover considered as forested and those below 30% classified as non-forested, following widely used global standards for forest monitoring(Hansen et al., 2013). This binary classification allowed for consistent identification of natural forests across diverse geographic regions.

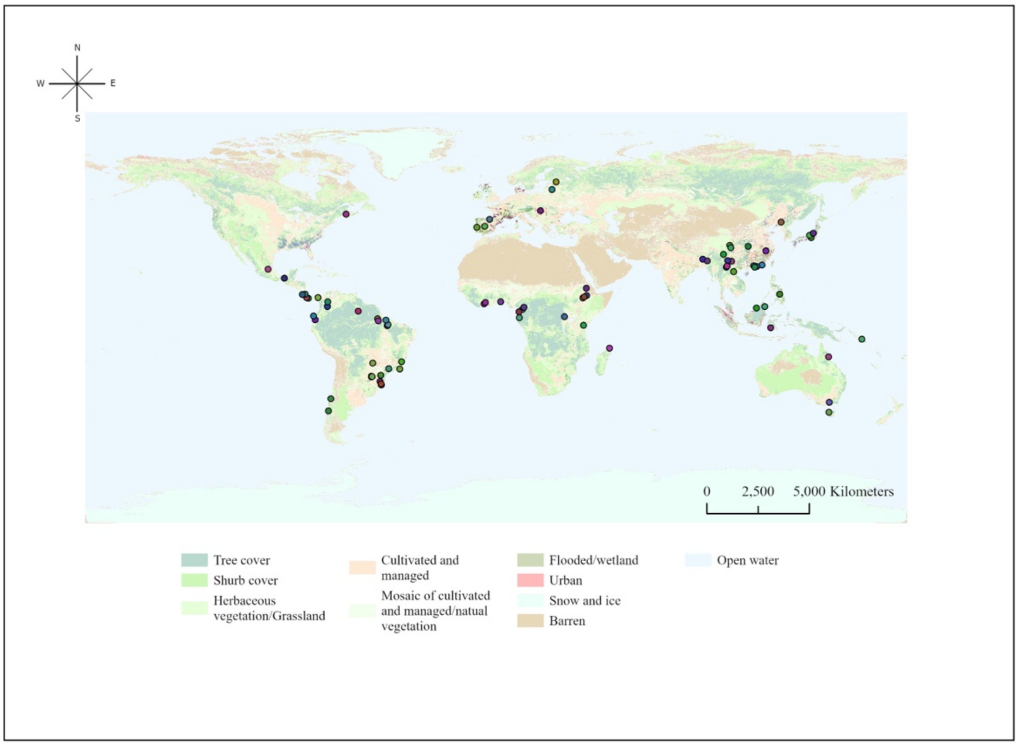

Figure 2. Global landcover, plantation, and studies extracted

To systematically evaluate forest structural attributes and their relationship with biodiversity, we calculated a suite of landscape metrics using Fragstats, categorized across the patch, class, and landscape levels. At the patch level, we measured total area (TA), perimeter (PERIM), perimeter–area ratio (PARA), core area (CA), and core area index (CAI). These metrics capture fundamental spatial properties of individual forest patches. For instance, TA and PERIM quantify patch size and boundary length, respectively, while PARA reflects shape complexity—higher PARA values often indicate irregular shapes prone to edge effects. CA and CAI estimate the area unaffected by edge influence, thus representing interior (core) habitat that is essential for edge-sensitive species. At the class level, we computed the shape index (SHAPE) and the Interspersion and Juxtaposition Index (IJI). SHAPE quantifies the geometric complexity of patches within a given class and can reveal the extent to which forest fragments deviate from compact forms. IJI, an aggregation metric, measures the degree of intermixing among patch types; higher IJI values suggest a more heterogeneous spatial pattern, which can enhance species movement and cross-habitat resource availability. At the landscape level, we calculated total area (TA) and total core area (TCA) to assess overall forest extent and the amount of edge-free habitat within the landscape. These metrics encompass both spatial composition (e.g., total area) and configuration (e.g., shape complexity, core area, spatial interspersion), providing a multidimensional understanding of landscape structure. Spatial configuration has been shown to influence ecological processes such as species dispersal, colonization, and persistence, thereby shaping biodiversity patterns. By incorporating these indices, we aimed to contextualize biodiversity responses with respect to habitat amount, shape, isolation, and connectivity.

2.2 Meta-analysis

A meta-analysis was conducted according to the studies extracted, using the “metafor” package in R and effect size was calculated according to Hedge’s g(Lipsey & Wilson, 2001)(Fomula 1) from standard mean difference (SMD), as it can quantify the difference in means between plantation and natural forests while accounting for variability within the populations. Because the studies were conducted globally and employed diverse measurement instruments, SMD was used to standardize measurements across studies by dividing the mean difference by the pooled standard deviation, thus enabling valid cross-study comparisons.

Hedge’s g

$$g = j * d$$

$$j = 1\text{-}\left(\frac{3}{4*(n1+n2-2)-1}\right)$$

$$d=\left(\frac{\overline{x1}-\overline{x2}}{Spooled}\right)$$

$$S_{pooled}=\sqrt{\frac{s1^2(n1-1)+s2^2(n2-1)}{n1+n2-2}}$$

Fomula 1. The calculation of effect size

A random effect model was used to conduct the meta-analysis, and it revealed high heterogeneity (Q = 19,355.96, $p < 0.0001$) as the data were collected from global scale, which needed further subgroup analyses to explore moderator effects. Subgroup

analyses were further conducted based on several categorical variables, including the type of surrounding biodiversity forest (i.e., primary or secondary forest), biodiversity indicators (abundance, richness, or Shannon–Wiener index), plantation pattern(mixed-species or single-species), biodiversity taxonomic group (fungi, invertebrates, vertebrates, or plants), and plantation age.
In terms of plantation age, three categrogies were evident from the collected samples, which were young plantation(less than 25 years old), mid plantation(25 to 50 years) and old plantation(older than 50 years)(Ohsawa, 2005; Ohsawa & Nagaike, 2006). Plantation age not mentioned in the articles were imputed by random imputation using observed category proportions within R(Rubin, 1986).

2.3 Meta-regression

To understand whether various landscape metrics and characteristics of natural forests directly impact biodiversity in plantation forests, a series of meta-regression analyses were conducted. Given the hierarchical structure of the data,we used mixed-effects meta-regression models to properly account for within-study dependencies, which means multiple observations were extracted from the same study. Specifically, we applied multilevel meta-analytic models using the lme4 and rma.mv function from the metafor package in R(Viechtbauer, 2010).

In addition to landscape structure, climate variables such as mean temperature and annual precipitation were also included in th regression model, based on the evidence that their roles in shaping biodiversity in forest ecosystems(Jactel et al., 2018). The data of temperature and precipitation are collected from Google Earth Engine. Temperature and precipitation were both collected from NOAA's Climate Prediction Center(CPC), both at a spatial resolution of 30m. The temperature dataset provides gridded daily maximum and minium surface air temperatures, from which we calculated the annual mean temperature (in Kelvin) for each grid cell. Precipitation data were aggregated to annual total precipitation (in mm). Both variables were averaged over the period from 2000 to 2022 to represent the long-term climatic comditions during eh study period.

To ensure comparability and reduce multicollinearity among predictors, only a subset of these metrics was selected for statistical analysis. Specifically, we focused on variables that were ecologically meaningful and showed relatively low intercorrelation($r > 0.7$)(Schober & Vetter, 2020). These selected metrics were then included as predictors in the meta-regression models to examine their influence on biodiversity levels in plantation forests.

Prior to running the meta-regression, I calculated Pearson's correlation coefficients among predictors to examine potential collinearity. Based on these results, I removed highly correlated variables(Core Area Index and the percentage of plantation in the total landscape) to avoid multicollinearity(Appendix Table 1). After this adjustment, the meta regression model could produce more statistically significant results.

In running a meta regression, a full model was specified with effect size as the response viariable, landscape metrics, including log-transformed total area, shape index, and interspersion and juxtaposition index (IJI) as the predictor virables， and the formula was created as follow:
Effect size (y_i) = ß_0 + ß_1 Log_Area + ß_2 Plantation_Age + ß_3(Primary or Secondary forests)+ ß_4(Annual temperature (°C)`) + ß_5(Annual precipitation (mm)) + ß_6((Natural forest(%)) + ß_7 Shape-Index + ß_8 IJI

Results

Meta-Analysis

Our meta-analysis provided a quantitative synthesis of the overall impact of tree plantations on biodiversity, offering critical insights into how anthropogenic land-use changes shape ecological communities. By pooling data across diverse studies, we found a significant negative effect of tree plantations on biodiversity, with an overall effect size estimate of -0.9367 (SE = 0.1443, Z = -6.49, $p < .0001$). The 95% confidence interval ranged from -1.2195 to -0.6538, indicating a consistently negative trend. These findings suggest that, on average, biodiversity is markedly reduced in tree plantations compared to natural and secondary forests, reinforcing concerns about the conservation value of such managed ecosystems. This general pattern sets the stage for further exploration of variation in effect sizes across different taxa, geographic regions, and plantation types.

The examination of 6 subgroup analysis provided the opportunity to make novel insights into how to interpret and understand the conservation value of anthropogenic habitats.

First, I looked into biodiversity indicators, both abudance and richness exhibited significantly negative effect sizes, indicating that biodiversity in plantation forests is markedly lower than in natural forests. In contrast,the Shannon-Wineer index showed nosignificant interhabitat comparisons between forests types(Figure 3). Next, I examined biodiversity types in the plantation forests by comparing plant, fungi, vertebrates and invertebrates of observed species. Only plant and vertebrates showed significant negative trends at $P < 0.05$ between natural forests and plantation forests(Figure 4). Then I explored how the plantation age can influnce the biodiversity level inside the plantation forest, and found that young and mid-aged plantation had significant negative association with biodiversity inside the plantation forest (Figure 5). Comparing to primary and secondary forests, both primary and secondary forest inside the whole landscape post negative effects on biodiversity level in plantation area(Figure 6). According to the plantation pattern, single-species plantation would have significant negative impact（$p<0.05$）on biodiversity level comparing to mix-species plantation(Figure 7). In addition, biodiversity responses varied notably depending on the proportion of plantation within the surrounding landscape (Figure 8). In landscapes where plantations accounted for less than 50% of the area, the biodiversity loss within plantations was significant($p < 0.05$). In contrast, when plantation cover exceeded 50%, the effect was weaker and statistically non-significant. These findings suggest that biodiversity within plantations is more negatively affected when they are embedded in more heterogeneous landscapes, possibly due to greater contrast with adjacent land covers or more fragmented habitat structures.

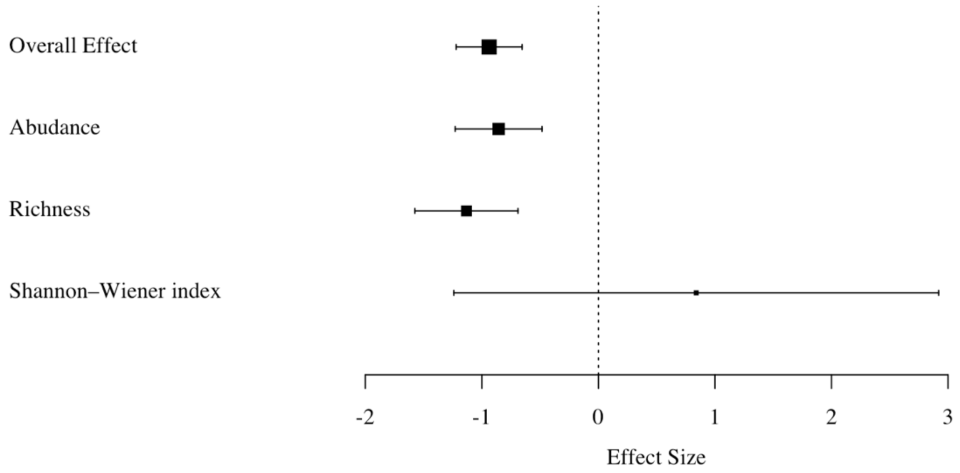

Figure 3. Overall meta analysis efeect of tree plantation on biodiversity and subgroup analysis of biodiversity indicators. Overall effect size = –0.94 (SE = 0.14, 95% CI: –

1.22 to –0.65, $Z = –6.49$, $p < 0.0001$). Significant negative effect of tree plantations on biodiversity (***). Abundance had a mean effect size of −0.86 with a 95% CI of [−1.23, −0.48], indicating a significant reduction in abundance in plantation forests relative to natural forests.Richness showed a mean effect size of −1.13 [−1.57, −0.69], also reflecting a significant negative impact.Shannon–Wiener index had a mean effect size of 0.84 [−1.24, 2.92], which was not statistically significant as the confidence interval crossed zero.

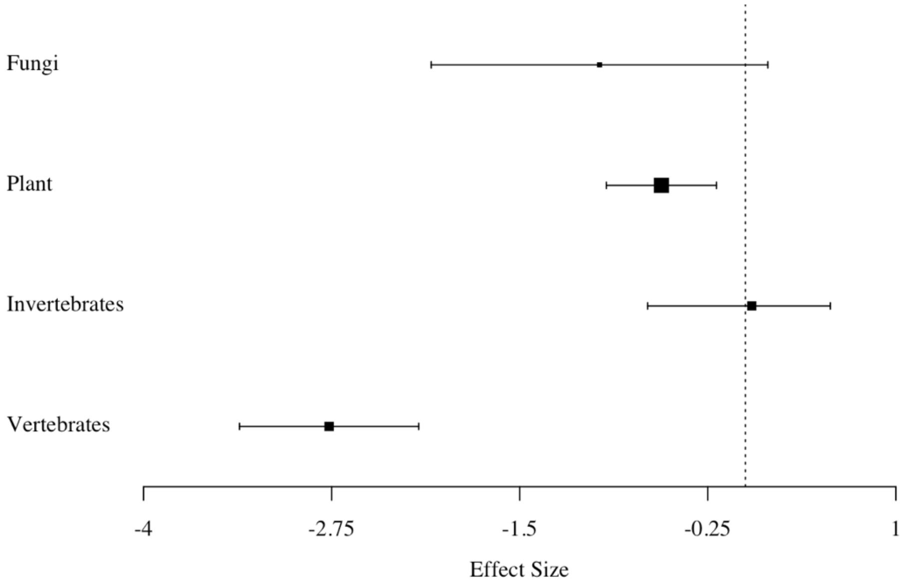

Figure 4. Subgroup analysis by biodiversity taxmomic groups. Fungi had a mean effect size of −0.97 [−2.09, 0.15], which was not statistically significant as the confidence interval crossed zero. Plants exhibited a significant negative effect with a mean effect size of −0.56 [−0.92, −0.19]. Invertebrates showed a near-zero effect size of 0.04 [−0.56, 0.65], indicating no clear impact. Vertebrates experienced a strong and significant negative impact with a mean effect size of −2.77 [−3.36, −2.17].

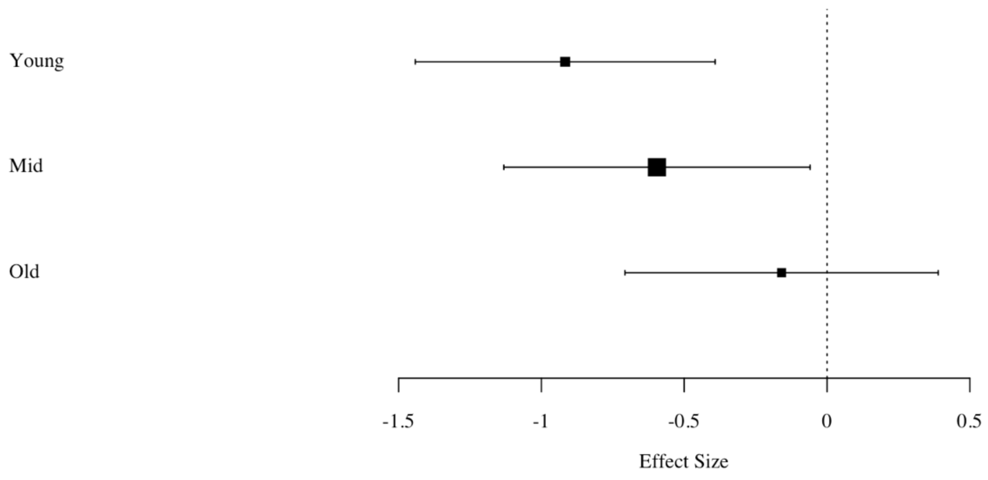

Figure 5. Subgroup analysis of plantation age. Young plantations had a mean effect size of −0.92 with a 95% confidence interval of [−1.44, −0.39], indicating a significant negative impact on biodiversity. Mid-aged plantations showed a mean effect size of −0.60 [−1.13, −0.06], also reflecting a statistically significant reduction. Old plantations had a mean effect size of −0.16 [−0.71, 0.39], which was not statistically significant as the confidence interval overlapped zero.

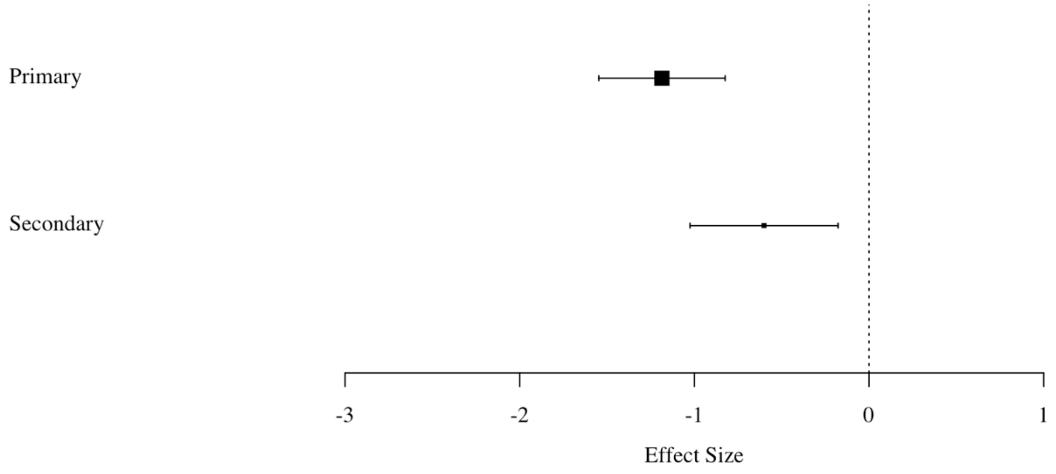

Figure 6. Subgroup analysis of plantation types(primary vs. secondary forest). Primary forests showed a significantly negative effect size of −1.19 [−1.55, −0.82], reflecting a strong decline in biodiversity in plantations relative to primary forests. Secondary forests had a less negative but still significant mean effect size of −0.60 [−1.03, −0.18].

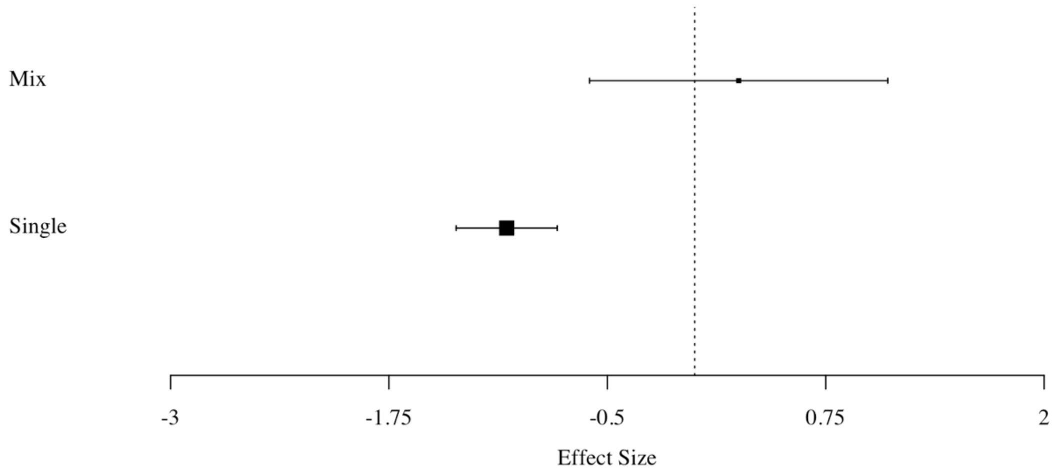

Figure 7. Subgroup analysis of plantation patterns. Mixed-species plantations had a non-significant positive effect size of 0.25 [−0.60, 1.11], as the confidence interval included zero. In contrast, single-species plantations had a significant negative effect on biodiversity with a mean effect size of −1.08 [−1.37, −0.79].

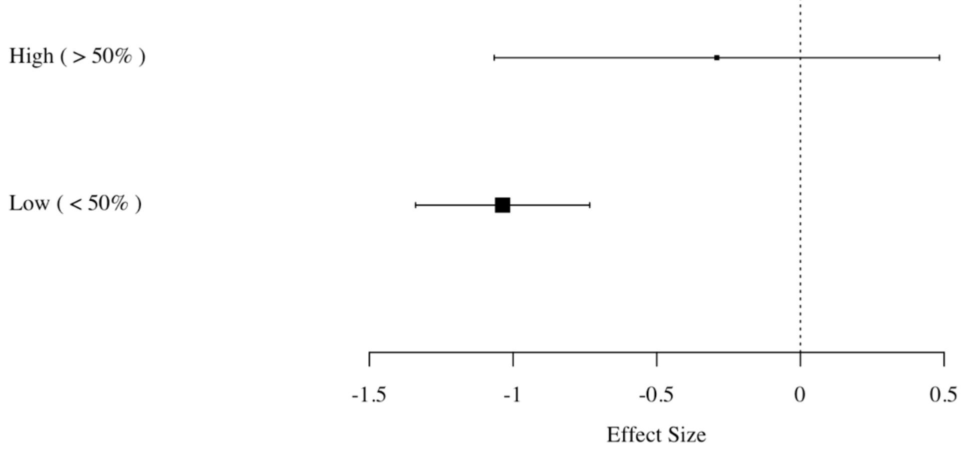

Figure 8. Subgroup analysis of the percentage of plantation. Areas classified as having a low percentage of plantation (<50%) show a significantly negative effect on biodiversity, with a mean effect size of –1.04 and a 95% confidence interval (CI) of [–1.34, –0.73] ($p < 0.0001$), In contrast, areas with a high percentage of plantation (>50%) exhibit a weaker and statistically non-significant effect, with a mean effect size of –0.29 and a 95% CI of [–1.07, 0.48] ($p = 0.46$).

Meta Regression

The meta-regression model identified several significant predictors influencing biodiversity responses within plantation landscapes (Figure 5). Notably, log-transformed patch size positively associated with effect size ($\beta = 0.4368$, $p = 0.0073$), indicating that larger plantation patches tend to support higher biodiversity.

Plantation age was also a strong determinant: mid-aged plantations had a significantly higher effect size compared to younger ones ($\beta = 0.3057$, $p = 0.0002$), and the effect was even more pronounced in older plantations ($\beta = 0.7264$, $p < 0.0001$)(Figure 9), suggesting that biodiversity tends to recover over time within plantation systems.

Annual precipitation had a weak but significant positive association with biodiversity ($\beta = 0.0009$, $p = 0.0110$), whereas annual temperature showed no significant effect ($\beta = -0.0533$, $p = 0.236$), indicating that moisture availability may play a more crucial role than temperature in shaping biodiversity within these landscapes.

Other variables, including forest type (primary vs. secondary) ($p = 0.0951$), percentage of natural forest cover in the surrounding landscape ($p = 0.6173$), shape index ($p = 0.3170$), and interspersion and juxtaposition index (IJI) ($p = 0.1478$), were not statistically significant, though some showed weak trends. The marginal significance of forest origin suggests a potential influence of historical land use on biodiversity recovery, warranting further investigation.

These results emphasize the importance of patch size and plantation age as key drivers of biodiversity outcomes in plantation landscapes, and support the idea that structural continuity and time since establishment can substantially enhance conservation value within managed forests.

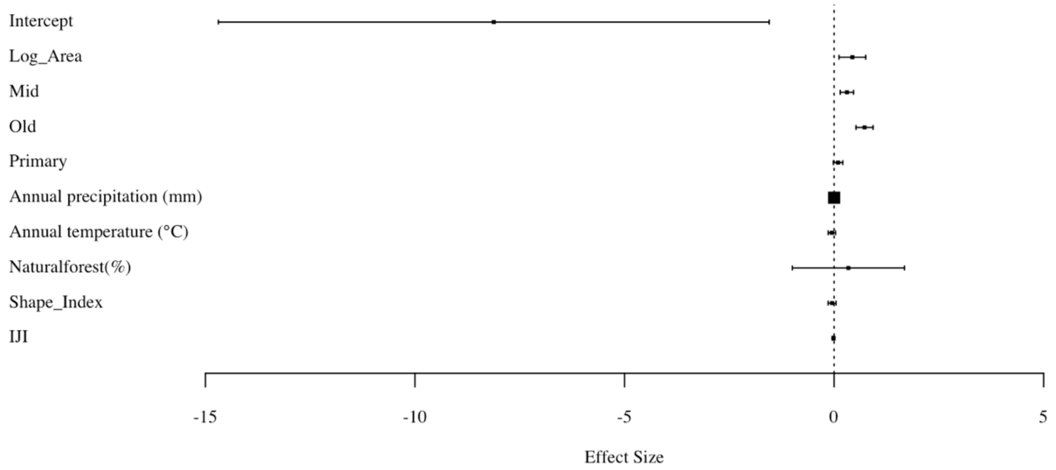

Figure 9. Forest Plot of Adjusted Meta regression coefficients. The intercept was −5.85 [−10.81, −0.89]. Annual temperature (coefficient = −0.11, 95% CI: [−0.16, −0.06]) and log-transformed plantation area (0.28, 95% CI: [0.07, 0.48]) were statistically significant, plantation age (Mid: −0.57 [−1.31, 0.17]; Old: −0.80 [−1.66, 0.05]), forest type (Primary: 0.13 [−0.46, 0.72]), natural forest percentage in the surrounding landscape (−0.04 [−0.11, 0.02]), shape index (0.04 [−0.04, 0.11]), and interspersion and juxtaposition index (0.00 [−0.01, 0.02]) showed no statistically significant associations with biodiversity effect size.

Discussion

This study contributes to addressing the landscape-scale knowledge gap identified in the introduction by empirically examining how spatial attributes influence biodiversity within plantation-dominated systems(with plantation greater than 50%). While much of the existing research has concentrated on local-scale comparisons between plantations and adjacent primary or secondary forests(Gibson et al., 2011), our meta-regression provides a broader perspective by evaluating the effects of landscape composition and structure across diverse geographic and ecological contexts. Notably, total patch area emerged as a significant positive predictor of biodiversity response. This finding partially contrasts with our initial hypothesis, which predicted a negative association between total patch area and biodiversity based on the assumption that larger plantation patches, often dominated by monocultures or fast-growing species, may reduce habitat heterogeneity and connectivity. However, one possible reason for reduced biodiversity in and around plantations is that planted trees are often selected for their fast growth or high economic value, such as exotic or pioneer species. These species may exhibit invasive traits and negatively impact native ecosystems by outcompeting local flora and altering habitat conditions in adjacent natural forests (Ledgard, 2001, Brockerhoff et al., 2008). In addition to this, the patch-area effects may vary between species group and among landscapes. And there were findings that if a landscape has intermediate forest cover, it would generate positive patch-area effect on species, while this pattern did not apply on generalist species which are irrespective of landscape context(Pardini et al., 2010). But the findings in the meta regression prove our hypothesis, though it was not significant, and because of many factors were added to the regression equation, it would generate more appropriate results. On the other hand, as edge effects are typically discussed in the context of natural forest systems and sensitive species, large plantation patches may still support higher biodiversity under certain landscape contexts. For instance, increasing plantation area can reduce patch fragmentation and increase core habitat area, potentially benefiting generalist species that thrive under semi-disturbed conditions. Moreover, larger and more contiguous plantation patches can enhance within-habitat connectivity, reduce internal edge density, and contribute to landscape-level structural complexity, all of which can influence species distribution and movement (Santos et al., 2017). Thus, although plantations may not replicate the ecological function of natural forests, their spatial configuration remains a key driver of biodiversity outcomes within production-dominated landscapes.

Artificial forests are often established in areas that were historically forested but had lost their native plant and animal communities long before the introduction of plantations. When afforestation is carried out on intensively managed agricultural land, which typically harbors a highly degraded flora and fauna, it often leads to conservation benefits, although exceptions have been documented. This is especially important in regions where natural forests have undergone significant decline. In such scenarios, plantation forests can serve as a critical mechanism for restoring elements of natural forests through processes such as natural succession, as explored in the section "How much time has passed since plantation establishment, and has colonization by native species occurred? " from the article: Plantation Forests and Biodiversity: Oxymoron or Opportunity? (Brockerhoff et al., 2008), plantations can support the gradual re-establishment of native biodiversity over time, depending on species colonization dynamics and site history.

The likelihood of plantation forests resembling natural forests and supporting biodiversity increases when they are composed of locally native tree species. In certain cases, older plantation stands may even become virtually indistinguishable from natural forests(Brockerhoff et al., 2008). Another explanation is that, as the effect of plantation dependent on the previous landcover that was replaced. Non-native trees are not always with its drawbacks(Horák et al.., 2019), nor is it that the greater the proportion of native or secondary forest, the better for biodiversity(Carrara et al., 2015). For instance, many of these plantations were established on previously degraded agricultural lands, rather than replacing intact natural forests. In such contexts, plantation forests may actually facilitate biodiversity recovery compared to the prior land use (Brockerhoff et al., 2008), particularly if they involve native species or retain structural complexity. Therefore, it is important to distinguish whether plantations replace natural forests or agricultural land, as this baseline condition can strongly influence biodiversity outcomes.

Apart from that, there was also study showed that plantations of native species maintained higher biodiversity than plantations of foreign species, which might result from three mechanisms working independently or in combination(Wang. et al., 2022). As native species plantations tend to resemble primary forests more closely in terms of habitat structure compared to exotic species plantations(Wagner et al., 2007). As a result, the more suitable canopy coverage and greater plant diversity found in native species plantations may support higher aboveground faunal diversity. Additionally, many exotic species plantations are primarily designed for rapid wood production over short-term periods(*The State of Food and Agriculture 2006*) which often limits their ability to replicate the ecological complexity of natural forests.

In addition to the characteristics of the plantations themselves, the role of surrounding natural forests warrants further investigation. Previous studies have highlighted that not only the amount, but also the connectivity of native forest remnants, plays a critical role in facilitating species movement and gene flow(Christie & Knowles, 2015).Fragmented landscapes with isolated forest patches may act as barriers to dispersal, reducing the potential for recolonization and species persistence in adjacent plantation areas(Spiesman et al., 2018b). In contrast, well-connected natural forest networks can function as biodiversity reservoirs and stepping stones, enhancing species spillover into planted systems. Therefore, future studies should incorporate explicit connectivity metrics to better assess how spatial arrangement of native forest patches mediates biodiversity recovery in plantation-dominated landscapes. This would allow for a more nuanced understanding of how landscape-level ecological processes interact with forest management to shape biodiversity outcomes.

Conclusion

In conclusion, the findings of this study underscore the complex relationship between plantation forests and biodiversity. While plantation forests, particularly single-species or exotic plantations, generally exhibit lower biodiversity levels compared to natural forests, they can still play a significant role in ecological restoration and biodiversity recovery under certain conditions. Native species plantations, with their habitat structures more closely resembling primary forests, tend to support higher aboveground faunal diversity, highlighting the importance of species selection in plantation design. Furthermore, mixed-species plantations, whether composed of native or non-native species, can enhance biodiversity by providing diverse microhabitats and increasing resistance to natural disturbances, thereby contributing to more sustainable forest management practices.

Notably, plantation forests can facilitate forest succession on degraded lands by improving microclimate conditions, suppressing invasive species, and attracting seed-dispersing wildlife, which aids in the re-establishment of native species. However, the long-term dynamics of biodiversity recovery and the role of plantation management practices remain underexplored. Future research should focus on evaluating the effects of different plantation management regimes, including mixed-species plantations, restoration efforts, and landscape-level connectivity, to better understand how plantation forests can balance production goals with biodiversity conservation.

Additionally, the positive effects of non-native tree species in certain contexts suggest that their inclusion in plantation designs should not be dismissed outright. Instead, a nuanced approach that considers the ecological functions of both native and non-native species, as well as their interactions with surrounding natural habitats, is essential for mitigating the negative impacts of plantation forests on global biodiversity. By integrating these insights into forest management strategies, we can work towards creating plantation systems that not only meet economic and production needs but also contribute to biodiversity conservation and ecosystem resilience in the face of global environmental change.

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Supplementary Documents

Appendix

Influence Factor		estimate	se	z-value	p-value	ci.lb	ci.ub	
Surrounding Area	Primary Forest	-1.1857	0.1845	-6.4255	<.0001	-1.5474	-0.824	***
	Secondary Forest	-0.6013	0.2163	-2.7804	0.0054	-1.0251	-0.1774	**
Form of Plantation	Mix Species	0.2515	0.4355	0.5775	0.5636	-0.602	1.105	
	Single Species	-1.076	0.1477	-7.2841	<.0001	-1.3656	-0.7865	***
Plantation Age	Young	-0.8531	0.1756	-4.8573	<.0001	-1.1973	-0.5089	***
	Mid	-1.0489	0.334	-3.1407	0.0017	-1.7034	-0.3943	**
	Old	-1.1665	0.3937	-2.9631	0.003	-1.9381	-0.3949	**
Biodiversity Indicator	Abundance	-0.9115	0.1907	-4.7802	<.0001	-1.2852	-0.5378	***
	Richness	-1.2065	0.2226	-5.4203	<.0001	-1.6428	-0.7702	***
	Shannon-winner index	0.838	1.042	0.8043	0.4212	-1.2042	2.8803	
Biodiversity Type	Fungi	-0.9666	0.5561	-1.7382	0.0822	-2.0565	0.1233	
	Invertebrates	0.0766	0.29	0.264	0.7918	-0.4918	0.6449	
	Plant	-0.6368	0.1849	-3.4439	0.0006	-0.9992	-0.2744	***
	Vertebrates	-2.7524	0.2972	-9.2618	<.0001	-3.3349	-2.17	***

Appendix Table 1. Subgroup analysis coefficient

Collinearity calculation

	CAI	log_area	Shape Index	plantation(%)	Natrual forest(%)	Annual precipitation(mm)	Annual temperature(°C)	IJI
CAI	1	0.67467	-0.2641	0.18234	-0.3327	-0.1473	-0.2296	0.30077
log_area	0.67467	1	0.14226	0.60035	-0.458	-0.3158	-0.552	0.29483
Shape Index	-0.2641	0.14226	1	0.21293	-0.0437	-0.0652	-0.1127	-0.0759
plantation(%)	0.18234	0.60035	0.21293	1	-0.5069	-0.4159	-0.6969	0.17224
Natrual forest(%)	-0.3327	-0.458	-0.0437	-0.5069	1	0.48448	0.44139	-0.3695

Annual precipitation(mm)	-0.1473	-0.3158	-0.0652	-0.4159	0.48448	1	0.43947	-0.2378
Annual temperature (°C)	-0.2296	-0.552	-0.1127	-0.6969	0.44139	0.43947	1	-0.181
IJI	0.30077	0.29483	-0.0759	0.17224	-0.3695	-0.2378	-0.181	1

Appendix Table 2. Pearson Correlation Matrix Among Landscape and Environmental Variables

This table(Appendix Table 2.) presents the Pearson’s r correlation coefficients among eight key landscape and environmental variables used in the meta-regression analysis, including core area index (CAI), log-transformed patch area (log_area), shape index, percentage of plantation and natural forest within the landscape, annual precipitation, annual temperature, and interspersion and juxtaposition index (IJI). The correlation matrix reveals several notable relationships among the variables. Log-transformed patch area (log_area) is strongly and positively correlated with plantation proportion ($r = 0.60$), and moderately correlated with CAI ($r = 0.67$), suggesting that larger plantation patches are often associated with higher core area values and plantation dominance within landscapes. Therefore, to reduce potential multicollinearity and avoid redundancy among highly correlated predictors, CAI and plantation proportion were excluded from the final meta-regression model.

Meta regression

	estimate	se	zval	pval	ci.lb	ci.ub	
intrcpt	-8.1196	3.3519	-2.4224	0.0154	-14.689	-1.5499	*
log_area	0.4368	0.1627	2.6847	0.0073	0.1179	0.7557	**
Mid-plantation	0.3057	0.0807	3.7904	0.0002	0.1476	0.4638	***
Old-plantation	0.7264	0.104	6.9864	<.0001	0.5226	0.9302	***
primary	0.0952	0.057	1.6691	0.0951	-0.0166	0.2069	.
Annual precipitation (mm)	0.0009	0.0003	2.544	0.011	0.0002	0.0015	*
Annual temperature	-0.0533	0.0449	-1.1861	0.2356	-0.1413	0.0348	
Natural Forest(%)	0.3412	0.6828	0.4997	0.6173	-0.9971	1.6795	
Shape index	-0.0484	0.0484	-1.0006	0.317	-0.1432	0.0464	
IJI	-0.015	0.0103	-1.4473	0.1478	-0.0352	0.0053	

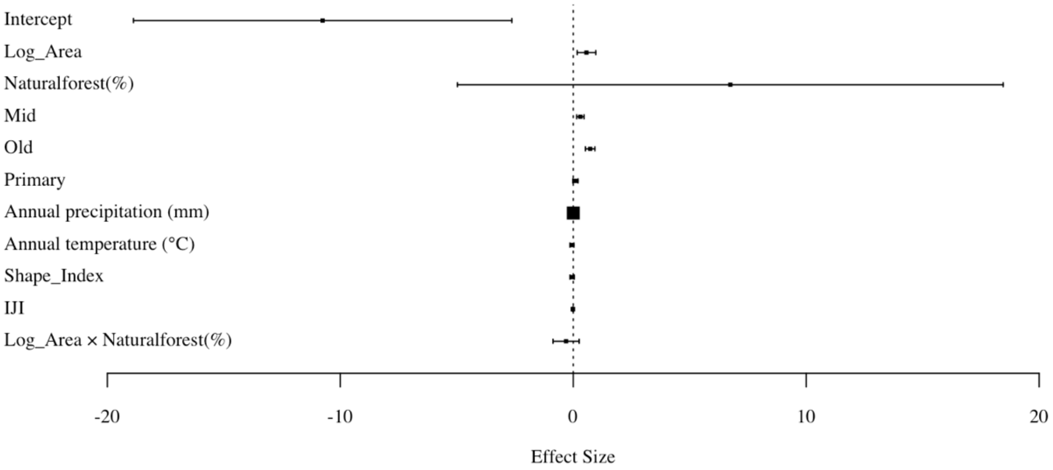
Appendix Table 3. Meta regression coefficient

Meta Regression Model Selection

To further investigate whether the effect of plantation patch size on biodiversity is moderated by the surrounding natural forest cover, we included an interaction term between log-transformed patch size (log_area) and the percentage of natural forest (% natural forest) in the meta-regression model(Appendix Table 4 & Figure 1). The results showed a significant positive effect of patch size on biodiversity (β = 0.5690, *p* = 0.0052), suggesting that larger plantation patches are generally associated with higher biodiversity. However, neither the main effect of natural forest percentage (β = 6.7423, *p* = 0.2592) nor the interaction term (β = –0.3080, *p* = 0.2810) reached statistical significance. This indicates that the positive relationship between patch size and biodiversity does not vary substantially across landscapes with differing levels of natural forest cover.

	estimate	se	zval	pval	ci.lb	ci.ub	
intrcpt	-10.757	4.1443	-2.5956	0.0094	-18.8796	-2.6344	**
log_area	0.569	0.2036	2.795	0.0052	0.17	0.968	**
Natural Forest(%)	6.7423	5.9761	1.1282	0.2592	-4.9707	18.4552	
Mid-plantation	0.3054	0.0807	3.787	0.0002	0.1474	0.4635	***
Old-plantation	0.7265	0.104	6.9881	<.0001	0.5228	0.9303	***
primary	0.0946	0.057	1.6593	0.0971	-0.0171	0.2064	.
Annual precipitation (mm)	0.0008	0.0003	2.3557	0.0185	0.0001	0.0015	*
Annual temperature (°C)	-0.0561	0.0448	-1.2514	0.2108	-0.144	0.0318	
Shape Index	-0.0483	0.0482	-1.0009	0.3169	-0.1427	0.0462	
IJI	-0.0149	0.0103	-1.4407	0.1497	-0.0351	0.0054	
log_area:Natural Forest(%)	-0.308	0.2857	-1.0782	0.281	-0.8679	0.2519	

Appendix Table 4. Results of the meta-regression model including an interaction term between plantation patch size and surrounding natural forest percentage.

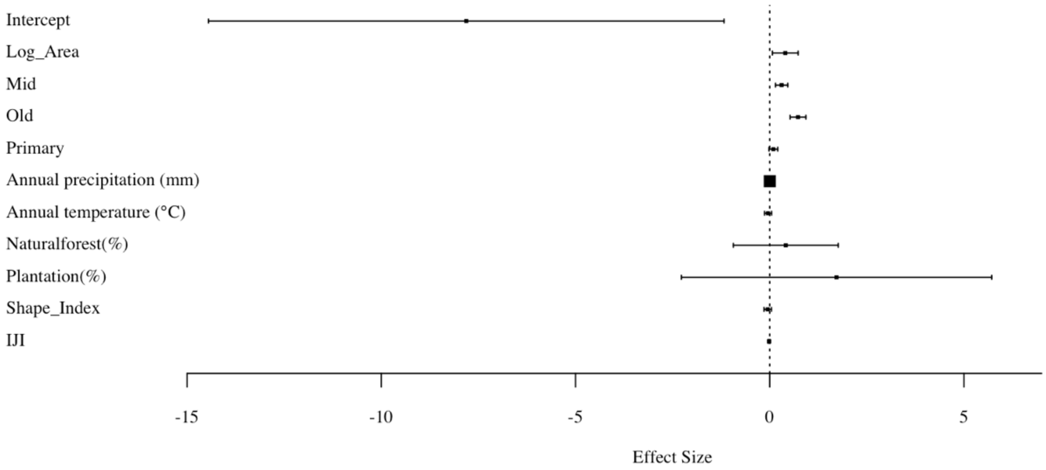


Appendix Figure 1. Forest plot of adjusted meta-regression coefficients including interaction terms. The intercept was −10.76 (95% CI: [−18.88, −2.63]). Log-transformed plantation area (coefficient = 0.57, 95% CI: [0.17, 0.97]), plantation age (Mid: 0.31 [0.15, 0.46]; Old: 0.73 [0.52, 0.93]), and annual precipitation (0.00 [0.00, 0.00]) were statistically significant predictors of biodiversity effect size. Forest type (Primary: 0.09 [−0.02, 0.21]), annual temperature (−0.06 [−0.14, 0.03]), shape index (−0.05 [−0.14, 0.05]), and interspersion and juxtaposition index (−0.01 [−0.04, 0.01]) did not show significant associations. The percentage of surrounding natural forest (6.74 [−4.97, 18.46]) and its interaction with plantation area (−0.31 [−0.87, 0.25]) were also not statistically significant, suggesting high variability and limited modifying effects on the relationship between plantation size and biodiversity.

An alternative model was run by incorporating the percentage of plantation area within the surrounding landscape as an independent predictor, rather than using interaction terms (Appendix Table 5 & Figure 2). The results reaffirmed that plantation patch size (log-transformed) had a significant positive association with biodiversity effect size (β = 0.4005, *p* = 0.0179), and plantation age remained a key factor, with both mid-aged (β = 0.3063, *p* = 0.0001) and old plantations (β = 0.7273, *p* < 0.0001) contributing positively. Annual precipitation also had a weak but significant positive effect (*p* = 0.0096). In contrast, the proportion of plantation within the landscape (β = 1.7202, *p* = 0.3986) did not show a statistically significant relationship with biodiversity, similar to the non-significant results observed for natural forest percentage (β = 0.4138, *p* = 0.5481). Compared with the earlier interaction model, which tested whether the effect of plantation area depended on surrounding natural forest cover and yielded non-significant interaction effects, this simplified model further highlights that while patch size and stand age are reliable predictors, the broader composition of the surrounding landscape alone may not consistently explain biodiversity patterns within plantations.

	estimate	se	zval	pval	ci.lb	ci.ub	
intrcpt	-7.8118	3.3861	-2.3071	0.0211	-14.4484	-1.1753	*
log_area	0.4005	0.1691	2.3681	0.0179	0.069	0.7319	*
ageMid	0.3063	0.0807	3.7977	0.0001	0.1482	0.4644	***
ageOld	0.7273	0.104	6.9947	<.0001	0.5235	0.9311	***
primary	0.0945	0.057	1.6561	0.0977	-0.0173	0.2062	.
Annual precipitation (mm)	0.0009	0.0003	2.5914	0.0096	0.0002	0.0015	**
Annual temperature (°C)	-0.043	9 0.0465	-0.945	0.3447	-0.135	0.0472	
Natural Forest(%)	0.4138	0.689	0.6006	0.5481	-0.9367	1.7643	
Plantation(%)	1.7202	2.0378	0.8441	0.3986	-2.2738	5.7142	
Shape Index	-0.0519	0.0487	-1.0658	0.2865	-0.1475	0.0436	
IJI	-0.0164	0.0105	-1.5608	0.1186	-0.037	0.0042	

Appendix Table 5. Results of the meta-regression model including the perecentage of plantation forests in the total landscape.

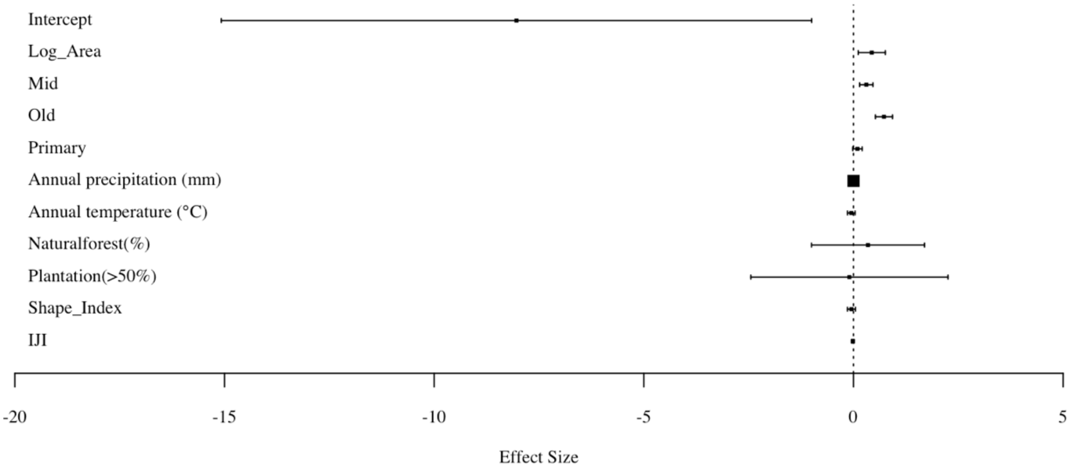


Appendix Figure 2. Forest plot of adjusted meta-regression coefficients including plantation percentage as a predictor. The intercept was −7.81 (95% CI: [−14.45, −1.18]). Log-transformed plantation area (0.40, 95% CI: [0.07, 0.73]), plantation age (Mid: 0.31 [0.15, 0.46]; Old: 0.73 [0.52, 0.93]), and annual precipitation (0.0009 [0.0002, 0.0015]) were statistically significant predictors of biodiversity effect size. In contrast, forest type (Primary: 0.09 [−0.02, 0.21]), annual temperature (−0.04 [−0.14, 0.05]), shape index (−0.05 [−0.15, 0.04]), and interspersion and juxtaposition index (−0.02 [−0.04, 0.00]) were not significant. Notably, the percentage of natural forest (0.41 [−0.94, 1.76]) and plantation percentage (1.72 [−2.27, 5.71]) showed no statistically significant effects, indicating high variability and limited predictive power in this model.

Another alternative meta-regression model was developed by including a binary variable representing whether the surrounding plantation cover was above 50% (Appendix Table 6 & Figure 3). The results remained broadly consistent with previous models. Log-transformed plantation patch size continued to show a significant positive relationship with biodiversity (β = 0.4367, p = 0.0081), and plantation age had a strong effect, with both mid-aged (β = 0.3058, p = 0.0002) and old plantations (β = 0.7268, p < 0.0001) positively associated with biodiversity recovery. Annual precipitation again emerged as a weak but significant predictor (p = 0.0114), whereas temperature showed no significant effect. Notably, the binary indicator representing high plantation coverage (>50%) also showed no significant effect (β = 0.0971, p = 0.9355), echoing earlier findings that the mere proportion of plantation area in the surrounding landscape may not be a reliable standalone predictor of biodiversity in plantation forests.

	estimate	se	zval	pval	ci.lb	ci.ub	
intrcpt	-8.1342	3.3803	-2.4063	0.0161	-14.7596	-1.5089	*
log_area	0.4367	0.1649	2.6485	0.0081	0.1135	0.7598	**
Mid-Age	0.3058	0.0807	3.791	0.0002	0.1477	0.4639	***
Old-Age	0.7268	0.104	6.9893	<.0001	0.523	0.9306	***
primary	0.0952	0.057	1.6691	0.0951	-0.0166	0.207	.
Annual precipitation (mm)	0.0009	0.0003	2.5293	0.0114	0.0002	0.0015	*
Annual temperature (°C)	-0.052	6 0.0464	-1.1343	0.2567	-0.1435	0.0383	
Natural Forest(%)	0.3468	0.6879	0.5042	0.6142	-1.0015	1.6952	
Plantation(>50%)	0.0971	1.1993	0.0809	0.9355	-2.2536	2.4477	
Shape Index	-0.0486	0.0488	-0.9969	0.3188	-0.1442	0.047	
IJI	-0.0151	0.0104	-1.4466	0.148	-0.0355	0.0054	

Appendix Table 6. Results of the meta-regression model including the low/ high percentage of plantation in the total landscape.



Appendix Figure 3. Forest plot of adjusted meta-regression coefficients with plantation landscape categorized by high coverage (>50%). The intercept was −8.13 (95% CI: [−14.76, −1.51]). Log-transformed plantation area (coefficient = 0.44, 95% CI: [0.11, 0.76]), plantation age (Mid: 0.31 [0.15, 0.46]; Old: 0.73 [0.52, 0.93]), and annual precipitation (0.00 [0.00, 0.00]) were statistically significant predictors of biodiversity effect size. Forest type (Primary: 0.10 [−0.02, 0.21]), annual temperature (−0.05 [−0.14, 0.04]), shape index (−0.05 [−0.14, 0.05]), and interspersion and juxtaposition index (IJI: −0.02 [−0.04, 0.01]) did not show significant associations. Neither the percentage of surrounding natural forest (0.35 [−1.00, 1.70]) nor the binary indicator for high plantation coverage (>50%) (0.10 [−2.25, 2.45]) were significantly associated with biodiversity outcomes.

	df	AIC
Original Model	11	7658.998
Model with interaction term	12	7655.844
Model with Higher Plantation(>50%)	12	7655.331
Model with plantation (%)	12	7654.947

Appendix Table 7. Comparison of Model Performance Based on Akaike Information Criterion (AIC)

To assess model performance and parsimony, Akaike Information Criterion (AIC) values were compared across four alternative meta-regression models. The original model (Appendix Table 7) had an AIC of 7658.998, while the model including an interaction term between plantation area and natural forest percentage (Appendix Table 7) showed a slightly lower AIC of 7655.844. Models incorporating the percentage of plantation (Model with plantation: AIC = 7654.947) and a binary classification of high plantation cover (Model with Higher Plantation: AIC = 7655.331) yielded similarly small improvements in AIC. These minimal differences indicate that all models performed comparably in terms of explanatory power and model fit, and that no single modification substantially enhanced predictive accuracy. Thus, model selection may reasonably be guided by theoretical interpretability rather than AIC alone.

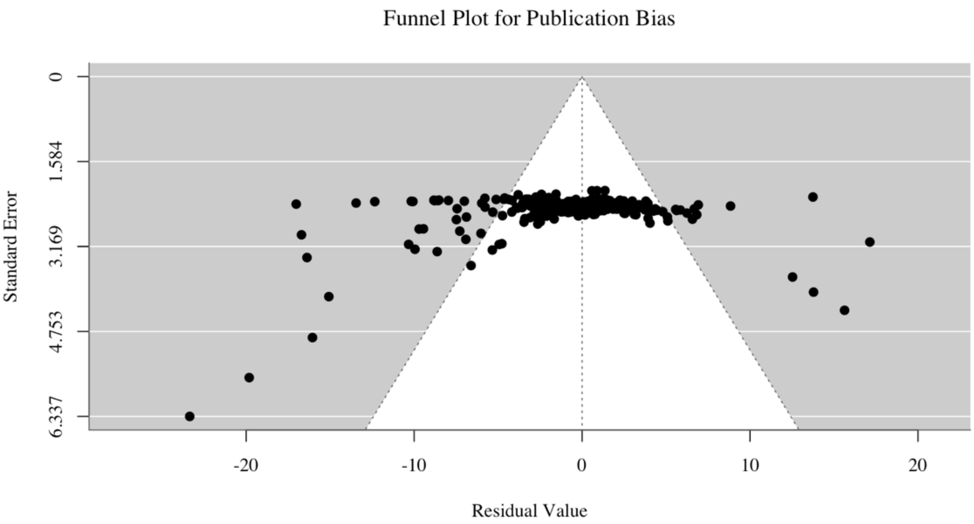
Robustness Checks:

Coef.	**Estimate**	**SE**	**Null value**	**t-stat**	**d.f. (Satt)**	**p-val (Satt)**	**Sig.**
intrcpt	-8.119588	3.779516	0	-2.148	22.3	0.0428	*
log_area	0.436787	0.222284	0	1.965	24.06	0.0611	.
ageMid	0.305728	0.248676	0	1.229	4.96	0.2741	
ageOld	0.726403	0.331881	0	2.189	4.33	0.0887	.
primary	0.095177	0.135323	0	0.703	9.66	0.4984	
Annual precipitation (mm)	0.000852	0.000532	0	1.603	24.65	0.1218	
Annual temperature (°C)	` -0.05327	2 0.057476	0	-0.927	30.34	0.3613	
Natural forest(%)	0.341201	0.41212	0	0.828	1.91	0.4982	
Shape Index	-0.048395	0.055923	0	-0.865	16.53	0.3992	
IJI	-0.014971	0.012843	0	-1.166	37.02	0.2512	

Appendix Table 8 Robustness checks

To assess the robustness of our meta-regression results, we applied cluster-robust variance estimation (CRVE) using the clubSandwich package(Pustejovsky, 2016), treating each article as a cluster. Compared to the standard model, robust standard errors were generally larger, and significance levels of several predictors were reduced(e.g., mid-aged plantations and precipitation). Notably, the effect of patch size (log-transformed area) remained marginally significant (p = 0.061), and older plantations still exhibited a positive trend in supporting biodiversity (p = 0.089).These findings suggested that the core relationships identified in this study are not overly sensitive to within-study dependencies, supporting the overall robustness of the meta-regression model.

Publication bias



Appendix Figure 4. Funnel plot of publication bias

Funnel plot analysis revealed a slightly asymmetrical distribution of effect sizes, with a higher density of negative residuals, suggesting a potential publication bias favoring studies reporting negative impacts of plantation forests on biodiversity. However, the overall distribution remained largely within the expected funnel range, indicating that the risk of publication bias is limited and unlikely to critically undermine the robustness of the meta-analysis findings.