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Article

Scientometric Analysis of Biodiversity Offset Mechanisms in the Northern Ecuadorian Amazon

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Abstract: The accelerated loss of biodiversity associated with the expansion of extractive activities, landscape fragmentation, and intensive land-use change represents one of the most pressing socio-environmental challenges in megadiverse regions such as the northern Ecuadorian Amazon. In this context, biodiversity offsets have emerged as a central instrument within environmental management frameworks to address unavoidable residual impacts; however, their ecological, social, and institutional effectiveness remains widely debated. This study aims to critically analyze the evolution, structure, and orientation of scientific production on biodiversity offsets in the northern Ecuadorian Amazon, identifying research trends, knowledge gaps, and discrepancies between the normative principles underpinning this instrument and its practical implementation. The research adopts a qualitative, critical-interpretive approach, based on a systematic review of peer-reviewed scientific literature, environmental regulations, and relevant technical documents, complemented by a scientometric analysis. The results reveal persistent gaps in the definition of ecological equivalence, the incorporation of functional connectivity, and the consideration of temporal scales consistent with Amazonian ecological processes. Moreover, the reviewed literature indicates that biodiversity offsets are frequently implemented as administrative mechanisms linked to environmental licensing rather than as effective landscape-scale conservation tools, thereby reproducing social tensions and institutional limitations. The study underscores the need to strengthen context-specific methodological frameworks and to promote a more robust scientific production capable of aligning normative principles with ecologically effective and socially legitimate biodiversity offset practices in highly complex socio-ecological territories.

Keywords: Biodiversity offsets; Environmental governance; Landscape fragmentation; No net loss; Socio-ecological complexity.

Resumen: La pérdida acelerada de biodiversidad asociada a la expansión de actividades extractivas, la fragmentación del paisaje y la transformación intensiva del uso del suelo constituye uno de los principales desafíos socioambientales en regiones megadiversas como la Amazonía norte del Ecuador. En este contexto, las compensaciones por pérdida de biodiversidad se han consolidado como un instrumento central de la gestión ambiental para abordar impactos residuales inevitables; sin embargo, su efectividad ecológica, social e institucional continúa siendo objeto de debate. El presente estudio tiene como objetivo analizar de manera crítica la evolución, estructura y orientación de la producción científica sobre las compensaciones por pérdida de biodiversidad en la Amazonía norte del Ecuador, identificando tendencias de investigación, vacíos de conocimiento y brechas entre los principios normativos que sustentan este instrumento y su implementación práctica. La investigación se desarrolló bajo un enfoque cualitativo de carácter crítico interpretativo, basado en una revisión sistemática de literatura científica, normativa ambiental y documentos técnicos relevantes, complementada con un análisis cienciométrico. Se identifican brechas persistentes en la definición de equivalencias ecológicas, la incorporación de la conectividad funcional y la consideración de escalas temporales acordes con los procesos ecológicos amazónicos. Asimismo, la literatura revisada muestra que las compensaciones tienden a operar como mecanismos administrativos asociados al licenciamiento ambiental, más que como herramientas efectivas de conservación a escala de paisaje, reproduciendo tensiones sociales y limitaciones institucionales. Se subraya la necesidad de fortalecer marcos metodológicos contextualizados y de promover una producción científica más robusta que contribuya a alinear los principios normativos con prácticas de compensación ecológicamente efectivas y socialmente legítimas.

Palabras clave: Compensaciones de biodiversidad; Gobernanza ambiental; Fragmentación del paisaje; Ausencia de pérdida neta; Complejidad socioecológica.

1. Introduction

He accelerating loss of biodiversity associated with the expansion of extractive activities, linear infrastructure, and intensive transformations of land use and land cover constitutes one of the most pressing contemporary socio-environmental challenges, particularly in tropical regions characterized by high levels of biological diversity and socio-ecological complexity (Simpson et al., 2022). Over the last decade, these processes have intensified significantly in countries such as Ecuador, where the convergence of global demand for raw materials, national development dynamics, and limited environmental governance frameworks has generated persistent patterns of deforestation, fragmentation, and ecosystem degradation (Bezombes et al., 2018). This phenomenon is neither isolated nor exclusively local, but rather embedded within a broader global trend in which the promise of development with environmental safeguards is operationalized primarily through regulatory instruments such as Environmental Impact Assessment (EIA) (Soto & Sarmiento, 2014) and, where unavoidable residual impacts remain, through biodiversity offset schemes aimed at achieving no net loss or even net gain of biodiversity (Arbeláez & Sagre, 2015).

Nevertheless, the gap between the normative principles underpinning these instruments and their actual ecological and social performance has been widely documented and remains the subject of ongoing academic and policy debate (Bonilla et al., 2022). Critical assessments have consistently shown that EIAs, conceived as the main preventive filter, exhibit structural deficiencies that limit their ability to avoid significant impacts on irreplaceable ecosystems (Maseyk et al., 2016). In contexts of weak institutional capacity, impact studies tend to underestimate risks, rely on incomplete baseline data, and inadequately assess medium- and long-term ecological processes, particularly for cryptic or poorly studied taxa (Laurance, 2022). These shortcomings shift the burden of environmental management toward the compensatory phase, substantially increasing the technical, political, and ethical demands placed on offset schemes to ensure real ecological equivalence and socially legitimate outcomes (Tranberg et al., 2024).

Biodiversity offsets frequently produce ambiguous and, in many cases, insufficient results to counterbalance the losses generated by development projects (Yang et al., 2023). In mining and conservation scenarios involving changes in local community behavior, studies have documented combinations of environmental benefits and social costs that ultimately generate perceptions of net loss among households most dependent on natural resources (Droste et al., 2022). These perceptions are exacerbated by temporal mismatches between immediate land-use restrictions and deferred benefits or benefits accrued by external actors, thereby eroding project legitimacy and compromising long-term sustainability (Bezombes et al., 2018; Carreras Gamarra et al., 2018; Niner et al., 2017a). Such dynamics highlight that biodiversity offsets are not merely technical instruments, but mechanisms of environmental governance that reconfigure power relations, access to resources, and benefit distribution, directly engaging principles of environmental justice (Carreras Gamarra et al., 2018; J. Zhong et al., 2024).

The limitations of offsetting approaches become even more evident in singular and irreplaceable ecosystems, where ecological replicability is virtually nonexistent (Schulz & Ohmura, 2024). Cases such as the ferruginous canga ecosystems of southeastern Brazil demonstrate how weak regulatory frameworks, combined with information deficits and fragile equivalence criteria, can lead to net biodiversity losses and increased extinction risk despite the rhetoric of no net loss (Carmo & Kamino, 2023). The uncritical application of offset schemes may thus legitimize irreversible destruction under the appearance of ecological equivalence, generating perverse outcomes that undermine conservation objectives (Zapata-Ríos et al., 2022).

These limitations are compounded by structural challenges associated with biodiversity credit markets (de Witt et al., 2019). Event experiences indicate that even in regulated systems supported by electronic platforms and sophisticated matching algorithms, the coexistence of multiple credit types and complex exchange rules tends to produce markets with high transaction costs and persistent difficulties in efficiently and ecologically matching supply and demand (Plott et al., 2023). The effectiveness of such schemes depends critically on regulatory design, information quality, and long-term monitoring and verification capacity, which remain major sources of uncertainty in both terrestrial and marine contexts (Chamas et al., 2020).

In Latin America, these challenges acquire a particular dimension due to the convergence of high biodiversity, social inequality, and economic dependence on extractive activities (Abatayo et al., 2023). The adoption of biodiversity offset policies has been heterogeneous and often fragmented, more closely linked to environmental licensing requirements than to comprehensive national conservation strategies (Taherzadeh & Howley, 2018). Early experiences associated with large infrastructure and mining projects generated relevant lessons in planning and participation, yet their effectiveness was constrained by regulatory gaps, technical deficits, and limited transparency in outcome verification (Arbeláez & Sagre, 2015). This structural asymmetry, high biodiversity coupled with low institutional capacity has resulted in offset schemes that frequently reproduce territorial inequalities and prioritize corporate interests over the needs of local communities and long term conservation goals.

The contemporary debate on the effectiveness and legitimacy of biodiversity offsets is embedded in a deeper conceptual tension between strong conservation paradigms and sustainable development approaches (Codeço, 2023). While the former emphasizes the preservation of intact ecosystems, the latter accepts a certain degree of transformation under the premise of compensatory ecological balance (Durango, 2019). This balance has been shaped by economic pressure to expand extractive frontiers, limited availability of ecological information, and institutional capacity constraints affecting the design and implementation of robust measures (Malmir et al., 2023; Soto & Sarmiento, 2014).

Recent evidence suggests that even in contexts with consolidated legal frameworks, methodological errors, benefit overestimation, and lack of transparency lead to persistent net losses (Yang et al., 2023). Studies on koala habitats in Australia, for example, reveal that only a small fraction of analyzed projects effectively compensated impacts, underscoring that policy performance depends more on actual implementation than on theoretical design (Tran & Maron, 2024).

In Europe, supposedly advanced schemes such as biodiversity net gain policies in England have produced suboptimal outcomes for both biodiversity and local communities, largely due to spatial constraints imposed by local planning processes that limit ecological gain potential (Mancini et al., 2024). These findings carry direct implications for Amazonian regions, where ecological heterogeneity and spatial dispersion demand more flexible, integrated, and landscape-sensitive approaches (Meng et al., 2019).

Within this global and regional context, the northern Ecuadorian Amazon emerges as a paradigmatic case where cumulative pressures, information gaps, and institutional challenges converge(Mejia et al., 2021). This region one of the most biodiverse and culturally rich areas on the planet supports endemic species and Indigenous communities that depend directly on ecosystem services (García-Villacís et al., 2021). At the same time, it faces increasing threats from oil exploitation, deforestation, agricultural expansion, and urbanization, processes that have generated significant biodiversity loss and persistent socio-environmental conflicts (Bidaud et al., 2017; Bilsborrow et al., 2004; Zapata-Ríos et al., 2022). In provinces such as Sucumbíos, deforestation associated with oil activity and demographic dynamics has reached critical levels, with substantial losses of primary forest over the past two decades (S. Gao et al., 2023).

The environmental history of the Ecuadorian Amazon is further marked by episodes of severe contamination linked to hydrocarbon exploitation, with documented impacts on water quality and community health (San Sebastián & Hurtig, 2004). These challenges are compounded by the growing pressure of legal and illegal mining, reopening debates on the future of biodiverse regions and the need to balance economic interests, environmental conservation, and local rights (Feeney, 2024). In this context, biodiversity offsets are often presented as a potential tool to mitigate residual impacts and promote a more balanced coexistence between development and conservation. However, their effective application faces substantial obstacles, particularly in socio-environmentally vulnerable territories where ecological and social indicators reflect high levels of fragility (Chamas et al., 2020).

Ecological accounting must incorporate connectivity, resilience, and landscape dynamics, avoiding out-of-kind substitutions unless robustly justified and supported by verifiable net gains (Arbeláez & Sagre, 2015; Zhu & Pan, 2025). Simultaneously, participation and transparency mechanisms must internalize costs and benefits at appropriate scales and among relevant actors, aligning with environmental justice principles and strengthening the social legitimacy of interventions (Sessin-Dilascio et al., 2024).

Against this backdrop, the present article aims to analyze the evolution, structure, and orientation of scientific production on biodiversity offsets in the northern Ecuadorian Amazon through a systematic literature review and scientometric analysis, in order to identify research trends, knowledge gaps, dominant conceptual and methodological approaches, and the main discrepancies between the normative principles underpinning this instrument and its ecological, social, and institutional implementation in a territory characterized by high biodiversity, landscape fragmentation, and pronounced socio-ecological complexity.

2. Methodology

2.1. Methodological Approach and Research Design

The methodological design of this study is grounded in a qualitative, critical–interpretive approach with a socio-ecological orientation, defined in accordance with the nature of the research object and the epistemological and ethical conditions that delimit research in Amazonian contexts. The choice of this approach is justified by the non-experimental nature of the phenomenon under analysis and by the impossibility of applying experimental or quasi-experimental designs in settings where environmental and social impacts derived from extractive activities are already ongoing, and where direct researcher intervention could exacerbate pre-existing situations of vulnerability (Taherzadeh & Howley, 2018).

Accordingly, the study was conceived as an analytical–interpretive study aimed at understanding, from an integrated perspective, the normative, institutional, and conceptual frameworks that structure biodiversity offset mechanisms. Rather than measuring discrete empirical effects or establishing experimental causal relationships, the methodological approach seeks to examine the principles, assumptions, institutional arrangements, and implementation conditions underlying biodiversity compensation in the northern Ecuadorian Amazon.

The overall methodological design follows a documentary and normative analysis logic with a regional scope, focusing on the northern Ecuadorian Amazon as the reference socio-ecological context.

2.2. Spatial and Temporal Scope

The spatial scope of the study is restricted to the northern Ecuadorian Amazon and encompasses regulatory frameworks, institutional arrangements, territorial conditions, and documented biodiversity offset experiences directly associated with this region.

The temporal scope was determined according to the validity, relevance, and availability of the documentary sources included in the analysis. Priority was given to documents reflecting the current configuration of biodiversity offset mechanisms and their immediate regulatory, institutional, and conceptual antecedents. This delimitation enabled the analysis to consider both the evolution of the compensation framework and the conditions under which it is currently implemented.

2.3. Units of Analysis and Selection Criteria

The units of analysis do not correspond to individuals, specific communities, or individual ecosystems. Instead, they comprise sets of regulatory instruments, institutional arrangements, ecological equivalence criteria, territorial considerations, and documented biodiversity offset experiences.

The selection of these units was based on three main criteria: (i) direct relevance to the research objective; (ii) contribution to assessing the internal coherence of the biodiversity offset model; and (iii) capacity to provide evidence regarding the underlying rationales, ecological assumptions, and institutional logics that structure biodiversity compensation mechanisms. This analytical delimitation allowed the study to examine biodiversity offsets as a multidimensional governance mechanism rather than as an isolated environmental management instrument.

2.4. Documentary Sources and Data Collection

All information analyzed in this study was obtained from secondary sources. The documentary corpus was structured into four main analytical categories:

1. peer-reviewed scientific literature;
2. environmental regulations and legal instruments;
3. technical reports and official public policy documents; and
4. territorial and ecological studies based on satellite data and previously published analyses.

Documentary data collection was conducted through a systematic search and subsequent selection process. Sources were screened according to explicit criteria of thematic relevance, source quality, geographical applicability, and analytical significance for the study objectives. The search and selection process was designed to identify documentary evidence capable of supporting the integrated examination of the normative, ecological, territorial, and institutional dimensions of biodiversity offsets in the northern Ecuadorian Amazon.

2.5. Documentary Corpus Management and Systematization

To strengthen transparency, traceability, and reproducibility in the document review process, the Parsifal.ai platform was incorporated as a support tool for the management and systematization of the scientific literature corpus. Its use was strictly limited to instrumental functions related to the organization, filtering, and systematization of documentary material. Specifically, the platform supported the structured registration of the identification, screening, selection, and classification stages of the reviewed scientific sources, as well as the documentation of inclusion and exclusion criteria, removal of duplicate records, and organization of relevant bibliographic metadata.

Parsifal.ai was not used to generate interpretations, establish methodological criteria, or introduce additional analytical techniques or metrics. Therefore, its incorporation did not modify the qualitative, critical–interpretive orientation of the study. Instead, the platform functioned as a technical support mechanism to improve internal consistency, auditability, and reproducibility in the management of the bibliographic corpus.

2.6. Analytical Procedure

The analytical process was conducted in three sequential phases.

Phase 1: Systematization and coding of documentary information: The selected documentary corpus was reviewed and systematized through the identification of recurring analytical categories across the different types of sources. This phase allowed regulatory, ecological, territorial, institutional, and conceptual information relevant to biodiversity offset mechanisms to be organized under a common analytical structure.

Phase 2: Construction and integration of analytical matrices: The identified categories were subsequently incorporated into analytical matrices linking the normative, ecological, territorial, and institutional dimensions. This procedure enabled systematic comparison among different sources and facilitated the identification of convergences, inconsistencies, interactions, and tensions between the formal principles of biodiversity compensation and the socio-ecological conditions characterizing the northern Ecuadorian Amazon.

Phase 3: Critical–interpretive analysis: Finally, the integrated information was subjected to critical interpretation to assess the viability of biodiversity offset mechanisms in the study region. Particular attention was given to gaps between normative principles and practical implementation, the ecological assumptions underlying compensation and equivalence mechanisms, and the structural and institutional factors that may condition their effectiveness.

Through this process, the analysis moved from documentary description toward an integrated interpretation of the conditions that influence the applicability and effectiveness of biodiversity offsets in the northern Ecuadorian Amazon.

2.7. Triangulation and Analytical Robustness

Triangulation was employed to strengthen the internal consistency of the analysis and reduce potential biases associated with reliance on a single type of information. Evidence derived from scientific literature, environmental regulations, official and technical documents, and territorial and ecological studies was comparatively examined to identify areas of convergence, complementarity, and contradiction.

In addition, the combination of normative, ecological, territorial, and institutional analytical perspectives enabled the findings to be examined from multiple dimensions of the biodiversity offset process. This methodological triangulation strengthened the interpretive robustness of the study by ensuring that conclusions were not based exclusively on a single documentary category or analytical perspective(Feeney, 2024).

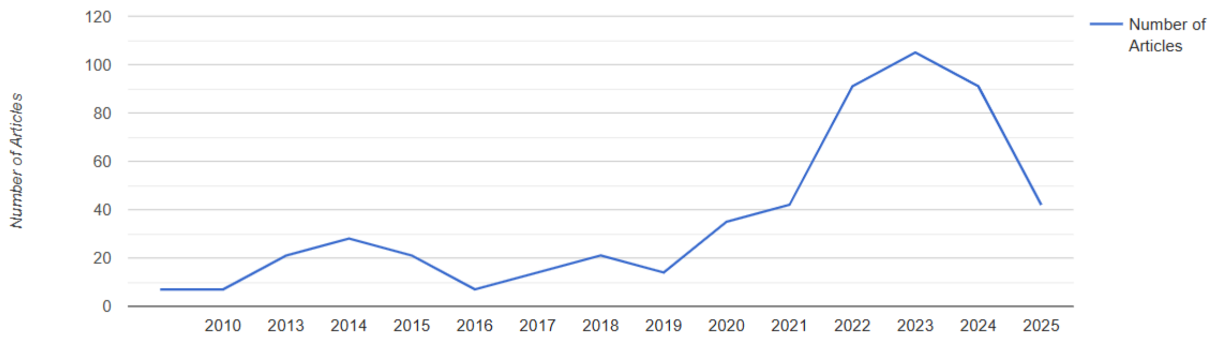
3. Results

During the identification and retrieval phase of the scientific literature, the results obtained through Parsifal.ai reveal a clearly differentiated distribution of sources according to their thematic specialization and editorial scope. PubMed concentrated the largest number of relevant records (n = 53), reflecting a high volume of studies related to biodiversity, ecological impacts, and bio-environmental approaches with indirect relevance to the analysis of biodiversity offsets. This predominance suggests that discussions on biodiversity loss are more extensively developed within biological and environmental sciences than within policy-oriented or governance-focused publication venues.

The decrease observed in 2024 and 2025 does not invalidate the general trend but may be interpreted as a lag in database indexation or as a consequence of the partial closure of the analysis period. Overall, these results confirm that scientific engagement with biodiversity loss has intensified over the past decade, although thematic specificity regarding biodiversity offsets applied to Amazonian contexts such as the northern Ecuadorian Amazon remains an emerging and still insufficiently developed field (Figure 1).

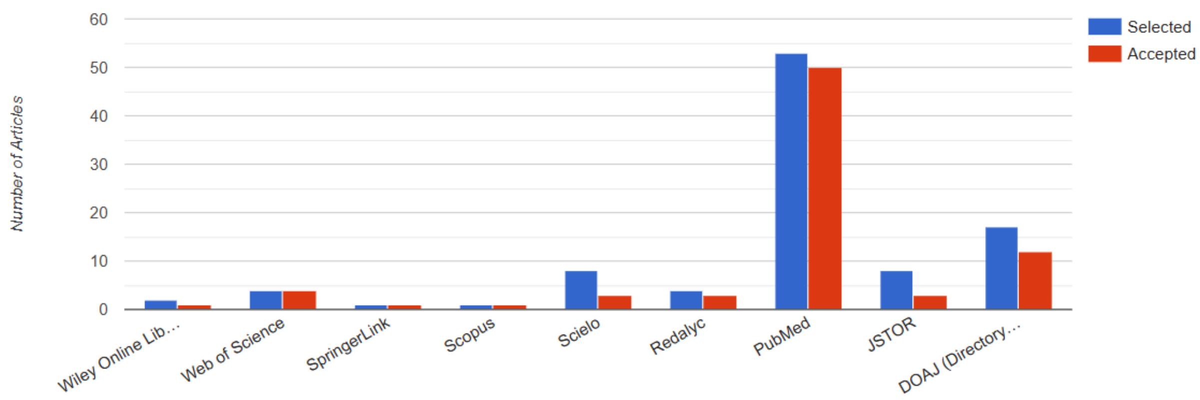
Figure 1

Temporal analysis of scientific production



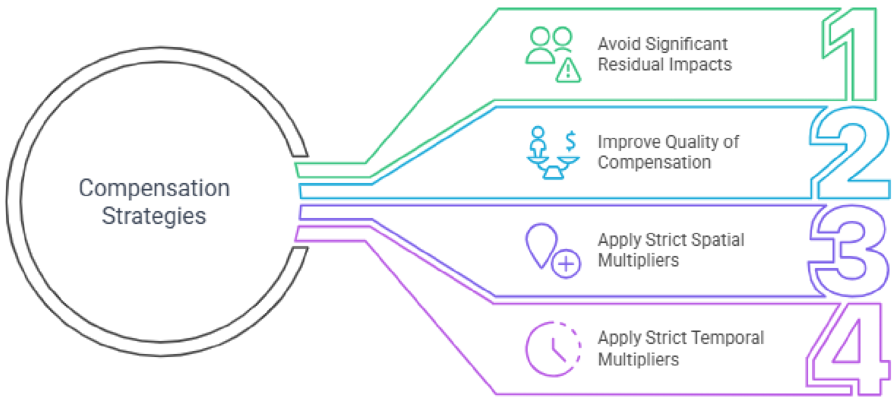
The results of the study selection and acceptance process reveal a marked asymmetry among databases in terms of both volume and acceptance rates of literature relevant to biodiversity offset analysis (Figure 2). PubMed dominates both the number of selected and accepted articles, reinforcing its role as a repository of studies focused on biodiversity and ecological impacts, albeit not necessarily specialized in offset instruments. Conversely; in contrast, high-impact multidisciplinary databases such as Web of Science, Scopus, and SpringerLink exhibit a marginal contribution, with very few selected and accepted records, suggesting limited representation of biodiversity offset research within global editorial circuits. Regional and open-access platforms, including Scielo, Redalyc, and DOAJ, show intermediate participation, with a moderate reduction between selected and accepted articles, indicating stricter thematic and methodological filtering but greater contextual relevance for Latin American environmental governance studies. JSTOR contributes a smaller number of accepted works, primarily of a theoretical or conceptual nature.

Figure 2
Accepted Articles Per Source



Additional relevant experiences arise from biodiversity offset approaches oriented toward achieving net positive impacts. Moilanen & Lehtinen, (2025) identify three operational pathways for delivering net positive outcomes, emphasizing that the most effective schemes are those that significantly restrict developer flexibility and prioritize verifiable ecological gains over nominal equivalence. In these cases, relative success does not stem from technical sophistication per se, but from the effective enforcement of the mitigation hierarchy, whereby compensation functions strictly as a last resort (Figure 3)

Figure 3.
Operativos de impactos - compensaciones



Empirical evidence provided by Shumway et al., (2023) further explores the implications of spatial flexibility in offset location, showing that under certain conditions, allowing off-site compensation can yield higher ecological benefits. However, the study also highlights significant risks of spatial mismatch and loss of social legitimacy when such flexibility is not subject to strict ecological criteria (Tranberg et al., 2024). uccessful experiences are associated with contexts in which flexibility is constrained by explicit ecological considerations, including functional connectivity, conservation priority, and biogeographical coherence (Moilanen & Kotiaho, 2021). The transferable lesson is that spatial flexibility is not inherently detrimental, but requires robust normative and technical frameworks to prevent simplified ecological substitution.

Further insights derive from offset interventions based on concrete restoration or management actions (Liu & Yuan, 2023) . Tranberg et al. (2025) document that deadwood translocation as a compensatory measure can benefit saproxylic beetle communities, provided that local habitat conditions and biological response timescales are adequately considered. This study provides direct empirical evidence that offsets can generate measurable ecological benefits when they are ecologically informed and context-specific, while also underscoring that such benefits are neither automatic nor universally applicable (Yang et al., 2023).

4.Discussion

4.1. Temporal Evolution of Scientific Production on Biodiversity Offset

The temporal analysis of scientific production derived from Parsifal.ai outputs shows a non-linear but overall upward trend in academic interest in biodiversity-related topics and, indirectly, in biodiversity offset mechanisms. Between 2010 and 2015, an initial phase of moderate growth is observed, characterized by a gradual increase in publications, followed by a marked decline around 2016, suggesting a period of thematic dispersion or limited consolidation. From 2017 onwards, the trend resumes an upward trajectory, intensifying significantly after 2020 and reaching a peak during the 2022–2023 period.

This expansion likely reflects growing global concern over biodiversity loss, the effectiveness of environmental management instruments, and the incorporation of offsetting and ecological restoration approaches into research agendas (Chang et al., 2024; Kalliolevo et al., 2025; Koh et al., 2019a; Li & Chen, 2025; Peng et al., 2025; Xu et al., 2024). However, this temporal pattern should be interpreted as representative of the scientific corpus analyzed in this study rather than as an exhaustive representation of all global research on biodiversity offsets.

4.2. Institutional and Methodological Conditions Associated with Successful Biodiversity Offsets

Experiences considered relatively successful in the field of biodiversity offsets are not defined by strict compliance with the No Net Loss objective, but rather by the presence of institutional, methodological, and governance conditions that reduce the probability of ecological failure. In this sense, the literature converges on the notion that success is not a binary outcome but a gradient shaped by design quality, baseline information availability, and long-term monitoring capacity. Empirical studies conducted in European contexts over the past decade indicate that cases with comparatively better outcomes are those in which compensation measures are restricted to clearly residual impacts and accompanied by explicit definitions of the biodiversity components subject to offsetting (Bezombes et al., 2018).

Evaluations of offset schemes implemented in France demonstrate that higher persistence rates of target habitats or species are associated with measures aimed at maintaining or enhancing pre-existing habitats, rather than with restoration or de novo creation actions, which involve substantially higher levels of ecological uncertainty (Souza et al., 2023). This finding highlights a key lesson: offsets based on the protection and management of already functional systems tend to offer greater reliability than those dependent on complex and long-term restoration processes.

4.3. Ecological Reliability: Protection and Management versus Ecosystem Creation

From a complementary methodological perspective, studies focused on the development of standardized biodiversity assessment frameworks provide relevant lessons for offset governance. The proposal of hierarchical schemes distinguishing between general and specific biodiversity levels, as well as differentiated spatial scales, helps reduce arbitrariness in indicator selection and improves transparency in the compensation process (Diao et al., 2024).

Although such approaches do not eliminate inherent ecological uncertainty, they contribute to clarifying what is being compensated and under which assumptions, thereby strengthening institutional traceability (D. Ma et al., 2023; Moilanen et al., 2024; Shan & Li, 2025; Zhang et al., 2025). Experiences analyzed in marine contexts, particularly in Australia, offer critical insights into the structural limits of offset approaches. Interview-based studies with key stakeholders reveal that even within formally robust regulatory frameworks, practical implementation is constrained by the technical complexity of measuring ecological losses and gains, as well as by political and economic pressure to approve development projects (Niner et al., 2021).

Nevertheless, these studies also identify a partially positive experience in the explicit institutional recognition that compensation is not always an appropriate instrument, opening space for more precautionary approaches aligned with the mitigation hierarchy (McMahon et al., 2024; Moulherat et al., 2023).

In low and middle income country contexts, case studies indicate that experiences deemed ecologically successful often obscure the social costs associated with biodiversity offsets (Tosini et al., 2023). Analysis of the Madagascar case shows that while some offset programs have succeeded in financing the expansion of protected areas, these outcomes have been accompanied by significant restrictions on community access to resources, generating unresolved socio-ecological tensions (Bidaud et al., 2018; Kalliolevo et al., 2025). The primary lesson derived from these cases is that offset success cannot be assessed solely through ecological metrics but must explicitly incorporate dimensions of environmental justice and the distribution of costs and benefits.

4.4. Structural Constraints on Biodiversity Offset Implementation

Experiences considered relatively successful in the field of biodiversity offsets are not defined by strict achievement of the No Net Loss objective, but rather by the presence of institutional, methodological, and governance conditions that reduce the likelihood of ecological failure (Y. Gao & Yu, 2024; Hanson & Olsson, 2023; Vardon et al., 2025). In this regard, the literature consistently emphasizes that success should be understood as a gradient rather than a binary outcome, shaped by design quality, baseline data availability, and long-term monitoring capacity.

Empirical studies conducted in European contexts in recent years indicate that cases with comparatively better outcomes are those in which offset measures are strictly limited to clearly residual impacts and accompanied by explicit definitions of the biodiversity components subject to compensation (Tranberg et al., 2025). Evaluations of offset schemes implemented in France show that higher persistence rates of target habitats or species are associated with measures focused on the maintenance or enhancement of pre-existing habitats, as opposed to restoration or de novo habitat creation, which entail substantially higher levels of ecological uncertainty (Kujala et al., 2015). This evidence reinforces the lesson that offsets grounded in the protection and adaptive management of already functional ecosystems tend to offer greater reliability than those dependent on complex, long-term restoration trajectories (Z. Ma et al., 2025; Salès et al., 2023; S. Yu et al., 2017).

From a complementary methodological perspective, studies aimed at developing standardized biodiversity assessment frameworks provide important governance-related insights. Hierarchical schemes that distinguish between general and specific biodiversity components, as well as between different spatial scales, contribute to reducing arbitrariness in indicator selection and improving transparency in offset design and implementation (Z. Ma et al., 2025; J. Wang & Wang, 2023; S. Yu et al., 2017).

While these approaches do not eliminate the inherent uncertainty of ecological systems, they enhance clarity regarding what is being compensated and under which assumptions, thereby strengthening institutional traceability and accountability. Experiences analyzed in marine environments, particularly in Australia, offer critical lessons regarding the structural limits of biodiversity offsetting (Eckert et al., 2024). Interview-based studies with key institutional actors reveal that even under formally robust regulatory frameworks, practical implementation is constrained by the technical challenges of quantifying ecological losses and gains, as well as by political and economic pressures to authorize development projects (Moilanen & Lehtinen, 2025). Nonetheless, these analyses also identify a partially positive experience in the explicit acknowledgment by regulatory authorities that biodiversity offsets are not always an appropriate instrument, thereby opening space for more precautionary approaches consistent with the mitigation hierarchy (Niner et al., 2017b; Xu et al., 2024; S. Yu et al., 2024).

In low- and middle-income country contexts, case studies demonstrate that experiences framed as ecologically successful often obscure the social costs associated with offset implementation (Diao et al., 2024) . El Analysis of biodiversity offset programs in Madagascar illustrates that, although certain initiatives have succeeded in financing the expansion of protected areas, these achievements have been accompanied by significant restrictions on local communities' access to natural resources, generating unresolved socio-ecological tensions (Bidaud et al., 2018). The key transferable lesson from these cases is that offset effectiveness cannot be assessed solely through ecological indicators, but must explicitly incorporate dimensions of environmental justice and the equitable distribution of costs and benefits.

4.5. Ecosystem-Service Valuation and Quantitative Compensation Standards

A particularly relevant set of experiences emerges from horizontal ecological compensation mechanisms, extensively documented in studies conducted in China (Cao et al., 2022; Koh et al., 2019b; Souza et al., 2023; K. Wang et al., 2020; Yang et al., 2023; Z. Yu & Zhao, 2022; X. Zhong et al., 2023) These studies demonstrate that fiscal ecological compensation schemes, when grounded in quantifiable environmental indicators and integrated into intergovernmental transfer systems, can generate statistically significant improvements in regional environmental quality. The distinctive feature of these mechanisms lies in the explicit internalization of ecological externalities between territories that provide and those that benefit from ecosystem services, thereby moving beyond traditional vertical subsidy logics.

The principal transferable lesson from these experiences is that compensation mechanisms tend to be more effective when they explicitly recognize territorial interdependencies and allocate financial responsibilities in a differentiated manner, based on actual flows of ecological benefits. Complementary analyses by Y. Liu & Yuan, (2023) further show that the profitability and long-term stability of horizontal compensation schemes depend critically on the clarity of rights and obligations among participating actors, as well as on the existence of transparent metrics to estimate ecological costs and benefits. Their findings indicate that the most stable schemes are those in which compensation is conceived not merely as a monetary transfer, but as a territorial rebalancing instrument capable of incentivizing structural changes in land-use patterns (Amiri et al., 2024; Pope et al., 2021).

Finally, studies focusing on ecosystem services and spatial valuation approaches demonstrate that multiscalar assessments of ecosystem service provision and demand can reveal patterns that remain invisible under single-scale analyses (Yang et al., 2023). Research on ecological compensation in cultivated lands further offers relevant experiences in defining quantitative compensation standards. These studies show that the use of improved models whether from food security perspectives or adjusted ecological footprint approaches allows for compensation estimates that more closely reflect the real costs of conservation (Gardner et al., 2013; Wen et al., 2024; X. Zhong et al., 2023).

4.6. Limitations

Several limitations should be considered when interpreting the findings of this study. First, the analysis is based exclusively on secondary documentary sources. Consequently, the study does not include primary ecological measurements, field observations, interviews with institutional actors, or direct assessments of affected communities. The conclusions therefore reflect patterns, principles, and limitations identified in the reviewed scientific, regulatory, technical, and territorial evidence rather than direct measurement of biodiversity offset outcomes in the northern Ecuadorian Amazon.

Second, the availability and accessibility of documentary evidence may introduce a publication and documentation bias. Biodiversity offset initiatives with formal monitoring programs, peer-reviewed publications, or publicly available institutional reports are more likely to be represented in the analytical corpus than poorly documented, unsuccessful, discontinued, or informal experiences. As a result, the available evidence may not fully capture the entire range of implementation outcomes.

Third, the considerable heterogeneity among the reviewed studies limits direct comparison across cases. Biodiversity offset mechanisms differ in their regulatory frameworks, ecological indicators, spatial scales, ecosystems, compensation objectives, monitoring periods, and definitions of success. Consequently, the findings should be interpreted as transferable analytical lessons rather than as directly equivalent empirical outcomes.

Fourth, experiences derived from Europe, Australia, China, Madagascar, and other geographical contexts cannot be transferred uncritically to the northern Ecuadorian Amazon. Differences in biodiversity, governance structures, land tenure, indigenous and local community relationships, extractive pressures, institutional capacity, and socio-political conditions substantially influence the feasibility and effectiveness of compensation mechanisms. International experiences were therefore used as comparative references rather than as directly replicable models.

Fifth, the temporal analysis of scientific production reflects the documents identified and retained within the search and selection strategy employed in this study. It should therefore not be interpreted as an exhaustive bibliometric representation of the global evolution of biodiversity offset research.

Finally, although the use of Parsifal.ai strengthened the traceability and organization of the documentary review process, the platform does not eliminate interpretive or selection biases inherent in qualitative documentary research. Decisions concerning inclusion, exclusion, analytical categorization, and interpretation ultimately depend on the methodological criteria established by the researchers.

These limitations do not invalidate the findings but define the scope within which they should be interpreted. They also highlight the need for future research combining documentary and regulatory analysis with field-based ecological assessments, stakeholder participation, and longitudinal monitoring to evaluate the practical feasibility of biodiversity offset mechanisms in the northern Ecuadorian Amazon.

5. Conclusions

Biodiversity offsetting in the Northern Amazon of Ecuador constitutes an instrument of limited viability when contrasted with the ecological, territorial, and institutional complexity that characterizes this region. Evidence derived from the systematic review and the scientometric analysis indicates that, although the conceptual framework of No Net Loss and Net Gain has gained prominence in academic and normative discourse, its operational translation in Amazonian contexts remains constrained by structural deficits in ecological information, asymmetric institutional capacities, and a fragmented application of the mitigation hierarchy principles. Under these conditions, biodiversity offsets tend to function more as administrative mechanisms for licensing closure than as effective conservation tools at the landscape scale.

A persistent gap is evident between the normative design of biodiversity offsets and their practical implementation, particularly with regard to the definition of ecological equivalence, the consideration of functional connectivity, and the integration of temporal scales compatible with Amazonian ecological processes. This gap is further reinforced by a scientific output that remains incipient and poorly visible within high-impact international circuits, thereby limiting the consolidation of robust and context-specific methodological frameworks for megadiverse regions. Moreover, the analysis highlights that the ecological effectiveness of biodiversity offsets cannot be assessed in isolation from their social and institutional implications, as territorial costs and socio-environmental tensions directly influence their legitimacy and long term sustainability.

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