UNIVERSIDADE FEDERAL DE MINAS GERAIS

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Sofia Peixoto Mourão

ALÉM DA CAVA: Sintetizando o Conhecimento Científico Sobre Mineração, Biodiversidade e Funções e Serviços Ecossistêmicos

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No dia 18 de julho de 2025, às 14:00 horas, por videoconferência, teve lugar a defesa de dissertação de mestrado no Programa de Pós-Graduação em Ecologia, Conservação e Manejo da Vida Silvestre, de autoria do(a) mestrando(a) Sofia Peixoto Mourão, orientando(a) do Professor TATIANA GARABINI CORNELISSEN, intitulada: ALÉM DA CAVA: Sintetizando O Conhecimento Científico Sobre Mineração, Biodiversidade e Funções e Serviços Ecossistêmicos". Abrindo a sessão, o(a) Presidente da Comissão, Doutor(a) TATIANA GARABINI CORNELISSEN, após dar a conhecer aos presentes o teor das normas regulamentares do trabalho final, passou a palavra para o(a) candidato(a) para apresentação de seu trabalho. Estiveram presentes a Banca Examinadora composta pelos Doutores: Yumi Oki (UFMG), Vanessa Ribeiro (UFV) e demais convidados. Seguiu-se a arguição pelos examinadores, com a respectiva defesa do(a) candidato(a). Após a arguição, apenas os senhores examinadores permaneceram no recinto para avaliação e deliberação acerca do resultado final, sendo a decisão da banca pela:

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“Era um arado torto, deformado, que penetrava a terra de tal forma a deixá-la infértil, destruída, dilacerada.”

- Torto Arado, Itamar Vieira Junior

Resumo

Esta dissertação apresenta uma revisão sistematizada da literatura científica com o objetivo de compreender os impactos da mineração sobre a biodiversidade, serviços ecossistêmicos (ES) e as funções ecológicas (EF) globalmente. Examinamos como os registros têm sido avaliados, representados e medidos em estudos acadêmicos, analisando criticamente os componentes metodológicos das publicações científicas, considerando os tipos de indicadores (*proxies)* utilizados para representar a atividade mineradora, as variáveis de resposta selecionadas e as abordagens metodológicas empregadas. A análise abrangeu 252 estudos publicados entre 1926 e 2024, resultando em 1.062 observações independentes. Foram consideradas dimensões geográficas, ecológicas e técnicas da literatura minerária, revelando uma forte concentração de estudos em países do Norte Global, no Reino biogeográfico Paleártico. A biodiversidade permanece como o foco mais frequente, especialmente com enfoque nas métricas de diversidade taxonômica. Em contraste, os serviços e funções ecossistêmicas foram avaliados com menor frequência e, muitas vezes, de forma indireta, com inferências baseadas em mudanças no uso da terra ou outros fatores ambientais, sem medições diretas das variáveis ecológicas envolvidas. As funções ecossistêmicas, em particular, foram pouco abordadas e raramente nomeadas explicitamente como tal, mesmo quando processos funcionais (como a decomposição ou a produtividade) foram analisados. Observou-se também o predomínio de abordagens baseadas em coletas ambientais (por exemplo coletas de dados em campo e experimentos em laboratório), seguido pelo uso de dados espaciais, com uso limitado de dados quantitativos. Além disso, a maioria dos estudos concentrou-se exclusivamente em ecossistemas terrestres, com pouca atenção a ambientes aquáticos ou a interações entre ambos os sistemas, indicando uma lacuna na literatura. Embora algumas análises avaliem impactos diretos da mineração por meio de comparações com áreas controle ou gradientes espaciais, muitas publicações se restringiram à descrição de padrões espaciais associados à mineração, sem avaliação formal de impacto, limitando a estimativas quantitativas como meta-análises. A presente dissertação discute os desafios metodológicos e epistemológicos dessa produção científica, incluindo a escassez de estudos interdisciplinares e a sub-representação de contextos tropicais e de países megadiversos, como o Brasil. Concluiu-se que o avanço no entendimento dos impactos ecológicos da mineração depende do fortalecimento de abordagens integradas, que considerem simultaneamente múltiplas dimensões ecológicas e sociais.

Palavras-chave: Impacto antrópico, Metodologia, Tendências de pesquisa

Abstract

This dissertation presents a systematic review of the scientific literature aimed at understanding the impacts of mining on biodiversity, ecosystem services (ES), and ecological functions (EF) globally. We examined how these elements have been assessed, represented, and measured in academic studies by critically analyzing the methodological components of the scientific publications, including the types of indicators (proxies) used to represent mining activity, the response variables selected, and the methodological approaches employed. The review covered 252 studies published between 1926 and 2024, resulting in 1,062 independent observations. Geographical, ecological, and technical dimensions of mining-related studies were considered, revealing a strong concentration of research in Global North countries, particularly within the Palearctic biogeographic realm. Biodiversity remains the most frequently addressed topic, especially through taxonomic diversity metrics. In contrast, ecosystem services and functions were assessed less frequently and often indirectly, with inferences based on land-use change or other environmental factors, without direct measurements of the ecological variables involved. Ecosystem functions, in particular, were rarely addressed or explicitly named, even when functional processes (such as decomposition or productivity) were analyzed. There was also a predominance of approaches based on environmental data collection (e.g., field surveys and laboratory experiments), followed by the use of spatial data, with limited use of qualitative data. Furthermore, most studies focused exclusively on terrestrial ecosystems, with little attention to aquatic environments or interactions between both systems, indicating a relevant gap in the literature. Although some analyses assessed mining impacts through comparisons with control areas or spatial gradients, many publications were limited to spatial pattern descriptions associated with mining, lacking formal impact assessments and preventing the use of quantitative estimates analysis such as meta-analyses. This dissertation discusses the methodological and epistemological challenges in this body of literature, including the scarcity of interdisciplinary studies and the underrepresentation of tropical contexts and megadiverse countries such as Brazil. It concludes that advancing our understanding of the ecological impacts of mining depends on strengthening integrated approaches that simultaneously consider multiple ecological and social dimensions.

Keywords: Anthropic impact, Methodology, Research trends

List of figures

List of tables

Summary

1 Introduction

1.1 Background

Mining has historically been one of the key drivers of economic development, providing essential raw materials for industries worldwide (Sonter et al., 2018). However, economic benefits associated with this activity have often come at a significant environmental and social cost. Mining activities have been associated with the degradation of ecosystems, including deforestation, soil and water contamination, and the loss of biodiversity (Xu et al., 2023). In addition, the footprint of mining extends well outside the pit boundaries: roads, worker settlements, and ancillary infrastructure penetrate surrounding wilderness, promoting and enhancing the habitat loss (Sonter *et al*., 2017; Siqueira-Gay & Sánchez, 2021).

Recent evidence indicates that mining is increasingly encroaching upon biodiversity hotspots, with approximately 79% of global metal ore extraction in 2019 occurring within the world's five most species-rich biomes (see Luckeneder et al., 2021). In the Brazilian Amazon, for example, both industrial and artisanal mining have contributed to forest loss extending beyond mine boundaries due to road construction and associated human settlements (Sonter et al., 2017). In addition to chronic impacts, mining also causes catastrophic events that exemplify its most acute ecological and social consequences. The Ok Tedi copper-gold mine in Papua New Guinea, for instance, discharged untreated tailings into the Ok Tedi–Fly River system, destroying over 1,000 km^2 of rainforest and harming indigenous fisheries (Hettler et al., 1997). In 2000, a gold mine in Baia Mare, Romania, spilled ~100,000 m^3 of cyanide-laden wastewater into the Danube basin, contaminating water supplies and killing aquatic life (Soldán et al., 2001). In Brazil, the Fundão (2015) and Brumadinho (2019) dam failures released 43 and 11.7 million m^3 of toxic tailings, respectively, resulting in river pollution, biodiversity loss, and hundreds of fatalities (Neves et al. 2016, do Carmo et al., 2017; Porsani et al., 2019).

Beyond acute accidents, ongoing mining practices can also inflict disaster-scale damage; for instance, mountaintop removal coal mining in the Appalachian region of the United States has caused long-term landscape degradation, stream burial, and chronic pollution, impacting ecosystems and public health (Palmer et al., 2010). In the Brazilian Espinhaço mountain range, for example, mining is intense and intensifying over time. Recent studies have indicated a significant decrease of suitable habitats for both birds and anurans associated with mountaintops (Pena et al., 2017), highlighting biodiversity loss. In addition, mining activities in this region have been associated with alterations in groundwater recharge and reduced water availability downstream, placing further pressure on provisioning ecosystem services (Gonçalves et al., 2020; Silva et al., 2016).

Just as biodiversity is essential for sustaining life, ecosystem services (ES) and ecosystem functions (EF) are also critical to the maintenance and stability of natural systems. Biodiversity, EF, and ES represent interconnected dimensions of ecosystem integrity. Biodiversity supports key ecological processes, such as nutrient cycling, productivity, and decomposition, as these processes are mediated by living organisms (Oliver et al., 2015; Hong et al., 2022; Correia & Lopes, 2023). Moreover, biodiversity enhances the temporal stability of ecosystem functioning (Cardinale et al., 2012), which in turn underpins the provision of services essential to human well-being (IPBES, 2019; Weiskopf et al., 2022). The long-lasting debate in ecology regarding the role of biodiversity in ecosystem functioning (BEF) highlights how species richness and functional traits drive ecosystem resilience and productivity (Hooper et al. 2005, Tilman et al. 2014). Mining activities disrupt these relationships by altering habitat structure, reducing species diversity, and impairing functional processes such as decomposition and nutrient cycling (Hooper et al., 2005; Boldy et al., 2021; Mosquera et al., 2024). Understanding these disruptions is critical for assessing the full ecological consequences of mining and also to develop strategies to mitigate its impacts on ecosystem stability and service provision.

Mining disrupts ecological integrity through different pathways in addition to biodiversity: it also alters ecosystem functions (Mosquera et al., 2024) and ecosystem services (Boldy et al., 2021). Conversely, the degradation of ecological functions can reduce habitat quality and disrupt the conditions necessary for maintaining biological diversity (IPBES, 2019; Lee et al., 2023). Given these reciprocal relationships, examining the effects of mining through the lenses of biodiversity, EF, and ES offers a comprehensive understanding of its ecological consequences and provides a robust basis for assessing socio-ecological sustainability (Boldy et al., 2021; Weiskopf et al., 2022).

1.2 Conceptual framework

The scientific literature employs diverse and sometimes overlapping terminology when referring to biodiversity, ecosystem services (ES), and ecosystem functions (EF). Here, we aim to conceptualize and separate how literature addresses these terms. From an ecological standpoint, biodiversity encompasses taxonomic, functional, and phylogenetic diversity, that is, the variety of species, traits, and evolutionary lineages within an ecosystem (Magurran, 2004; Mace et al., 2012). The scientific recognition that biodiversity is multi-dimensional marked a shift from early species-centric views, especially in the late 20th century, when ecology began integrating evolutionary and functional attributes into its assessments of community and ecosystem structure (Naeem et al., 1996; Petchey & Gaston, 2002). However, despite these theoretical advances, the term “biodiversity” is often used imprecisely in applied studies, frequently serving as a generic *proxy* for ecological quality or resilience. This occurs, for example, in studies that rely on population estimates (using abundance or density metrics), or species richness without clarifying whether they refer to taxonomic, functional, or phylogenetic diversity (Cardinale et al., 2012; Santana, 2014). Such oversimplification is particularly problematic in mining-impact studies, where a narrow focus on species lists (e.g., presence/absence data) obscures the functional roles of organisms – roles that ultimately determine ecosystem recovery, stability and service provision post-disturbance.

The concept of ecosystem services (ES) emerged as a formal term in the early 1980s, with Ehrlich and Mooney (1983) among the first to refer systematically to the benefits humans derive from ecological systems. However, it was only in 1997 that the idea gained global prominence with the publication of two landmark works: Nature’s Services (Daily, 1997) and a seminal article in Nature estimating the global monetary value of ES (Costanza et al., 1997). The latter estimated the annual value of global ecosystem services to be approximately USD 33 trillion, an amount exceeding the world’s GDP (Gross Domestic Product) at the time. This provoked widespread debate, both for highlighting the economic invisibility of ecosystem contributions and for reducing nature to monetary terms, which critics argued was excessively anthropocentric (McCauley, 2006; Costanza et al., 2017). Nonetheless, this valuation was instrumental in shifting ecosystem services into mainstream economic and policy debates.

Although a lot has advanced from the initial definition and valuation of ES, a key conceptual distinction in environmental science lies in the difference between ecosystem functions (EF) and ecosystem services (ES). EF refers to the biophysical processes and interactions, such as primary production, nutrient cycling, and decomposition, that sustain ecosystem structure and dynamics, whether or not their outcomes are utilized by humans. (see Cardinale et al., 2012; La Notte et al., 2022). In contrast, ES are the subset of those functions that directly or indirectly contribute to human well-being, such as food provision, water purification, or climate regulation (Costanza et al., 1997; MEA, 2005). While all services depend on underlying functions, not all functions are services (Guerry et al., 2015). In this view, a function like pollination becomes a service only when it benefits humans, such as through agricultural productivity. This distinction is crucial for both ecological assessment and policy-making, as it allows researchers to track how ecological integrity (functions) underpins societal benefits (services) and supports more accurate valuations and conservation strategies (Costanza et al., 2017; La Notte et al., 2022).

To systematize these benefits from the ES, several classification frameworks have been proposed. The Millennium Ecosystem Assessment (MEA, 2005) was a major milestone that categorized ES into four groups: provisioning, regulating, cultural, and supporting services. Later, the TEEB initiative (2010) adopted this same structure, while emphasizing economic valuation. The Common International Classification of Ecosystem Services (CICES) restructured the original categories to better suit environmental accounting purposes by emphasizing final services, those directly used or appreciated by humans, and excluding supporting functions to reduce the risk of double-counting (Costanza et al., 2017; Haines-Young, 2023). Provisioning services include tangible outputs like food and water; regulating services refer to benefits from ecological regulation such as climate moderation and flood control; cultural services involve recreation, aesthetics, and spiritual value; and supporting services encompass primary productivity and habitat functions, which underpin all other services (Costanza et al., 2017). A central challenge in ES research is the valuation of these services. Because most policy decisions are based on trade-offs, valuation helps incorporate ecological benefits into cost-benefit frameworks (Pascual et al., 2010; Costanza et al., 1997). Although monetary valuation remains dominant, often expressed as willingness to pay, other approaches, such as time or labor-based metrics, have been proposed (Costanza et al., 2017). Each method comes with limitations: for instance, many ES are poorly perceived or operate at large spatial or temporal scales, complicating valuation efforts (Pascual et al., 2010). To address this issue, recent efforts emphasize integrated and pluralistic valuation approaches, combining monetary and non-monetary methods, and engaging stakeholders to reflect broader values (Jacobs et al., 2016; Kenter, 2016).

1.3 Previous reviews

Systematic reviews and meta-analyses have become essential tools to synthesize existing knowledge and support evidence-based decisions in environmental science. In the context of mining and its environmental impacts, a growing number of reviews have aimed to assess the consequences of extractive activities on biodiversity and ecosystem processes across terrestrial and marine ecosystems. Some studies focus on specific ecological systems or regions, such as the canga formations in Brazil, where Boyer and Wratten (2010) explored the potential of earthworms to accelerate ecosystem restoration in opencast mining areas, emphasizing their role in improving soil structure, fertility, and biological activity, and highlighting their underutilized contribution to restoring ecosystem services and ecological function in post-mining landscapes. Skirycz et al. (2014) reviewed the unique biodiversity and restoration challenges linked to iron mining in metalliferous soils. Furthermore, Montserrat et al. (2019) provides a comprehensive environmental baseline of the Rio Grande Rise, evaluating its geomorphology, ecosystem services, and potential ecological impacts of deep-sea mining, with a focus on cobalt-rich ferromanganese crusts and the need for strategic environmental management in this underexplored region of the South Atlantic. Daipan et al. (2023) evaluated biodiversity assessment practices in mining areas across the Philippines, identifying commonly used methods, indices, and gaps in data reporting, and offering practical guidelines to improve biodiversity monitoring and conservation planning within mining landscapes. Damseth et al. (2024) examined the ecological consequences of riverbed mining, focusing on its multifaceted impacts on water quality and aquatic biodiversity, and emphasizes the urgent need for sustainable management practices and regulatory frameworks to mitigate long-term damage to riverine ecosystems.

Previous reviews have also emphasized the effects of mining on a broader scale: Liu et al. (2022) conducted a global meta-analysis to examine how human disturbances affect ecosystem services across spatial and temporal scales, revealing complex patterns of impact (including lag, spillover, and cumulative effects) and emphasizing the importance of managing these dynamics for sustainable mine area development. Seki (2022) presented a global systematic review of the environmental impacts of subterranean mining on biodiversity and ecosystem services, identifying patterns of direct and indirect effects across taxa and reporting a predominance of negative outcomes. Shanmukha et al. (2024) published an extensive overview of the multifaceted impacts of mining on biodiversity, detailing mechanisms of ecological degradation, case studies from India and emphasizing the need for integrative conservation, legal reforms, and community engagement to mitigate biodiversity loss. Dossou Etui et al. (2024) provided a global synthesis of the impacts of artisanal and small-scale gold mining (ASGM) on biodiversity, highlighting widespread environmental degradation and emphasizing the need for integrated policies, geospatial monitoring, and site rehabilitation to mitigate damage to ecosystems and protected areas.

Several studies also addressed ecological consequences of mining in high-biodiversity regions. Pascal et al. (2008) examined the severe threats posed by mining to the highly endemic biodiversity of New Caledonia, highlighting how extensive extraction activities have devastated habitats on metalliferous soils, and calling for urgent conservation efforts and international scientific attention to prevent irreversible species loss. Giam et al. (2018) presented a quantitative meta-analysis of the impacts of coal mining on stream biodiversity in the U.S., showing that mining significantly reduces taxonomic richness and abundance across invertebrates, fish, and salamanders, and concludes that existing regulations under the Clean Water Act and Surface Mining Control and Reclamation Act (SMCRA) are insufficient to protect freshwater biodiversity. Paredes-Vilca et al. (2024), analyzed the state of knowledge on the environmental impacts of mining and agricultural activities in Latin America, highlighting how both contribute to pollution and biodiversity loss. Other works explicitly addressed knowledge gaps or regional underrepresentation: Boldy et al. (2021) examines how mining affects ecosystem services (ES), identifying key gaps in the literature such as inconsistent terminology, lack of standardized methods, and limited assessment of ES beyond biophysical supply, and proposes a research agenda to improve ES management across all mining stages. Hubert-Ta et al. (2023) examined the use of biodiversity offsetting by mining companies in Madagascar as a corporate social responsibility strategy, highlighting its emergence due to state retreat, its socio-environmental shortcomings, and the challenges it poses for long-term biodiversity conservation and local communities' rights.

These beforementioned review studies span diverse scales, regions, and approaches, revealing the varied impacts of mining on biodiversity, ecosystem services, and socio-environmental systems, as well as key methodological and governance gaps. In contrast, this study offers a meta-perspective on how such impacts have been methodologically assessed, measured, and represented in the scientific literature. Rather than evaluating the effects themselves, we examined the proxies used to represent mining, the types of response variables measured, and the methodological frameworks employed. This approach fills a critical gap by revealing conceptual and operational biases, underrepresented ecological dimensions (such as ecosystem functions), and geographical imbalances in research coverage. By identifying these patterns and omissions, our study provides a foundational critique to inform future empirical assessments and policy-relevant research on mining impacts.

1.4 Aims of this review

Although the previous reviews offer important contributions, ranging from region-specific syntheses to thematic analyses focused on biodiversity, ecosystem services, or restoration practices, most studies adopt a narrative or theoric reviews, often limited to a single ecological dimension or geographic context. In an effort to broaden this understanding, the present review adopts a comparative and integrative perspective, encompassing a broader set of studies to examine how mining impacts are assessed across multiple ecological perspectives, including biodiversity, ecosystem functions and services. This systematic review aimed to synthesize the current state of knowledge on biodiversity, ecosystem services (ES), and ecosystem functions (EF) in mining contexts. In order to address this objective, we analyzed how scientific studies conceptualize and measure mining impacts, with particular attention to the methodological structures used to operationalize such assessments by examining (i) the *proxies* used to represent mining pressure (e.g., land-use change, mining activity), (ii) the impact response metrics employed to measure biodiversity, ES and EF (e.g., species richness, food supply, decomposition), and (iii) the methodological approaches applied (e.g., environmental sampling, geospatial models, qualitative assessments). In doing so, we aimed to provide a reference point for future impact evaluations, highlighting the tools, metrics, and conceptual frameworks most used in the available literature. Our review also seeks to assist researchers and practitioners in mapping the structure of knowledge production in this field, identifying both strengths and critical gaps.

Specifically, we aim to elucidate how studies investigated the impacts of mining on biodiversity, ES, and EF. We were guided by the following questions:

1 What is the global geographic distribution of research on biodiversity, ES, and EF in mining contexts?
2 What are the most frequently investigated mining resources extracted, ecosystem types, methodological approaches, and focus of assessment?
3 Which mining context (e.g., surface, underground, tailings/wastes) are most frequently assessed in relation to the different focus of assessment (BIO, ES, and EF)?
4 Which types of data collection methods (geospatial, environmental, or qualitative) are employed in each focus of assessment?
5 What are the most studied proxies of mining impact?
6 What are the most frequently used impact response metrics?
7 Which taxonomic groups, EF, and ES are most frequently assessed?

2 Materials and Methods

2.1 Data collection

2.1.1 Searching strategy

We conducted a systematic search for scientific journals that addressed biodiversity, ecosystem services (ES), and ecosystem functions (EF) in the context of mining. The search was carried out in three searching engines: Web of Science (WoS), Scopus, and SciELO. We chose these platforms because they cover a broad range of environmental science journals and provide complementary coverage of international and regional publications. The following search string was applied across all databases: "(mining OR mine OR mineration OR mines OR “mineral extraction” OR quarries OR quarrying OR quarry) AND (biodiversity OR “species richness” OR “taxonomic diversity” OR “ecosystem services” OR ecoservice* OR pollinat* OR decomposit* OR predat* OR “nutrient cycling” OR “seed removal” OR “environmental services” OR herbivor* OR “ecosystem function*” OR “ecofunctions”)”. Search was restricted to the title field in order to target studies that explicitly addressed the selected topics and to minimize the inclusion of unrelated records. Although this restriction limited the scope of retrieved articles, it was necessary given the initial volume of results (over 5,000 records), which made broader strategies unfeasible for screening. Our aim was not to capture the entire universe of studies related to ecological processes, but rather to understand how the literature explicitly frames the relationship between mining impacts and key ecological concepts, such as biodiversity, ecosystem services, and ecosystem functions. We refined the results using subject area filters available in each database. Searches were performed up to December of 2024. Detailed information about the search strategy and the final database are described in APPENDIX A. A total of 690 records were retrieved. After removing duplicates, 429 studies remained for screening. The subsequent selection process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (O’Dea et al., 2021), and the steps are illustrated in Figure 1.

2.1.2 Inclusion/Exclusion criteria

To be included in the review, studies had to explicitly assess biodiversity, ecosystem services (ES), or ecosystem functions (EF) within the context of mining. The following exclusion criteria were applied:

1 Studies addressing biodiversity, ES or EF with no reference to mining;
2 Studies addressing mining without assessing any aspect of biodiversity, ES or EF;
3 Studies unrelated to the topic, such as those focused on engineering, physics, or computational mining;
4 Review articles;
5 Studies not written in English or Spanish.

Initial screening based on titles and abstracts resulted in 320 records selected for full-text assessment. Of these, 22 studies could not be retrieved, resulting in 298 full-text articles assessed for eligibility. Among these, 22 were excluded due to language criteria and 24 were identified as review articles, resulting in a final number of 252 studies included in the systematic review.

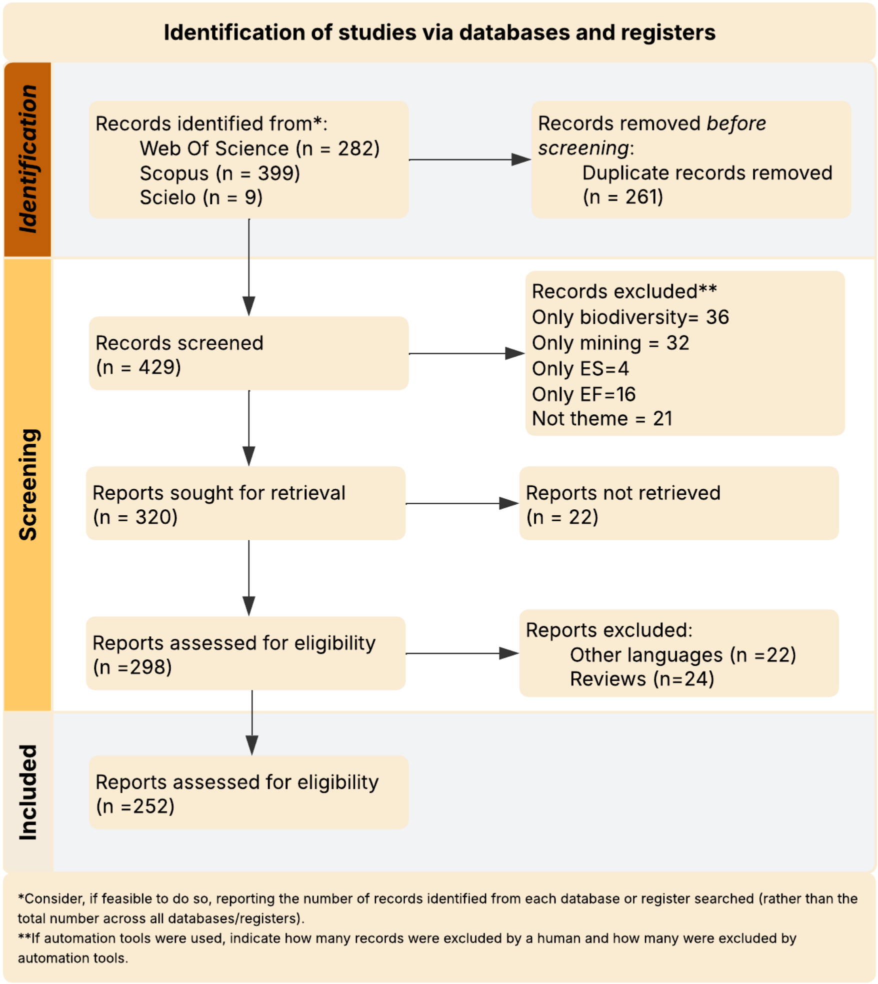

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) steps and criteria for article eligibility.

2.1.3 Data extraction

For the qualitative stage of our systematic review, we extracted data from all 252 included studies, collecting information on publication details, study location, ecological context, methodological approaches, and thematic focus. The dataset was structured to capture both general characteristics and the analytical orientation of each study. We then performed a more detailed extraction for the 95 studies that conducted impact assessments (37.6% of all studies), focusing on mining impact predictor and response variables, encompassing ecosystem services, ecosystem functions, and taxonomic groups evaluated. Ecosystem services were recorded as reported by the authors and later standardized using the Common International Classification of Ecosystem Services (CICES V5.2), while ecosystem functions were maintained using the original terms reported in the literature. The information extracted are summarized in APPENDIX B.

All data were manually extracted from the full texts, using content from the methods, results, and/or discussion sections. When not explicitly presented, interpretative criteria were applied to infer key elements, such as comparisons between mined and unmined areas, type of mining operation, and the nature of the variables and methods used. Metrics specific to ecosystem service change (ES change) and value change (ESV change) were catalogued separately to avoid category overlapping and ensure clarity in the results. All extracted data were then structured according to the analytical framework described in the following section.

Graphical analyses were applied to synthesize and compare multidimensional categorical data in a concise and interpretable format. The analyses developed from the extracted data are presented below, organized into six main components. Additionally, we adopted two levels of analytical resolution: study-level and observation-level. In total, 1,062 observations were extracted across the dataset. This distinction allowed us to capture both the breadth of study-level trends, and the depth of analytical detail reported across the literature. Some analyses were conducted using the number of studies, particularly when summarizing general characteristics such as ecosystem type or mineral resource. Other analyses, however, required a finer resolution based on the number of observations, which represent independent analytical entries extracted from each study (e.g., distinct combinations of predictor and response variables, or different methodological approaches used within the same study). This distinction allowed us to capture both the breadth of study-level trends, and the depth of analytical detail reported across the literature.

2.1.4 Framework for categorizing assessment components

Given the diversity of study designs, variables, and thematic scopes identified during the data extraction process; to support the synthesis and interpretation of the selected studies, we developed an analytical framework that reflects how mining-related impacts are investigated in the published scientific literature. This framework was structured based on five key dimensions, each representing a core component of the analytical structure adopted in this review (Figure 2). See supplementary material (APPENDIX C) for terms that were used based on this framework.

The first dimension is the focus of assessment, which corresponds to the main thematic axis explored in each study. We categorized this into biodiversity (BIO), ecosystem services (ES), ecosystem service valuation (ESV), and ecosystem functions (EF), providing a basis to understand the predominant research scope. To clarify the use of the category BIO, it is important to note that although this label initially referred to studies evaluating biodiversity, a consistent lack of standardization and fidelity to the scientific use of the term “biodiversity” was observed during data extraction. Therefore, for the purposes of this review, BIO was adopted as a broader category encompassing studies that assessed biodiversity components, including taxonomic groups, species abundance, biomass, or other biological descriptors, regardless of whether they explicitly framed their analyses in terms of biodiversity. Throughout this work, the term *biodiversity* is thus used as an umbrella concept, referring to these diverse components rather than strictly to measures of species diversity. Additionally, it is worth mentioning that, although ecosystem service valuation (ESV) was not defined as a distinct focus at the outset of this review, the analysis revealed the relevance of treating it separately from ecosystem service (ES) evaluations. While ESV remains conceptually linked to ES, we identified that studies often assessed ecosystem services without performing valuation, and vice versa.

The second dimension refers to the ecosystem type assessed among the studies, classified as terrestrial, aquatic, or terrestrial–aquatic (mixed). This categorization supports the identification of patterns in how mining impacts are assessed across different ecological environments. Studies categorized as terrestrial focused on ecological attributes of land-based systems, including land use, vegetation, landscape structure, or soil conditions, often evaluated through landscape ecology or land-based environmental assessments. Conversely, aquatic studies involved ecological evaluations of aquatic environments, such as the modeling of hydrological processes or assessments of in-stream functions, water quality, or aquatic biota. Studies classified as terrestrial–aquatic (mixed) included the direct and simultaneous analysis of ecological elements in both systems, such as biotic responses or environmental variables explicitly measured in aquatic and terrestrial habitats within the same investigation. Notably, studies modeling hydrological services (e.g., water regulation or sediment export) based solely on land cover or vegetation proxies were not considered terrestrial–aquatic unless ecological responses from both terrestrial and aquatic systems were explicitly analyzed in relation to the investigated disturbance.

The third dimension captures the methodological approach used in the studies. Approaches were classified as environmental (field-based or experimental data), geospatial (spatial modeling or remote sensing), or qualitative (interviews or narrative-based analyses).

The fourth dimension concerns the mining impact *proxies*, which are the predictor variables used to represent mining-related disturbances. These include, for example, land use change, mining activity, distance from mining areas, mining area, among others. The original terms used to describe these *proxies* were extracted directly from the studies (as reported) and then categorized into broader thematic groups to allow for cross-study comparisons. This categorization process involved interpreting how each study described the mining-related factor being analyzed and grouping similar descriptors under consistent proxy categories.

The fifth and last dimension includes the impact response metrics, referring to the response variables used to evaluate the observed effects of mining. These metrics encompass biological, ecological, functional, and economic indicators, such as species diversity, abundance, biomass, and ecosystem service change. As with the *proxies*, the terminology related to assessment metrics was first recorded exactly as presented in the original articles and subsequently standardized into broader categories to facilitate comparative analysis. The classification required careful interpretation of the studies aims and measured outcomes to ensure consistency and minimize overlap between categories.

This analytical framework provided a consistent basis for classifying and comparing studies with diverse methodological designs and environmental scopes. It also guided the structure of the visual and quantitative analyses presented in the following section.

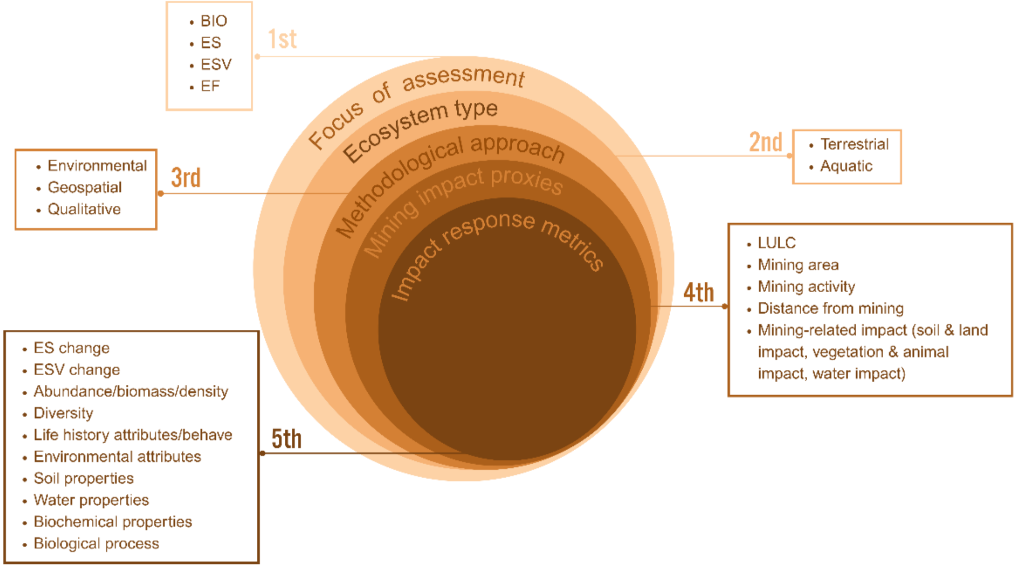

Figure 2. Conceptual framework for categorizing assessment components of the studies associated with the effects of mining on biodiversity (BIO), ecosystem functions (EF), and ecosystem services (ES). The framework includes the identification of proxies used to represent mining activities, the types of response variables measured, and the methodological approaches employed in the reviewed studies.

2.2 Data analysis

To explore and synthesize the qualitative patterns identified in the systematic review, a series of graphical analyses was conducted using the software R (version 4.5.0) within the RStudio environment. The heatmap and bubble plots were generated using *ggplot2* package (Wickham et al., 2016). The Sankey diagrams were produced to represent flows between categorical variables and were generated using *networkD3* package (Allaire et a., 2025). The

Sunburst plots were employed to visualize hierarchical relationships across multiple nested categories, and were generated using *plotly* package (Sievert, 2020). It is important to note that, for each analysis, the dataset was processed using unique entries. This means that, for each plot, a deduplicated dataset was generated in order to avoid overrepresentation of studies with multiple observations. As a result, the total number of observations varies across the different topics analyzed.

2.2.1 General overview

To assess the current state of knowledge on biodiversity (BIO), ecosystem services (ES), and ecosystem functions (EF), we mapped the geographic distribution of observations by biogeographic realm (Olson et al., 2001). Using a custom base map developed for this analysis, we plotted pie charts to illustrate the proportion of observations across focus of assessment categories.

In addition, to provide an overview of the temporal distribution of research effort, we recorded the publication year of all studies included in the review. This information was used to analyze trends in scientific output related to mining, biodiversity, ecosystem functions, ecosystem services. Two complementary visualizations were produced using different data structures: in panel (a), each study was counted once and categorized based on whether it conducted an impact assessment or not; in panel (b), each observation was treated as a unique entry, without distinguishing between studies that did or did not perform impact assessments.

In a separate set of visualization, we plotted the number of studies by mineral resource extracted and by ecosystem type separately, using bar graphs. Studies were categorized according to the ten most frequently reported mineral resources (e.g., coal, gold, iron) and by ecosystem type (terrestrial, aquatic or both). Additionally, we plotted, the number of observations by methodological approach (environmental, qualitative, and geospatial) and focus of assessment (BIO, ES, ESV, and EF), which captures unique analytical entries extracted from the observations as regards the methodological approach and focus of assessment.

2.2.2 Mining context and focus of assessment

To further investigate the distribution of studies across mining contexts, we generated a heatmap showing the number of observations for each combination of mining context and focus of assessment (BIO, ES, ESV, and EF), separated by whether or not the study conducted an impact assessment. The dataset was grouped by mining context, focus of assessment, and impact assessment. Observations lacking information on mining context were excluded. The heatmap was constructed with a continuous gradient representing the frequency of studies per combination. Faceting by impact assessment status allowed for a comparative view of research focus under each mining scenario.

2.2.3 Data collection methods and focus of assessment

We generated a Sankey plot to explore which types of data collection methods (geospatial, environmental, or qualitative) were employed in each assessment focus (BIO, ES, EF, and ESV). We first filtered the dataset to include only observations from articles that conducted impact assessments. Then, we grouped the data based on the columns “focus of assessment” and “methodological approach” to count the number of observations for each combination. The unique values of these two variables were used to define the plot nodes, where the source nodes represent the focus of assessment and the target nodes represent the methodological approaches. The width of each connection corresponds to the frequency of that specific combination in the dataset.

2.2.4 Mining impacts proxies

To identify the most studied proxies for mining impacts and their overall distribution, we generated a horizontal bar plot. To explore the relationship between impact proxies and the focus of assessment, and to visualize the frequency of combinations, we created a bubble plot. The x-axis represented contextual variables (“Section of ES”, “Environmental Service Class”, and “Taxonomic Group”), while the y-axis represented the mining impact *proxies*. The dataset was first filtered to include only records from studies with impact assessments and was reshaped into a long format. We further filtered the data to remove combinations that were not analytically meaningful, for example, cases where impact proxies were not associated with any relevant contextual category (e.g., in ES section or taxonomic group reported) or where the same *proxy* appeared redundantly due to overlapping classifications. The final plot was faceted by focus of assessment and contextual variable category, allowing for a comparative overview. Additionally, we created a Sankey diagram using the same workflow as in the previous visualizations, based on the columns “impact *proxies*” and “ecosystem type”, to analyze which impact proxies are most assessed in relation to the different ecosystem type.

2.2.5 Impact response metrics

To visualize the distribution and frequency of the most studied impact response metrics, we developed a horizontal bar plot. Following the same workflow described in the previous section for the bubble plot, we analyzed the frequency of combinations between impact response metrics and mining impact proxies, to explore how different metrics are operationalized in relation to the proxies used. This analysis helps reveal potential biases in metric selection based on *proxy* type and highlights the methodological link between how impacts are framed and how they are measured. Also, through a bubble plot, we analyzed the frequency of combinations among impact response metrics and focus of assessment, to see how the metrics were used among the focus of assessment types.

2.2.6 Taxonomic groups, ecosystem functions, and ecosystem services

To answer the question of which taxonomic groups, ecosystem functions (EF), and ecosystem services (ES and ESV) are most frequently assessed in the literature, we conducted separate frequency analyses based on the observation-level dataset. For biodiversity (BIO), we extracted and grouped all taxonomic groups explicitly evaluated in impact assessments, organizing them by major organism categories (e.g., invertebrates, mammals, plants). This analysis was based on an observation-level dataset, where only unique entries per article were considered. The number of observations per group was summarized and visualized using a horizontal bar plot, allowing for straightforward comparison of representation across taxa.

For ecosystem functions (EF), we isolated all observations categorized under the EF focus and recorded the functional process assessed in each case. Here we also used the observation-level dataset, and their frequencies were represented in a pie chart.

For ecosystem services (ES), we first extracted the services as reported by the original authors. These were subsequently classified according to the Common International Classification of Ecosystem Services (CICES V5.2), assigning each service to its respective section (e.g., provisioning, regulation and maintenance, cultural) and division. In CICES, sections are the broadest categories of ecosystem services (e.g., provisioning, regulation and maintenance, cultural), while divisions represent more specific groupings within each section (e.g., biomass, water, among other) A sunburst chart was generated to display the proportion of observations per category and subdivision, focusing on the biotic/biophysical dimension.

Similarly, for ecosystem service valuation (ESV), we applied the same classification framework, aggregating observations by CICES section and division. A separate sunburst chart was created for ESV observations to explore whether valuation studies differ in focus from general ES assessments. These analyses allowed us to identify dominant assessment themes and detect underrepresented services dimensions in the mining-related literature.

3 Results

3.1 General overview

A total of 252 studies met the inclusion criteria and were evaluated. The biogeographic distribution of observations reveals a marked concentration in the Palearctic realm (143 observations; Figure 3), followed by the Nearctic (48), Neotropical (40), Afrotropic (20), Indo-Malayan (19), and Australasian (16). Additionally, 8 observations were classified under "several," referring to studies that covered more than one biogeographic realm, and 12 observations lacked sufficient information to allow for classification.

Beyond geographic distribution, the thematic focus also varied across realms. BIO was the most frequently assessed focus in all realms, particularly in the Palearctic (67 obs.), Nearctic (24 obs.), and Neotropical (27 obs.). ES and EF followed with lower, but regionally variable frequencies : ES were most commonly assessed in the Palearctic (35 obs.), followed by the Neotropical, Afrotropical Nearctic (5 obs. each) realms; EF assessments were concentrated in the Palearctic (21 obs.) and Nearctic (19 obs.), with lower representation in the Neotropical, Indo-Malayan, and Australasian realms (5 obs. each), while ESV was the least represented, mostly limited to the Palearctic (20 obs.) and with only a few studies in the Indo-Malayan and Neotropical realms (2 obs. each). The Palearctic realm also concentrated on the highest number of ESV-related observations (20). The proportion of observations without impact assessment exceeded those with impact assessment in most realms, notably in the Palearctic (60% No, 40% Yes), Neotropical (65% No), and Australasian (62% No). Only the Afrotropic realm showed an equal distribution (50% Yes, 50% No), and the Nearctic and Indo-Malay realms presented a relatively more balanced proportion (48% Yes, 52% No, and 42% Yes, 58% No).

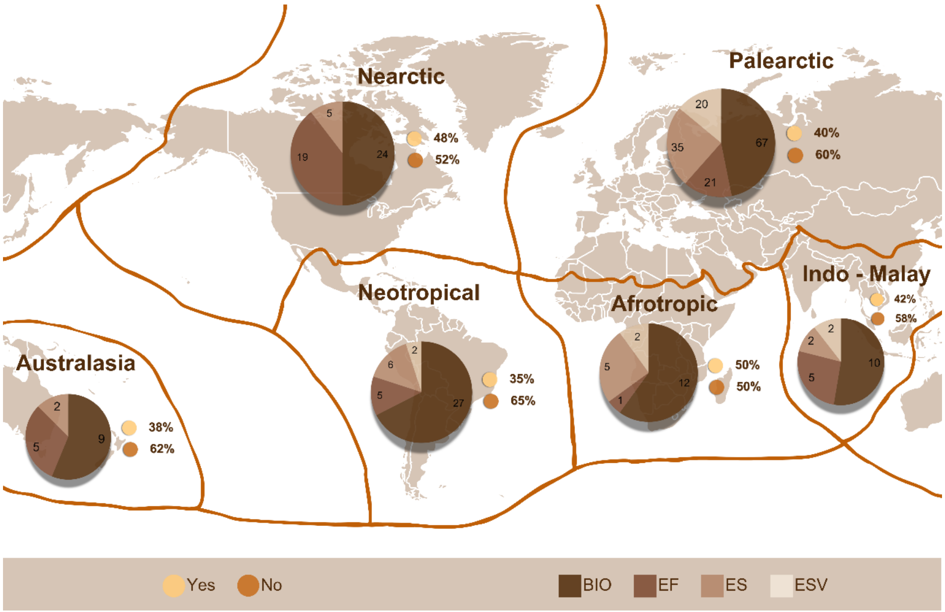

Figure 3. World map showing the biogeographic realms and the distribution of studies. "Yes" and "No" indicate whether the study included an impact assessment. "BIO", "EF", "ES", and "ESV" represent the number of independent observations per focus of assessment within each biogeographic realm.

The temporal distribution of studies and analytical observations reveals a marked expansion in mining-related ecological research over the past decades (Figure 4). The panel A) display the annual number of studies, evidencing a sharp rise after 2010, with growth particularly pronounced from 2016 onward. Studies that did not conduct explicit impact assessments ("No") consistently outnumbered those that did ("Yes") and exhibited a steeper growth rate. Panel B), which illustrates the number of independents observations per year by focus of assessment, reinforces this trend by revealing increasing thematic depth. BIO remained the dominant focus across the entire period, with a pronounced rise after 2010. However, since 2020, there has been a clear upward trend in observations related to ES and ESV, suggesting a progressive diversification of research themes.

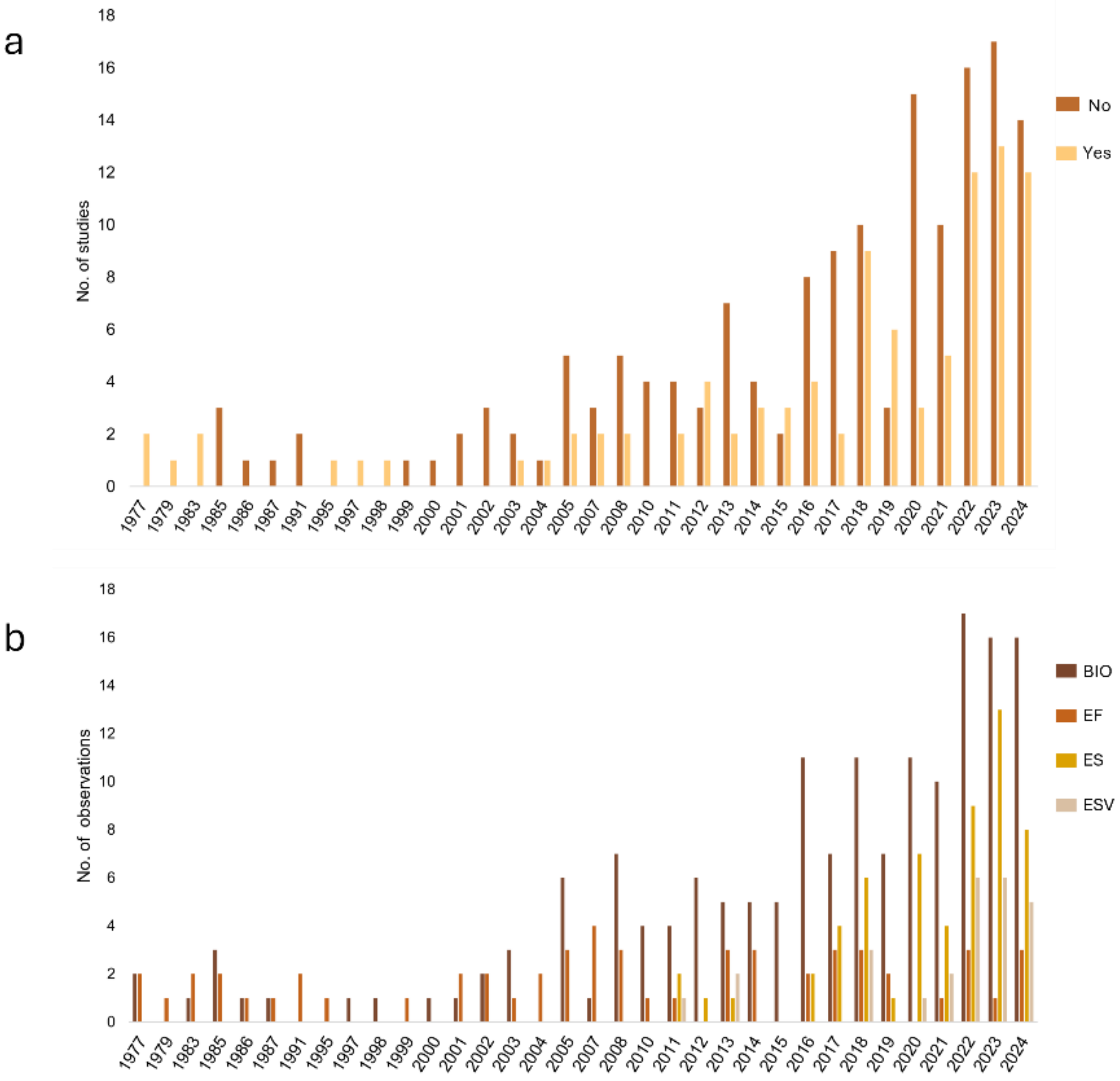

Figure 4. (a) Temporal distribution of studies addressing mining, biodiversity, ecosystem services, and ecosystem functions, separated by whether they conducted explicit impact assessments (Yes) or not (No). (b) Annual number of analytical observations categorized by focus of assessment: biodiversity (BIO), ecosystem functions (EF), ecosystem services (ES), and ecosystem service valuation (ESV).

Among all 252 studies included in this review (Figure 5), 61.9% (156 studies and 409 observations) did not evaluate the impacts of mining on BIO, ES or EF, while the remaining

38.1% (96 studies and 653 observations) explicitly assessed such impacts. Regarding the mineral resources reported in the study regions (Figure 5a), coal was the most frequently cited, followed by studies involving multiple minerals ("several") and gold. Coal-related studies accounted for the highest number in both groups, with a particularly strong presence in “No” group (44 studies vs. 36 studies). In addition, gold was more frequently associated with studies that assessed mining impacts (9 studies vs. 5), whereas iron appeared more often in studies without impact assessment (9 vs. 4). Other minerals such as bauxite, copper, and uranium were less commonly represented and tended to appear more often in studies lacking impact evaluation. In terms of ecosystem type (Figure 5b), terrestrial environments remained dominant in both groups, with 61 studies in the “Yes” group and 117 in the “No” group. Aquatic ecosystems were nearly equally represented in the yes and no group (33 and 31 studies, respectively). Combined terrestrial–aquatic systems were rare overall and appeared more frequently in studies without impact assessment (8 studies) than in those with impact assessment (2 studies). For methodological approaches (Figure 5c), environmental methods were predominant in both groups, with 63 observations among studies with impact assessment and 133 among those without. Geospatial approaches followed, with 52 observations in the “Yes” group and 36 in the “No” group. Qualitative methods were the least used overall, appearing in 5 observations from impact assessment studies and 17 from non-assessment studies. Finally, in terms of focus of assessment (Figure 5d), BIO remained the most frequently addressed focus in both groups, with 54 observations in studies with impact assessment and 112 in those without. EF and ES were similarly represented across groups, with EF slightly more frequent in the “Yes” group (18 vs. 12 observations) and ES nearly balanced (28 vs. 30). ESV was the least frequent focus, particularly in the “No” group (6 observations), though 20 entries were identified among impact assessment studies.

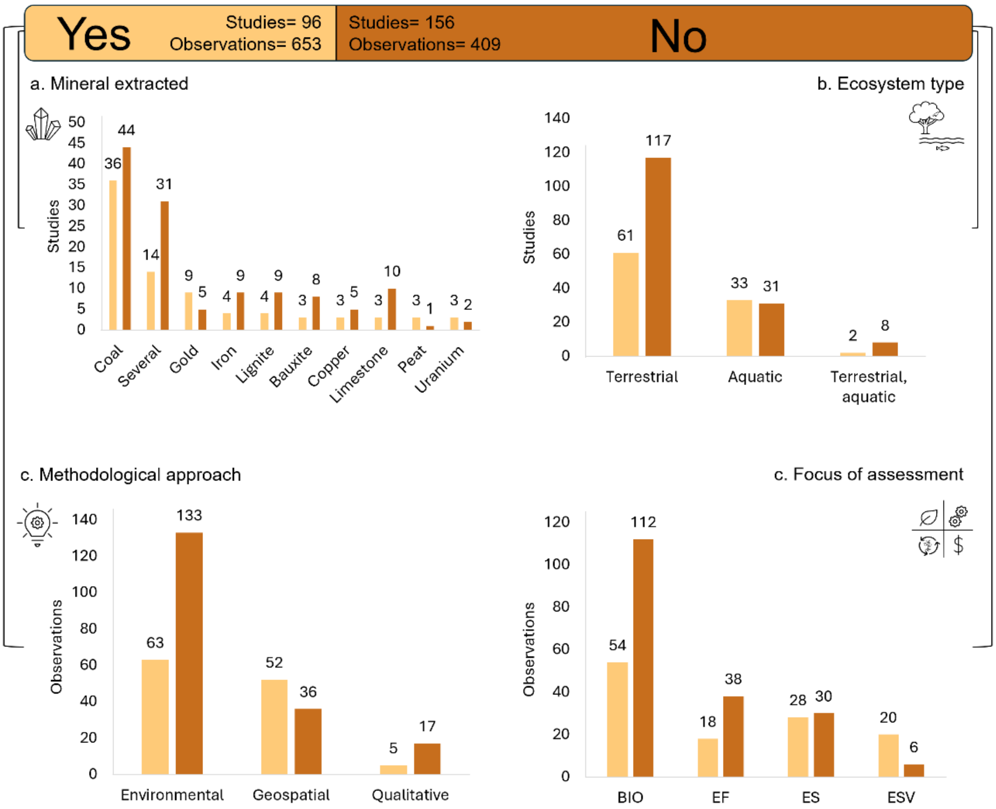

Figure 5. Summary of the main categories among studies with and without impact assessment. (a) Number of studies by mineral resource extracted in the study region; (b) Number of studies by ecosystem type; (c) Number of observations by methodological approach; (d) Number of observations by focus of assessment (BIO = biodiversity, ES = ecosystem services, EF = ecosystem functions, ESV = ecosystem service valuation). Panels (a) and (b) represent study counts, while (c) and (d) present the number of analytical observations extracted from the dataset.

3.2 Mining contexts and focus of assessment

A total of 292 observations were included in the heatmap (Figure 7), which illustrates the distribution of mining contexts across assessment focuses and impact evaluation status. Surface mining contexts dominated both groups, those with and without impact assessments, with BIO and ES as the most frequently assessed topics. Among studies with impact assessments, BIO and ES were primarily evaluated in surface and tailings/waste contexts. In contrast, underground and deep-sea mining were notably had less observations across all focuses and impact categories. ESV appeared sparsely and only in surface mining contexts, reinforcing its marginal role in literature. Observations without impact assessment also concentrated in surface mining, particularly for BIO. Additionally, the “several” context category (indicating multiple mining types) was more common in observations without impact assessment, suggesting a broader but less precise treatment of mining contexts. A total of 12 observations were excluded from this analysis due to missing information on mining context (9 BIO, 2 ES, 1 EF).

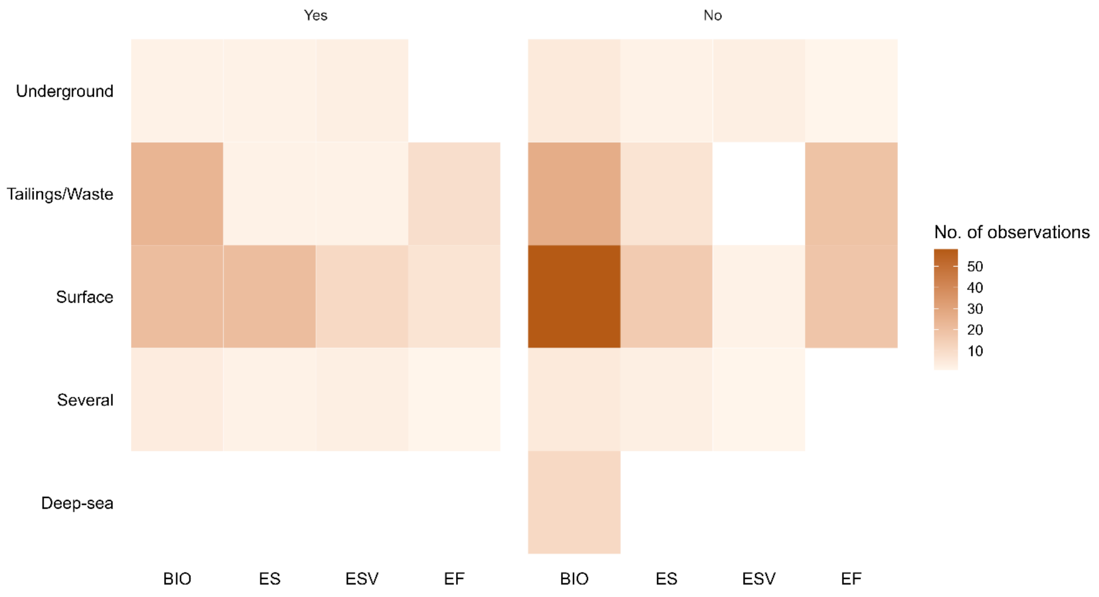

Figure 6. Heatmap showing the number of observations (292) for each mining context and focus of assessment (BIO = biodiversity, ES = ecosystem services, ESV = ecosystem service valuation, EF = ecosystem functions), separated by whether or not the study conducted an impact assessment (Yes or No). Color intensity corresponds to the number of studies. Observations lacking information on mining context were excluded

3.3 Data collection methods and focus of assessment

A total of 120 observations were included in the Sankey, from 96 impact-assessing studies (Figure 7). BIO was most frequently associated with environmental methods (approximately 81.5%, 44 observations), followed by geospatial approaches (18.5%, 10 observations). EF were exclusively linked to environmental methods (100%, 29 observations). In contrast, ES) and ESV were predominantly assessed using geospatial approaches, with 90.3% (28 observations) and 95% (19 observations), respectively. Qualitative methods were minimally represented, appearing in only a few ESV studies (1 observation) and in 3 ES observations. These patterns demonstrate a strong methodological distinction: BIO and EF are typically investigated using field-based environmental data, whereas ES and ESV rely predominantly on spatial modeling and remote sensing tools.

Figure 7. Sankey diagram showing the relationships between focus of assessment and methodological approach, based on 120 observations from 95 impact-assessing studies. The left nodes represent the focus of assessment categories: biodiversity (BIO), ecosystem functions (EF), ecosystem services (ES), and ecosystem service valuation (ESV). The right nodes correspond to the methodological approaches employed in the studies: environmental, geospatial, and qualitative. The width of each connection is proportional to the number of observations linking each assessment focus to a given methodological approach.

3.4 Mining impacts proxies

A total of 126 observations were included in the plot (Figure 8). The most frequently employed proxies were mining activity and land use/land change (LULC), appearing in 39 (31%) and 36 observations (29%), respectively. These were followed by mining area (14 obs., 11%) and distance from mining (13 obs., 10%). Proxies referring to specific environmental impacts were less common: soil & land impact appeared in 10 observations (8%), while vegetation & animal impact and water impact were each represented in 7 observations (6%). These results highlight a clear predominance of spatial proxies related to landscape configuration and proximity, such as land use patterns and extent of mining, over direct environmental impact descriptors such as mining-related impacts (water impacts, vegetation

& animal impact, and soil & land impact).

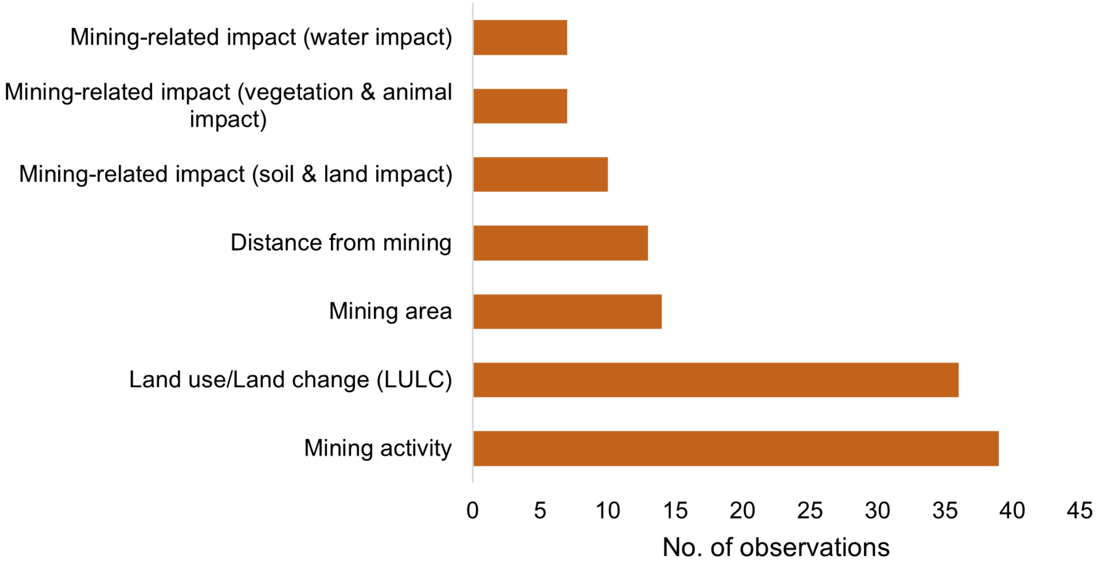

Figure 8. Mining-related proxies used in impact assessment studies (126 observations). The y-axis shows the categories of proxies employed, while the x-axis indicates the number of observations recorded for each category across the reviewed studies.

Across the 599 observations analyzed (Figure 9), the most frequently used proxies were mining activity and Land Use/Land Cover (LULC), both broadly distributed across different focus of assessment. LULC was predominantly used in studies evaluating ecosystem services, especially within Regulation & Maintenance (Biotic/Biophysical) and Provisioning (Biotic/Biophysical). Mining activity appeared more frequently in studies focused on biodiversity, particularly involving Invertebrates and Microorganisms, as well as in ecosystem function assessments such as Decomposition. Spatial proxies like Distance from mining and Mining area were also frequently applied, with higher concentrations in biodiversity assessments, especially those focusing on Invertebrates and Mammals, and in ES categories involving Regulation & Maintenance (Biotic/Biophysical). Conversely, proxies related to specific environmental impacts, such as Soil & Land, Vegetation & Animal, and Water impacts, were less commonly applied. When present, these tend to be associated with more sensitive or specialized taxonomic groups, including Amphibians, Fish, and Microorganisms. Notably, services like Cultural (Biotic/Biophysical) were assessed using a narrower set of predictors, suggesting limited methodological diversity in that domain.

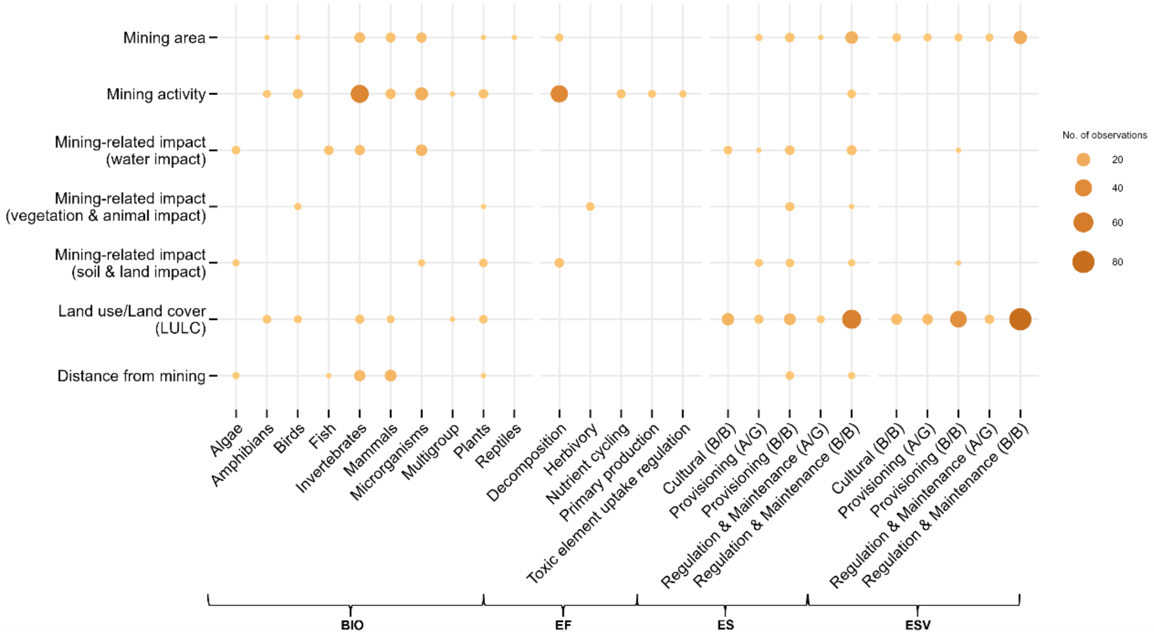

Figure 9. Frequency of predictor types used across studies (599 observations), grouped by assessed taxonomic group, ecological function, ecosystem service or ecosystem service value category. Circle size indicates the number of observations in which a given predictor was used for each category. Predictors include general mining activity, spatial attributes (e.g., distance from mining), land use and land cover (LULC), and direct environmental impacts (e.g., water, vegetation, soil). Ecosystem service categories are based on the CICES (2023) framework and are grouped by section and biotic/abiotic origin.

Our results also revealed a strong dominance of terrestrial ecosystems (10; 125 observations), where nearly all proxies were applied. The most frequently used proxies in terrestrial contexts were land use/land cover (LULC, 29 obs.), mining activity (19 obs.), and mining area (13 obs.), with LULC standing out as the primary indicator of landscape disturbance. Aquatic ecosystems accounted for 42 observations and were associated with a narrower set of proxies, notably mining activity (18 obs.), LULC and distance from mining (7 obs.), and water-related impact (6 obs.). Studies encompassing both terrestrial and aquatic systems were rare, with only one observation in mining-related impact (vegetation & animal impact), one in mining-related impact (soil & land impact), one in mining-related impact (water impact) and one in mining activity.

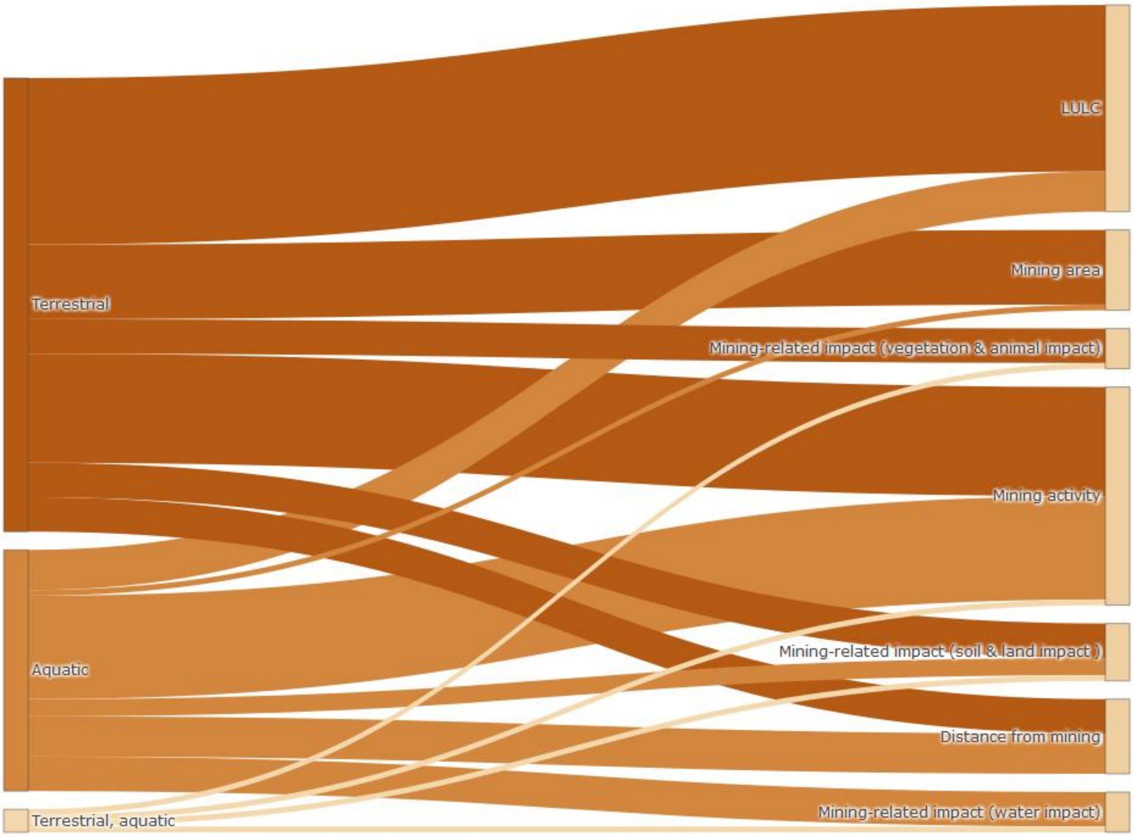

Figure 10. Relationship between ecosystem type and mining impact proxies used in the reviewed studies (n = 125). The Sankey diagram displays the number of observations linking terrestrial, aquatic, and mixed (terrestrial–aquatic) ecosystems to the different proxies used to assess mining impacts. Proxies include spatial and environmental indicators such as land use/land cover (LULC), mining activity, mining area, and specific environmental impacts (e.g., water, soil, vegetation). Thicker flows represent higher frequencies of use.

3.5 Impact response metrics

The most frequently assessed impact response metric across the reviewed studies (172 obs.) was: diversity (37 observations; 11), followed by ecosystem service change (28), biological processes (24), and environmental attributes (18). Other commonly evaluated metrics included abundance/biomass/density and ecosystem service value change (ESV; 17 each). Biochemical properties appeared in 12 observations, while water and soil properties were assessed in 8 and 7 observations respectively. Life history attributes or behavior were recorded in 4 observations. Notably, ES change and ESV change represent metrics that inherently require methodological frameworks for quantification. Within the ES change category, the most common approach was the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) modeling tool (8 observations), followed by own modelling methods (7), multi-model assessments (3), and interview-based assessments (2). Other single-use approaches included DPSIR (Driving force/Pressure/State/Impact/Response) model, GEP (gross ecosystem product) and LCA (Life Cycle Assessment) tools, and machine learning methods. For ESV change, most studies relied on the valuation coefficients proposed by Costanza et al. (1997) (7 observations), while others used remote sensing (2), the method developed by Xie et al. (2008) (2), Barbier (2011) (1), geospatial analysis (1), interview-based valuation (1), and own modelling frameworks (1).

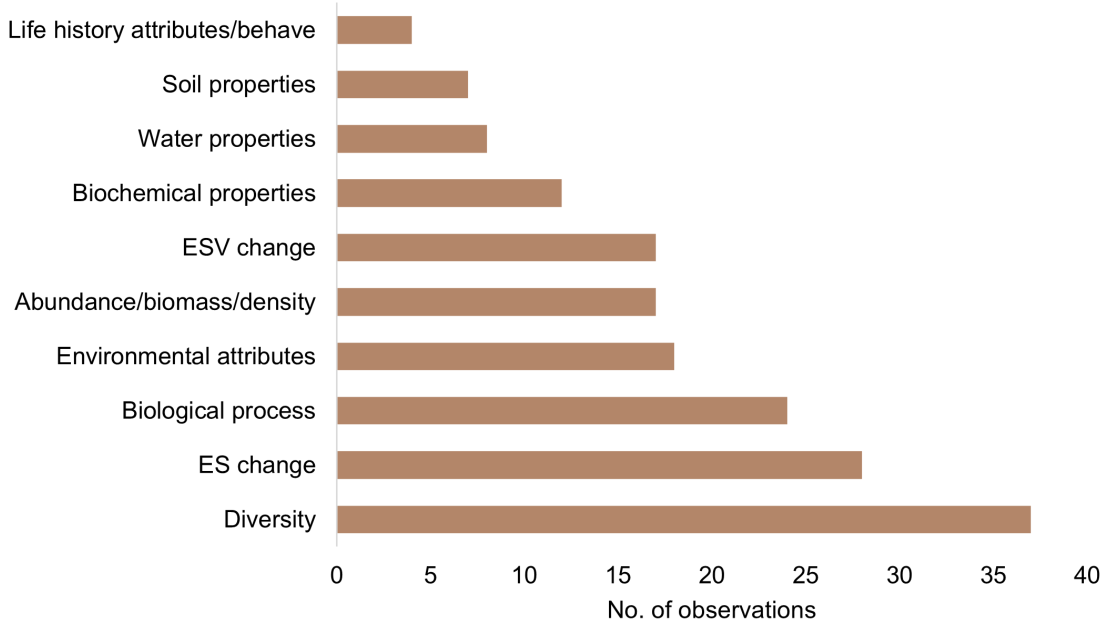

Figure 11. Frequency of impact response metrics assessed across studies (172 observations). Bars represent the number of observations classified under each standardized response category.

Across the 653 observations analyzed (13), the most frequently assessed metrics were ecosystem service valuation (ESV change) and ecosystem service change (ES change), both of which were primarily associated with Land use/Land cover (LULC) as a predictor. Biodiversity metrics such as diversity, abundance, and biological processes were also common and frequently associated with mining activity proxies. Some metrics- like environmental attributes and biochemical properties- exhibited broader proxy associations but were evaluated less frequently. In contrast, more specific indicators such as soil and water properties or life history traits appeared in a limited number of studies and were typically linked to direct impact proxies.

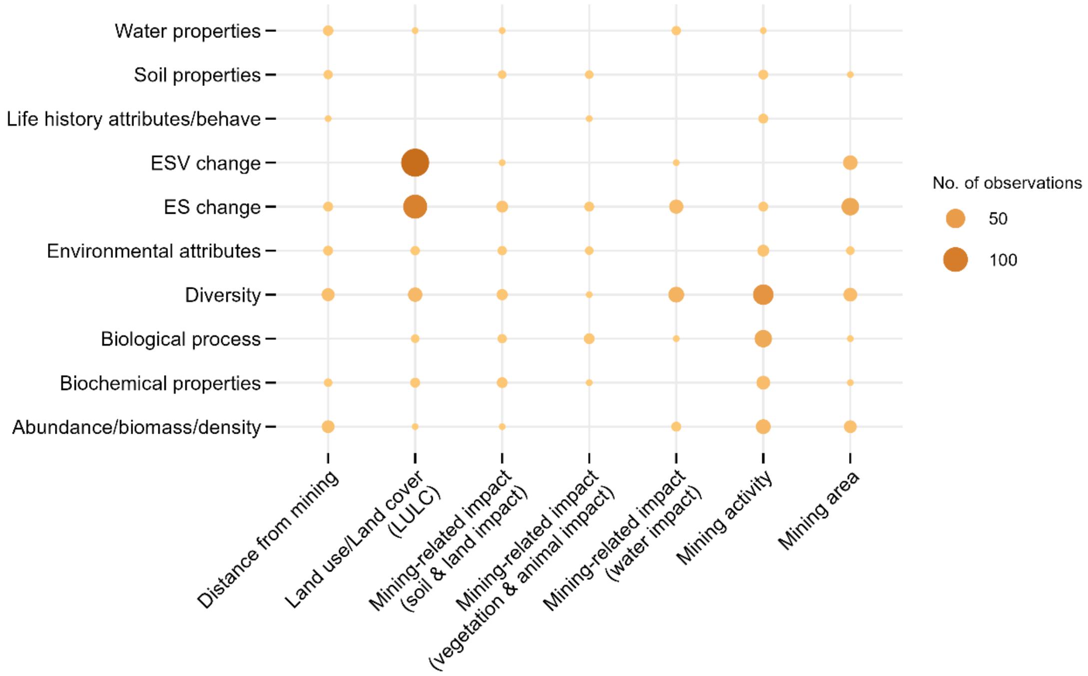

Figure 12. Bubble plot showing the number of observations (653 obs.) for each combination of impact response metrics and the impact proxies. Circle size and color intensity indicate the number of observations per combination.

Among 605 observations across different response variables and their respective assessment focus (Figure 13), BIO (biodiversity), EF (ecosystem functions), ES (ecosystem services), and ESV (ecosystem service valuation). The results reveal a markedly segmented structure, with limited overlap in the metrics used across different focus. BIO assessments were dominated by diversity-related metrics (such as richness and biodiversity indexes), followed by abundance/biomass/density and biological processes, each associated with distinct taxonomic groups. EF studies were largely concentrated on decomposition, while ES and ESV assessments focused on service change and valuation metrics, respectively, most frequently within regulating and provisioning services.

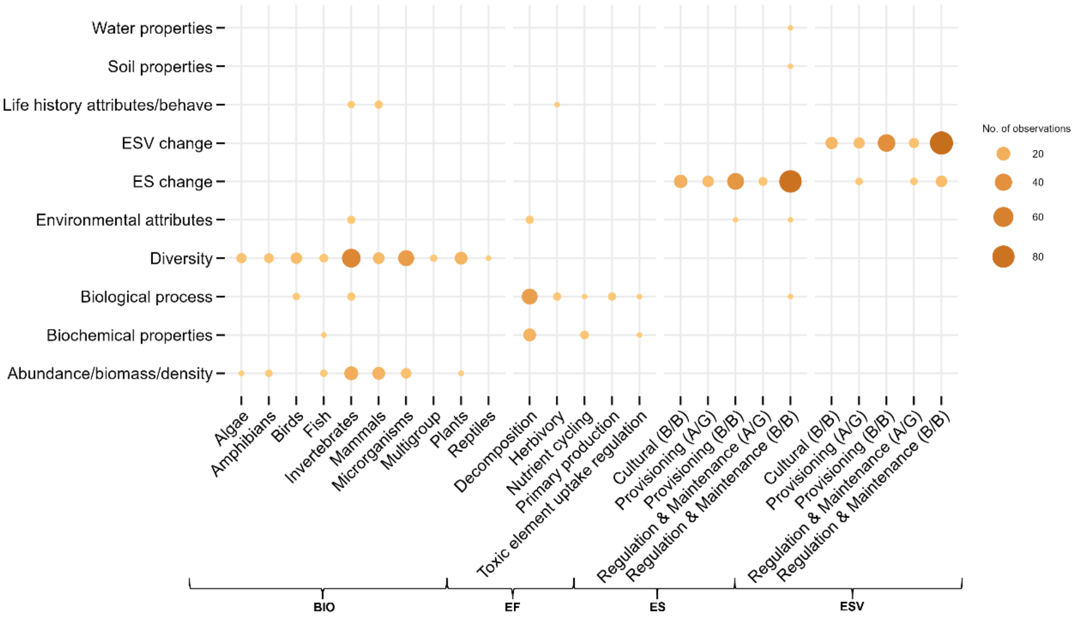

Figure 13. Distribution of assessment metrics across assessment focus of assessment (BIO = biodiversity, EF = ecosystem functions, ES = ecosystem services, ESV = ecosystem service valuation). Each dot represents the number of observations (n = 605) in which a given metric was applied within a specific assessment focus. Circle size is proportional to the number of observations.

3.6 Taxonomic groups, ecosystem functions, and ecosystem services

Among the studies that assessed BIO, a total of 61 observations could be attributed to specific taxonomic groups, while 20 additional observations were excluded from this analysis due to missing information of the mining context. Invertebrates were by far the most frequently evaluated group (22 observations, Figure 14), followed by microorganisms (10) and plants (7). Mammals (6), amphibians (4), and birds (4) appeared less frequently, while algae and fish were assessed in only 3 observations each. Multigroup assessments and reptiles were the least represented, with just 1 observation each. These findings reinforce a predominant focus on small-bodied or highly responsive taxa, particularly invertebrates and microorganisms, in biodiversity assessments related to mining, while also indicating limited attention to other vertebrate groups and cryptic taxa such as algae and reptiles.

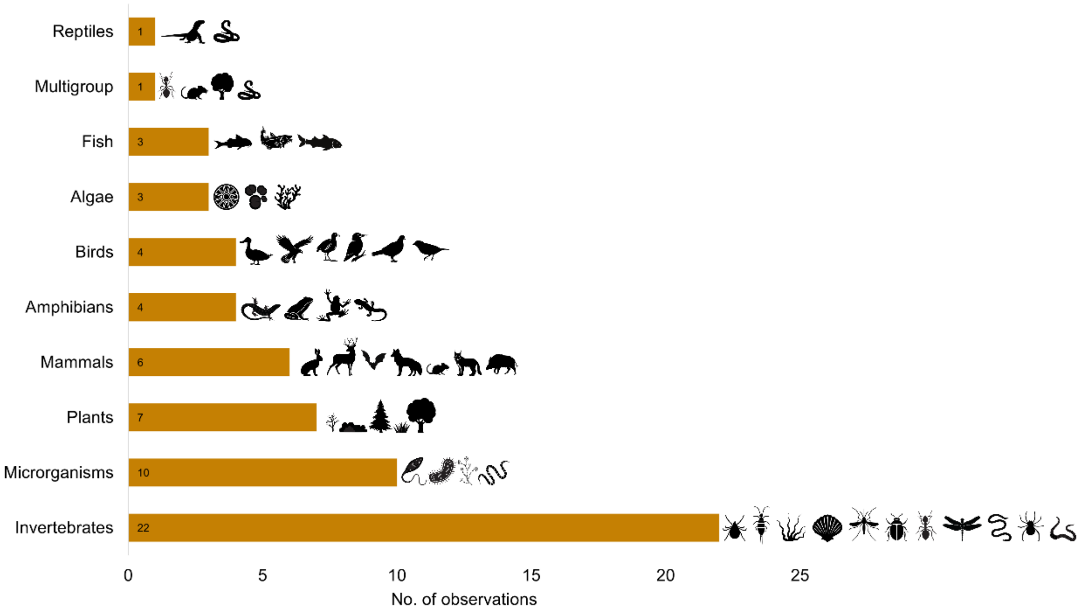

Figure 14. Number of observations per taxonomic group evaluated in mining-related impact assessments (61 obs.). Illustrative silhouettes are used to enhance visual identification of each taxon that appeared in studies.

Among the 22 observations focusing on ecosystem functions, decomposition stood out as the most frequently evaluated process, accounting for 64% of the cases (Figure 14). Nutrient cycling and primary production were each assessed in 3 observations (14% each), while herbivory and toxic element uptake regulation were the least represented, with only one observation each (4%). These results reveal a clear bias toward processes associated with organic matter breakdown, suggesting that decomposition is often used as a proxy for ecosystem functionality in mining contexts. Meanwhile, functional aspects such as trophic interactions or contaminant dynamics remain underexplored.

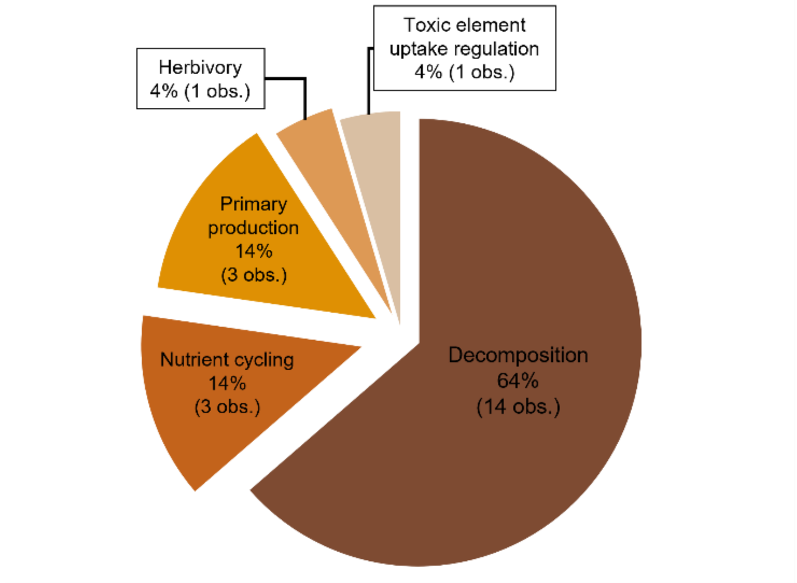

Figure 15. Distribution of assessed ecosystem functions among the 22 observations extracted from the reviewed studies. Values represent the percentage and number in parentheses indicate the number of observations.

The sunburst chart (Figure 16) illustrates the distribution of ecosystem services assessed in mining-related impact studies (80 observations). The inner segments represent the broader ES sections, while the outer rings display the corresponding divisions. Regulation & Maintenance (Biotic/Biophysical) dominated the dataset, accounting for 51% of the total observations (41 obs.). Within this section, most assessments focused on the regulation of physical, chemical, and biological conditions (54%, 22 obs.) and on baseline flows and extreme events (41%, 17 obs.), with a small fraction related to the transformation of inputs to ecosystems (5%, 2 obs.). Provisioning (Biotic/Biophysical) was the second most represented section, making up 20% (16 obs.), all of which were linked to biomass supply. Cultural services (Biotic/Biophysical) contributed 11% (9 obs.), with physical and experiential interactions comprising the majority (56%, 5 obs.). Provisioning (Abiotic/Geophysical) accounted for 13% (10 obs.), predominantly focused on water supply (90%, 9 obs.), while Regulation & Maintenance (Abiotic/Geophysical) made up the remaining 5% (4 obs.), related to transformation of inputs. These results indicate a prevailing focus on biotic regulating services, while cultural and abiotic services remain comparatively underexplored in the mining context.

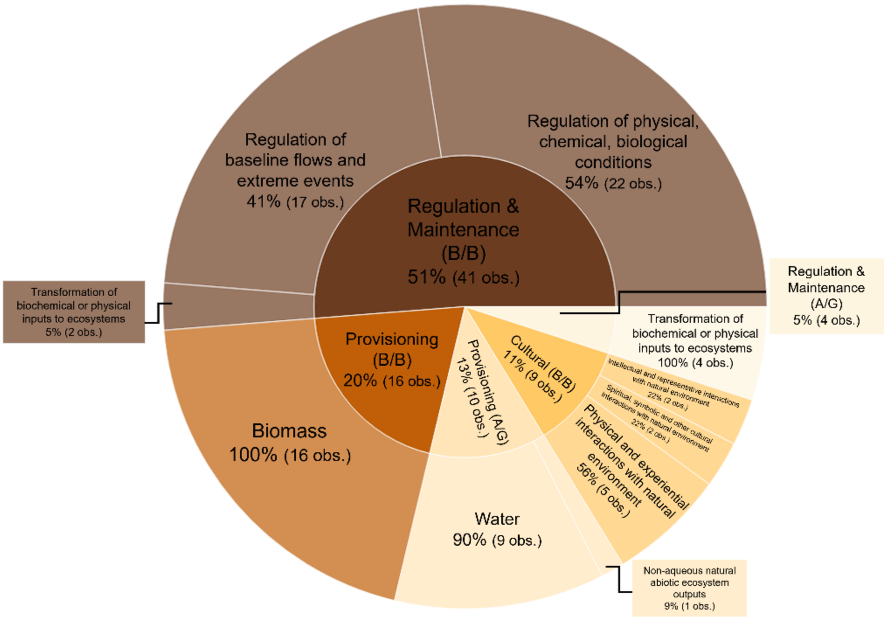

Figure 16. Distribution of ecosystem services assessed in mining-related impact studies (80 observations), based on the Common International Classification of Ecosystem Services (CICES V5.2). The inner darker segments represent the Sections of ecosystem services: Regulation & Maintenance (Biotic/Biophysical), Provisioning (Biotic/Biophysical and Abiotic/Geophysical), and Cultural (Biotic/Biophysical). The outer lighter segments correspond to the Divisions, which detail the specific service categories within each section. The values represent the proportion and total number of observations within each category.

Ecosystem service valuation (ESV) assessments were predominantly concentrated in the Regulation & Maintenance (Biotic/Biophysical) section (Figure 17), which accounted for 42% of the observations (27 obs.). Within this category, most valuations focused on the regulation of physical, chemical, and biological conditions (59%, 16 obs.), followed by the regulation of baseline flows and extreme events (37%, 10 obs.), and a small fraction related to transformation of ecosystem inputs (4%, 1 obs.). Provisioning (Biotic/Biophysical) services comprised 23% of the valuations (15 obs.), primarily associated with biomass supply (87%, 13 obs.), while other biotic resources were rarely valued. Valuations of Cultural (Biotic/Biophysical) services represented 11% (7 obs.), evenly divided between physical and experiential interactions (43%, 3 obs.), intellectual and representative interactions (43%, 3 obs.), and symbolic values (14%, 1 obs.). Abiotic services-both Provisioning and Regulation & Maintenance (Abiotic/Geophysical)- made up 23% of the observations (15 obs.), with an emphasis on water provision (89%, 8 obs.) and transformation of inputs (6 obs.). These findings highlight a strong emphasis on biotic services in valuation studies, particularly those related to tangible and extractable resources, while intangible cultural values and non-biological services remain underrepresented. In addition, it's remarkable all ESV observations were linked to ecosystem services that had already been assessed, indicating that valuation analyses were applied exclusively to previously identified ES categories.

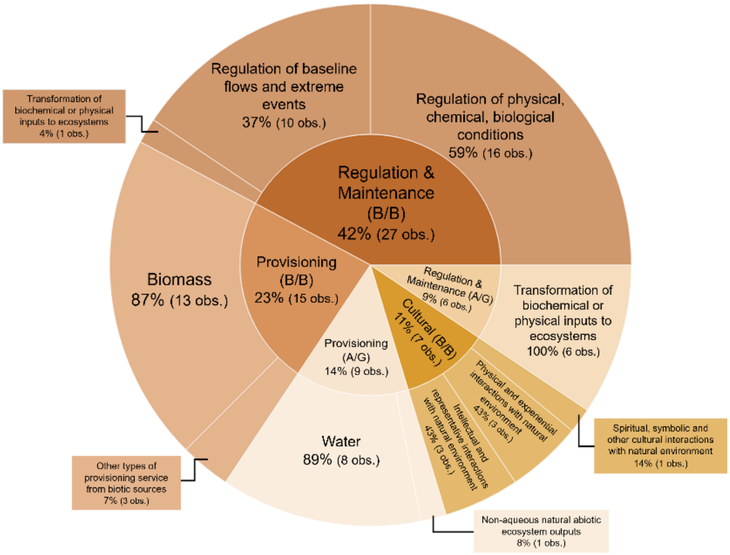

Figure 17. Representation of ecosystem service valuation categories investigated in mining-related impact studies (64 observations), based on the Common International Classification of Ecosystem Services (CICES V5.2). As in the previous figure, the darker central segments indicate the broader Sections: Regulation & Maintenance (Biotic/Biophysical and Abiotic/Geophysical), Provisioning (Biotic/Biophysical and Abiotic/Geophysical), and Cultural (Biotic/Biophysical). The lighter outer segments reflect the Divisions, which detail the specific service flows being valued within each section. The values shown correspond to the proportion and total number of valuation observations recorded for each category.

4 Discussion

This review provides a comprehensive synthesis of how scientific literature has methodologically approached the ecological knowledge of mining, biodiversity, ecosystem functions and services, revealing a fragmented and imbalanced research landscape. BIO remains the dominant focus across studies, especially in the Palearctic realm, which also concentrates the largest number of publications. In contrast, regions such as the Neotropical, Afrotropical, and Indo-Malay realms remain underrepresented. A notable share of studies (over 60%) did not explicitly assess mining impacts, and those that did rarely examined both terrestrial and aquatic ecosystems simultaneously. BIO assessments predominantly relied on traditional environmental data collection methods, whereas ES and EF were less frequently investigated and often measured indirectly through geospatial proxies such as land use/land cover. These patterns highlight not only the prevailing thematic and geographic biases in mining-related ecological research. They also reveal the methodological segmentation that limits integrative assessments across ecological components and ecosystem types.

4.1 Persistent and emerging themes

Temporal trends revealed a notable increase in research effort over the past decade, particularly after 2010, possibly reflecting broader scientific and policy concerns over the environmental consequences of mining (Mancini et al., 2013). Despite this expansion, most studies still do not perform direct impact assessments, highlighting a persistent gap in evidence-based evaluations. Throughout the analyzed period (1977 to 2024), biodiversity remained the dominant theme. This prominence is rooted in the historical development of ecology, where biodiversity has long served as a central concept, supported by standardized field metrics such as species richness and abundance.

In contrast, ES and ESV are emerging themes that gained visibility especially after 2010, following the expansion of ecosystem service mapping efforts (Anderson et al., 2021; Assumma et al., 2022). This growth also coincided with institutional developments, such as the launch of the journal *Ecosystem Services* in 2012 (Costanza, 2017) and increasing global awareness of natural capital loss (Beddoe et al., 2009).

This thematic imbalance partly reflects the historical trajectory of ecological research. While biodiversity assessments require substantial field effort and taxonomic expertise, their methodological centrality has been sustained by a well-established tradition and the availability of standardized indicators (Yoccoz et al., 2001). Meanwhile, the rise of remote sensing and geospatial modeling has enabled new possibilities for ecological analysis, yet this methodological innovation has not been matched by a proportional thematic shift. Emerging frameworks such as ES and EF are increasingly recognized, but they still occupy a smaller analytical space compared to biodiversity. Although thematic diversification is progressing, it remains uneven and shaped by longstanding research priorities and structural publication patterns, as discussed below.

4.2 Publication bias

The concentration of studies in the Palearctic realm reflects the scientific leadership of countries within this region. According to Borthakur & Singh (2018), among the top 25 countries leading global research output in “Environmental Science,” 19 are located in the Palearctic and 2 in the Nearctic. This geographic trend is consistent with our findings, which show that the Palearctic and Nearctic realms account for the highest number of studies assessing mining impacts on biodiversity, ecosystem functions, and services. Although mining occurs globally, regions such as the Indo-Malay, Afrotropical, and Neotropical realms remain markedly underrepresented in the scientific literature. These realms encompass a substantial portion of countries classified as developing nations (United Nations, 2023), where governance structures, regulatory enforcement, and mitigation capacities are often weaker. Consequently, mining impacts in these regions may be more severe, both ecologically and socially, due to limited oversight, high biodiversity, and strong local dependence on ecosystem services (Boldy et al., 2021).

A significant finding of our review concerns the relatively low number of peer-reviewed studies explicitly assessing mining impacts (n = 96). This discrepancy does not necessarily indicate an absence of assessments, but rather highlights the limited integration of environmental impact assessments (EIAs) into the academic literature. In fact, EIAs are mandatory for mining projects in most jurisdictions worldwide (IRMA, 2018). As an example, in Chile alone, more than 2,800 mining projects were submitted to the national environmental evaluation system between 1994 and 2019 (Rodríguez-Luna et al., 2022). However, most of these assessments remain confined to regulatory or internal documentation and are seldom converted into peer-reviewed publications (Kelly et al., 2007; Harries et al., 2024). This structural disconnection may reflect a broader pattern: while EIAs generate substantial ecological data on biodiversity, water quality, emissions, and other variables, these datasets are often inaccessible to the scientific community due to confidentiality restrictions, institutional barriers, or the absence of academic engagement. Although gray literature such as technical reports and regulatory assessments is valuable, this review focused exclusively on peer-reviewed scientific publications to ensure methodological consistency and analytical comparability. Many mining-related assessments exist outside academia, but they are often archived in government repositories and remain largely inaccessible. Our goal was not to capture all existing knowledge, but to examine how mining impacts have been framed and disseminated within the scientific literature.

In line with the recent growth of mining-related ecological research, a clear emphasis was observed: Coal was the most frequently addressed mineral, likely due to its long-standing role as one of the most extensively exploited natural resources (IEA, 2021), as well as its legacy of environmental degradation. This pattern may also reflect a regional bias, as several of the world’s leading coal producers, such as China (BP p.l.c., 2020), are simultaneously among the highest-ranking nations in scientific output (Nature Index, 2023).

The predominance of terrestrial systems in ecological research on mining reflects both methodological convenience and historical research priorities. This reflects both the prevalence of land-based extractive activities and the greater accessibility of terrestrial systems for monitoring (Maus et al., 2020). Terrestrial systems have also historically dominated ecological literature since the 1970s, while aquatic systems began receiving more attention only in the

1990s and remain underrepresented (Anderson et al., 2021). Although mining activities often affect marine and freshwater systems such as rivers, wetlands, and groundwater, these ecosystems were seldom addressed. This reflects a persistent bias in ecological research, as freshwater biodiversity remains poorly studied due to conservation efforts being historically concentrated on terrestrial systems (Darwall et al., 2011). The scarcity of studies addressing terrestrial and aquatic systems simultaneously further suggests a tendency toward compartmentalized analyses, which may hinder integrated evaluations of cumulative or cross-system impacts (Fernández et al., 2021). This separation is especially problematic in mining regions where ecological processes are tightly coupled. For example, iron ore deposits often occur in mountainous areas that coincide with headwater catchments and springs, so mining in these zones can directly affect freshwater quantity and quality at the source (Mercado-García et al., 2018). This spatial overlap highlights the importance of integrative studies capable of capturing both terrestrial disturbances and downstream aquatic consequences. Moreover, freshwater ecosystems remain underprioritized in global conservation research, with major geographic and thematic gaps persisting despite their high biodiversity and vulnerability (Maede et al., 2021).

Regarding methodological approaches, environmental data collection was the most frequent, even in the context of growing technological advancements. This finding aligns with the predominance of biodiversity-related assessments in our review, as field-based ecological data remains essential for evaluating biodiversity components, variables that cannot be fully captured through remote sensing or modeling (Yoccoz et al., 2001; McKenna et al., 2020. In parallel, the substantial use of geospatial approaches indicates an increasing trend toward remote sensing and spatial modeling in mining impact studies. These methods are especially useful for capturing landscape-scale patterns and for analyzing large or inaccessible areas, and their rise coincides with the broader shift toward spatially explicit analyses observed in recent years (Siqueira-Gay et al., 2019; Werner et al., 2019; García Pardo et al., 2022).

However, geospatial approaches tend to rely on proxies derived from visible land cover or satellite imagery, which limits their ability to detect subtler ecological or socio-environmental dynamics (Abdelmajeed & Juszczak, 2024). As a result, only phenomena that are spatially explicit and optically detectable, such as vegetation cover or land-use change, are typically captured, while other critical variables, such as species interactions, soil properties, or local community perceptions, remain unaccounted for (Werner et al., 2019; Lechner et al., 2019). Compared to *in situ* methods, geospatial analyses may therefore offer lower resolution, reduced accuracy, and a narrower scope of ecological inference. While efficient and scalable, these limitations may compromise the analytical depth and precision of impact evaluations, especially in studies that do not incorporate ground-truthing or direct biological sampling (Delaney et al., 2023).

Qualitative approaches, which encompass social interviews and community-based assessments, were the least represented among the reviewed studies. These aspects are difficult to access through environmental metrics or spatial data, and their exclusion reveals an important gap, particularly in assessments related to ES and ESV, which often depend on local perceptions, cultural knowledge, and context-specific values.

Finally, the literature reveals a marked predominance of surface mining contexts in ecological assessments, both in studies that assessed impacts and those that did not. This pattern is likely associated with the greater visibility and accessibility of surface operations, which facilitate monitoring through both field-based methods and remote sensing techniques. This helps explain why biodiversity stood out in surface mining contexts. Additionally, surface mining causes detectable alterations in land cover, allowing the use of satellite imagery and geospatial tools to monitor vegetation loss, soil exposure, and land-use change over time (Padmanaban et al., 2017). These methodological compatibilities may also explain the greater focus on ES in surface contexts, where spatial proxies are more easily applied. In contrast, underground and deep-sea mining remain underrepresented, particularly in studies addressing EF, ES, and ESV. This gap stems from a combination of high operational costs, logistical and technological challenges, and the absence of specific regulatory frameworks, especially in offshore contexts (Miller et al., 2021; Nomani, 2021). Additionally, the predominance of coal among the minerals investigated may further reinforce the prevalence of surface mining in ecological research, since open-pit extraction is the most common method used for coal worldwide and is inherently tied to terrestrial environments (Bandyopadhyay & Maiti, 2022).

4.3 Knowledge gaps

BIO and EF were predominantly investigated using environmental methods, reflecting ecology’s disciplinary focus on empirical, field-based data (Yoccoz et al., 2001). This reflects the necessity of *in situ* data when dealing with ecological processes and biological diversity, for example. While this approach ensures robustness in the evaluation of biological processes, it may also constrain the integration of more interdisciplinary or socially embedded methodologies. In contrast, ES, and especially their valuation (ESV), were mainly assessed using geospatial approaches. These rely on remote sensing and land-use modeling to perform large-scale analyses, often favoring proxies like vegetation cover or land-use classes (Siqueira-Gay et al., 2019; García-Pardo et al., 2022). Qualitative methods were rare, particularly in ESV and cultural ES, likely due to challenges in quantifying local perceptions and relational values (Costanza et al., 2017). Yet, qualitative approaches are essential to capture human-nature dynamics and long-term social impacts of mining that remain invisible in conventional assessments (Horstmann et al., 2021).

Patterns in proxy selection reveal significant methodological and thematic trends across the mining-ecology literature. “Mining activity” and “Land Use/Land Cover (LULC)” were the most frequently employed proxies, particularly in studies focusing on BIO and ES, respectively. Their prevalence reflects both data availability and functional relevance. LULC, for instance, captures visible landscape-level changes and was especially common in ES and ESV assessments (García-Pardo et al., 2022), where it supports analyses of provisioning and regulating services through spatial modeling. The frequent use of LULC proxy reflects not only the functional relevance of land cover in ecological assessments but also the broader availability of spatial data suited for geospatial analysis, a trend consistently observed throughout this review. Conversely, “mining activity” proxies were dominant in biodiversity assessments, especially those involving invertebrates and microorganisms, as they enable operationally feasible comparisons between impacted and control areas, strengthening causal inference. Meanwhile, direct impact proxies such as “water impact”, “soil & land impact”, and “vegetation & animal impact” were rarely used, likely due to the difficulty of directly attributing ecological change to mining, except in evident cases such as acid mine drainage or heavy metal contamination (Gomes & Valente, 2024).

A clear terrestrial bias in proxy application was observed: most proxies, particularly LULC and mining activity, were predominantly used in terrestrial ecosystems, where spatial data are more readily available. In contrast, aquatic systems were underrepresented. The proxy “water impact” was almost exclusively applied in freshwater studies, with only one exception: a terrestrial study evaluating soil pollution through a water-based assay. This strong association between terrestrial systems and spatial proxies underscores the scarcity of integrative approaches; only two studies performed a terrestrial-aquatic analysis. The rarity of such cross-ecosystem assessments reflects a compartmentalized research agenda, which limits our ability to understand cascading and cumulative impacts, such as sedimentation or pollutant transfer from terrestrial to aquatic environments (Fernández et al., 2021). This bias has biological consequences as well: fish and amphibians, which are tightly linked to aquatic ecosystems, were seldom evaluated, reinforcing the broader underrepresentation of freshwater and marine systems in mining-related ecological research.

The selection of impact response metrics is closely linked to the type of proxy employed, shaping how mining effects are conceptualized and measured in ecological research. ES change and ESV change were most often assessed using Land Use/Land Cover (LULC), highlighting the centrality of spatial data and modeling tools in these analyses. In contrast, proxies like “mining activity” and “mining area” demonstrated broad applicability across multiple metric types, indicating their versatility in ecological assessments. These generalist proxies allow comparisons between impacted and reference sites and are commonly employed in studies examining biodiversity, abundance, and functional attributes. Water and soil properties were also underused as response metrics, suggesting a persistent underrepresentation of abiotic parameters despite their ecological importance. Moreover, proxies like “water impact” and “vegetation & animal impact” showed limited association with functional metrics, maybe reflecting challenges in linking specific ecological effects to localized mining stressors. These gaps suggest that direct impacts, although ecologically relevant, are more difficult to operationalize methodologically.

Diversity remained the most frequently used response metric, reaffirming its role as the dominant analytical lens in biodiversity research. Interestingly, not all studies categorized under BIO assessed biological diversity per se. The frequent use of metrics such as biochemical properties, biological processes, environmental attributes, life history traits/behave, and abundance/biomass/density suggests that many studies addressed biological composition or functioning without explicitly measuring diversity. This pattern reinforces the need for future analyses to examine how such metrics are used in combination, which could help clarify the observed gap in the consistent application of biodiversity metrics.

Taxonomic groups were unevenly represented across the reviewed studies. Invertebrates were the most frequently assessed, likely due to their recognized sensitivity to habitat disturbance, high diversity, and ease of sampling (Borges et al., 2021). They are often employed as indicators of ecological condition and restoration success, and some authors even argue they outperform vertebrates in mining assessments (Bisevac & Majer, 1999). Microorganisms and plants were moderately represented, primarily in studies focused on soil-related processes. Their inclusion reflects their roles in regulating nutrient cycling, biogeochemical balance, and soil structure (Madejón et al., 2006; Ortiz & Sansinenea, 2022). The integration of vegetation indicators with soil parameters can improve the detection of degradation or recovery patterns. Microbial communities, in particular, are highly sensitive to abiotic stressors such as pH changes, heavy metal contamination, and nutrient shifts, making them effective indicators of ecological disturbance and resilience (Zhang et al., 2020). In contrast, vertebrates, including mammals, birds, amphibians, and reptiles, were rarely included, likely due to logistical, regulatory, and financial barriers. The need for permits, extended sampling periods, and higher costs can limit their use in ecological assessments. Only one study adopted a multigroup approach, but it failed to specify which taxa were included, undermining its contribution to broader syntheses. Finally, aquatic taxa such as algae and fish were also underrepresented, reinforcing the broader trend of neglecting aquatic ecosystems in mining-related ecological research. This lack of attention restricts our ability to understand the full ecological consequences of mining, especially in freshwater environments (Azevedo-Santos et al., 2021).

Although EF are increasingly recognized for their ecological importance, their conceptual treatment in the reviewed literature remains inconsistent and fragmented. Of the 55 studies classified under EF, fewer than half used the term explicitly: only seven explicitly used the term “ecosystem functions” in their titles and consistently throughout the text and three used the term consistently in the body only. Seventeen studies mentioned the term briefly along in text, often only once or twice, frequently substituting it with expressions such as “ecosystem processes,” “biological functions,” or “major functions.” Notably, 28 studies did not mention EF or any related terminology at all, despite clearly evaluating functional processes like decomposition, nutrient cycling, or primary production. This widespread omission reflects a conceptual gap, where relevant processes are empirically assessed but not identified within the appropriate functional framework. The use of function-specific keywords in our search strategy was essential to detect these cases and highlights the need for greater conceptual clarity in future assessments of ecosystem functioning.

From a quantitative perspective, most ecosystem service assessments in the reviewed studies focused on biotic and biophysical components, particularly those within the “Regulation and Maintenance” category. This pattern appears to reflect not only ecological priorities but also the availability of modeling tools. Notably, the InVEST suite (Integrated Valuation of Ecosystem Services and Tradeoffs), developed by the Natural Capital Project, offers widely adopted models to assess services such as sediment retention, carbon storage, water yield, and habitat quality (Natural Capital Project, 2024).

Provisioning services were less frequently assessed but still showed consistent representation, as they also align with available InVEST models and rank second in model availability. In contrast, cultural services were rarely considered. A major limitation is the challenge of standardizing and spatializing subjective values, such as aesthetic appreciation, spiritual meaning, and cultural identity, which are locally rooted and highly context-dependent. These difficulties are compounded by the scarcity of localized and qualitative data, restricting the integration of CES into geospatial frameworks (Lechner et al., 2019; Costanza et al., 2017). As Chan et al. (2012) emphasize, cultural services are often overlooked due to methodological and epistemological biases that prioritize tangible and biophysical indicators. The authors argue that dominant valuation methods fail to account for relational values and community-based meanings, which are essential for inclusive and equitable assessments of human–nature relationships. Without suitable tools and frameworks, cultural services remain underrepresented in both research and decision-making, despite their growing relevance in conservation debates.

The patterns observed in ESV assessments closely mirror those found in the broader set of ES assessments, reflecting the fact that, almost all valuation studies are a subset of ES analyses. This structural dependency helps explain the quantitative asymmetry between ES and ESV observations found. Most of the valuations were concentrated in regulating and provisioning services, particularly those involving biotic regulation and biomass production. These categories include services such as carbon storage, water regulation, and crop yield, functions that are not only ecologically relevant but also more easily translated into monetary terms (Costanza et al., 2017). In contrast, cultural and abiotic services were markedly underrepresented in valuation studies. Although these services were present in the ES dataset, few were carried through to the valuation stage. This drop-off has been noted in previous reviews as well, where intangible or non-market services tend to receive less attention in economic assessments due to methodological and conceptual difficulties (Costanza et al., 2017). This imbalance highlights a recurring pattern: valuation efforts tend to concentrate on the most tangible and economically tractable services, potentially reinforcing a narrow view of ecosystem value.

5 Conclusion

This dissertation revealed structural imbalances in the ecological literature on mining, with a persistent focus on biodiversity, a strong terrestrial bias, and the underrepresentation of aquatic ecosystems, ecosystem functions, and qualitative approaches. Scientific production remains concentrated in the Palearctic and Nearctic realms, while the Neotropical, Afrotropical, and Indo-Malayan regions remain understudied. Coal and surface mining dominate the literature, reflecting both extractive trends and research feasibility. These imbalances hinder the development of context-sensitive environmental policies, especially in Global South regions.

Geospatial methods have become widespread, particularly in studies on ecosystem services and valuation, using proxies like land use/land cover (LULC). Although efficient for large-scale assessments, these methods should be complemented with field-based ecological data and qualitative insights to capture finer ecological dynamics and sociocultural values. The near absence of qualitative research, especially in cultural ES, limits our understanding of local perceptions and relational values.

Conceptual inconsistencies remain, particularly around EF: although several studies assessed ecological processes, few explicitly adopted EF terminology, reducing comparability and synthesis potential. Proxies such as “mining activity” played a central role in biodiversity and ecosystem function assessments, allowing for comparisons across impacted and control areas and supporting more robust ecological inference. However, more direct and mechanistic proxies, e.g., water and soil contamination, were rarely used, reflecting operational challenges. Biodiversity metrics such as diversity and abundance dominated, especially for invertebrates and microorganisms, whereas abiotic and functional responses were underexplored.

The dominance of geospatial tools also reflects a technocratic trend in ES assessments, often overlooking plural value systems. As Costanza et al. (2017) and Jacobs et al. (2017) argue, monetary valuation alone is insufficient and should be complemented by biophysical and sociocultural approaches.

Though global in scope, this review highlights how national policy shifts can have major environmental consequences. In Brazil, for instance, legislative changes such as PL 2.159/2021 threaten to weaken environmental licensing, despite past disasters like Mariana, Brumadinho, and the ongoing Braskem case in Maceió. These cases illustrate broader tensions between development agendas and ecological safeguards.

Future research should address thematic, geographic, and methodological gaps by including neglected biomes and aquatic systems, explicitly framing ecosystem functions, and incorporating cultural ES and qualitative approaches. Combining geospatial, field-based, and participatory methods will enhance the relevance and explanatory power of ecological studies. Interdisciplinary collaboration, especially with local communities and policy actors, is essential for producing ecologically sound and socially just environmental governance in mining regions.

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Supplementary material

APPENDIX A- Search specifications

Table 1. Search strategy, keyword strings and searching engine results for the literature on mining and biodiversity.

Search Engine	Publication Year	Key Words	Refined By	Number Of Articles found
WOS	1977-2024	TI=(mining OR mine OR mineration OR mines OR “mineral extraction” OR quarries OR quarrying OR quarry) AND TI=(biodiversity OR "species richness" OR "taxonomic diversity" OR "ecosystem services" OR ecoservice* OR pollinat* OR decomposit* OR predat* OR "nutrient cycling" OR “seed removal” OR “environmental services” OR herbivor* OR "ecosystem function*" OR "ecofunctions")	**Web of Science Categories** • Environmental Science • Ecology • Environmental Studies • Biodiversity Conservation • Engineering Environmental • Marine Freshwater Biology • Multidisciplinary Science • Plant Sciences • Water Resourses • Biology • Forestry • Evolutionary Biology • Microbiology • Limnology • Zoology • Remote Sensing • Entomology • Agronomy • Ornithology **Document Types** • Article • Review Article •Early Access **Research Areas** • Environmental Science Ecology • Science Technology Other Topics • Biodiversity Conservation • Marine Freshwater Biology • Plant Science • Water Resources • Agriculture • Forestry • Evolutionary Biology • Microbiology • Remote Sensing • Zoology	282

Scopus	1926-2024	TITLE (mining OR mine OR mineration OR mines OR "mineral extraction" OR quarries OR quarrying OR quarry) AND TITLE (biodiversity OR "species richness" OR "taxonomic diversity" OR "ecosystem services" OR ecoservice* OR pollinat* OR decomposit* OR predat* OR "nutrient cycling" OR "seed removal" OR "environmental services" OR herbivor* OR "ecosystem function*" OR "ecofunctions") AND (LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "AGRI") OR LIMIT-TO (SUBJAREA , "EART") OR LIMIT-TO (SUBJAREA , "MULT") OR LIMIT-TO (SUBJAREA , "DECI")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "ch") OR LIMIT-TO (DOCTYPE , "bk"))	**Subject Area** • Agriculture and Biological Science • Environmental Science • Earth and Planetary Science • Multidisciplinary • Decision Science **Document Types** • Article • Review • Book Chapter • Book	399
Scielo	2011-2022	(ti:(mining OR mine OR mineration OR mines OR “mineral extraction” OR quarries OR quarrying OR quarry)) AND (ti:(biodiversity OR "species richness" OR "taxonomic diversity" OR "ecosystem services" OR ecoservice* OR pollinat* OR decomposit* OR predat* OR "nutrient cycling" OR “seed removal” OR “environmental services” OR herbivor* OR "ecosystem function*" OR "ecofunctions"))	**No refining**	9

APPENDIX B- Data collected from publications

Table 2. Data extracted from publications by the authors.

Information extracted	Description
Year	Year of publication
Country	Country where the study was conducted
Biogeographic realm	Assigned based on Olson et al. (2001)
Mineral resources	Mineral resources extracted in the study area
Mining context	Context related to mining activity in the study area (e.g., surface, underground, and tailings/waste)
Ecosystem type	Ecosystem assessed in the study, classified as aquatic, terrestrial, or both
Methodological approach	Classified as: qualitative (interviews or narrative-based analysis); environmental (experimental or field-based studies); or geospatial (remote sensing or spatial modeling)
Focus of assessment	Classified as BIO for analyses involving taxonomic groups or environmental aspects, ES for analyses involving ecosystem services, ESV for studies addressing ecosystem service valuation, and EF for analyses of ecosystem functions
Impact assessment	Classified as Yes if the study explicitly assessed mining impacts, and No otherwise
Impact proxies	Predictor variables used to represent mining pressure in the studies
Assessment metrics	Response variables measured to evaluate mining impacts (e.g., species diversity, biomass, ecosystem service value)
Ecosystem services (as reported by the authors)	Standardized using the Common International Classification of Ecosystem Services – CICES V5.2; (Haines-Young, 2023)
Ecosystem functions (as reported by the authors)	Functions assessed in the studies, categorized based on the authors' terminology
Taxonomic groups	Biological groups evaluated in the studies, categorized into plants, reptiles, amphibians, fish, microorganisms, mammals, algae, birds, and invertebrates

APPENDIX C- List of ecosystem services, mining proxies and impact response metrics as originally reported across studies

Table 3. List of ecosystem services reported across studies and their corresponding classification within the CICES framework (Haines-Young, R., 2023). Each service, as originally described by the authors, was grouped into the main CICES sections: Regulation & Maintenance, Provisioning and Cultural.

Ecosystem Service as reported	Section of Ecosystem Service (CICES)
Climate regulation	Regulation & Maintenance (Biotic/Biophysical)
Gas regulation/conditioning	
Biodiversity maintenance/protection/conservation	
Water yield	
Crop pollination	
Nutrient retention	
Plant biodiversity	
Soil productivity/erosion	
Water conservation/contamination/retention/quality/regulation/purification	
Soil conservation/retention/formation/protection/maintenance/regulation	
Carbon sequestration/storage	
Flow regulation	
Pollination	
Erosion regulation	
Nutrient cycling	
Fire control	
Flood control/protection	
Soil quality regulation	
Climate regulation	
Pest control	
Loss of water self-restraint	
Soil nutrition loss	
Forest	
Soil fertility	
Air purification/quality/conditioning	
Dust deposition	
Atmospheric regulation	
Microclimate regulation	
Sediment retention/transport/export	
Primary productivity (NPP)	

Habitat quality/provision/support /function	
Waste treatment/disposal	Regulation & Maintenance (Abiotic/geophysical)
Food production/control/provision	Provisioning (Biotic/Biophysical)
Raw materials	
Crop production/yield	
Timber production	
Traditional Medicine	
Genetic resources	
Livestock	
Capture fisheries	
Wild food	
Bushmeat	
Biomass fuel	
Animal skin	
Ornamental resources	
York plant	
Fibers/resins	
Aquaculture	
Productivity	
Loss of farmland cultivation/ fruit cultivation/land productivity/ agricultural land	
Availability of non-timber forest products	
Food supply	
Fisheries	
Agriculture	
Aquatic products	
Water supply	Provisioning (Abiotic/geophysical)
Freshwater	
Sand and clay	
Water/bodies/availability/supply/ irrigation	
Water loss	
Sand material	
Cultural identity	Cultural (Biotic/Biophysical)
Aesthetic experience	
Tourism	
Spiritual experience/value	
Ethical value	
Cognitive value	
Symbolic value	
Social memory	
Education	

Mental and physical health
Sense of place
Inspiration
Recreation
Aesthetic
Cultural activities/identity
Scientific research

Table 4. Original mining impact proxies (predictor variables) as reported by the authors and their corresponding standardized categories used in this review.

Predictor variable as reported	Predictor variable standardized
Distance from quarry center	Distance from mining
Location relative to mining (core vs. peripheral)	
Distance from mining areas	
Proximity to high disturbance areas	
Buffer zone management policies	
Proximity to mining areas	
Quarry proximity to farms	
Distance from the mine	
Distance from mining site	
Proximity to mining operations	
Distance from processing facilities	
Proximity to tailings deposition sites	
Distance from tailings sources	
Distance from tailings deposition sites	
Proximity to tailings	
Proximity to mining site, sediment contamination	
Proximity to mining site	
Proximity to mining waste disposal site	
Distance from tailings discharge point	
Proximity to discharge point (upstream vs. downstream)	
LULC (constructed land, forest decrease)	Land use/Land change (LULC)
LULC	
LULC (expansion and conversion from vegetation cover)	
LULC (conversion to construction land & subsidence waterbodies)	
LULC (expansion due to subsidence)	
LULC (formation of mining-related ponds)	
LULC (increase in mining/urban expansion)	
Area of lost vegetation due to mining	
Land use area	
Land use type (before and after mining/reclamation	
Changes in land use area (destroyed)	

LULC types, mining-induced landscape changes
temporal evolution in mining areas
Land Cover Factor
LULC changes (percentage area change over time, vegetation loss)
Mining activities (e.g., land-use change, deforestation)
Loss of specific ecosystem services (e.g., crops, livestock, freshwater)
Mining operations and landscape alterations
Land-use types (pre-mining, mining, post-mining)
Land use change
Land cover type, temporal trajectory
Land use/cover change (1987–2018)- Waterlogged areas due to mining
Land use/cover change (1987–2018)- Vegetation degradation
Land use and coal production
Mining-induced deforestation
Land-use land-cover (LULC) transformation due mining
Illegal mining (galamsey)
Mining area expansion
Mining-induced forest loss
Vegetation type, canopy cover, areas
Mining activity intensity, land use change, temporal factors (years).
Land use type changes due to mining.
Land use type transformation
Land use changes due to mining activities
Vegetation presence (vegetated vs. non-vegetated)
Farmland to Construction Land
Waterbody Expansion (due to subsidence)
Farmland to Unused Land
Forested Land to Farmland
Waterbody Change (Increase due to mining)
Construction Land Expansion
Land use type (Farmland vs. Built-up land)
Land use type (Grassland vs. Built-up land)
Land use type (Forests vs. Built-up land)
Land use type (Farmland vs. Built-up land;before vs. after mining).
Land type (mined, restored, reference).
Land type (mined, restored).
Sand mining activities (Framework DPSIR)
Mining activity(intensity and distance)
Reclamation stage, mining type
Land use/land cover (mining and reclamation)
Mining activity, reclamation phase
Land use/land cover, mining presence
Accessibility, land use (mining effects)
Land use changes due to subsidence
Mining status (mined vs. unmined bogs)

Mining activity (area of extraction)	
Mining intensity (land use change)	
Mining vs. conservation scenarios	
Mining activities, land use type	
Predicted land use scenarios	
Land-use scenarios (Mining	
Land-use scenarios (Mining)	
Mining activities, land use changes	
Mining activities	
Forest type (post-mining, mature)	
LULC (mining)	
Year (2000–2030), CMI (Coal Mining Intensity)	
CMI, Overlap areas (Mining vs. Control)	
Mining activity	Mining activity
Peat chemistry, moisture content	
Level of disturbance	
specific mining sectors (coal, nickel, precious metals)	
Mining activities (intensity, area disturbed)	
Quarry vs. reference site	
Quarry abandonment time (Class I, II, III)	
Quarry vs. traditional landscape	
Geographic zones (mining zone, close to water, shurbland, control)	
Zone type (riparian, dehesa, etc.)	
Mining activity (natural soil vs. mine spoils)	
Habitat type (undisturbed bog dome, 20-year post-extraction site, 40-year post-extraction site)	
Soil nutrients (P, S, Mo)	
Rhizosphere microbiome structure and composition	
Habitat type (mined, mined with vegetation, unmined)	
Habitat type (mined vs. unmined)	
Anthropogenic activities (open-pit mining	
Anthropogenic activities(underground mining)	
Soil samples (20 plots, reference site)	
Coppern and pH	
Soil samples (20 pce site)	
Type of area (gob piles or primary area)	
areas	
Mining disturbance	
Soil pH (low <4.5, moderate ≥5.0).- areas	
Hydrology (flooded vs. saturated)	
Water quality (metal concentration, hydrology)	
Wetland type (volunteer vs. treatment)	
Water acidity (pH), metal concentrations	
pH, redox potential	
microbial activity	

Sediment conditions (pH, redox)	
Habitat type (subsidence pools vs. other habitats)	
Habitat characteristics (e.g., vegetation cover, water quality)	
Habitat type (subsidence pools, natural ponds, artificial reservoirs)	
Sediment contamination levels	
Pond type (Quarry vs. Control)	
pH of water	
pH and water chemistry of wetlands (circumneutral, acidic, very acidic)	
Litter origin (circumneutral vs. acidic wetlands)	
Water quality (pH, heavy metal concentrations)	
Water pH	
Distance to forest edge	
Copper concentration in water and sediments	
Water quality (polluted vs. non-polluted streams)	
Litter origin (polluted vs. non-polluted sites)	
Water temperature (upstream vs. downstream)	
Water pH, conductivity	
AMD (treated vs. untreated vs. reference streams)	
specific conductance	
Subsidence stage (initial, middle, late)	
TDS	
Dissolved Oxygen (DO)	
Habitat type (natural vs. post-mining lakeshore)	
Soil nutrient content; Forest type	
increase mining zone scenarios (habitat quality)	Mining area
mining Surface increase scenarios (10%, 20%, 50%)	
mining cover, natural cover	
landscape scale(mining area transformed	
Destroyed land area	
Abandoned mining residues (sludge, waste dumps)	
Mining intensity (Resource Mining Factor (RMF)	
Mining scenarios (area mined)	
mining area expansion	
Expansion of stone quarrying and crushing areas	
Mining coverage (proportion of land mined)	
Presence of mine waste (mine waste vs. pasture).	
Open-cast mining expansion (1990–2020)	
Mining impact area (1990–2020)	
Surface mining expansion (1990–2015)	
Surface mining expansion (2000–2015)	
Number of mines; Location of mines	
Number of mines; Interaction of mines	
Sampling groups (G1, G2, G3), tailings, and sludge.	Mining-related impact (soil
Metal(loid) concentrations in soils and spatial data	
Runoff from tailings and dumps into streams and reservoir	

Heavy metal contamination in soils Soil composition, HM concentrations HM concentrations in soil Soil heavy metal levels (Zn, Cd, Cu, Pb), pH, Na Bioavailable and soluble metal levels (Zn, Cd, Pb, Cu) Soil type (natural soil, mine spoils, revegetated soils) Coal mining sinks (economic and environmental loss due to mine sinks) Coal waste impact Concentration of heavy metals (As, Cd, Zn, Sb) Soil gperties (pH, TP, TOC, TN) Population growth, urbanization, infrastructure development Saline intrusion, land erosion Metal concentrations (Pb, Hg), land cover changes Tailings dispersion (sediment concentration, plume extent)	& land impact)
Vegetation type (Reduction in species availability due to land conversion) Dust concentration Metal contamination levels Metal type (Pb, Zn, Cr, Tl) Contaminated soils (G1, G2, G3) Plant species, soil contamination Soil adherence to roots and shoots Coal dust coverage on leaves Metal and arsenic concentrations in blood Contaminant concentration	Mining-related impact (vegetation & animal impact)
Heavy metal contamination in water Sand mining, boat traffic River flow alteration, sedimentation Groundwater pumping volume Seawater intake volume, brine discharge Volume of water supplied Water supply scenario (average and worst-case) Environmental conditions (e.g., sunlight, pH) Mining-related disturbances (water abstraction, berm construction) Sedimentation, physical barriers Sedimentation caused by mining Mining activity, river flow Mining activity, seasonality Mining-induced river morphology changes Specific conductivity Specific conductivity gradient	Mining-related impact (water impact)

Table 5. Original impact response metrics (response variables) as reported by the authors and their corresponding standardized categories used in this review.

Response variable as reported	Response variable standardized
Daily abundance; Wolf sightings (Canis lupus)	Abundance/biomass/density
Daily abundance; Fox sightings (Vulpes vulpes)	
Daily abundance; Lynx sightings (Lynx lynx)	
Daily abundance; Wild boar sightings (Sus scrofa)	
Daily abundance; Jackal sightings (Canis aureus)	
Daily abundance; Hare sightings (Lepus europaeus)	
Small mammals Abundance	
Abundance (bats)	
Abundance (dung beetles)	
Shoot biomass (plant growth)	
abundance	
Bacterial population abundance	
Actinomycetes population abundance	
Fungal population abundance	
Mite population abundance	
Springtail population abundance	
Bacterial standing crop (direct counts on leaf litter)	
Macroinvertebrate abundance	
Abundance (fish)	
Abundance (benthic)	
Juvenile fish density,	
abundance (benthic)	
abundance	
Species abundance	
biomass	
Amphibian abundance	
Microbial biomass- fulgal	
Epilithon abundance	
Abundance of macroinvertebrates	
Macroinvertebrate abundance	
macroinvertebrate shredder abundance	
Relative abundance	
Density (ind/m^2)	
Biomass	
Abundance (arthropod)	
Abundance (collembola)	
Abundance (Diptera)	
nutrients contents	Biochemical properties
Total fatty acid content	
total phenolic content	
ergosterol content	
Shoot concentrations of Cd, Pb, U	
forage quality	
Annual phytoextraction rates for HM	
As, W contente plant issue	
macronutrients (N, P, K)	
B, Sr, Ba content in plant tissues	
B, Sr, Ba content in decomposing litter over time	

Leaching loss of B from leaf litter	
C:B, C:Sr, C:Ba ratios after 12 months	
Heavy metal concentrations (Cd, Cr, Pb in bees).	
Heavy metal concentrations (Cd, Cr, Pb in honey).	
Heavy metal concentrations (Cd, Cr, Pb in pollen).	
Nitrogen content	
Phosphorus content	
14C retention in soil	
Humic-fulvic acid content	
Metal concentrations (Pb, Zn, Cd, Hg) in liver, muscle, blood, otoliths	
Pb, Zn, Cd, Hg concentrations	
Litter traits (C:N ratio, lignin content)	
Foliar nutrients (N, P, K, Mg, Ca, micronutrients)	
Sulfate concentration	
sulfide concentrations	
phosphate concentration	
nitrate concentration	
Aerobic CO_2 production	Biological process
anaerobic CO_2 production and CH4 production	
CH4 oxidation	
biomass loss (litter)	
relative decomposition rate (litter)	
Intake rates of Cd, Pb, U by herbivores	
Predicted genes related to S, P, and Mo cycling (via PICRUSt)	
Bioaccumulation factor (BCF) of As and W	
Decomposition rate of litter (measured as weight loss over time)	
soil respiration rate	
Decomposition rate of litter (weight loss over time)	
Microbial activity (Pmax and Tmax)	
Reproduction of Enchytraeus bigeminus	
Reproduction of Hypoaspis aculeifer	
Leaf consumption (leaf area eaten)	
Survival rate of larvae and neonates (number of larvae)	
Developmental progression (instar transition)	
Ash-free mass loss	
Urease activity	
Degradation rate (%) of cyanide	
Litter decomposition rates (g/day)	
Ash-free dry mass loss of litter	
Percent ash-free dry mass remaining	
Leaf litter decomposition rates (g/day)	
Microbial respiration rates (CO_2 release)	
Litter decomposition rates (g/day)	
Microbial respiration rates (CO_2 release)	
Decomposition rate (percentage of biomass remaining)	
Physiological parameters (e.g., gill damage, blood chemistry)	
Litter decomposition rate	
Microbial activity (dehydrogenase)	

Leaf decomposition rate Chlorophyll a concentration on tiles Leaf decomposition rate Reproductive success (number of fledglings) Mortality Net primary productivity (NPP) Decomposition rate Chlorophyll a BOD (biochemical oxygen demand)	
Small mammals Richness species Diversity Cultural plant species richness Species richness within buffer zones Biodiversity loss (measured by global species loss per square meter). Biodiversity loss (measured by global species loss per square meter).aiBiodiversity loss (measured by global species loss per square meter). species richness (bats) Diversity (bats) species richness (dung beetles) Diversity (dung beetles) species richness (dung beetles) species richness Shannon entropy Beta diversity (calculated via dissimilarity indices) Gamma diversity Species composition Shannon index Species richness Number of species per group Phylogenetic composition Species ricSpecies richness (OTUs) Dominance of bacterial phyla Carabid species composition species richness Shannon index vegetation cover per species species composition presence of peatland species Species distributions (569 species: flora and fauna) Microbial beta diversity (PCoA based on weighted UniFrac distances) Alpha diversity indices (Observed species, Chao1, ACE, Shannon, Simpson) keystone OTUs Number of soil fungal genera (presence/absence) Microbial diversity (α-diversity indices) Species richness (Angiosperms) Species richness (Arthropods) Species richness (Vertebrates) Phylogenetic diversity (Angiosperms) Phylogenetic diversity (Arthropods)	Diversity

Phylogenetic diversity (Vertebrates)
Species endemism (Angiosperms)
Species endemism (Arthropods)
Species endemism (Vertebrates)
Number of species of Querco-Fagetea
Number of species of Vaccinio-Piceetea
species rishness (ants)
species diversity (ants)
insect family richness (presence/absence)
Bacterial genera composition
Fungal genera composition
Diversity indices
diversity indices (fish)
diversity indices (benthic)
species richness (fish)
Benthic species richness
Species richness
evenness
Species richness
diversity indices
Species composition
Species richness
diversity indices
Species richness
diversity indices
Species richness
Growth form diversity
species richness
Parasite diversity (species richness)
Amphibian species richness
Species richness (benthic)
Diversity indices (Shannon and Simpson)
Microbial taxa composition
Epilithon composition
macroinvertebrates composition
richness of macroinvertebrates
Species richness (Odonata)
Species composition (Odonata)
Macroinvertebrate diversity
Taxa richness
community structure

Sensitive and tolerant taxa (via TITAN)- tipo nicho eco
Species richness (bacteria)
Species richness (Fungal)
Species richness (Reach-wide macroinvertebrate)
Species richness (leaf-pack macroinvertebrate)
Similarity (species composition)
beta diversity
macroinvertebrate shredder species rishness
Richness
Diversity (shannon)
Richness (arthropod)

EPT taxa Functional feeding groups composition shannon taxa richness	
Deforestation Forest degadation Forest cover in surrounding areas Crop yield Plant biodiversity Vegetation cover (%) plant persistence Plant cover % MiBiD index scores (calculated for biodiversity impact assessment) Biodiversity pressure metrics based on MiBiD scores Vegetation degradation/increase (NDVI) Litter accumulation- deph Cyanide levels in atmosphere (mg/m^3) Biotic indices (e.g., BMWP score) Coral coverage (%) Cumulative impact scores for ecosystems Percent of exposed substrate Vegetation loss (NDVI reduction) % Ash-free dry mass remaining (litter) Isotopic niche size (δ13C, δ15N) Litterfall production forest and vegetation cover	Environmental attributes
ES Assessment Loss of ES; carbon sequestration Loss of ES;habitat quality Loss of ES; Sediment retention Loss of ES; water yield Loss of ES; crop production Loss of ES; timber production Loss of ES; crop pollination Loss of ES; Nutrient retention Availability of provisioning services Loss in ES cultural for indigenous people Decrease in provisioning services (water and food supply). Carbon storage Water yield sediment export Nitrogen export Carbon sequestration Soil conservation Flow regulation Relational values (e.g., cultural identity, social cohesion, mental health) ES Loss of farmland cultivation, loss of fruit cultivation Loss of water self-restraint (forest, lawn) Soil nutrition loss, water loss	ES change

Water yield
Soil conservation
Carbon sequestration
Biodiversity maintenance
Loss of agricultural land, forest, and water bodies
Water availability
Water quality
Soil fertility
Availability of non-timber forest products (NTFPs)
Cultural activities (e.g., celebrations related to Brazil nut harvest)
Gross Ecosystem Product (GEP).
Carbon sequestration
Habitat provision
Water retention
Soil retention
Sandstorm retention
Air purification
Climate regulation
Carbon sequestration
Air quality regulation
Soil conservation
Water yield
Ecological storage (ESS, ESP, ESC)
Biodiversity Protection (BP)
Climate Regulation (CR)
Gas Regulation (GR)
Soil Formation and Retention (SFR)
Water Supply (WS)
Waste Treatment (WT)
Natural habitat (km²)
Water retention (×10^6 t)
Net Primary Productivity (NPP, t)
Grain production (t)
Food Production
Raw Materials
Water Supply
Gas Regulation
Climate Regulation
Water Regulation
Waste Treatment
Erosion Control
Agricultural area (km²)
Soil retention capacity (t/ha)
Carbon storage (tC/ha)
Habitat quality index
Dust deposition control (t/ha)
Sand consumption
Riverbed morphology, sediment transport
Water quality (turbidity, nutrient levels)
Species abundance
fish migration routes
Income stability, agricultural output

Carbon sequestration rate Flood protection capacity Tourism & recreation, national (d) Tourism & recreation, foreign (d) Food production, Mollusk production Food production, Algae production Food provision: mollusks (kg) Food provision: algae (kg) Carbon sequestration (kg CO_2) Flood retention (m^3) Visitor days (tourism and recreation, national) Visitor days (tourism and recreation, foreign) Total ES loss (kg, m^3, visitor days) water quality (turbidity) Carbon pools (aboveground, belowground, soil, dead matter) Sediment retention (tons/year) Water quality metrics, availability Habitat quality index Visitation rates, recreational index Sediment retention index Sediment export Sediment retention Soil conservation Water yield Habitat quality Trade-offs and synergies among ES pairs	
ESV Assessment ESV Ecosystem service value (ESV) over different periods Sensitivity Index (SI) of ecosystem service value Variation in total ESV of the mining area Ecosystem service values (total and by category: provisioning, regulating, supporting, cultural) Ecosystem service values (specific to land use change) Value of ecosystem services (provisioning) Value of ecosystem services (regulating) Economic cost of ecosystem services (e.g., $300/month per household) Treatment cost of coal ash and stone; loss of land productivity Cumulative ecosystem service value Ecosystem service value (ESV) per pixel Ecosystem service value (ESV) reduction across clusters Change in ESV Ecosystem service value (ESV) Total ESV (US$/year) Water regulation service value (US$/year) Carbon storage value (US$/year) Soil retention service value (US$/year) Total ESV (US$/year)	ESV change

Economic value of ES (US$) Economic value of ES (USD/ha) Economic value of ecosystem services (USD) Ecosystem Service Value (ESV) Future ESV ESV change	
Movement rate Efficiency of movement Resource selection (avoidance of disturbed areas) life history traits (body size, dispersal power, breeding strategy) Feeding behavior (preference, larvae and neonates). habitat preferences	Life history attributes/behave
Soil erosion Concentrations of Pb, Zn, Tl, Cr Spatial distribution of Pb, Zn, Tl, Cr Bioaccumulation Factor (BF) for Tl, Cr, Zn, Pb. Physico-chemical parameters. Geoaccumulation Index (Igeo) Accumulation of Pb, Zn, Tl, Co, Cr, Ni in vegetation Heavy metal concentrations (mg/kg for soil) Organic carbon, nitrogen, and sulfur content Heterotrophic carbon production, degradation rates Pb, Zn, Cd, Hg levels in sediments Soil nutrients (P, K, Mg, Ca, Al, ECEC)	Soil properties
Water contamination Concentration of Tl (64 µg/L), Zn (9.1 µg/L) in reservoir waterGeoaccumulation Index (Igeo) Heavy metal concentrations (mg/L for water). Cyanide levels (mg/L) Cyanide concentration in water bodies Suspended sediment concentration (SSC) Sediment loads (tons/year) Sediment transport dynamics, channel width Grain size, metal concentration Dissolved Pb, Zn, Cd, Hg concentrations Water availability and salinity changes	Water properties