

Financial risks of biodiversity loss: a review

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Financial risks of biodiversity loss: A review

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ABSTRACT

In this paper, we review the burgeoning literature on financial risks stemming from biodiversity loss. To build our literature database, we systematically collect 444 journal articles and preprints written in English and published between 1989 and 2024, retrieved from Scopus. The selection focuses on studies in the fields of business, economics, and finance, identified through a transparent and reproducible query-based approach. We contribute to the literature by providing the first comprehensive synthesis of the emerging literature on biodiversity-related financial risks. Specifically, we compare existing biodiversity loss metrics and evaluate their strengths and limitations for finance research, while also reviewing evidence on firms' and financial systems' exposure to biodiversity physical and transition risks, as well as the influence of these risks on asset pricing. The review underscores that no single metric "outperforms" the others; rather, valuable insights arise from examining multiple indicators, with the choice of metric depending on the specific analytical objective. It also shows that the financial sector is highly, albeit indirectly, exposed to biodiversity physical risk, and that firms – and their value chains – exert substantial impacts on biodiversity. In addition, the review of the literature highlights that investors are increasingly demanding higher premiums to firms exposed to biodiversity risks, suggesting that financial markets deem such risks material. Finally, we identify key research gaps and discuss potential future developments for this field of study, outlining a possible research agenda on biodiversity-related financial risks.

1. Introduction

Biodiversity is the variety of life on Earth and it is vital for the economy because it supports essential resources and services that businesses and societies depend on, such as food, water, and raw materials. Recent estimates point out that half of the world's Gross Domestic Product (GDP) moderately or highly depends on *ecosystem services* (ES) (World Economic Forum, 2020), that is, the benefits provided by nature (Ehrlich & Ehrlich, 1981), highlighting the fundamental role of natural resources in supporting the global economy. Biodiversity plays a crucial role in this context, as research has shown its essential role in sustaining and generating ES (see Balvanera et al., 2006; Gamfeldt et al., 2013; Isbell et al., 2011; Lefcheck et al., 2015; Wardle, 2001). However, biodiversity has been seriously compromised in the last decades (IPBES, 2019; MEA, 2005). Suffice it to say that the World Economic Forum (2020) estimates that USD 44 trillion (more than 50% of the global GDP) is at risk due to businesses being highly dependent on ES, making biodiversity loss an additional source of economic and financial risks¹ (Morgan, 2023; MSCI, 2023). For these reasons, economists have long understood the importance of biodiversity for the economy and vice versa, as exemplified by the vast academic

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¹ Indeed, biodiversity loss is among the major threats that humans will have to fight in the coming decades together with climate change (Pfenning-Butterworth et al., 2024; Pörtner et al., 2023). Notably, biodiversity loss is linked to climate change but it is also a distinct and serious issue on its own. As a matter of fact, the degradation of natural capital can exacerbate climate change (and vice versa, see Bellard et al., 2012; Gatti et al., 2021; NHM, 2024a; Sala et al., 2000), but damages provoked by biodiversity loss can also be independent of climate-related events (see for instance Zurek et al., 2022, on the risks of lack of diversity

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literature on the economics of biodiversity (see Dasgupta, 2021; Frank & Sudarshan, 2024; Metrick & Weitzman, 1996; van der Heide et al., 2005; Weitzman, 1998).

Unlike economists, finance scholars have only recently begun to show interest in biodiversity. While in the last years there has been an unprecedented large increase in interest in climate finance (see Carè & Weber, 2023), so-called *biodiversity finance* is in its infancy, driven by a growing recognition among financial professionals of the risks that biodiversity loss poses to firms and investments (Morgan, 2023), and by the view that the financial sector cannot achieve a sustainable transition without academic guidance (Karolyi & Tobin-de la Puente, 2023). Notably, the first paper published in a top finance journal was recorded only last year (see Garel et al., 2024) and there are a number of issues that finance research has started to address only recently. Giglio et al. (2025) apply textual analysis to corporate 10-K reports to measure firms' exposure to biodiversity risk. Garel et al. (2025) develop a framework to assess corporate nature dependency and examine its impact on downside risk, while Liu et al. (2025) analyse whether mitigating biodiversity risk through nature-based solutions reduces the risk of housing price devaluation. Coqueret et al. (2025) and Garel et al. (2024) investigate whether firms with a higher biodiversity impact command a biodiversity premium in equity markets, and Guidolin and Pedio (2025) find that commodities with greater biodiversity impact – hence more exposed to transition risk² – earn significant premia. Akbari et al. (2025) show that biodiversity-related regulatory oversight is associated with lower corporate profitability. Finally, Becker et al. (2025) and Hoepner et al. (2023) examine how investors and creditors respond to firms' exposure to biodiversity-related risks.

We contribute to this emerging field by providing a comprehensive and critical review of the literature on biodiversity-related risks in finance. While studies on biodiversity risks, their measurement, and financial implications have grown rapidly in the past two years, a systematic synthesis of this body of work is still lacking. Our paper addresses this gap by focusing on two core dimensions of biodiversity finance: the measurement of biodiversity loss and the financial risks stemming from biodiversity loss.³ Unlike existing reviews that adopt a quantitative bibliometric approach to identify patterns and trends in the literature (Guer et al., 2024; Hutchinson & Lucey, 2024), we provide a qualitative and thematic assessment that enables a deeper evaluation of methodologies, empirical findings, interdisciplinary connections, and emerging developments. In particular, although a number of studies have proposed biodiversity loss indicators (Alkemade et al., 2009; Mair et al., 2021; Scholes & Biggs, 2005), no previous work has systematically compared these measures or assessed their respective strengths and limitations in the context of finance research, a crucial issue given the absence of a universally accepted biodiversity loss metric (Morgan, 2023). Furthermore, drawing on studies that examine firms' and financial systems' exposure to biodiversity dependencies and impact risks across sectors and countries (Calice et al., 2021; Hadji-Lazaro et al., 2024; Van Toor et al., 2020), we adopt a comparative perspective that allows for more generalisable conclusions and highlights sectors most exposed to the double materiality of biodiversity loss and its growing role in risk pricing (Coqueret et al., 2025; Garel et al., 2024; Giglio et al., 2025). Finally, by identifying key gaps in the literature, we outline promising avenues for future research that can guide the next steps in integrating biodiversity considerations into financial analysis and decision-making. In summary, our review provides scholars interested in the emerging field of biodiversity finance with a comprehensive framework to study financial risks arising from biodiversity loss and to identify future research directions to address existing gaps. At the same time, it informs policymakers and practitioners about the measurement and management of biodiversity-related financial risks, highlighting, based on the empirical literature, the sectors most exposed to biodiversity transition risk and the exposure of financial systems to biodiversity physical risk across countries.

A specific focus on these topics is of central importance. As discussed above, existing biodiversity loss metrics differ substantially in terms of their conceptual foundations, strengths, and limitations, and they capture biodiversity loss in different ways; consequently, the choice of metric must be carefully considered. For instance, if the objective of an analysis is to assess and mitigate biodiversity loss driven by climate change, the selected metric must explicitly incorporate climate change-related damages in its calculation. Using an inappropriate measure of biodiversity risk may therefore lead to incorrect assessments and, ultimately, to the misallocation of financial resources. Moreover, the assessment of biodiversity-related risks requires methodologies that bridge the ecological and financial literatures, and thus cannot be approached unilaterally. Only collaboration between researchers from these two fields can help close existing research gaps: ecologists contribute the technical expertise needed to improve biodiversity loss metrics and models, while finance scholars are best positioned to apply these tools effectively in financial risk analysis. Interdisciplinarity is therefore key not only to improving the measurement of biodiversity loss, but also to fostering the development of new models that quantify biodiversity damage and the ecological footprints of economic activities, which finance researchers must fully understand before integrating them into financial analyses.

The timing of this study is particularly relevant given the current economic and political context and the rapid evolution of sustainability regulation. Biodiversity loss has recently moved to the forefront of the global policy agenda, alongside climate change,

in cultivation of bananas in Colombia). Notably, recent surveys highlight that companies are starting to acknowledge the materiality of biodiversity risk beyond climate change (Gjerde et al., 2025).

² Biodiversity transition risk arises from the shift towards a nature-positive economy, driven by factors such as stricter environmental regulations, taxes, and reputational pressures. These forces mainly affect firms whose activities have a negative impact on natural ecosystems (Hadji-Lazaro et al., 2024). The biodiversity finance literature typically assesses firms' exposure to transition risk by examining their biodiversity footprint (see Becker et al., 2025; Coqueret et al., 2025; Garel et al., 2024; Guidolin & Pedio, 2025; Hadji-Lazaro et al., 2024). However, the extent to which this risk becomes material depends largely on regulatory priorities in protecting nature and on consumers' preference for sustainable businesses.

³ In this review, we do not consider the financial risk arising from investing in biodiversity conservation (e.g., not attaining the goal and losing capital), which is more related to the matter of financing nature, and hence falls outside the scope of our paper (see Cosma et al., 2023; Flammer et al., 2025; Gonon et al., 2024; Seidl et al., 2024, for further information). Moreover, readers interested in the literature on biodiversity accounting and reporting – which has progressed further in addressing biodiversity concerns than the field of finance – are referred to the recent review by Blanco-Zaitegi et al. (2022).

as governments and international institutions increasingly recognise its systemic implications for economic stability and financial markets (see [Department for Environment Food and Rural Affairs, 2021](#); [French Ministry of Economics, Finance and Industrial and Digital Sovereignty, 2021](#); [Kunming Declaration, 2021](#); [NGFS, 2024b](#)). Importantly, this period coincides with the emergence of new and forthcoming biodiversity-related disclosure frameworks, such as the Taskforce on Nature-related Financial Disclosure (TNFD, 2023) and the progressive integration of biodiversity considerations into sustainable finance regulations and corporate reporting standards ([European Commission, 2022](#)). As these initiatives move from voluntary adoption towards broader regulatory uptake, financial institutions, firms, and supervisors face increasing pressure to measure, disclose, and manage biodiversity-related risks. However, the lack of harmonised metrics and clear guidance on how biodiversity loss translates into financial risk remains a key obstacle. Against this backdrop, our review is timely in synthesising the rapidly expanding literature, clarifying the strengths and limitations of existing biodiversity loss metrics, and assessing the empirical evidence on biodiversity-related financial risks. By doing so, the study provides a critical foundation for both academic research and policy implementation at a moment when disclosure requirements are expanding and the integration of biodiversity risks into financial decision-making is becoming increasingly unavoidable.

Our review answers the following research questions:

1. How is biodiversity measured in finance?
2. What financial risks arise from biodiversity loss, and how do they impact asset prices?
3. What are the most promising research directions on financial risks in biodiversity finance?

Our review begins with the systematic collection of relevant literature. To this end, we design a targeted query for the bibliographic database Scopus and apply transparent, reproducible filtering criteria. Using this approach, we identify 444 journal articles and preprints in the fields of business, economics, and finance, which together constitute our bibliographic database. We proceed with an examination of how biodiversity can be measured in finance, providing a comprehensive overview of the available metrics, their computation, strengths, and limitations. We highlight that no single metric consistently outperforms the others and that valuable insights can be obtained by considering multiple indicators (e.g., MSA, PDF), although the choice of metric should align with the specific objectives of the analysis (for instance, the MSA is more appropriate than the PDF when the aim is to preserve original biodiversity, since the PDF does not capture changes in species composition). We then examine the financial risks of biodiversity loss, focusing on the double materiality of biodiversity and reviewing both dependencies and impacts. The evidence shows that the financial sector in many countries is highly exposed to biodiversity-related physical risks through the nature dependencies of the assets in their portfolios, with sectors reliant on water-related ES and emerging economies particularly vulnerable. On the impact side, firm-induced biodiversity loss is especially pronounced in land-intensive sectors such as agriculture, food, beverage, and tobacco, often occurring through supply chains. We further discuss the presence of a biodiversity risk premium, noting that investors appear to demand such a premium from firms exposed to higher biodiversity-related financial risks, with policy initiatives, such as the [Kunming Declaration \(2021\)](#), influencing market assessments. Finally, our review identifies key research gaps and avenues for future study, including the integration of spatial and remote sensing data into financial analysis, macroeconomic modelling of biodiversity risks, and pricing of marine biodiversity risk. Although the collection of reliable biodiversity data remains challenging, growing attention from scholars, policymakers, and practitioners, combined with interdisciplinary collaboration, is likely to drive substantial advancements in the field and address numerous existing gaps.

The paper is organised as follows: Section 2 describes the bibliographic data collection process, Section 3 discusses measurement of biodiversity, Section 4 reviews the finance literature on the double materiality of biodiversity, including biodiversity in asset pricing, and Section 5 discusses a possible research agenda on biodiversity financial risks. Section 6 concludes.

2. Bibliographic search

Following [Hutchinson and Lucey \(2024\)](#), we collect the papers to review from the bibliographic database Scopus, in December 2024. To construct the bibliographic database, we design a comprehensive query aimed to retrieve the literature on biodiversity-related financial risks. Our query builds on that of [Hutchinson and Lucey \(2024\)](#) (“biodiversity AND finance”) by incorporating additional terms to better align the database with our specific research focus on the financial risks associated with biodiversity loss. We input the query “biodiversity AND financ* OR (financ* W/10 risk*) OR (asset* W/10 pric*)” into the article title, abstract, and keywords research fields; the * operator retrieves all papers with a word that starts with, e.g., “financ” in the selected fields (for example, finance, financial) and the W/10 operator specifies that one term must appear within 10 words of another in any order (see for instance [Rodríguez-Soler et al., 2020](#), for a similar approach). Notably, there is some redundancy in the query, namely, financ* OR (financ* W/10 risk*), as the latter refers to a subgroup of the former. However, first, including only the term “risk*” would have been overly broad, as “biodiversity AND risk” can encompass results beyond the financial sphere and, second, given the well-documented limitations of Scopus (see [Franceschini et al., 2016](#)), incorporating some redundancy in the query enhances the robustness and completeness of the retrieved results. As a result, the automatic search provides us with 4221 scholarly articles, spanning from 1989 to 2024.⁴ To narrow down the database to better align with our purpose, we apply a series of screening criteria:

⁴ We do not impose any temporal restrictions on the literature collection process; that is, the bibliographic search is not limited by publication year. All relevant studies matching our query are included, and the first available year in our dataset (1989) simply reflects the earliest publication retrieved by the search, rather than a time constraint set by us.

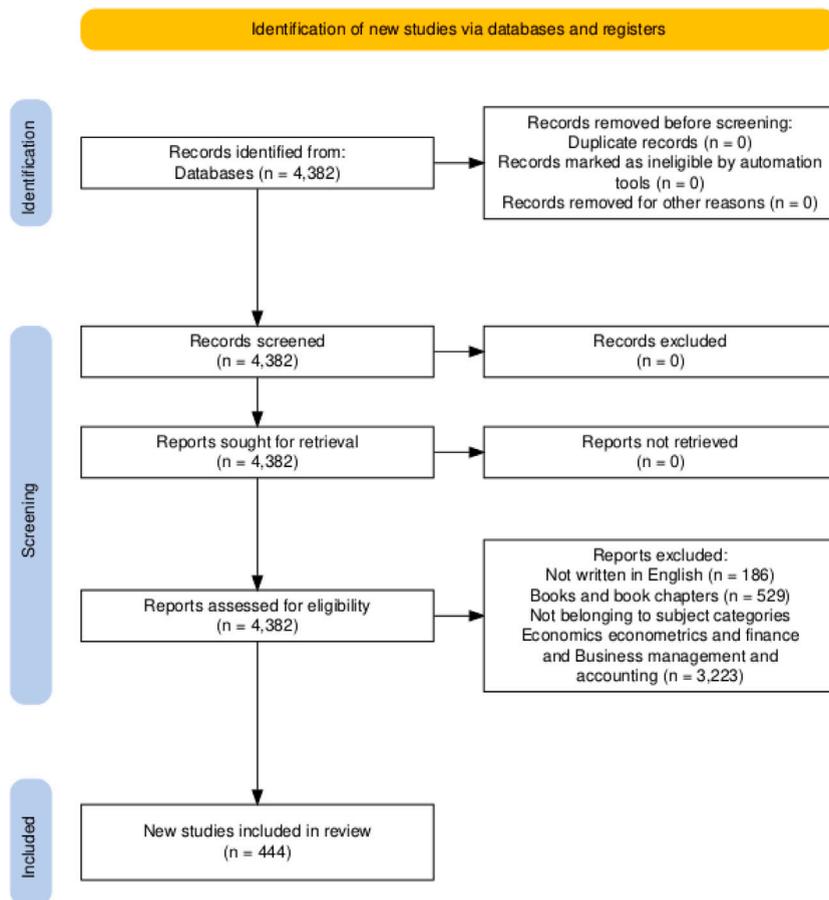


Fig. 1. Visual representation of the construction process of the bibliographic database.

- include only articles written in English;
- exclude books and book chapters;
- include only papers in the subject categories Economics, econometrics and finance, and Business, management and accounting.

This strategy results in a database of 383 articles. This substantial decrease stems from the fact that most articles fall exclusively within the fields of environmental, agricultural, and biological sciences. Given the novelty of the field and that several relevant papers have not yet been published in academic journals at the moment of the data collection (see for instance [Coqueret et al., 2025](#); [Flammer et al., 2025](#); [Giglio et al., 2025](#)), we also collect from Scopus 161 preprints, written in English, appearing in the SSRN, Research Square, bioRxiv, and arXiv repositories.⁵ Since, to this day, it is not possible to screen preprints in Scopus based on the field of study, we manually select preprints that match the subject categories used to screen articles; this results in 61 preprints. The final database comprises the 383 journal articles plus the 61 preprints, for a total of 444 bibliographic records. In [Fig. 1](#) we present a visual representation of the construction process of the final bibliographic database, starting from the initial set of 4221 journal articles and 161 preprints ($n = 4221 + 161 = 4382$) to the final database of 444 bibliographic records ($n = 383 + 61 = 444$).

Since biodiversity finance is a quite new research field, one may think that a database of over 400 papers contradicts such a statement. However, it is pivotal to stress that while biodiversity finance has only recently emerged as a distinct and significant field of study, financial analyses of biodiversity were already being conducted and published in non-finance journals in previous years. For instance, [Naidoo et al. \(2011\)](#) examine the effects of large wildlife species on financial benefits to indigenous communities in Namibia and [Clasen et al. \(2011\)](#) study the financial risk and compensation associated to the loss of trees. Moreover, the question of how to finance biodiversity restoration has long been debated in the past 20 years (see [Simpson & Sedjo, 1996](#)), though predominantly in the ecology and economics literature.⁶ While not explicitly finance-focused, these less recent studies can still provide valuable insights into the understanding and careful examination of biodiversity risk.

⁵ Scopus covers preprints from 2017 onwards from the following repositories: arXiv, ChemRxiv, bioRxiv, medRxiv, SSRN, TechRxiv, and Research Square.

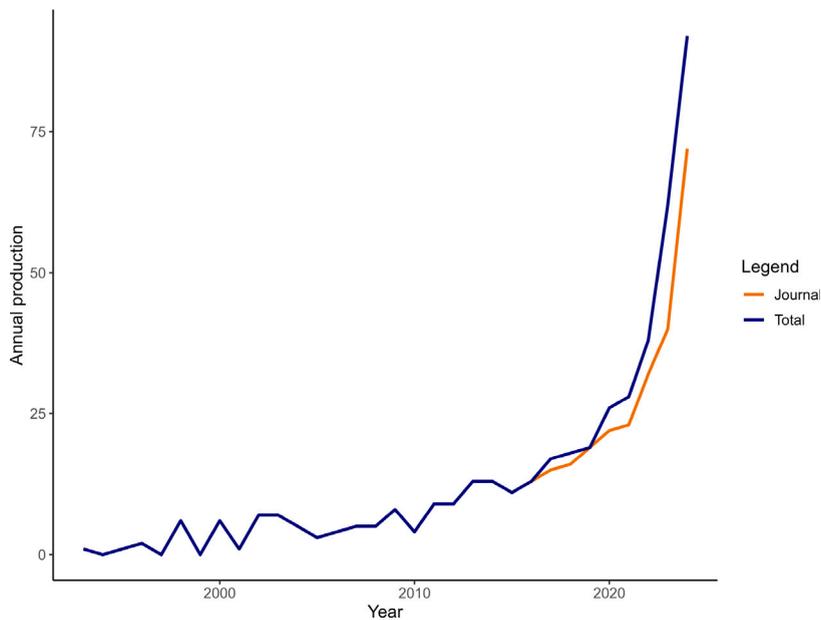


Fig. 2. Number of journal articles (Journal) and journal articles plus preprints (Total) published annually, in our database.

Fig. 2 displays the annual scientific production that constitutes our database. We notice that there has been a substantial growth in the last years, with over 70 papers published in academic journals in 2024. Fig. 3 reports the 10 journals that published the highest number of articles. Ecological Economics ranks first with 42 articles, followed by other journals in social sciences related to the environment, such as Forest Policy and Economics (26 papers) and Marine Policy (21). We can clearly notice that these journals are not strictly related to finance, although they publish articles which can be of interest also to scholars in finance, which remarks what we stated in the Introduction about the disregard that finance has generally shown for biodiversity, differently from economic sciences. As a matter of fact, the first journals in finance we can find in this list rank only at the 16th position (not reported). These are Finance Research Letters and the Journal of Sustainable Finance and Investment, which published 3 articles each, way below journals in environmental business and economics.

3. The measurement of biodiversity and biodiversity loss in finance

Biodiversity refers to the variety of life on Earth. As a matter of fact, multiple living organisms that belong to different species contribute to creating biodiversity and ecosystems, i.e., complex systems formed by abiotic components (e.g., climate, soil) and the interactions of different plant and animal species. Biodiversity can be tracked at the local (α diversity), between-site (β diversity), and at the region (γ diversity) levels (Colwell, 2009; Marquardt et al., 2019) and the distribution and population of species can differ depending on the location considered. For instance, some regions may have particular flora and fauna which cannot be found elsewhere on the planet, such as Madagascar, which is well known for having several endemic species (Ralimanana et al., 2022). This strong geographical and local component, jointly with the difficulties in detecting species and inferring their correct number, pose a number of difficulties in measuring biodiversity (see Colwell, 2009).

Currently, there is no widely-accepted indicator of biodiversity loss risk (Karolyi & Tobin-de la Puente, 2023; Morgan, 2023). Indeed, while in climate finance the CO₂e metric is recognised as the main measure to track climate impacts (Morgan, 2023), there are several aspects of ecological diversity that can be measured, using different sets of metrics. Kok et al. (2020) report that biodiversity indices can be classified into three main categories, measuring as many particular biodiversity-related aspects: genes, ecosystems, and species. Indicators measuring *genetic* diversity use genetic research techniques to assess genetic differences in organisms and their evolutionary response (Colwell, 2009). Measures of *ecosystem* biodiversity look at vegetation structure and coverage, and land use, using indices such as mean vegetation height and arable land-to-grassland ratio. *Species*-related biodiversity indices are the most popular – 83% of the studies surveyed in Kok et al. (2020) employ them – and measure aspects such as species abundance (number of individuals of a species), species richness (number of species) and species composition and function. Well-known indicators of both abundance and richness include Shannon Entropy (Shannon, 1948), Simpson (Simpson, 1949), and Pielou's evenness (Pielou, 1966) indices. Furthermore, this category also encompasses novel indicators such as the Mean Species

⁶ For years, the funding of biodiversity and the “biodiversity financing gap” have been subject of interest in ecology and economics, but have gained significance in finance only recently (see Flammer et al., 2025; Karolyi & Tobin-de la Puente, 2023).

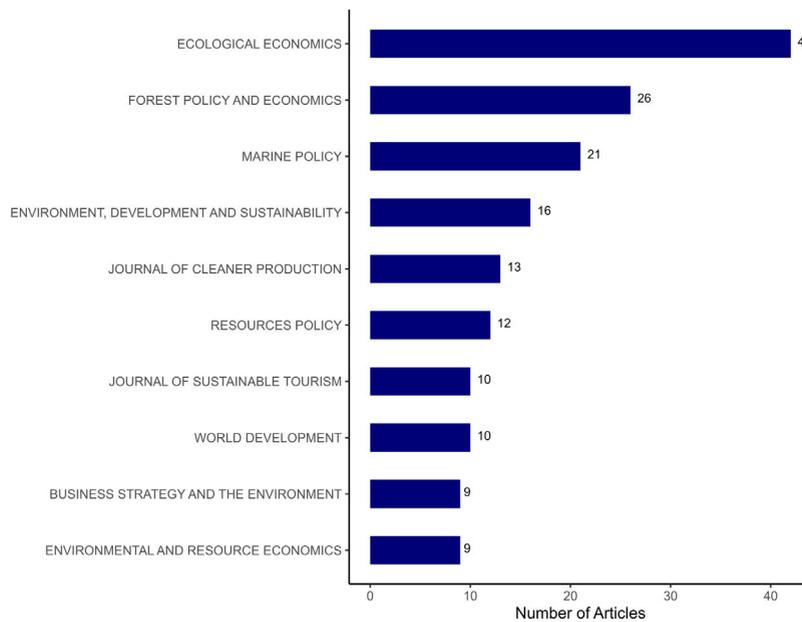


Fig. 3. The ten journals in our database with the highest number of publications.

Abundance (MSA) and the Potentially Disappeared Fraction of Species (PDF), which model biodiversity loss linked to environmental pressures, compared with a reference undisturbed ecosystem.

It is worth noting that providers of ESG ratings already incorporate biodiversity loss into their assessment of E ratings. For instance, MSCI incorporates biodiversity loss into its ESG ratings through its Nature and Biodiversity Solutions framework, which includes metrics to measure corporate impacts and risks related to biodiversity loss, focusing on activities such as deforestation, resource use, and pollution.⁷ However, Garel et al. (2024) argue that E ratings that include biodiversity do not capture well financial risk, since ESG scores are not quantitative measures of firms' dependencies and impacts on the environment. In addition, Zhu and Carrasco (2025) assert that current ESG assessments insufficiently capture or reflect biodiversity issues. For this reason, research on how to adequately incorporate biodiversity risk in E ratings is still ongoing (see for instance Kopnina et al., 2024; Rossi et al., 2024). It is important to note that the development of robust biodiversity loss metrics is essential for assessing how investors and creditors respond to biodiversity-related risks, as examined in studies such as Becker et al. (2025) and Hoepner et al. (2023).

In general, biodiversity finance is more interested in estimating biodiversity changes due to human activities rather than biodiversity itself. When assessing potential financial risks from biodiversity loss, investors should arguably focus on the intensity of biodiversity impacts, and metrics based on footprinting models allow for such an evaluation. Moreover, with such metrics, it is possible to compare sectors and companies (Morgan, 2023). For this reason, we devote special attention to available biodiversity impact metrics, starting from the MSA and the PDF, proposed by scholars in ecology. In addition, we provide a concise overview of existing databases that provide biodiversity loss indices.

In this review, we discuss metrics that can be applied to a single species but are generally applied to thousands of taxonomies. It is important to stress that models designed for broad-scale biodiversity assessments may not capture the specific habitat requirements and behaviours of individual species as accurately as models calibrated on specific species (see Crispim-Mendes et al., 2024; Gardner et al., 2020; Powney et al., 2019). Moreover, since these indices track several species, they rely heavily on modelling (Ben Rejeb-Mzah et al., 2024), yet purely data-driven calibration of ecological models may sometimes produce unrealistic parameter values (Gardner et al., 2020). However, biodiversity finance is typically more interested in the assessment of biodiversity in general and in the consequences of biodiversity loss for companies and the financial sector, rather than in tracking a few particular species with a very high degree of precision.

Finally, it is worth noting that the metrics discussed can be applied at both micro and macro levels. At the macro level, biodiversity loss indices can be used to assess the nature degradation of a region or country, enabling macroeconomic analyses. At the micro level, their key advantage lies in their applicability to more localised assessments – for example, measuring biodiversity loss in a specific area where a company operates. Consequently, these metrics can also be extended to assess biodiversity-related

⁷ Examples of biodiversity measures used by rating providers are the MSCI's biodiversity & land use exposure score and Refinitiv's biodiversity impact reduction indicator. MSCI assesses a firm's exposure to biodiversity and land-use risks on a 0–10 scale, where 10 indicates the highest level of risk. The score is designed to capture three main risk channels: the potential loss of a firm's license to operate; litigation risks arising from landowners and other affected stakeholders; and higher costs associated with land protection and reclamation. Refinitiv's measure is a binary indicator capturing whether a firm discloses information on its impact on biodiversity or on activities aimed at mitigating this impact.

risks across a portfolio of companies. We will explore the financial applications of these metrics in greater detail in Section 4, where we review the literature on biodiversity risk measurement and asset pricing.⁸

3.1. Mean species abundance

The first metric we discuss is the MSA. The MSA was proposed as the designed footprinting metric of the GLOBIO3 model (Alkemaded et al., 2009), a mathematical framework reliant on remote sensing data developed to evaluate changes in relative species abundance consequent to human-induced pressures. Mathematically, the MSA of site S with respect to the reference state of the same site S_{ref} , can be defined as follows:

$$MSA = \frac{1}{M_{S_{ref}}} \sum_{i=1}^{M_{S_{ref}}} \min\left(\frac{N_{i,S}}{N_{i,S_{ref}}}, 1\right) \tag{1}$$

where $N_{i,S}$ is the abundance of species i in site S , and $M_{S_{ref}}$ is the total number of species in site S_{ref} . The MSA ranges from 0 to 1, where 0 indicates that there has been a complete loss of the original biodiversity, while 1 means that the ecosystem remains completely unchanged. In other words, the MSA measures the abundance of species under a particular pressure relative to the abundance of species in a pristine ecosystem. The MSA has become a popular metric in biodiversity finance, but it has a number of downsides (see Finance for Biodiversity, 2024; OECD, 2023). First, the MSA treats all species as equally important, whereas it can be argued that some species are more important than others from an economic point of view (see Metrick & Weitzman, 1996); moreover, it does not account for an increase in species, and does not capture soil degradation and damages caused by invasive species. Garel et al. (2024) also point out that it is the loss in ES, rather than the abundance of species, to be the ultimate quantity of interest, but such a critic can be extended to further impact measures.

A spatial dataset at 300 m² at the equator for the MSA at the global level is provided in the GLOBIO website by the PBL Netherlands Environmental Assessment Agency and is free to access (see PBL, 2024a, for the link). Besides, some data vendors, such as Iceberg Data Lab and Carbon4 Finance are starting to provide biodiversity loss data at the company level, that is, biodiversity footprint of companies, expressed in MSA-km². The methodology underlying the computation of the MSA at the firm-level and the implications that such a metric has for finance will be discussed thoroughly in Section 4.

3.2. Potentially disappeared fraction of species

Another biodiversity index mentioned previously is the PDF. The PDF quantifies the potential extinction of species due to environmental pressures (see De Schryver et al., 2010) and, as reported in Crenna et al. (2020), is the mostly adopted metric in Life Cycle Analysis (LCA), which is a method to assess the environmental consequences of a product or service throughout its life span (see Section 4). The PDF can be defined as follows:

$$PDF = \frac{1}{N_{S_{ref}}} \sum_{i \in S_{ref}} x_{i,S} \tag{2}$$

where $x_{i,S}$ is equal to 1 if species i is not present in site S and 0 otherwise. The PDF ranges from 0 (intact ecosystem) to 1 (extinction of all species). As reported in Ben Rejeb-Mzah et al. (2024), the PDF is a measure of local biodiversity (α). However, while a locally-extinct species can be reintroduced, global extinction is forever. To calculate a PDF at the global level, Kuipers et al. (2021) propose to scale the PDF by a Global Extinction Probability (GEP) factor. The GEP of species group g in region j is equal to:

$$GEP_{g,j} = \frac{\sum_i A_{S,j,i} \cdot O_{S,j,i} \cdot TL_S}{\sum_{j,i} A_{S,j,i} \cdot O_{S,j,i}} \tag{3}$$

where $A_{S,j,i}$ is the area of spatial unit i in region j occupied by species S (which belongs to group g), $O_{S,j,i}$ is a weight [0–1] indicating the certainty of the occurrence of species S in spatial unit i and region j , and TL_S is a weight [1–8] representing the IUCN threat level of species S . A global PDF for a species group g in region j can be computed as:

$$PDF_{g,j}^{Global} = GEP_{g,j} \cdot PDF_{g,j} \tag{4}$$

The PDF has some drawbacks. First, similarly to the MSA, it weighs all species equally and, second, disregards whether the species measured are endemic or alien (Ben Rejeb-Mzah et al., 2024; Kok et al., 2020). This can lead the PDF to produce misleading results: if all the endemic species populating an ecosystem were to disappear and replaced by the same number of species, the PDF would be unchanged because the number of species in the reference ecosystem would be unaltered. For this reason, Kok et al. (2020) argue that the MSA is more reliable when the aim is to preserve original biodiversity. The MSA, on the other hand, does not take into account increases in a species outside the reference ecosystem. Furthermore, Morgan (2023) argue that the PDF is more conservative

⁸ The indices discussed have not yet been widely applied in the finance literature; however, the MSA index appears to be the most commonly employed, as it is used to construct the Corporate Biodiversity Footprint metric, employed in several studies such as Coqueret et al. (2025), Cosma et al. (2023), and Garel et al. (2024). For further details, see Section 4.

than the MSA, since extinction of species implies that no improvements in the indicator can be obtained in the future. However, the MSA does not account for an increase in a species with respect to the baseline ecosystem (see Garel et al., 2024), hence, arguably, the MSA presents the traits of a conservative metric, too.

Publicly available data on the PDF can be downloaded from the LC-Impact (Verones et al., 2020) website, which houses data on ecosystem quality, obtained through LCA, expressed in PDF·m² (see LC-Impact, 2024, for the download). Moreover, providers of investment solutions such as Institutional Shareholder Services (ISS) are using the PDF as well as the MSA to measure the impact of investment portfolios on biodiversity.

3.3. Biodiversity intactness index

A further alternative to the MSA and PDF is the Biodiversity Intactness Index (BII), proposed by Scholes and Biggs (2005). The BII is the footprinting metric adopted for the PREDICTS project (Hudson et al., 2014; Purvis et al., 2018), and expresses in percentage the extent to which the original biodiversity survives human-induced pressures, where 0 means that there has been a complete loss of biodiversity in the area considered and 1 that the ecosystem is in its pristine state. The BII of site S is computed as follows:

$$BII = \frac{2 \sum_{i=1}^P \min(N_{i,S} N_{i,S_{ref}})}{\sum_{i=1}^P (N_{i,S} + N_{i,S_{ref}})} \quad (5)$$

where P is the total number of species, both native and invasive. The BII calculated for the PREDICTS projects considers a set of around 58,000 plant, animal, and fungal species and how they are impacted by human pressures such as land use change, human population growth and landscape simplification (NHM, 2024b). The BII, differently from the MSA, considers the appearance of alien species as harmful to biodiversity, but it disregards whether such a species is neutral or invasive to existing living organisms. Moreover, the BII also suffers from attaching equal importance to all species in the database, as does the MSA (Ben Rejeb-Mzah et al., 2024).

Although proposed initially by Scholes and Biggs (2005), the BII was developed for the first time at spatial scale by Newbold et al. (2016). Martin et al. (2019) argue that the BII overestimates biodiversity and that spatial correlation with global indicators produced in other studies is too low to be attributed to noise. Newbold et al. (2019) acknowledge that such striking results are due to some limitations of their model, in particular, the use of an inaccurate baseline and unrefined land-use estimates. However, they show that the expansion of the database and the use of more accurate estimates allow them to obtain results which are closer to those of other studies. Since then, the refinement of the model as well as the expansion of the database for the calculation of the BII have been ongoing, such that the NHM (2024b) states that “the PREDICTS database is the most comprehensive of its kind”.

The NHM (2024b) provides country-level data for the BII as well as a global spatial dataset at 10 km² resolution. Country-level data are available from 1970 to 2020 while maps are available every 5 years. The NHM also computes a BII at a higher resolution, but such maps are not available for download. Geospatial data for the BII are also used by Bloomberg to measure the extent to which company assets are exposed to biodiversity risk.

3.4. Species threat abatement and restoration

The Species Threat Abatement and Restoration (STAR), a metric proposed by Mair et al. (2021), may be useful for investors. STAR quantifies the risk of extinction of species due to human-induced threats and the potential for actions aiming to restore habitat. Differently from MSA, PDF and BII, it is not an intactness metric, that is, it has no undisturbed ecosystem that works as reference. However, it can still be a valuable tool for investors because it helps to identify locations which, on the one hand, may be impacted by future regulation, and, on the other hand, to which direct funds to preserve and restore biodiversity (Finance for Biodiversity, 2024). There are two STAR metrics available: one evaluates global abatement threats (STAR_T), the other assesses the percentage of restorable area to conserve the species of interest (STAR_R). The STAR_T metric for site S and threat t is calculated as follows:

$$STAR_T = \sum_i^{N_S} P_{i,S} W_i C_{i,t} \quad (6)$$

where $P_{i,S}$ is the area of habitat (AOH) of each species i in location S , W_i is the IUCN Red List category weight of species i (ranging from 1, near threatened, to 4, critically endangered), $C_{i,t}$ is the relative contribution of threat t to the extinction risk of species i , and N_S is the total number of species at location S . $C_{i,t}$ is computed as the percentage population decline from threat t divided by the sum of percentage population decline from all threats to species i . STAR_T for species i at the global level varies from 0 (least concern) to 400 (critically endangered).

The STAR_R score for site S and threat t is computed in the following way:

$$STAR_R = \sum_i^{N_S} H_{i,S} W_i C_{i,t} M_{i,S} \quad (7)$$

where $H_{i,S}$ the size of the restorable AOH for species i in location S , and $M_{i,S}$ is a scaling factor (in Mair et al., 2021, $M_{i,S} = 0.29$).

Mapping the likelihood of extinction of all species is not possible. Mair et al. (2021) focus on amphibians, birds and mammals, but they argue that their metric can be extended to further species (in Mair et al., 2023, the STAR metric has been applied to track the extinction risk of vascular plants). Nonetheless, a fundamental problem remains how to determine the AOH. Furthermore, the

STAR metric does not account for spatial variation in the intensity of threats across species' ranges and alone is not sufficient to identify conservation priorities (Mair et al., 2021). Finally, STAR does not report threats to habitat (Finance for Biodiversity, 2024).

The Integrated Biodiversity Assessment Tool (IBAT) provides geospatial data for the STAR metric (IBAT, 2024). IBAT is a web-based platform that provides access to several global biodiversity datasets, such as the IUCN Red List of Threatened Species and the World Database on Protected Areas. Finance for Biodiversity (2024) argues that IBAT is a mature and authoritative tool, used by an increasingly larger number of companies across several sectors. However, access to IBAT data comes with the payment of a licence fee.

3.5. Human footprint index

The last metric we present is the Human Footprint Index (HFI). Proposed for the first time by Sanderson et al. (2002) to map the human influence on ecosystems, the HFI initially included only the impact on nature attributable to population density, land transformation, accessibility, and electrical power infrastructure, all of which are weighted based on estimates of their relative levels of human pressure⁹ and summed together to create an aggregate index. In other words, the HFI for location S is computed as:

$$HFI = \sum_m^M w_m P_{m,S} \quad (8)$$

where M is the total number of pressures considered, $P_{m,S}$ is the m th human pressure in location S and w_m is the associated weight. Later, the HFI has been upgraded by Venter et al. (2016) at a 1 km² resolution, ranging from 0 (wilderness) to 50 (highly modified area). Moreover, Venter et al. (2016) show that the updated HFI is useful for analysing pressures within areas that are rich in biodiversity. The index received a further update in 2022, when Mu et al. (2022) released a public annual dataset of the global HFI from 2000 to 2018, at 1 km² resolution. Although the HFI makes an interesting tool for investors, as it allows them to identify sites vastly affected by human activities, there are some points to consider: first of all, the HFI measures human pressures on Earth rather than impacts on biodiversity, second, not all human pressures are taken into account in the calculations¹⁰ (Venter et al., 2016). To assess the potential impact on biodiversity, the HFI can be used together with additional datasets on plant and animal species.

Overall, there is no “winning” metric. All the indices discussed present strengths and limitations and evaluate biodiversity according to different approaches. Moreover, all the indices discussed may suffer from huge discrepancies in data collection and, since they rely significantly on modelling to track species (with the exception of the HFI, which focuses on human impact), such indices may reflect especially impacts on larger animals. Since the different metrics express different but complementary dimensions of biodiversity, such as, e.g., intactness and restoration, we argue that investors should consider different biodiversity indices rather than pick one to implement investment decisions, although the use of a set of metrics complicates the decision-making process. However, investors and researchers alike should favour a particular metric based on their goal: for instance, as discussed, the MSA should be preferred to the PDF when the objective is to preserve the original biodiversity, because the PDF is not sensitive to changes in species composition. Hence, the choice of the biodiversity metric must be pondered carefully and, still, relying on more than one metric can provide additional insights. A summary of the biodiversity indices discussed, their strengths and weaknesses, as well as the provider of the data is reported in Table 1.

4. The double materiality of biodiversity risks

The concept of the double materiality of biodiversity descends from the concept of *materiality* in accounting and reporting. The International Accounting Standards Board (IASB) states that “information is *material* if omitting, misstating or obscuring it could reasonably be expected to influence the decisions that the primary users of general purpose financial statements make on the basis of those financial statements, which provide financial information about a specific reporting entity” (IFRS, 2020). From this definition, it is evident that whichever information about possible risks to which the entity is exposed must be reported. For instance, in the context of biodiversity finance, firms should disclose biodiversity-related impacts on the company, which would, of course, influence the decisions of the stakeholders.

As reported in Täger (2021), double materiality takes the concept of materiality “one step further”, as not only impacts of environmental factors on companies are material, but also vice versa. In this regard, Boissinot et al. (2022) argue that this approach aims to assess both the risks to which firms are exposed and how firms contribute to increasing those risks. While the risks arising from the impact of the environment on firms are, in general, easier to grasp (for instance, pollution from chemical discharge into water may lead to a shortage of fishery resources), risks descending from the impact of firms on nature are more difficult to assess. On the one hand, environmental footprint may negatively impact firms due to future regulations (Boissinot et al., 2022); on the other hand, the firm's consumption rate of natural resources may be unsustainable, leading to the depletion of the natural stock and further intensifying environmental impacts on the firm's sales. For this reason, as argued in Hadji-Lazaro et al. (2024), firms' dependencies on nature fall under biodiversity *physical risks*, whereas impacts of companies on nature can be considered proxies for biodiversity

⁹ For instance, for land transformation, Sanderson et al. (2002) assign a value of 10 to built environments, lower scores to agricultural land cover and 0 to land cover types such as forests and grasslands.

¹⁰ Arguably, a similar problem affects the indices previously introduced: mapping biodiversity completely is impossible, so it is normal that existing metrics heavily rely on modelling and partial datasets (Ben Rejeb-Mzah et al., 2024). For instance, the very large dataset of 58,000 species tracked by the BII account for just 2% of all known species (NHM, 2024b).

Table 1
Summary of biodiversity metrics for finance.

Index	Type	Strengths	Weaknesses	Provider	Formula
BII	Intactness	Penalises the introduction of invasive alien species	Equal importance of all species; disregards whether the invasive species is harmful or neutral	NHM (2024b)	$BII = \frac{2 \sum_{i=1}^P \min(N_{i,S}, N_{i,S_{ref}})}{\sum_{i=1}^P (N_{i,S} + N_{i,S_{ref}})}$
MSA	Intactness	Sensitive to changes in the composition of original species	Equal importance of all species; does not account for an increase in species; does not capture soil degradation and damages from invasive species	PBL (2024a)	$MSA = \frac{1}{M_{S_{ref}}} \sum_{l=1}^{M_{S_{ref}}} \min\left(\frac{N_{i,S}}{N_{i,S_{ref}}}, 1\right)$
PDF	Intactness	Requires fewer data than MSA and BII	Equal importance of all species; disregards whether the species are endemic or alien	LC-Impact (2024)	$PDF = \frac{1}{N_{S_{ref}}} \sum_{i \in S_{ref}} x_{i,S}$
HFI	Human pressure	Identifies sites with high human-induced pressures and areas of interest for conservation	Limited amount of pressures considered; measures pressures rather than impacts; must be combined with other datasets to identify biodiversity impacts	Mu et al. (2022)	$HFI = \sum_m^M w_m P_{m,S}$
STAR _T	Extinction	Evaluates abatement threats; it can help to identify conservation actions	Does not account for spatial variation in the intensity of threats across species' ranges; does not report threats to habitats; determining the area of habitat can be difficult	IBAT (2024)	$STAR_T = \sum_i^{N_S} P_{i,S} W_i C_{i,d}$
STAR _R	Restoration	It can help to identify conservation actions; easily interpretable by investors	Must be combined with other datasets to identify conservation actions; determining the area of habitat can be difficult	IBAT (2024)	$STAR_R = \sum_i^{N_S} H_{i,S} W_i C_{i,d} M_{i,S}$

transition risks.¹¹ This interpretation is backed by Article 29 of the French Energy and Climate Act, which states that financial institutions should disclose on how their biodiversity footprints translate into transition risk, and by the Network for Greening the Financial System (NGFS and INSPIRE, 2022). However, transition risk may be less material than physical risk, as the former involves the regulator's interest in protecting nature (Boissinot et al., 2022). Thus, there may exist a gap between environmental materiality and financial materiality. Nonetheless, firms misaligned with actions aimed at protecting nature (which are often those that have a negative impact on the environment and thus more exposed to transition risk, see NGFS, 2024b) may face greater financial risks from current environmental policies, such as the European Union (EU) Environmental Liability Directive (European Parliament and Council, 2004) – which holds polluters financially responsible for remediating environmental damage – rather than from future physical impacts arising from biodiversity shocks. Finally, Gourdel et al. (2024) point out, in the context of climate change, that physical and transition risks can reverberate through the financial system (e.g., banks that invested in affected companies would experience adjustments in probability of default, non performing loans, and VaR), which, in turn, will affect the economy and finally climate change. Arguably, the same double feedback loop can be applied to biodiversity loss (see Fig. 4).

The mechanisms through which biodiversity physical and transition risks translate into adverse financial impacts differ. Physical risk arises from the direct consequences of biodiversity loss on the natural systems that firms depend on for their operations. For instance, the decline in pollination services, soil fertility, or water availability can reduce productivity and increase operational costs of agricultural firms (75% of food crop types rely on pollinators, see World Economic Forum, 2019; World Economic Forum & PWC, 2020), or disrupt supply chains of firms in the food and beverage industry. These risks typically materialise gradually (drawing from climate finance, see Venturini, 2022, these risks can be considered *chronic*) but can also manifest suddenly through extreme environmental events and ecosystem collapses (*acute* risks) caused by the introduction of invasive species or pests in an ecosystem, or by the outbreak of a new disease. In contrast, transition risks stem from the policy, regulatory, technological, and market changes associated with the shift towards a nature-positive economy. Firms with significant negative impacts on biodiversity may face higher compliance costs, reputational damage, restricted market access, or even asset stranding as new environmental regulations and consumer preferences evolve. For example, when the European Regulation on Deforestation-free Products (European Commission, 2023) will take effect, firms that have a strong negative impact on biodiversity (through practices such as deforestation and habitat destruction) will face heightened transition risk, as they must invest in costly supply chain adjustments, risk losing access to the European market if unable to comply, and may suffer reputational damage, all of which can significantly reduce their profitability. In summary, while physical risks stem from ecological degradation, transition risks are primarily policy-driven; as a result, the former

¹¹ The bipartition of biodiversity risks into firm impacts and dependencies was already proposed by Mulder (2007) over 15 years ago, without labelling them as transition and physical risks.

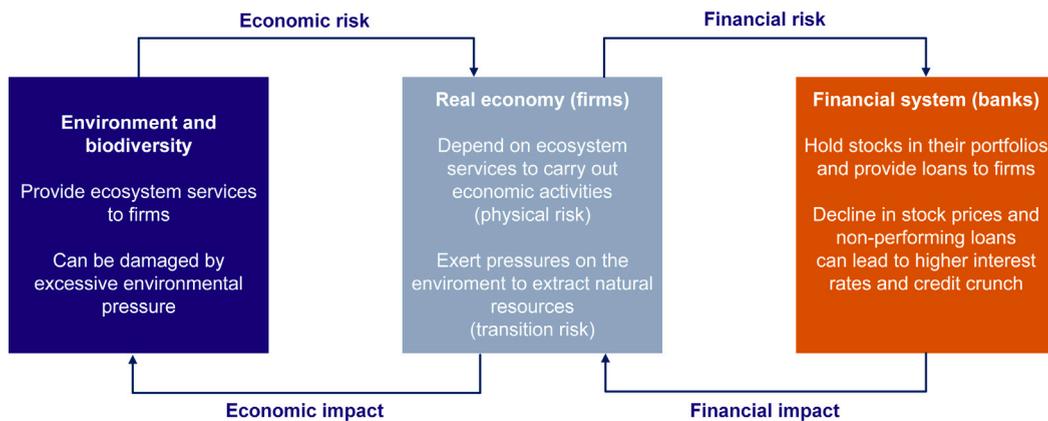


Fig. 4. Double materiality of biodiversity in the economy and finance.
Source: Adapted from Gourdel et al. (2024).

mainly affect firms with high dependencies on nature, whereas the latter predominantly impact those with high environmental footprints (see Hadji-Lazaro et al., 2024; Van Toor et al., 2020).

Physical and transition risks can also interact. First, some industries can have both a high dependence and a high impact on biodiversity, thus being exposed to both kinds of risks (Coqueret et al., 2025; Giglio et al., 2025). For example, the agricultural sector both depends heavily on biodiversity for essential ecosystem services and simultaneously exerts a significant impact on it through land use, pesticide application, and habitat alteration. Moreover, one risk can amplify or even trigger the other (Rudgley & Seega, 2021; World Bank, 2020). For instance, the materialisation of physical risk (such as the collapse of an ecosystem or a severe loss of biodiversity) can accelerate regulatory responses and public pressure, thereby intensifying transition risk. Conversely, poorly coordinated or narrowly designed biodiversity protection policies can inadvertently shift, rather than reduce, environmental degradation, thus transforming transition risk into additional physical risk. For example, stringent regulations aimed at protecting tropical forests may restrict agricultural expansion in those areas. However, firms facing production constraints might respond by intensifying their use of other ecosystems (such as wetlands) to source substitute material resources (in a manner analogous to the substitution effect described in microeconomics, see Mas-Colell et al., 1995). This displacement of pressure can lead to overexploitation of soil, loss of habitats, and reduced ecosystem resilience in those newly targeted regions, thereby generating new forms of physical risk. This mutual reinforcement highlights that physical and transition risks are not independent, but rather two sides of the same coin in the complex context of biodiversity-related financial risk. Finally, indirect linkages could transmit both physical and transition risks along the supply chain (NGFS, 2024b). Lower biodiversity among a firm's suppliers can lead to reduced availability of raw materials throughout the supply chain, ultimately constraining the firm's own production and profitability (an example of indirect physical risk). In contrast, indirect transition risk arises when firms within the supply chain have a high negative impact on biodiversity, prompting stricter environmental regulations or taxes. These regulatory pressures may force suppliers to reduce output or incur additional compliance costs, which are then passed on to the focal firm through higher input prices, whether due to tax mark-ups or reduced material availability.

The double materiality of biodiversity has several implications for asset pricing. Risks stemming from biodiversity loss can impact firms' profits in multiple ways, for instance, by disrupting supply chains (physical risk) or by leading governments to strengthen environmental regulations (transition risk), and a crucial question is whether investors price such risks. As a matter of fact, stocks with a large biodiversity footprint may incur higher transition risks and, therefore, investors should ask for a compensation (Garel et al., 2024); on the other hand, green stocks may outperform stocks with a large footprint due to shifts in investors' preferences, or biodiversity risks may not be factored in stock prices at all. In addition, as Giglio et al. (2025) argue, biodiversity risk exposure varies according to the sector: sectors such as construction and agriculture that are highly reliant on natural capital and hence are severely exposed to physical risk; in contrast, the mining sector, which has a large environmental footprint, is vulnerable to transition risk. Some sectors are also highly exposed to both physical and transition risks (Coqueret et al., 2025).

In this review, we discuss the double materiality of biodiversity by considering both papers that examined firms' dependencies and impacts on biodiversity. We review the main tools employed to assess physical and transition risks, channels through which firms affect biodiversity and vice versa, literature findings, and economic and financial implications. Finally, we examine the literature on the pricing of biodiversity risk.

4.1. Physical risk: firm dependencies on biodiversity

To estimate economic dependencies on biodiversity, one of the most used tools is ENCORE (Exploring Natural Capital Opportunities, Risks and Exposure), an online database that helps organisations to understand their dependencies and impacts on ES (ENCORE Partnership, 2024a, 2024b). ENCORE evaluates 271 economic activities for direct dependencies on 25 ES and assigns

materiality ratings – ranging from very high to very low – based on the degree of reliance each activity has on these services. When sufficient data are available, the materiality rating is determined through a combination of qualitative and quantitative assessments¹²; otherwise, a purely qualitative approach is used. Initially, ENCORE concentrated exclusively on direct dependencies on ES. However, it has recently incorporated indirect dependencies, which are identified through upstream and downstream value chain connections (ENCORE Partnership, 2024b).

Several studies using ENCORE to assess the dependencies of firms on biodiversity focus on portfolios of financial institutions (see Table 2 for a summary). In particular, many of these studies are carried out by central banks (see for instance Boldrini et al., 2023; Svartzman et al., 2021; Van Toor et al., 2020) to evaluate the exposure of the domestic financial system to risks stemming from biodiversity loss, which are increasingly becoming a cause for concern for central banks and financial supervisors – especially those belonging to the European Union¹³ (see Mauderer, 2023; Meyer & Nerlich, 2024; Salin et al., 2021) – due to the alarming depletion of natural resources (IPBES, 2019). Van Toor et al. (2020), from the central bank of The Netherlands, conduct a pioneering study evaluating the dependence on ES of Dutch financial institutions' portfolios, totalling EUR 1400 billion. To do so, financial assets are linked to ES through firm business processes. They find that 36% of the portfolio (EUR 510 billion) is highly or very highly dependent on one or more ES, highlighting the exposure to physical risk of the Dutch financial system. Comparable figures were also found for French (42%, Hadji-Lazaro et al., 2024), Brazilian (46%, Calice et al., 2021), and Malaysian (54% World Bank & BNM, 2022) financial institutions, whereas the UK has a lower level of high or very high ES dependency (10%, Wolstenholme et al., 2024). On the other hand, for the euro area, Boldrini et al. (2023) find that as much as 75% of corporate loans are highly dependent on at least one ES. However, Laurinaityte and Borges (2023), who find a similar figure for Lithuanian bank loans, argue that such a dependency might not be alarming for Lithuania, as the likelihood of disruption of ES provision is lower than in other European countries, owing to its geographic characteristics. In this context, while it is important to acknowledge that the likelihood of dependencies evolving into financial risks varies based on a country's territorial features and location, it is equally crucial to note that, at the time of analysis, ENCORE did not account for indirect dependencies. Consequently, biodiversity physical risk may still be significant through supply chains. As a matter of fact, when indirect dependencies are taken into account (using the supply chain data from EXIOBASE), portfolios of firms become more exposed to biodiversity physical risk (see Boldrini et al., 2023; Hadji-Lazaro et al., 2024), also for firms in sectors that have no direct dependencies, such as education, information and communication services (Kulionis et al., 2024). However, according to Ranger et al. (2024), a limitation of these pioneering studies is that they focus on the economy's reliance on nature, while offering only minimal insight into the materiality of financial risks for firms.

Another interesting result concerns ES dependencies in emerging markets. Calice et al. (2023) find that the banking systems of 20 emerging countries display the highest dependencies on climate regulation and flood and storm protection ES. Similarly, World Bank and BNM (2022) estimate that banks in Malaysia are indirectly dependent on climate regulation ES, such as carbon storage (26%), and flood and storm protection (16%). These findings highlight that developing economies, which are often highly exposed to physical climate risk, such as sea level rise (UNEP, 2023), are also highly dependent on nature-related benefits that mitigate climate risk. Hence, for these countries, biodiversity physical risk can evolve into climate physical risk. As a result, protecting nature becomes crucial for reducing climate risk.

Finally, we report that the findings highlight the risks arising from dependence on water (Boldrini et al., 2023; Kulionis et al., 2024; Schrapffer et al., 2022; Van Toor et al., 2020). For instance, Hadji-Lazaro et al. (2024) find that surface and ground water are essential to 40%–50% of the firms in the portfolio of French financial institutions. Moreover, Kulionis et al. (2024) argue that ground water is highly important also in the primary sector (e.g., agriculture, mining), suggesting that a significant portion of the economic system would be at risk if water provision services were to deteriorate. As a matter of fact, sectors which are most exposed to the materiality of biodiversity physical risk, such as agriculture and food, beverage and tobacco are highly dependent on water (Giglio et al., 2025; Hadji-Lazaro et al., 2024; Schrapffer et al., 2022), for instance for the cultivation of crops. Therefore, we argue that policies that prevent water stress and ensure its provision ought to become a priority of firms and financial supervisors alike. Moreover, Van Toor et al. (2020) emphasises that also the loss of animal pollination poses a significant threat to financial systems and the real economy, given that over USD 500 billion of global crop production is directly reliant on animal pollination. Although these risks are manageable, the findings of Carvalho et al. (2023) – indicating that 54% of companies exposed to biodiversity-related physical risks in 2018 failed to implement appropriate management strategies – highlight the need for firms to strengthen their efforts in addressing such risks effectively.

4.2. Transition risk: the impact of businesses on biodiversity

Biodiversity transition risk stems from the global shift towards a nature-positive economy, driven by factors such as tighter environmental regulations, taxation, and reputational pressures. These developments primarily affect firms whose operations exert negative impacts on natural ecosystems, which are thus more exposed to transition risk (Hadji-Lazaro et al., 2024; NGFS, 2024b). For this reason, in the biodiversity finance literature, exposure to this form of risk is commonly assessed through measures of firms' or portfolios' biodiversity footprint (see Becker et al., 2025; Coqueret et al., 2025; Garel et al., 2024; Guidolin & Pedio,

¹² ENCORE utilises quantitative indicators derived from EXIOBASE (Stadler et al., 2018), an Environmentally-Extended Multi Regional Input-Output model. The details of the model are discussed in the next paragraph.

¹³ In this regard, the EU is making considerable efforts in protecting biodiversity and ensuring the provision of ecosystem services (see the EU Biodiversity strategy for 2030 (European Commission, 2024a) and the INCA project (European Commission, 2024b) on the statistical framework for data on natural capital).

Table 2

List of studies that investigate the dependency of economic activities on biodiversity. For every study, the table reports the sample considered, the methodology, and the key results. ENCORE refers to version 1 of the database.

Paper	Sample	Methodology	Key results
Boldrini et al. (2023)	2500 eurozone banking groups	ENCORE and EXIOBASE	75% of corporate loans are highly dependent on at least one ES
Calice et al. (2021)	Portfolio of Brazilian financial institutions	ENCORE	46% of banks' corporate loan portfolio is highly or very highly dependent on one or more ES
Calice et al. (2023)	Portfolio of 20 emerging countries financial institutions	ENCORE	Around 50% of banks' corporate loan portfolio is highly or very highly dependent on one or more ES
Carvalho et al. (2023)	11,812 firms	ENCORE	21% of the companies in the sample are exposed to biodiversity dependency risk
Hadji-Lazaro et al. (2024)	Portfolio of French financial institutions	ENCORE and EXIOBASE	42% of banks' corporate loan portfolio is highly or very highly dependent on one or more ES
Kulionis et al. (2024)	MSCI ACWI Stock Index firms	ENCORE	Agriculture is the sector with the highest dependency on ES
Laurinaityte and Borges (2023)	Portfolio of Lithuanian financial institutions	ENCORE	70% of bank loans are very highly dependent on at least one ES
Schrapffer et al. (2022)	EuroStoxx 600 firms	ENCORE	57.8% of the portfolio is highly or very highly dependent on one or more ES
Van Toor et al. (2020)	Portfolio of Dutch financial institutions	ENCORE	10% of the portfolio is highly or very highly dependent on one or more ES
Wolstenholme et al. (2024)	Portfolio of UK financial institutions	ENCORE	36% of the portfolio is highly or very highly dependent on one or more ES
World Bank and BNM (2022)	Portfolio of Malaysian financial institutions	ENCORE	54% of the portfolio is highly or very highly dependent on one or more ES

2025; [Hadji-Lazaro et al., 2024](#)). However, the materiality of this risk largely depends on how strongly regulators prioritise nature protection.

In recent years, regulators and policymakers have increasingly focused on biodiversity-related financial risks. On the international front, particular importance is given to the Kunming Declaration and the subsequent Kunming-Montreal Global Biodiversity Framework (GBF) ([Secretariat of the Convention on Biological Diversity, 2022](#)), adopted at the UN Biodiversity Conference (COP15) in December 2022. The GBF represents a landmark global agreement aimed at halting and reversing biodiversity loss by 2030. Building on the commitments of the [Kunming Declaration \(2021\)](#), it brings together 190 governments pledging to protect and restore 30% of the planet's land and water by 2030 and to phase out subsidies harmful to nature. Notably, Target 15 urges countries to develop regulations requiring companies and financial institutions to disclose their biodiversity-related risks, dependencies, and impacts, fostering the creation of standardised biodiversity data, metrics, and reporting frameworks with far-reaching implications for the financial sector and corporate environmental accountability. The EU is also equipping itself with a comprehensive set of regulations to halt biodiversity loss, including the EU Biodiversity Strategy for 2030 ([European Commission, 2020](#)), the Regulation on Deforestation-free Products ([European Commission, 2023](#)) – which will apply from December 2025 for large and medium-sized companies and from June 2026 for micro and small enterprises – and the EU Taxonomy Regulation ([European Commission, 2021](#)). Under the Taxonomy framework, an economic activity cannot be classified as environmentally sustainable if it causes a significant adverse impact on any of the six environmental objectives, one of which is the protection of biodiversity and ecosystems. Finally, on the national side, countries such as France and the United Kingdom are adopting biodiversity-related policies, such as biodiversity targets and disclosure ([French Ministry of Economics, Finance and Industrial and Digital Sovereignty, 2021](#)) and ban on illegal deforestation in supply chains ([Department for Environment Food and Rural Affairs, 2021](#)). This growing body of national and supranational regulation makes biodiversity transition risk increasingly relevant for firms across many countries (e.g., EU member states, the UK). Consequently, the literature has sought to identify which sectors, firms, and financial systems exert the greatest negative impact on biodiversity and are therefore most exposed to transition risk.

Traditionally, scholars in ecology have estimated the impact of human activities on nature and biodiversity to trace the channels through which economic activities degrade ES (see for instance [Lenzen et al., 2020](#); [Pyay et al., 2019](#); [Soode-Schimonosky et al., 2017](#); [Wilting et al., 2017](#)), and propose more targeted and effective policies. However, in the last few years, it has been acknowledged that, in the context of the double materiality of biodiversity, damaging nature can be a source of risk for firms and financial institutions (e.g. [Boissinot et al., 2022](#); [Dempsey, 2013](#); [Hadji-Lazaro et al., 2024](#); [Van Toor et al., 2020](#)). Moreover, as firms are increasingly required to disclose their impact on nature ([Hudson, 2024](#)), the importance of assessing biodiversity footprints becomes progressively higher in accounting and finance. In this section, we review empirical studies that assess biodiversity damage attributed to firms (see [Table 3](#) for a summary).

As reported in [Wolff et al. \(2017\)](#), a number of methodologies have been proposed in ecology to assess human-induced pressures on biodiversity, as well as combinations of such methodologies. Commonly used methods include the Environmentally-Extended

Multi Regional Input Output (EEMRIO) model, the GLOBIO model, and Life Cycle Assessment (LCA). We provide a concise overview of these methods before examining the findings reported in the literature.

The EEMRIO model traces the flows of goods and services across sectors and countries and evaluates the environmental impact induced by supply chains (see, e.g., Boakes et al., 2024; Steinmann et al., 2018; Sun et al., 2022; Wilting & van Oorschot, 2017). As reported in Bruckner et al. (2023), the EEMRIO model calculates the matrix of the environmental impacts associated with the final demand of each sector and region, E , as follows:

$$E = \hat{c}(I - A)^{-1}Y \tag{9}$$

where \hat{c} is a diagonal matrix¹⁴ of environmental pressures (e.g., land use, CO₂ emissions) generated by the production of one unit for each sector in each region, A is the technology matrix, which specifies the amount of input each sector requires from all other sectors to produce a single unit of output, and Y is the matrix of final demand. Eq. (9) is an extension of the Input Output model (Leontief, 1936), which calculates the output that each sector should produce to satisfy the final demand, where the integration of environmental pressures allows for the computation of a sectorial environmental footprint. Hence, the crucial step in the EEMRIO model is the selection and computation of the environmental pressures \hat{c} . Schaffartzik et al. (2014) explain some assumptions of the EEMRIO model that may bias the results obtained; in particular, the model assumes that product groups are homogeneous – although, in many economies, input–output tables combine, in a single category, highly heterogeneous products – and so are prices. Hence, caution must be exercised when interpreting the results of input–output models.

GLOBIO (Alkemade et al., 2009; Schipper et al., 2020) is a mathematical model that combines pressure-impact functions with geospatial data (retrieved from the IMAGE model, see PBL, 2024b) to compute the intactness of terrestrial biodiversity at the local level, expressed in MSA, as a function of six human-induced pressures.¹⁵ MSA values are calculated based on a meta-analysis of selected empirical studies that provide data on species composition in both disturbed and undisturbed conditions, while cause–effect relationships are estimated by regressing MSA values on the pressure variable considered (Schipper et al., 2016). Finally, to obtain an overall MSA for grid cell i , values derived from each pressure are aggregated as follows:

$$MSA_i = \prod_{p=1}^6 MSA_{p,i} \tag{10}$$

where $MSA_{p,i}$ is the MSA associated to pressure p in cell i . Although Wolff et al. (2017) assert that the GLOBIO model does not allow for the assessment of the biodiversity footprint of a firm and its value chain, some studies employ it to evaluate impacts at the company level (see Van Toor et al., 2020). GLOBIO is a powerful tool to analyse the impact of human-related activities on biodiversity, but it has some drawbacks. Garel et al. (2024) argue that the reference points used in the model are dated, since they belong to the 1990s, and Finance for Biodiversity (2024) asserts that the model prioritises the tracking of the most extensively studied species and habitats.

The LCA methodology calculates the environmental impact of a product or service throughout its entire life cycle, where pressures usually include land use, climate change, and water use Kulionis et al. (2024). As reported in Hauschild et al. (2018), LCA consists of four methodological phases, i.e., Goal and scope definition, Inventory analysis (LCI), Life Cycle Impact assessment (LCIA), and Interpretation. Specifically, the LCA starts with the definition of the goal of the analysis, the functional unit, the activities and the processes that belong to the product life cycle, and the geographical and temporal scopes. Subsequently, data on input resources and environmental output (e.g., emissions, waste) are collected in the LCI phase. The LCIA phase lies at the heart of the LCA, as it converts the physical flows and interventions of the product system into environmental impacts, using models drawn from environmental science. In particular, in LCIA, elementary flows from the inventory are assigned to the selected impact categories (e.g., global warming, biodiversity loss) and environmental models are used to translate the flows into impacts (characterisation). As explained in Sadhukhan et al. (2021), the life cycle impact characterisation of substance x in impact category k , $LCIA_{x,k}$, measures how changes in its amount in the environment affect the impact category, compared to a reference substance r :

$$LCIA_{i=x,k} = \frac{\int_0^T a_{i=x,k}x(t)dt}{\int_0^T a_{i=r,k}r(t)dt} \tag{11}$$

where $a_{x,k}$ is the intrinsic property of substance x responsible for impact category k following an increase of one unit of x in the environment, $x(t)$ is the quantity of x remaining at time t , and T is the time horizon. Following, the total environmental impact in category k , E_k , can be computed:

$$E_k = \sum_i LCIA_{i,k} \cdot m_i \tag{12}$$

where m_i is the quantity of substance i in the environment. Impact categories can be further aggregated into a single impact by calculating the relative importance of E_k and computing a weighted average. Finally, the results are interpreted and validated using sensitivity analysis. In LCA, the impact is normally expressed using the PDF (Crenna et al., 2020), although the MSA can also be used. The LCA is a methodology with an established tradition and the literature discusses thoroughly its strengths and weaknesses.

¹⁴ The symbol \hat{c} means that vector c has been diagonalised into a matrix.

¹⁵ Namely, the six pressures included in GLOBIO are land use, road disturbance, fragmentation, hunting, nitrogen deposition, and climate change. See Schipper et al. (2016) for further details.

For instance, Finnveden (2000) explains that not all relevant environmental impacts are considered and the quality of the analysis depends on the reliability of the data. Nonetheless, the scholar argues that LCA should not be replaced since no other approaches allow for the comparisons of products along the whole life cycle.

Initially, the above methodologies have been applied to economic sectors at the aggregate level, providing interesting insights into the impact of economic activities. Kok et al. (2014) employ the GLOBIO model and find that food production contributes 60%–70% to global terrestrial biodiversity loss, followed by wood extraction (5%–10%). The agricultural sector, which is pivotal for food production, is one of the main drivers for biodiversity loss, especially through land use changes. Further studies employ EEMRIO models and confirm that the food sector is highly exposed to biodiversity transition risk, as it is largely responsible for the extinction of species and biodiversity loss through GHG emissions (Boakes et al., 2024; Irwin et al., 2022). On the other hand (Wilting & van Oorschot, 2017), building on the input–output model proposed by Acquaye et al. (2017), develop an innovative methodology that combines EEMRIO and GLOBIO to quantify the biodiversity footprint of the Dutch economic sectors.¹⁶ They find that sectors producing primary resources display the largest footprint and that the food, beverages and tobacco sector has the greatest impact. In addition, Wilting and van Oorschot (2017) show that the largest biodiversity losses attributable to supply chains occur in land- and energy-intensive sectors and that more than 50% of supply chain impact is caused abroad. Similarly, other studies underscore that biodiversity loss is caused by pressures exerted to satisfy an external demand, with wealthy nations damaging lower-income countries (Marques et al., 2019; Verones et al., 2017). These results highlight the relevance of the impact that businesses exert on the environment, the importance of considering the company supply chain (Scope 3) in calculating biodiversity footprint, and that firms employing land-related resources and with high energy use are significantly exposed to biodiversity transition risk, through their supply chains.

More recently, the methods previously described have been used to estimate the biodiversity footprint at the firm-level. For example, Van Toor et al. (2020), using the GLOBIO model, calculate the biodiversity footprint of a company based on its sector, continent, and turnover, assuming that companies within the same sector and region share a similar footprint per euro of turnover. The resulting measure accounts for both the direct impact of a company's production and its value chain. Kulionis et al. (2024), on the other hand, present a simple extension of the EEMRIO and LCA techniques to evaluate firms' total biodiversity footprint, where environmental impacts (E) are multiplied by a firm's revenue streams by sector and country to obtain its total impact on biodiversity. The results obtained are comparable to those related to sectorial footprints. Schrapffer et al. (2022) use ENCORE to assess the biodiversity footprint of the Euro Stoxx 600, finding that 77.58% of the securities in the portfolio have a strong or very strong impact on biodiversity, with companies that carry out extraction activities (mining, energy) achieving the largest impacts. Kulionis et al. (2024) consider the MSCI ACWII stock index and reveal that the food, beverage, and tobacco sector is the primary driver of biodiversity loss linked to the index. For many sectors, environmental impacts are mainly concentrated within the supply chain. Analogously, Wolff et al. (2017) use the Absolute Environmental Sustainability Assessment¹⁷ methodology (Bjørn & Hauschild, 2015) to examine pressures on natural capital exerted by the French mass market retail company Casino and its value chain, and show that the firms in Casino's value chain cause major and non sustainable pressures on biodiversity at the agricultural phase. Van Toor et al. (2020) examine the biodiversity footprint of a portfolio of over 8000 securities held by Dutch financial institutions, finding that the portfolio is responsible for the loss of over 58,000 km² of pristine nature. Similarly, Hadji-Lazaro et al. (2024) evaluate the biodiversity footprint originating from land use of a portfolio of 1126 securities held by French financial institutions using the Biodiversity Impact Analytics-GBS (BIA-GBS) developed by CDC Biodiversité and Carbon4 Finance.¹⁸ They find that the portfolio footprint is equivalent to a loss of 130,000 km² of nature and one million euros of securities from the portfolio of French financial institutions have a footprint of 0.13 MSA·km², comparable to that of the Van Toor et al. (2020)'s portfolio of Dutch banks (0.18 MSA·km²). Finally, Ceglar et al. (2023) calculate, over 4 million non financial firms, the biodiversity footprint generated by land use and climate change. It emerges that the portfolio's footprint is significantly larger than that found in Van Toor et al. (2020) and Hadji-Lazaro et al. (2024), equivalent to the loss of 5,820,000 km² of "pristine" nature. However, this figure appears reasonable when considering that Ceglar et al. (2023)'s sample is significantly larger.

Besides methodologies rooted in ecological studies, various finance-specific methods and tools have been developed to estimate biodiversity footprint at the sectorial- and company-level. Such methods and tools include spatial analysis (Calice et al., 2021), SASB Materiality Map (Carvalho et al., 2023), textual analysis (Giglio et al., 2025; He et al., 2024; Ma et al., 2024), and questionnaires (Giglio et al., 2025). In particular, Giglio et al. (2025), following Engle et al. (2020), design both an index capturing general sentiment towards biodiversity applying text mining techniques to the New York Times articles, and indices proxying transition risk by constructing a dictionary of regulatory terms related to biodiversity. Giglio et al. (2025) find that the number of mentions of biodiversity regulation risk increases over time. Ma et al. (2024) show that the correlation between biodiversity physical and transition risk indices is 0.49, hence a number of firms have both high dependency and impact on biodiversity, while

¹⁶ To calculate a sectorial footprint, Wilting and van Oorschot (2017) introduce matrix M , depicting biodiversity losses per unit of environmental pressures. By multiplying matrix M with matrix \hat{c} , it is possible to obtain the biodiversity loss corresponding to the pressure associated to the industrial activity. GLOBIO is used to obtain the biodiversity loss factors, expressed in MSA·km²·y, and among the pressures considered there are GHG emissions and land use. Moreover, Wilting and van Oorschot (2017) replace the matrix of final demand, Y , with the matrix of production.

¹⁷ The Absolute Environmental Sustainability Assessment (AESA) is a method to compare the environmental footprint exerted by an entity (e.g., an industrial process, a company) quantified in LCA with its carrying capacity. In other words, the method allows one to detect if the environmental impacts attributed to the entity in question are sustainable (see Rodrigues et al., 2021; Ryberg et al., 2021, for further applications).

¹⁸ The GBS (Global Biodiversity Score) is a metric, expressed in MSA·km², which measures firm-level impacts on biodiversity. The metric builds on Wilting and van Oorschot (2017)'s methodology and employs EXIOBASE in the first step to map trade flows into environmental pressures. In the second step, these pressures are converted into footprints using GLOBIO.

Table 3

List of studies that investigate the biodiversity impacts of economic activities. For every study, the table reports the sample considered, the methodology, the metric used to measure the impact on biodiversity, the pressures, and the key results. See the [Appendix](#) for the list of pressures.

Paper	Sample	Methodology	Impact measure	Pressures	Key results
Boakes et al. (2024)	Global food sector	EEMRIO	Local species richness and Rarity-weighted species richness	LU, CC	Methane emissions are responsible for 70% of the overall greenhouse gas-driven biodiversity footprint
Calice et al. (2021)	Loan portfolio of Brazilian financial institutions	Spatial analysis	None	None	Up to 38% of banks' corporate loan portfolio is exposed to transition risk
Carvalho et al. (2023)	11,812 firms	SASB materiality map	Ranking from 1 (Very low) to 5 (Very high)	None	10% of the firms were directly exposed to transition risk
Ceglar et al. (2023)	4.2 million of firms in 2500 EU banks' loan portfolio	EEMRIO and GLOBIO	MSA loss-ha-y	LU, CC	The impact of the economy on biodiversity is equivalent to the loss of 582 million hectares of "pristine" natural areas worldwide
Coqueret et al. (2025)	522 equities	CBF	MSA-km ² -y	LU, GHG, WP, AP	Land-intensive sectors are highly exposed to transition risk
Garel et al. (2024)	2106 equities	CBF	MSA-km ² -y	LU, GHG, WP, AP	Land-intensive sectors are highly exposed to transition risk
Giglio et al. (2025)	U.S. equities (textual analysis), 668 respondents among finance professionals, academics, and public employees (survey)	Textual analysis and survey	Score based on number of occurrences of related terms (textual analysis)	None	The energy sector is viewed as the most exposed to transition risk
Hadjilazaro et al. (2024)	Portfolio of listed shares, short-term debt, and long-term debt securities of French financial institutions	BIA-GBS	MSA-km ²	LU, FR, EN, NI	The portfolio footprint is equivalent to a loss of 130,000 km ² of nature
He et al. (2024)	4708 Chinese equities	Textual analysis	Score based on number of occurrences of related terms	None	Chinese companies are highly exposed to biodiversity risk, notably exceeding levels observed in the US
Irwin et al. (2022)	Global economic sectors	EEMRIO	non-normalised STAR	118 threats drawn from the IUCN Red List	The food and beverage sector is the greatest driver of consumption-induced extinction risk globally
Kok et al. (2014)	Global economic sectors	GLOBIO	MSA	CR, PA, FO, AAL, INF, EN, FR, BIO, NI, CC	Food production contributes 60%–70% to global terrestrial biodiversity loss
Kulionis et al. (2024)	3000 equities in the MSCI ACWI Stock index	EEMRIO and LCA	PDF-y-million \$	LU, CC, PH, TA, WS, WE	The food, beverage, and tobacco sector is the primary driver of biodiversity loss
Ma et al. (2024)	Chinese equity market	Textual analysis	Score based on number of occurrences of related terms (textual analysis)	None	The correlation between physical and transition risk indices is 0.49
Marques et al. (2019)	Global agriculture and forestry sectors	EEMRIO and others	Bird species richness	LU activities	Wealthy nations are exporter of biodiversity loss to lower-income countries
Schrapffer et al. (2022)	Euro Stoxx 600 equities	ENCORE	Ranking from 1 (Very low) to 5 (Very high)	WU, GHG, AP, WP, SP, SW, DI, FEU, TEU, OR	77.58% of the portfolio has a strong or very strong impact on biodiversity

(continued on next page)

Table 3 (continued).

Van Toor et al. (2020)	Portfolio of shares, corporate bonds, and loans of Dutch financial institutions	GLOBIO	MSA loss-km ² -y	LU, GHG	The portfolio is responsible for the loss of over 58,000 km ² of pristine nature
Verones et al. (2017)	Global economic sectors	LCA and EEMRIO	PDF	CC, WE, TA, LU	Wealthy nations are exporter of biodiversity loss to lower-income countries
Wiltling and van Oorschot (2017)	Dutch economic sectors	EEMRIO and GLOBIO	MSA-km ² -y	LU, INF, CC, and others	The food, beverages and tobacco sector has the greatest impact on biodiversity
Wolff et al. (2017)	French mass-market retailer Casino	LCA and AESA	Occupation of the Consumers' ecological Budgets (OCB)	CC, OD, PH, TA, TE, WE, FE, LU, SE, WD	Firms in the value chain cause major and non sustainable pressures on biodiversity at the agricultural phase

other firms are more exposed to one of these risks. However, a downside of the following approach lies in the reliance on the firm disclosure of possible biodiversity impacts and risks. In fact, firms may decide not to mention them either because they do not deem biodiversity risk material enough, or because they are unaware of the biodiversity footprint exerted through their supply chain, or for greenwashing reasons. Furthermore, such a methodology is more useful for capturing sentiment than for objectively measuring impact and transition risk. Moreover, Giglio et al. (2025) administer a survey to 668 finance researchers, practitioners, and public sector professionals, requesting them to identify the industry most significantly affected by biodiversity physical and transition risks. According to the respondents, sectors exposed to transition risk are not necessarily the same exposed to physical risk. In particular, the energy sector is viewed as the most exposed to transition risk, due to, for instance, oil spills and habitat destruction during drilling (Giglio et al., 2025). Other industries with considerably high transition risk are food, beverage and tobacco, and materials, which can incur higher operating costs due to increased regulation and control on the environment that can affect company operations. Coqueret et al. (2025) and Garel et al. (2024) also show that land-intensive sectors, such as forestry, agriculture, mining, and food, are highly exposed to transition risk, using the Corporate Biodiversity Footprint (CBF) metric.¹⁹

From the papers discussed above, it clearly emerges that firm operations account for a large share of biodiversity loss and, for some sectors, especially through supply chains. However, the magnitude of this impact does not necessarily mean that transition risk is material, nor does it imply that firms and financial institutions view it as such. In this context, the findings of Becker et al. (2025), which show a positive relationship between transition risk exposure and loan prices in the EU and the UK, and of Hoepner et al. (2023), where it is found that a one standard deviation increase in biodiversity performance results in a flattening of the ten-minus-one-year CDS slope by 21.6 bps, suggest that creditors are increasingly recognising nature-related risks as material.

4.3. Biodiversity and asset pricing

Biodiversity loss can be considered an additional source of financial risk, akin to climate change. Recently, there has been great interest in the pricing of climate risk in several markets, in particular the stock market (see the review by Venturini, 2022). Analogously, scholars have begun to explore whether biodiversity risk was priced in the capital market, especially after that the Kunming Declaration (2021) and the Montreal Agreement (2022) were signed, where the urgency of halting and reverting biodiversity loss was explicitly addressed.

As argued in this review, biodiversity risk can be both physical and transitional. For example, investors might be concerned about the loss of plant species essential for producing drugs and medicines, leading them to adjust their expectations for pharmaceutical sector stocks. Similarly, they may view the intensive drilling activities of the energy sector as highly impactful, anticipating potential future regulations or environmental fines that could affect the sector's valuation (Giglio et al., 2025). Ideally, a biodiversity risk measure should capture both kinds of risks (Soylemezgil & Uzmanoglu, 2024), although a measure focusing on a single type of risk can still provide valuable insights. After such a measure is available, it is possible to employ it as a variable in a regression model explaining stock returns, similarly to, e.g., GHG emissions in climate finance (see Bolton & Kacperczyk, 2023).

When a firm-specific risk measure is available, a number of studies employ a characteristic-based asset pricing model to examine the cross-section of returns. Garel et al. (2024) inspect if biodiversity is priced in the international stock market, using the CBF metric (see Section 4.2) as a measure of firm's negative impact on natural capital (transition risk). While no significant relationship with stock returns is observed between 2019 and 2022, higher returns are linked to larger CBF values following the Kunming Declaration in October 2021, indicating that investors began demanding a transition risk premium,²⁰ aligning with the pricing of

¹⁹ The CBF is a metric developed by Iceberg Data Lab to quantify the impact of companies on biodiversity. Using EEMRIO and LCA, the firm's environmental pressure are computed, based on the flow of goods and services on which its business depends on, including the value chain. Finally, pressures are converted into impacts, expressed in km²-MSA, using pressure-impact function and aggregated into a single metric. For a thorough description of the methodology, see Garel et al. (2024).

²⁰ Garel et al. (2024) identify two other possible channels through which biodiversity loss propagate to the financial market, that is, changes in investor preferences and unexpected cash flow shocks, which are not supported by their regression results.

Table 4
Studies on the biodiversity risk premium.

Study	Biodiversity risk measure	Methodology	Asset	Countries	Period	Is biodiversity risk priced?
Coqueret et al. (2025)	CBF	Factor-based	Stock	International	2012–2022	Yes
Huang et al. (2024)	$\frac{Bio-capacity}{Bio-footprint}$	Characteristic-based	Stock	International	1999–2021	Yes
Garel et al. (2024)	CBF	Characteristic-based	Stock	International	2019–2022	Yes
Giglio et al. (2025)	Textual analysis index	Factor-based	Stock	US	2000–2022	Yes
Giglio et al. (2025)	Textual analysis index	Factor-based	Municipal bond	US	2000–2023	No
Lai et al. (2024)	Giglio et al. (2025)'s 10-K index	Characteristic-based	Stock	US	2001–2020	Yes
Ma et al. (2024)	Textual analysis index	Factor-based	Stock	China	2005–2022	Yes
Naffa and Czupy (2024)	MSCI ESG Score	Factor-based	Stock	International	2013–2023	Yes
Soylemezgil and Uzmanoglu (2024)	Giglio et al. (2025)'s 10-K index	Characteristic-based	Corporate bond	US	2000–2022	Yes
Xin et al. (2023)	MSCI ESG Score	Factor-based	Stock	US	2013–2020	No

carbon transition risk (Bolton & Kacperczyk, 2023). This conclusion is further supported by the observed depreciation of stocks with high CBF values in the days immediately after Kunming. The event study conducted by Kalhor and Kyaw (2024) confirms that US companies more exposed to biodiversity risk – proxied by Giglio et al. (2025)'s biodiversity score, which captures sentiment towards both physical and transition risks – are hit hardest when Kunming takes place, although in the days following the key date such firms do not experience significantly lower abnormal returns. Consistently, other studies find that biodiversity risk exposure increases the implied cost of equity²¹ (Lai et al., 2024) and corporate bond yield spreads (Soylemezgil & Uzmanoglu, 2024). A higher biodiversity risk is also positively associated with stock price crash risk (Bassen et al., 2024; Liang et al., 2024), which strengthens the materiality of biodiversity risks, justifying the presence of a biodiversity premium. In contrast, Huang et al. (2024) construct a country-level physical risk index following the procedure detailed in Hong et al. (2019) and find that firms operating in countries with the lowest risk exposure generate higher annual returns compared to companies located in countries with the highest biodiversity physical risk. However, it must be noted that Huang et al. (2024)'s sample ends in 2020, prior to the Kunming Declaration (2021). A similar argument is valid also for Xin et al. (2023), who find no relation between US stock returns and biodiversity ESG scores between 2013 and 2020.

Other studies, by contrast, develop biodiversity factors that reflect market exposure to biodiversity, such as portfolios based on the biodiversity risk of assets or indices designed to capture market sentiment. Giglio et al. (2025) create firm-level measures of biodiversity risk exposure by carrying out textual analysis of firms' 10-K reports. Their findings show that biodiversity risks impact stock prices, as the returns of portfolios based on the measure of biodiversity risk tend to move in line with changes in overall biodiversity risk. However, the absence of correlation between the biodiversity news index and the returns of characteristic-sorted municipal bond portfolios seems to indicate that biodiversity risk is not priced in such a market. Consistent with these findings, Ma et al. (2024) show that a biodiversity risk measure based on textual analysis can forecast the market premium in the Chinese stock market. Coqueret et al. (2025) define a biodiversity factor as portfolios that are long on the quintile of firms with the highest CBF intensity and short on the quintile with the lowest CBF intensity and subsequently estimate the biodiversity premium using the Fama and MacBeth (1973) regression, controlling for the Fama and French (2015) factors. In the broader sector analysis, no significant biodiversity risk premium emerges, while in highly exposed sectors, the scholars identify a significant 7.2% risk premium (–1.5% in the case of expected returns). Furthermore, they show that the premium has become more pronounced since 2021. Coqueret et al. (2025) argue that these findings are in line with those of Garel et al. (2024), who document a negative price shock for stocks with a large biodiversity footprint after the Kunming Declaration, and of Giglio et al. (2025). Similar conclusions are reached by Naffa and Czupy (2024), who examine the presence of a biodiversity risk premium within investment portfolios that include strategies designed to manage and reduce biodiversity risks. Finally, several studies reveal industry differences in how biodiversity affects stock returns (Coqueret et al., 2025; Huang et al., 2024; Ma et al., 2024).

Overall, the empirical literature demonstrates that biodiversity physical and transition risks can be a source of financial risk for firms and that investors are starting to price such risks in the stock market, especially after 2021, when the Kunming Declaration (2021) was signed. In particular, biodiversity risk increases the cost of capital for firms highly exposed to the double materiality of biodiversity, as investors demand compensation to firms with biodiversity risk exposure, fearing that such companies may underperform with respect to firms with a low footprint and dependency on natural capital. As for other markets, such as municipal and corporate bond markets, more research is necessary to establish the presence of a biodiversity risk premium. In Table 4, we summarise the reviewed papers and the results obtained.

²¹ Pástor et al. (2008) demonstrate that the trade-off between risk and expected returns can sometimes be more effectively identified using the implied cost of capital rather than realised returns.

5. A research agenda on financial risks in biodiversity finance

Research on biodiversity finance is still in its early stages, and there remains a significant need for further exploration and understanding. Here, we suggest potential avenues for future research on biodiversity risk that can fill significant gaps in the literature. Notably, a limited number of studies have already begun to address some of these issues, strengthening the urgency of further research in this area.

As said, a fundamental matter in biodiversity finance is the geographical dimension of companies' dependencies and impacts on nature. We argue that a key issue is to understand *how biodiversity risk exposure varies across different geographical regions*. To answer this question, researchers may leverage geospatial and satellite data to geo-localise assets, such as factories, and the distribution of species, allowing for a precise mapping of impacts and dependencies in different geographical region. For instance, satellite data can be used to monitor deforestation over time in regions with a dense industrial activity, to integrate biodiversity into ESG scores (da Fontoura et al., 2024; Rossi et al., 2024), or to identify areas that are exposed to major environmental risks (Soto-Montes-de-Oca et al., 2020). In this regard, Caldecott et al. (2022) argue that "Spatial finance", especially when combined with cloud computing and artificial intelligence, may give rise to a sheer number of applications, both in research and industry. Furthermore, the empirical literature may also adopt spatial econometrics approaches to integrate the geographic component into models studying the impact of biodiversity on firm value (see Lucas & Mendes-Da-Silva, 2018, for an application in climate finance).

Research should investigate *how the economic and financial system adapts to nature-related shocks*, including asset devaluation (Allen et al., 2020) and financial contagion (Battiston et al., 2017), as highlighted by Hadji-Lazaro et al. (2024). In addition, given the significant attention that central banks are giving to biodiversity risks (see Bank of England, 2022; Ceglar et al., 2023; Chenet, 2024; Kedward et al., 2023), scholars should also explore the interrelation between biodiversity loss and macroeconomic policies. To do so, scholars can draw from macroeconomic models used in the context of climate change, such as IAM, E-DSGE and SVAR models²² (see Chan, 2020; Chan & Punzi, 2023; Nordhaus, 2018; Xiao et al., 2018). In biodiversity finance, all these applications are in their early stage. For example, Battiston et al. (2024) conducts a preliminary stress test on UK banks, Bordenave (2024) integrates forestry policy into an economic growth model, and Giglio et al. (2024) examine the two-way effect between ES and economic production.

Systemic risk represents an important yet largely overlooked dimension of biodiversity-related financial risk, with only limited research to date investigating how biodiversity loss could propagate shocks across the financial system (see Battiston et al., 2024; Mies, 2025). Recognised alongside physical and transition risks by the TNFD (2023), systemic biodiversity risk arises when the collapse of critical natural systems or the materialisation of transition risks triggers cascading effects that propagate through the real economy and the financial system, potentially undermining financial stability. We suggest that it is worth exploring *through which channels biodiversity loss propagates across the financial system and generate systemic risk*. Future research could investigate how shocks to natural capital affect firms' creditworthiness and financial institutions' portfolios, and how these impacts might spread through interconnected financial networks, using, e.g., measures of connectedness (see Billio et al., 2012). This includes analysing financial exposures that could amplify initial shocks, leading to contagion effects. Understanding these transmission mechanisms would provide valuable insights for regulators and financial institutions aiming to incorporate biodiversity-related systemic risk into stress testing, portfolio management, and macroprudential policy frameworks.

Current research on biodiversity finance relies on a relative narrow sample of firms, mainly looking at large or very large companies located in the main developed markets, especially the US. For example, the samples used in Coqueret et al. (2025) and Garel et al. (2024) consist of approximately 500 and 2000 firms, respectively, and, aside from China, the focus is predominantly on developed countries (see, for example, Giglio et al., 2025; Xin et al., 2023). In addition, Wagner (2023) reports that biodiversity loss and related events could have a severe impact on smaller companies, given their more limited scale. For all these reasons, we argue that it is crucial to examine *the extent to which the impact and dependencies on biodiversity vary across a larger and more diverse sample of firms, including smaller enterprises and those operating in different geographical regions*, as areas located in developing countries often encompass biodiversity-rich ecosystems and may exhibit different regulatory frameworks and environmental pressures that are not captured in studies focused on developed economies.

To our knowledge, studies have explored impacts and dependencies on terrestrial biodiversity and its pricing in the stock market. However, it remains an open question *whether companies are exposed to aquatic biodiversity risk* and if such risk is priced in the capital market. As a matter of fact, existing finance research has employed measures of terrestrial biodiversity (see Garel et al., 2024) or news-based indicators (see Giglio et al., 2025), not capturing the complexity of marine ecosystems, which provide us with important economic resources. For instance, the carrageenan is a polysaccharide extracted from red seaweed that exhibits tissue engineering properties and has applications in regenerative medicine (Jafari et al., 2022), hence the loss of red seaweed may be harmful to the pharmaceutical industry as well as humanity. Of course, measuring aquatic biodiversity is challenging, but some studies, such as Halpern et al. (2008) and Janse et al. (2015), are applying existing footprinting measurement models to marine flora and fauna.

²² IAM (Integrated Assessment Model), E-DSGE (Environmental-Dynamic Stochastic General Equilibrium), and SVAR (Structural Vector AutoRegression) are three different families of macroeconomic models, which differ in methodology and use cases: IAM extends the neoclassical growth model (see Eatwell & Solow, 1970) by including environmental damages (e.g., GHG emissions) as a negative capital and illustrates their impact on the economy, focusing on long-term interactions between the environment and the economy; E-DSGE are micro-founded models that include large systems of simultaneous, non-linear equations, where agents form expectations in a stochastic environment due to the presence of aggregate or individual shocks, and are employed to analyse the medium-term responses of macroeconomic variables to environmental shocks; SVAR are an extension of the classical unconstrained VAR (Sims, 1980) which impose additional identifying assumptions motivated by the economic theory and knowledge of the macroeconomic and environmental system dynamics, with a focus on short-term responses to structural shocks. For additional details, see Hashimzade and Thornton (2021) and NGFS (2024a).

Existing biodiversity indices rely heavily on modelling and hence they focus especially on trackable, rather than “useful”, species, and disregard the relationship among plant and animal species that generate ES. Arguably, it is not a loss of biodiversity *per se* that matters, but rather the degradation of ES (Garel et al., 2024). Thus, research ought to investigate *how to combine functional and impact indicators*, and include the importance of taxonomies according to their roles in ecosystems. In this regard, biodiversity indicators deem all species equally important (see for instance the MSA by Alkemade et al., 2009, Section 3), yet species’ weights should be adjusted based on the objective. We argue that the collaboration between experts in environmental sciences and economists can help to define conservation objectives, estimate the economic value of species – echoing the valuation of ES (see Bernard et al., 2009; Costanza et al., 1997; Jiang et al., 2021) – and weigh them accordingly.²³ In addition, according to Finance for Biodiversity (2024), scholars should consider innovative data collection methods, such as environmental DNA and bioacoustics to enhance existing footprinting models (e.g., collect DNA in sites where companies operate). In particular, genetic diversity – particularly among livestock breeds – is under threat (Simianer et al., 2003), highlighting the need for innovative methods in biodiversity assessments.

So far, research has explored how biodiversity risk associated to one company affects its financial performance. However, even in a relatively small region, the economic system remains complex, due to the presence of interrelations between multiple economic and environmental elements. We propose that research move past the one-to one approach and explores *how biodiversity risk spillovers emerge from interactions between multiple companies and ecosystems*, to better understand biodiversity loss mechanisms and assess the combined effects of natural capital reduction on company performance. To this purpose, scholars can employ complex system analysis and network theory, drawing from climate finance (see Mao et al., 2023; Xia et al., 2023).

Biodiversity indices provide aggregate measures of biodiversity. However, some industry sectors depend heavily on specific natural resources. Analysing the decline of a particular resource linked to a specific sector may yield deeper insights into that sector’s financial performance. In particular, the decline in the number of pollinators is a significant source of risk for the economy (Van Toor et al., 2020) and *how pollinators loss impacts the agricultural sector* is yet to be determined. A similar example concerns the bark of Pacific yew tree, a medicinal plant at risk of extinction (Brower, 2008) used to produce an anticancer compound. This micro approach to biodiversity may leverage spatial data to model species’ distribution, but, clearly, such an analysis would require a high precision that would entail an intensive field data collection process.

Finally, scholars could also investigate *what are the potential limitations of existing financial risk models when applied to biodiversity loss*. One such example is the Value-at-Risk, which Posth et al. (2024) adjust for biodiversity loss, proposing the novel bio VaR. Notably, the bio VaR is substantially different than the climate VaR (Dietz et al., 2016), due to the geospatial data integration necessary to assess a company’s biodiversity footprint.

Overall, the fact that biodiversity finance is an entirely new and emerging discipline means there are numerous research gaps and unanswered questions. At the same time, the emergence and pressing relevance of this field suggest that these and many other questions will soon find answers. Table 5 summarises the biodiversity financial risks research agenda proposed in this review.

6. Conclusions

In this paper, we review the burgeoning literature on financial risks of biodiversity loss. The review provides a detailed summary of the key current and emerging topics related to biodiversity risk, useful for both researchers and practitioners, highlighting a series of important points. Moreover, the review shows the importance of the mutual collaboration between scholars in different fields to tackle the problem of biodiversity loss, which can also help to mitigate the harmful effects of climate change.

First, the review describes how biodiversity can be measured in finance and reports a comprehensive list of biodiversity metrics in which investors may be interested, discussing their computation, strengths and drawbacks. It emerges that there is no metric which “outperforms” the others and interesting insights can be obtained by looking at multiple metrics, although some metrics should be favoured to others based on the goal of the analysis.

Second, we focus on the double materiality of biodiversity. We review the tools used to estimate industry and firm dependencies and impact on natural capital, channels through which they substantiate, and results obtained in the literature. Scholars have shown that the financial sector in several countries is highly exposed to biodiversity physical risk through the nature-related dependencies of the securities they hold in their portfolios. In particular, several sectors are highly dependent on water-related services and emerging economies are especially dependent on ES that mitigate climate risk. As for impacts, nature loss provoked by firms is shown to be relevant, with land-intensive sectors, such as agriculture and food, beverage and tobacco, displaying the largest footprint. For a number of sectors, impacts occur especially through the supply chain. Finally, we also report the main findings on the pricing of biodiversity risk, especially in the stock market. The empirical evidence demonstrates that investors have begun demanding a premium from firms exposed to biodiversity’s double materiality, due to the higher financial risks they may incur in the future. In particular, the Kunming Declaration seems to have had a significant effect on the pricing of biodiversity risk.

Finally, we identify research gaps and avenues for future research, such as the integration of spatial and remote sensing data in financial analysis, macroeconomic modelling of biodiversity risks, pricing of marine biodiversity risk, and several more. Although the collection and production of reliable biodiversity data remains difficult, the growing attention that biodiversity is receiving from scholars, policy makers and practitioners, will help to overcome this obstacle and enable researchers to advance knowledge in the field. Furthermore, we reiterate that collaboration among experts in different fields will be fundamental for making progress, and

²³ Other authors have also emphasised the importance of multidisciplinary studies. For instance, Jezeer et al. (2017) highlight the need to simultaneously quantify financial and biodiversity performance.

Table 5
Biodiversity risk research agenda.

#	Research question	Motivation	Data issues/ methodology	Methodological references
1	Are firms exposed to aquatic biodiversity risk and is this risk priced in the stock market?	Current studies focus on terrestrial biodiversity, but also marine biodiversity can be a source of physical and transition risks	Mapping marine biodiversity and assessing physical and transition risks for firms presents several challenges	Garel et al. (2024) , Giglio et al. (2025) , Halpern et al. (2008) and Janse et al. (2015)
2	What are the potential limitations of existing financial risk models when applied to biodiversity loss?	Existing risk metrics may fail to capture the specificity of biodiversity loss, in particular its geographic dimension	Research could draw from climate risk metric and adapt them to biodiversity risk	Dietz et al. (2016) and Posth et al. (2024)
3	Are biodiversity spillovers relevant in influencing biodiversity loss and financial performance?	Economic interdependencies and the complexity of value chains should be integrated into financial analysis to understand how biodiversity loss in a certain area affects the financial performance of firms located elsewhere	Network analysis serves as an effective tool for examining the interconnections between firms that influence biodiversity loss and its effect on financial performance	Mao et al. (2023) and Xia et al. (2023)
4	How can we combine functional and impact indicators?	A thorough measure combining biodiversity footprint and species interdependencies is necessary to evaluate usefulness of species in producing ES	The valuation of ecosystem services and innovative data collection methods (e.g., eDNA) could contribute to developing a more comprehensive metric	Alkemade et al. (2009) , Kok et al. (2020) and Sahu et al. (2023)
5	How does the economic and financial system adapts to nature-related shocks?	Biodiversity loss can have far-reaching consequences for asset values, financial stability, and economic growth	Macroeconomic models, particularly those used to model climate change (e.g., IAM, E-DSGE), could be adapted to address biodiversity loss	Bordenave (2024) , Chan (2020) , Nordhaus (2018) and Xiao et al. (2018)
6	How does the loss of pollinators impact the agricultural sector?	The agricultural sector depends heavily on pollinators, which are at risk of collapse and represent a source of substantial financial risk	Obtaining reliable maps of pollinator species distribution can be challenging, as greater emphasis should be placed on field data collection rather than solely on modelling	Baylis et al. (2021) and Gardner et al. (2020)
7	To what degree are smaller firms and those operating in developing markets vulnerable to biodiversity-related risks?	Biodiversity loss and related events could have a severe impact on firms operating in developing countries and smaller in scale	Innovative methods must be found to measure biodiversity risk exposure of smaller firms, based on available data	Cathcart et al. (2023, 2022) and Wagner (2023)
8	How does biodiversity risk exposure varies across different geographical regions?	Companies' dependencies and impacts on nature are geographic-specific and should be accounted for in footprinting models and the pricing of risk	Spatial dependencies and satellite imagery can be integrated in footprinting and econometrics models	Caldecott et al. (2022) , da Fontoura et al. (2024) , Rossi et al. (2024) and Soto-Montes-de-Oca et al. (2020)
9	Through which channels does biodiversity loss propagate across the financial system and generate systemic risk?	Diffuse ecosystem deterioration could impair firms' ability to repay credit and decrease portfolios' value, thereby heightening systemic risk and potentially affecting even those firms that are not directly dependent on nature	Research could use network analysis and contagion models to build interbank or cross-sector exposure networks and simulate how biodiversity-related shocks propagate	Battiston et al. (2024) and Billio et al. (2012)

that the emergence of biodiversity finance as a major research subject will drive substantial advancements in the field, addressing numerous existing research gaps.

The complexity of biodiversity loss makes it impossible to cover all its dimensions within a single review. In this paper, we focused primarily on transition and physical risks, discussing their interrelations and indirect linkages. Future reviews could expand this discussion by examining whether existing regulatory gaps hinder convergence in biodiversity measurement and how sectoral characteristics, such as firm size, may shape reporting obligations. Achieving consistent disclosure of biodiversity metrics across firms would enable the creation of comparable time series data, providing a valuable foundation for empirical research. We believe that substantial progress remains to be made in this direction, to which our review represents an initial contribution.

Table A.6

List of pressure labels used in Table 3.

Label	Pressure	Description
AAL	Abandoned agricultural land	Land previously used for farming but no longer cultivated
AL	Agricultural land	Areas designated for crop production and livestock grazing
AP	Air pollution	The presence of harmful substances in the atmosphere
BIO	Biofuels	Fuels derived from organic matter, such as crops or waste
CC	Climate change	Long-term alterations in temperature, precipitation, and weather patterns
CR	Crops	Cultivated plants grown for food, fuel, or other purposes
DI	Disturbances	Disruptions to ecosystems caused by natural or human activities
EN	Encroachment	Expansion into previously undisturbed natural areas
FE	Freshwater ecotoxicity	The impact of toxic substances on freshwater ecosystems
FEU	Freshwater ecosystem use	The exploitation or use of freshwater habitats and resources
FO	Forestry	The management and exploitation of forested areas
FR	Fragmentation	The breaking up of habitats into smaller, isolated patches
GHG	GHG emissions	Release of greenhouse gases, contributing to global warming
INF	Infrastructure	Physical structures, like roads and buildings, impacting the environment
LU	Land use	Human modification of land for various purposes
NI	Nitrogen deposition	Accumulation of nitrogen compounds in soil and water from air pollution
OD	Ozone depletion	Reduction of the ozone layer caused by chemicals like CFCs
OR	Other resources use	Consumption of non-renewable and renewable natural resources
PA	Pasture	Land used for grazing livestock
PH	Photochemical ozone formation	Production of ground-level ozone due to sunlight and pollutants
SE	Soil erosion	Loss of topsoil caused by wind, water, or human activities
SP	Soil pollutants	Harmful chemicals or substances contaminating soil
SW	Solid waste	Non-liquid waste materials generated by human activities
TA	Terrestrial acidification	Acid accumulation in soil due to deposition of pollutants
TE	Terrestrial eutrophication	Nutrient overload in terrestrial ecosystems, often from nitrogen or phosphorus
TEU	Terrestrial ecosystem use	Human use or alteration of land-based ecosystems
WD	Water depletion	Reduction of available freshwater resources
WE	Water eutrophication	Excess nutrients in water bodies, leading to algae blooms and oxygen depletion
WP	Water pollution	Contamination of water bodies with harmful substances
WS	Water stress	Insufficient water availability to meet demands
WU	Water use	Consumption or diversion of water resources

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used ChatGPT-4o in order to refine grammar and enhance stylistic clarity. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Appendix

See Table A.6.

Data availability

No data was used for the research described in the article.

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