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RESEARCH ARTICLE

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Biodiversity impact assessment for finance

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Abstract

Biodiversity loss, driven by human activities, significantly affects the environment, human societies, and economies. Using the extended multi-regional input–output (EEMRIO) and life cycle assessment (LCA) techniques, we offer insights into how these methodologies can be used to inform financial decisions related to biodiversity focusing on two key aspects: biodiversity impacts and ecosystem service dependencies. Our method combines spatially explicit characterization factors from LC-IMPACT with the Global Resource Input-Output Assesment (GLORIA) database to estimate biodiversity impacts. As a case study we assess the biodiversity impact of the MSCI All Country World Index (MSCI ACWI) which consist of about 3000 large- and mid-sized companies, from 23 developed and 24 emerging countries. The results demonstrate that most of the biodiversity impact is caused in the Americas, followed by Asia, despite its low representation in the index's country weight (6%). Europe shows the least impact. These results emphasize the need to account for global supply chain linkages as products sold in one country might have significant biodiversity impacts elsewhere due to sourcing of production inputs. Second, our results identify the main determinants of the index's impact: land use, followed by water stress and climate change. Although most of the impact is localized in few sectors, the distinct characteristics of these sectors require industry-specific mitigation approaches. Finally, double materiality results show both, the influence companies have on biodiversity and the reciprocal effects. Companies neglecting these impacts risk financial setbacks, making it a crucial concern for investors.

KEYWORDS
biodiversity, EEMRIO, environmental modelling, finance, industrial ecology, LCA

1 | INTRODUCTION

Human activities, including deforestation, pollution, and overexploitation of natural resources, have accelerated biodiversity loss at an alarming rate (IPBES, 2019). This decline has important implications, affecting not only the environment but also human societies and economies (Dasgupta, 2021). The latest planetary boundaries framework update finds that over 10% of genetic diversity of plants and animals may have been lost over the past 150 years, suggesting that biodiversity boundary is markedly exceeded (Richardson et al., 2023).

In response, numerous global initiatives have been established to combat biodiversity loss. The Kunming–Montreal Global Biodiversity Framework (GBF), adopted in 2022, will serve as the world's framework to safeguard and restore biodiversity (UNEP, 2022). The agreement includes measures to halt and reverse nature loss, including putting 30% of the planet and 30% of degraded ecosystems under protection by 2030 (CBD, 2023a). This effort is part of a broader movement to recognize and preserve the value of ecosystems and biodiversity, aligning with global commitments and initiatives such as The Economics of Ecosystems and Biodiversity (TEEB, 2010), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019), and the System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA; United Nations, 2021).

Amidst increasing awareness, there has been a notable surge in corporate reporting regulations. Instruments such as the EU taxonomy (European Parliament, 2020), the sustainability-related disclosure in the financial services sector (SFDR, see European Parliament, 2023), and Corporate Sustainability Reporting Directive (CSRD; see European Parliament, 2023) have been introduced, imposing new responsibilities on the corporate sector. These regulations mandate companies to measure and report on a diverse array of non-financial metrics. This shift underscores the global recognition that corporate performance evaluations should extend beyond traditional financial indicators to encompass environmental and social considerations.

The risks posed by biodiversity loss to economic and financial systems could be significant (Dasgupta, 2021). Increased efforts are required to prevent further biodiversity losses and the ecosystem services that it provides (Díaz et al., 2019; Leclère et al., 2018). Financial actors are uniquely positioned to direct capital into sectors and industries that can help reverse biodiversity loss and ensure that risks are minimized. The risks associated with declining biodiversity and the deterioration of ecosystem services have been assessed by Herweijer et al. (2020), which showed that half of the global value added is moderately or highly dependent on ecosystem services and is therefore exposed to biodiversity loss. Other studies by the Dutch central bank (Van Toor et al., 2020) and the French central bank (Svartzman et al., 2021) have reported similar findings. Coqueret et al. (2023) identified a distinct biodiversity risk premium, revealing that assets with lower biodiversity intensity incur a negative premium on expected returns in sectors highly exposed to biodiversity risks, a trend that has become more pronounced since 2021 as attention to biodiversity issues and risk aversion increased. Broer et al. (2021) examined the biodiversity footprint of financial institutions, identifying climate change and land use as the primary drivers of biodiversity loss.

The increasing integration of biodiversity considerations into financial decision-making highlights the sector's growing recognition of its role in addressing biodiversity loss and incorporating associated risks. The Taskforce for Nature-related Financial Disclosures (TNFD) aims to establish a harmonized framework for financial institutions to report on biodiversity-related financial risk (TNFD, 2023). Measuring biodiversity loss, however, presents inherent challenges. Unlike for greenhouse gas (GHG) emissions, there are no universally accepted indicators. New approaches, tools, and datasets are being developed to better understand the impacts and dependencies of financial institutions on biodiversity (Crenna et al., 2020; Finance for Biodiversity, 2022; Lammerant et al., 2021).

The field of industrial ecology offers promising methodologies suitable for private sector and financial institutions. Over the past decade, significant advancements in methodological approaches to measure environmental impacts have been made within this domain (Moran et al., 2020). However, the applicability of these methodologies for financial actors remains a topic of discussion. This paper aims to demonstrate how these methodologies can be used for assessing biodiversity impacts and dependencies' ecosystem services within financial markets.

1.1 | Relationship between finance, economy, biodiversity, and ecosystem services

All sectors of the economy are either directly or indirectly dependent on ecosystem services (Herweijer et al., 2020). Evidence demonstrates that 15 of the 24 ecosystem services (ES) are degraded or are being used in an unsustainable manner (Hanson et al., 2012). The loss of these services can result in significant economic and financial costs.

Financial institutions play a dual role by supporting companies that depend on or impact ecosystem services. For instance, agricultural firms might depend on natural insect pollination, a service estimated to contribute approximately €153 billion annually or about 9.5% of the total value of global agricultural food production (Gallai et al., 2009). On the other hand, the financial sector also finances businesses that have a negative impact on biodiversity, such as intensive agriculture, which, despite increasing food production, can lead to detrimental environmental effects like eutrophication from excessive fertilizer use. This creates a two-fold relationship between biodiversity and the financial sector, often termed as "double materiality." This relationship is depicted in Figure 1, based on Van Toor et al. (2020) and NGFS-INSPIRE (2022).

The concept of double materiality helps to evaluate both how a company affects biodiversity and how the loss of biodiversity can influence the company's financial performance. It highlights the need for a comprehensive risk management approach that considers both the exposure of financial institutions to biodiversity-related financial risks and their role in contributing to these risks.

Biodiversity-related financial risks are typically categorized into physical and transition risks (NGFS-INSPIRE, 2022). The physical risks arise due to dependence of economic actors on declining ecosystem services. As ecosystems degrade, companies that rely on ecosystem services face increasing vulnerabilities. For instance, a decline in pollinating insects could result in reduced crop yields, impacting agricultural firms. Financial

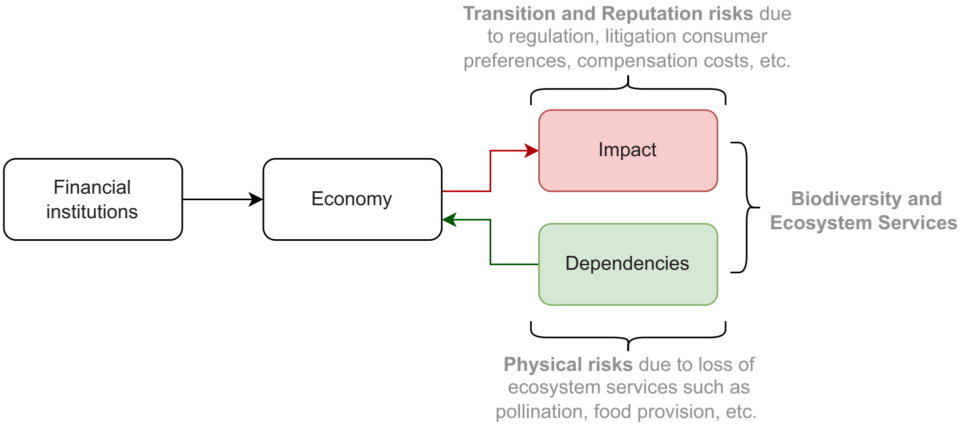

FIGURE 1 Relationship between finance, economy, and biodiversity.

institutions, which finance these companies, are thus exposed to these risks. If the current trajectory of ecosystem degradation persists, the operational and financial stability of many businesses could be put at risk, potentially posing significant challenges to the broader financial sector.

Transition risks arise from efforts aimed at mitigating or reversing biodiversity loss, including government regulations, technological innovations, litigation, and shifts in consumer behavior. The global targets set by the UN Convention on Biological Diversity in 2022 underscore the global commitment to conservation, potentially leading to new regulations that restrict natural resource exploitation or ban environmentally harmful products (CBD, 2023a). Additionally, technological innovations, change in business models, and evolving consumer or investor preferences can introduce further transition risks. Companies might be forced to adapt, leading to potential obsolescence of some business models, while others could become uncompetitive due to increased costs.

1.2 | Measuring biodiversity impacts and dependencies on ecosystem services

1.2.1 | Biodiversity impact

Within the LCA community, biodiversity impacts are measured using a systematic approach that evaluates the impact of products and services throughout their entire life cycle (Hellweg et al., 2023). Typically, the assessment considers impact categories such as land use change, climate change impacts, eutrophication, acidification, water use, and toxicity.

The potentially disappeared fraction (PDF) has emerged as the most widely adopted metric in LCA for evaluating impacts on ecosystem quality (Crenna et al., 2020). The PDF metric quantifies the potential extinction risk of species due to environmental pressures, offering insights into the severity of global or regional biodiversity loss (Verones et al., 2020). It is applicable across various taxonomic groups (e.g., birds, fishes, and plants) and environmental compartments (e.g., land and freshwater systems), and is underpinned by robust biodiversity data (Teixeira et al., 2016; Verones et al., 2017).

Another popular approach that has been used to quantify impacts on biodiversity through a life cycle perspective is based on mean species abundance (MSA) indicator (Crenna et al., 2020). The MSA provides a measure of the average abundance of original species relative to their pristine state (Alkemade et al., 2009; Schipper et al., 2020). It has been applied to assess biodiversity impacts at the national (Wilting et al., 2017), subnational (Wilting et al., 2021), and company level (CDC Biodiversite, 2021).

Marquardt et al. (2019) assessed differences between alpha (local within site diversity, e.g., MSA) and gamma (global across site diversity, e.g., global PDF) biodiversity indicators. They found that different alpha indicators show close alignment, but there was limited convergence between alpha and gamma biodiversity footprints. Their results highlight the relevance of considering both alpha (MSA) and gamma (global PDF) diversity indicators in biodiversity footprint calculations. Marquardt et al. (2019) examined only global PDF impact, but the PDF indicator can be used to quantify species loss at both regional and global levels. The regional PDF captures species loss of a community can be considered as alpha diversity indicator (Souza et al., 2015). The calculation of global PDF involves the application of vulnerability scores (see, e.g., Chaudhary et al., 2015), which is also referred to as global extinction probabilities (see, e.g., Kuipers et al., 2019; Verones et al., 2022).

The two approaches have been used extensively to assess biodiversity impacts at the national and subnational levels and to inform biodiversity-related targets (see, e.g., Frischknecht et al., 2018; Kulionis et al., 2021; Rounsevell et al., 2020). However, their application by businesses remains in a very early stage. This is likely due to the lack of necessary data for conducting biodiversity assessments at the company level and the absence of regulatory disclosure requirements. Corporate environmental disclosures predominantly encompass GHG emissions data, with occasional inclusions of water and hazardous waste metrics. While GHG emissions' disclosures often include both upstream and, in some instances, downstream impacts, water and waste metrics predominantly address only direct impacts. However, land use as well as pollutant emissions, which are among the most important impact categories, are typically absent from these disclosures. Incomplete disclosure and omission of critical environmental inventories complicates the assessment of a company's biodiversity impact based on the disclosed data. Consequently, practitioners often resort to alternative methods, with environmentally extended input–output (EEIO) analysis being a commonly employed approach (see, e.g., Butz, et al., 2018; Popescu et al., 2023).

1.2.2 | Dependencies on ecosystem services

Biodiversity loss threatens the availability of ecosystem services that benefit the economy, such as animal pollination of food crops, natural water treatment, and fertile soil. While the economic consequences of biodiversity loss can be severe, quantifying them remains complex. Various estimates, albeit subject to uncertainty, indicate that the economic value of ecosystem services is significant (Johnson et al., 2021).

Costanza et al. (1997) estimated that the annual value of ecosystem services in 1995 amounted to US$33 trillion, global GDP at the time was about US$35 trillion. Later update by the same lead author found that the annual value of ecosystem services in 2007 amounted to US$125 trillion which was about 1.5 times global GDP (Costanza et al., 2014). A more recent study by World Economic Forum (WEF) indicates that more than half of the world's total GDP is moderately or highly dependent on nature and its services, exposing it to risks from nature loss (Herweijer et al., 2020). Industries highly dependent on nature contribute 15% to global GDP, while those moderately dependent account for 37%. Highly dependent industries either directly extract resources or rely on ecosystem services like clean water, healthy soils, pollination, and a stable climate. If nature's ability to provide these services decreases, these sectors could face significant losses and affect supply chain of other sectors not directly depending on the ecosystem services.

2 | METHODS

The overall procedure to estimate biodiversity impact and dependencies on ecosystem services is displayed in Figure 2. In Section 2.2.1, we demonstrate how to measure biodiversity impact (expressed in terms of global PDF) using environmentally extended multi-regional input–output (EEMRIO) and LC-IMPACT methodologies. Specifically, the LC-IMPACT methodology allows for spatially explicit assessment of extinction risk which is highly important when considering biodiversity loss on a global level (Verones et al., 2017) it also aligns with the UNEP-SETAC Life Cycle Initiative best practice recommendations (Jolliet et al., 2018). In Section 2.2.2 we outline a methodological approach to measure the dependencies on ecosystem services using EEMRIO and ENCORE databases.

2.1 | Data

We use release 057 of the GLORIA global EEMRIO database (Lenzen et al., 2022), constructed in the Global MRIO Lab (Lenzen et al., 2017). The GLORIA database features time series EEMRIO tables from 1990 to 2027. These tables cover 160 countries (including four "rest of the world" regions) and 120 sectors and offers satellite accounts for land, water, material use, and emissions (see Supporting Information S1 for details). Nitrogen and phosphorus data were not available in GLORIA and were taken from EXIOBASE version 3.8.2 (Stadler et al., 2018). The linking procedure is explained in the Supporting Information S1 LC_IMPACT_to_GLORIA sheet.

We used the "core," "average" characterization factors (CFs) from the LC-IMPACT database (Verones et al., 2020), see Table 1 for more details. The CFs are used to translate the water, land, and emission inventory results into PDF impact. Note that impacts occur in marine, freshwater, and terrestrial ecosystems and therefore could be divided by 3 to get an average PDF over all ecosystems (which we do not do). All CFs except climate change are available at the regional level. Regionalization can be highly relevant because environmental conditions vary greatly through space (e.g., water availability, land types, number and degree of endemism of species present, and background concentration of reacting agents). In the current model we do not include ecotoxicity impacts because the required environmental inventory is not covered in GLORIA database. Other database such as EXIOBASE includes several airborne emissions and pollutants but does not account for soilborne and waterborne emissions of organic and inorganic compounds (Leclerc et al., 2023). Furthermore the units within the LC-IMPACT method are not directly comparable (Sanyé-Mengual et al., 2023) which further complicates the integration of ecotoxicity impacts at this stage. We also do not account for ocean acidification nor impact of invasive species because CFs for these impact categories are not available in the LC-IMPACT database. The model could further be improved by incorporating research from recent work on marine biodiversity (Scherer et al., 2022) and invasive species (Borgelt et al., 2024; Hanafiah et al., 2013).

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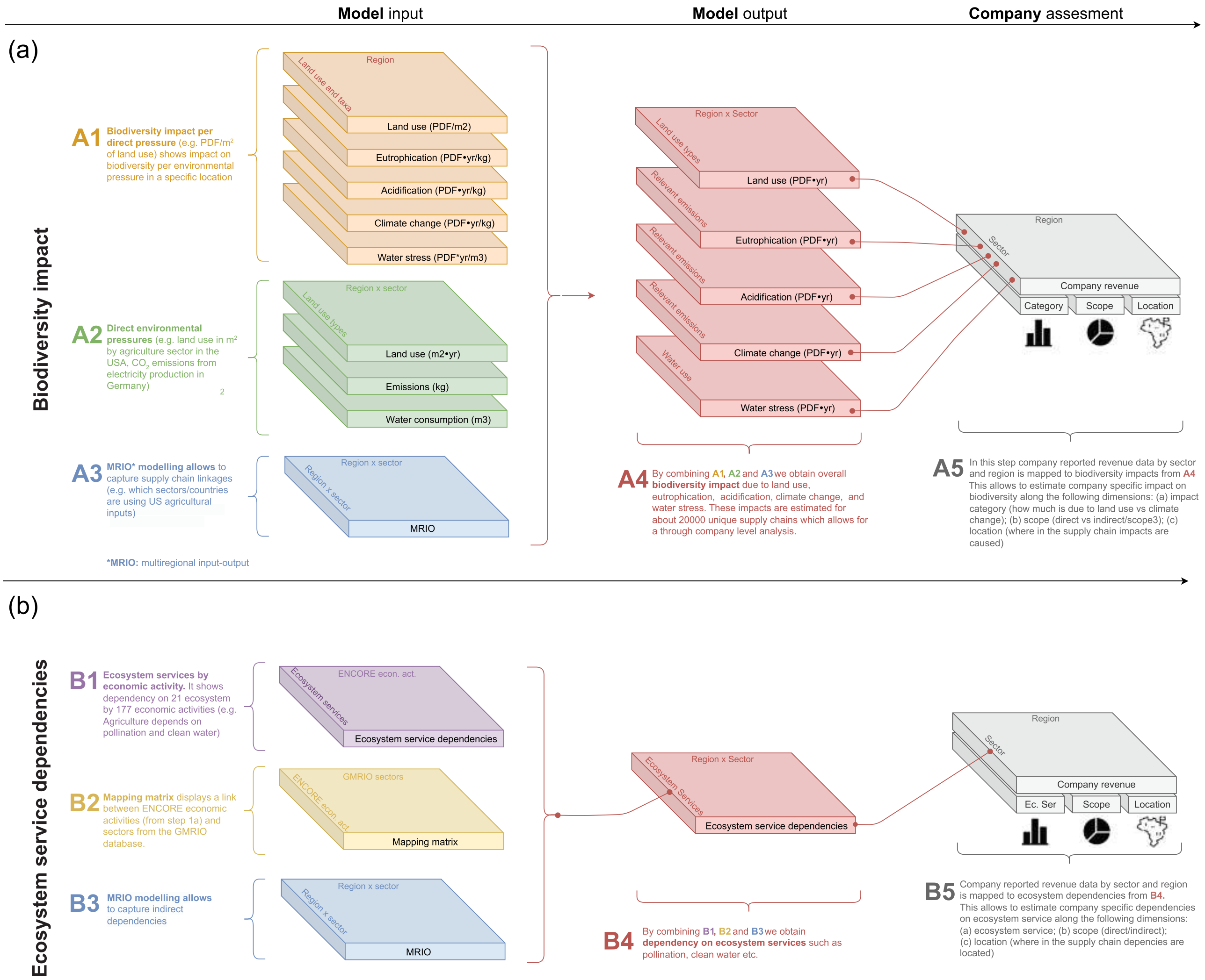


FIGURE 2 Implementation process for biodiversity impact (a) and ecosystem service dependencies (b).

TABLE 1 Environmental impact categories considered in this study.

Impact category	Version	Spatial scale	Pressures	Unit
Land use	Core	Regional	Land use	m^2. yr
Climate change	Core	Global	CO_2, CH_4, N_2O, SF_6, NF_3, HFCx	kg
Photochemical ozone formation	Core	Regional	Nox, NMVOC	kg
Terrestrial acidification	Core	Regional	Nox, NH_3, Sox	kg
Freshwater eutrophication	Core	Regional	P	kg
Water stress	Core	Regional	Water use	m^3
Ocean eutrophication	Core	Regional	N	kg

Note: Photochemical ozone formation is excluded from result figures as its impact was minimal. Ocean eutrophication and freshwater eutrophication are combined into one eutrophication category.

Dependencies on ecosystem services are taken from Exploring Natural Capital Opportunities, Risks and Exposure (ENCORE) database (ENCORE, 2023), which is designed to assist financial institutions in understanding and evaluating their exposure to natural capital risk. The database maps 177 economic activities to 21 ecosystem services (see Supporting Information S1 for details), illustrating dependencies on various services, such as pollination and clean water. To avoid double counting, ENCORE captures only direct dependencies, while indirect dependencies in the upstream supply chains are not included. To capture indirect dependencies, we apply an EEMRIO analysis.

To demonstrate how the methodology can be utilized by financial institutions, we assess the biodiversity impacts and dependencies on ecosystem services of the holdings within the MSCI ACWI stock index (MSCI, 2023). The MSCI ACWI is a stock index designed to track broad global equity market performance. It consists of about 3000 large- and mid-sized companies, from 23 developed markets and 24 emerging markets (countries).

2.2 | Methodology

2.2.1 | Biodiversity impact

Biodiversity impacts are estimated using EEMRIO (Leontief, 1936, 1970; Miller & Blair, 2009) analysis based on GLORIA database. The general version of the EEMRIO model applied in this study can be expressed as:

$$\mathbf{M} = \mathbf{S}(\mathbf{I} - \mathbf{A})^{-1} = \mathbf{S}L \tag{1}$$

where $\mathbf{A}$ is the technology matrix calculated by $\mathbf{Z}\hat{\mathbf{x}}^{-1}$ (the '^' symbol denotes diagonalization), $\mathbf{Z}$ is the intermediate demand, and $\mathbf{x}$ is the vector of total outputs. The $\mathbf{L}$ matrix represents total requirements (often known as the Leontief inverse, corresponds to Figure 2a3), $\mathbf{I}$ is the identity matrix, $\mathbf{M}$ gives total (direct + indirect) impacts per \$ of final demand and $\mathbf{S}$ is direct biodiversity intensity (that is biodiversity loss per \$). Matrix $\mathbf{S}$ is calculated as follow:

$$\mathbf{S} = (\mathbf{B} \circ \mathbf{F})\,\hat{\mathbf{x}}^{-1} \tag{2}$$

where $\mathbf{B}$ contains characterization factors showing impact on biodiversity per environmental pressures (e.g., PDF per m^2 of land use), this is shown in Figure 2a1. Matrix $\mathbf{F}$ contains relevant environmental pressures such as land use, CO_2 emissions, water use, and other relevant environmental pressures (shown in Figure 2a2). The "∘" symbol denotes element-wise multiplication which is used to capture spatially explicit pressures. The $\mathbf{S}$ and $\mathbf{M}$ are expressed as PDF·year per \$ of sales, giving sales or revenues as a functional unit.

To estimate company level impacts $\mathbf{S}$ and $\mathbf{M}$ matrices are multiplied with revenue data for individual companies as, $\mathbf{S}Y$ for direct impact and $\mathbf{M}Y$ for total impact (this step is depicted in Figure 2a5). Where $\mathbf{Y}$ contains revenue streams by sector and country for individual companies, it is constructed by using data on revenue streams by sector and region from FactSet (2024). Company revenue data can also be sourced from company reports, though compiling data for numerous companies for large-scale analysis may demand a substantial amount of work. The presented model applies gravel-to-gate perspective meaning that impacts the downstream phase from the use and end-of-life stages are not considered.

2.2.2 | Dependencies on ecosystem services

We begin with the $\mathbf{E}$ matrix which shows dependency of 177 economic activities on 21 ecosystem services (corresponds to Figure 2b1). The ENCORE database expresses dependency on a qualitative scale ranging from very low to very high. These dependencies are converted into following scores: 0 for no dependency, 0.2 for very low, 0.4 for low, 0.6 for medium, 0.8 for high, and 1 for very high dependency. Effectively this yields a matrix $\mathbf{E}$ with 21 rows and 177 columns that are filled with values from 0 to 1 where applicable. Next, we introduce a mapping matrix $\mathbf{C}$ which maps 177 economic activities from ENCORE database to 120 GLORIA sectors (corresponds to Figure 2b2 and see Supporting Information S1 for details). Combining $\mathbf{E}$ and $\mathbf{C}$ yields direct dependency for each sector from GLORIA database.

$$\mathbf{D}_{\text{direct}} = \mathbf{EC} \otimes \mathbf{i}_k \tag{3}$$

where $\mathbf{D}_{\text{direct}}$ shows direct dependency on 21 ecosystem services for 120 sectors and 164 countries, $\mathbf{i}_k$ is the vector of ones for k countries (= 164), and ⊗ is the Kronecker product. The $\mathbf{EC}$ part in Equation (3) gives direct dependency scores, $\otimes\,\mathbf{i}_k$ replicates these scores for k countries, which is needed to calculate indirect dependencies. Indirect dependencies are given by:

$$\mathbf{D}_{\text{indirect}} = \mathbf{D}_{\text{direct}}\left(\widehat{\mathbf{i}_{kn}(\mathbf{L} - \mathbf{I})}\right)^{-1}(\mathbf{L} - \mathbf{I}) \tag{4}$$

where $\mathbf{i}_{kn}$ is the summation vector consisting of ones for k countries and n sectors (= 120), $\mathbf{L}$ represents the Leontief inverse as defined in Section 2.2.1 and it corresponds to Figure 2a3. In Equation (4), direct dependencies are multiplied with the normalized Leontief inverse which shows shares of total inputs needed to produce one unit of output in each sector. Total dependencies are given by:

$$\mathbf{D}_{\text{total}} = \mathbf{D}_{\text{direct}} + \mathbf{D}_{\text{indirect}} \tag{5}$$

To estimate the dependencies of individual companies on ecosystem services, we adopt a similar approach to that explained in Section 2.2.1, multiplying the $\mathbf{D}_{\text{direct}}$ and $\mathbf{D}_{\text{total}}$ matrices by the regionalized revenue data $\mathbf{Y}$.

3 | RESULTS

As shown in Figure 2 the overall process leads to two set of outcomes: (i) model output at the sector level (Figure 2a4, b4), (ii) model output for individual companies (Figure 2a5,b5). We present the results for both.

3.1 | Model output

3.1.1 | Biodiversity impact

Impacts on biodiversity loss, categorized by individual impact types and scope, are illustrated in Figure 3 (underlying data are available in Supporting Information S2). To summarize the results, all impacts are grouped into broad International Standard Industrial Classification (ISIC) sector categories. The boxplot shows the variations in sectoral impacts across 164 countries. As evident from the figure, impacts can vary considerably between countries and among different sectors (note that the results are plotted on a log scale). This implies that production of the same good/service may have considerably different impact in different countries.

Figure 3 shows that direct impacts for land use (b) and eutrophication (c) occur only within a few selected sectors. This concentration suggests that most sectors in the economy do not significantly contribute directly to these specific environmental issues. Impacts for other sectors occur indirectly by using products from sectors with high direct impact. The prominence of direct impacts in a limited number of sectors underscores the possibility for targeted interventions in those specific sectors to address land use and eutrophication challenges effectively. It also indicates that for many sectors, environmental impacts occur mainly in the supply chain.

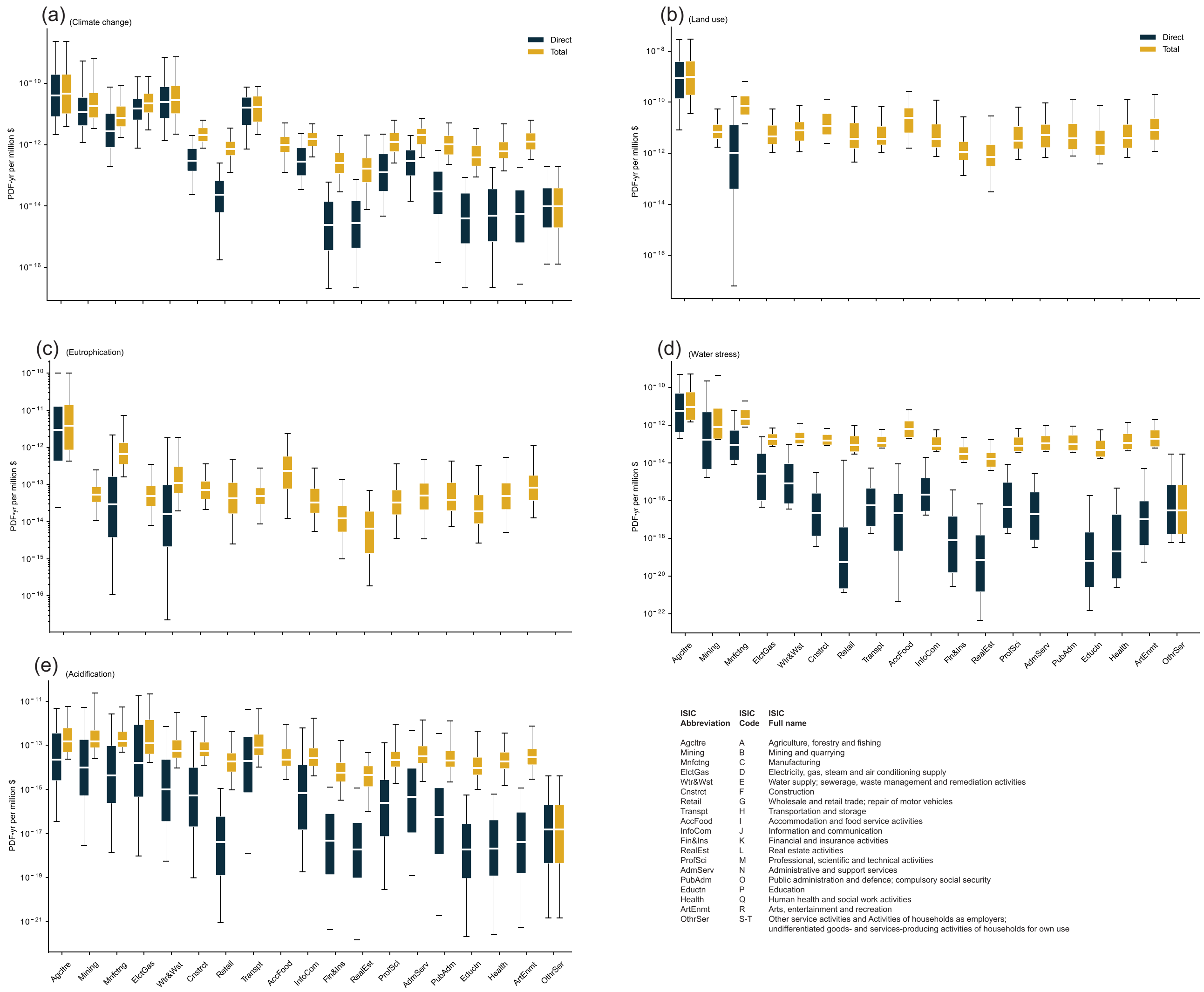
In contrast, for climate change (a), water stress (d), and acidification (e), direct impacts are distributed across a broader range of sectors. Notably, the total impact for primary sectors remains similar even after accounting for indirect impacts. However, for sectors in the middle and downstream chain, the disparity between direct and total impacts is significant. This can be attributed to the fact that primary sectors typically have simpler value chains and do not heavily depend on major upstream inputs. In contrast, sectors further down the value chain tend to have more complex supply chains and rely more on upstream inputs.

It is worth noting that the variation in direct impacts across countries seems to be more pronounced than that of the total impacts. This discrepancy likely arises because certain sectors in some countries operate more efficiently (have lower direct impact per $) than others. However, as value chains span over multiple countries, these impacts tend to converge toward similar levels for the total impacts.

3.1.2 | Ecosystem dependencies

Figure 4 (underlying data are available in Supporting Information S2) displays direct (Figure 4a) and total (Figure 4b) dependencies on ecosystem services. All sectors are assumed to have the same direct dependency regardless of the region. Each cell in the chart indicates the degree of dependency of a specific sector on a given ecosystem service. We have grouped the results into ISIC categories for practical reasons, but it comes at a cost of reduced granularity and sometimes may lead to distorted results. For example, the *Mnfctng* category combines many different sectors that may have different dependencies on ecosystem services, for instance, manufacture of pharmaceuticals and medicinal products will have a different profile from manufacture of machinery and equipment products. For a disaggregated version of the results see Supporting Information S2.

Total dependencies differ across regions because individual sectors may have different supply chain linkages and thus depend differently on ecosystem services. This difference is visible in Figure 4c. Sectors such as education, information, and communication services have no direct dependencies (Figure 4a) but depend on multiple ecosystem services indirectly (Figure 4b).



ISIC Abbreviation	ISIC Code	ISIC Full name
Agcltre	A	Agriculture, forestry and fishing
Mining	B	Mining and quarrying
Mnfctng	C	Manufacturing
ElctGas	D	Electricity, gas, steam and air conditioning supply
Wtr&Wst	E	Water supply; sewerage, waste management and remediation activities
Cnstrct	F	Construction
Retail	G	Wholesale and retail trade; repair of motor vehicles
Transpt	H	Transportation and storage
AccFood	I	Accommodation and food service activities
InfoCom	J	Information and communication
Fin&Ins	K	Financial and insurance activities
RealEst	L	Real estate activities
ProfSci	M	Professional, scientific and technical activities
AdmServ	N	Administrative and support services
PubAdm	O	Public administration and defence; compulsory social security
Eductn	P	Education
Health	Q	Human health and social work activities
ArtEnmt	R	Arts, entertainment and recreation
OthrSer	S-T	Other service activities and Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use

FIGURE 3 Biodiversity impact by sector and impact category: climate change (a), land use (b), eutrophication (c), water stress (d), acidification (e) and scope (direct vs. total). This shows the results of the step presented in Figure 2a4. The underlying data for this figure can be found in Supporting Information S2.

Ground water, *mass stabilization, and erosion control*, and *flood and storm protection* stand out due to their widespread importance across sectors. Notably, sectors like agriculture, mining, and manufacturing exhibit a strong reliance on this these ecosystem services. It plays an important role in diverse activities, from providing water for irrigation in agriculture to facilitating cooling processes in manufacturing.

3.2 | Company level assessment

To evaluate overall impacts of the ACWI index, we first calculate impacts for about 3000 individual companies and then aggregate the results based on their weights in the index. The results are displayed in Figure 5 (underlying data for this figure are available in Supporting Information S2). The results for individual companies are visible in Figure 5d.

As shown in Figure 5a the *Land Use* category accounts for the largest percentage of the overall impact. Following *land use*, the *water stress* category is the next most significant. This indicates growing issues with limited water availability and its effects on nearby ecosystems and their biodiversity. *Climate change* ranks as the third most important impact category, contributing approximately 10% to the ACWI index's overall impact. Meanwhile the *eutrophication* and *acidification* impact categories account for smaller portions.

When analyzing the geographic distribution of biodiversity impact on the ACWI index, the Americas emerge as the primary contributor. This is possibly due to the concentration of activity in the United States, as 62% of the listed companies have their headquarters there, but also because Latin America has a large agricultural production. Asia is the next major contributor. Despite representing only about 6% of the index, its impact is

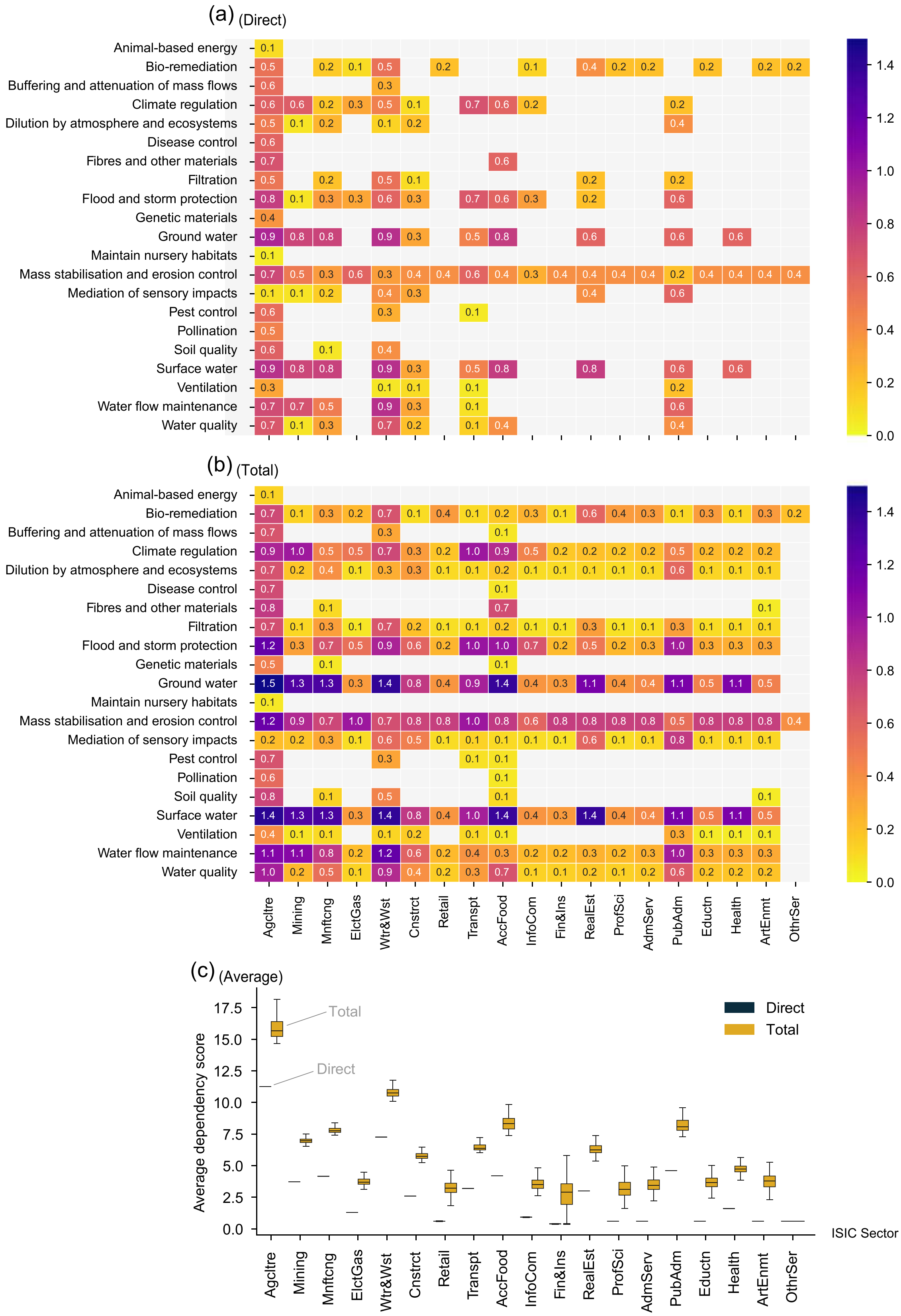


FIGURE 4 Sectoral dependencies on ecosystem services. Panel A: Direct dependencies on ecosystem services. Panel B: Total (direct + indirect) dependencies on ecosystem services. Panel C: Average dependency scores across countries and sectors. These results correspond to the step presented in Figure 2b4. The underlying data for this figure can be found in Supporting Information S2.

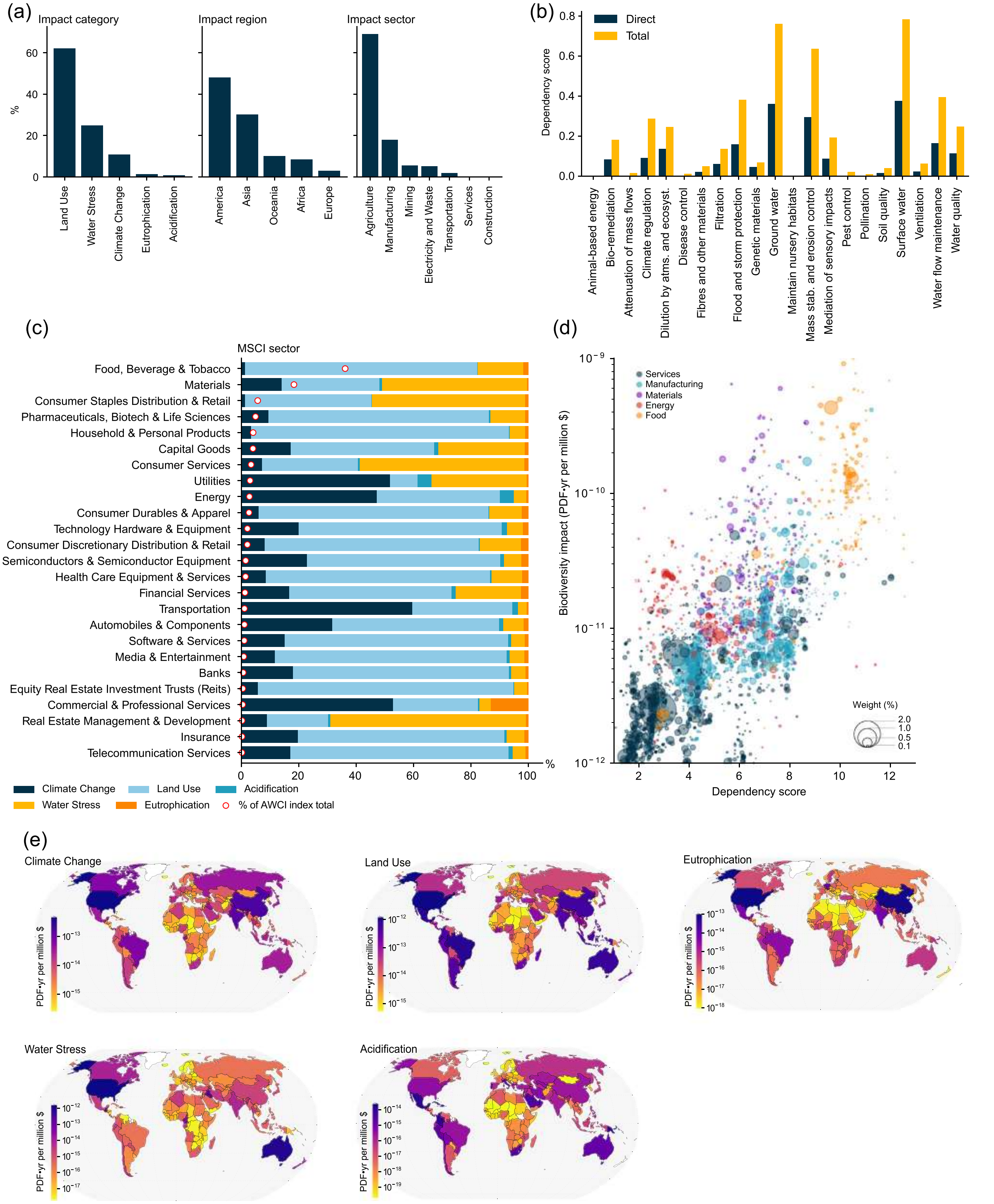


FIGURE 5 MSCI ACWI index dashboard. (a) Aggregate impacts for the index by impact category, region and sector. (b) Direct and total dependencies on ecosystem services. (c) Biodiversity impact results for broad sector groups. (d) Double materiality for individual stocks. (e) Detailed view of impact by region. This figure displays the results of the steps presented in Figure 2a5,b5. The underlying data for this figure can be found in Supporting Information S2.

substantial. This could be due to either less efficient resource use in the region or the presence of more diverse and vulnerable ecosystems, but also due to supply of the products in the primary sector to companies in other regions. When looking at which industries affect biodiversity the most, *agriculture* stands out. This is because farming uses a lot of land, water, and fertilizers that can harm the environment. *Manufacturing* is the second biggest contributor potentially due to resource-intensive processes, and pollution, associated with manufacturing activities.

Figure 5b illustrates the direct and total dependencies of the ACWI index on ecosystem services. The gap between direct and total dependency scores highlights the complex and interconnected nature of the economy, indicating that changes in one part of the economy or an ecosystem service might lead to cascading effects because of the indirect dependencies. For a more detailed breakdown of ecosystem service dependency scores, see Supporting Information S2.

Figure 5c demonstrates that different MSCI sectors have distinct environmental impact profiles. While certain sectors display a pronounced influence in specific impact categories, others present a more diversified impact across multiple areas. The dots provide insight into the relative magnitude of each sector's cumulative environmental impact. Notably, the "*Food, Beverage & Tobacco*" sector, together with the "*Materials*" sector, account for the largest contribution to the overall index impact.

Figure 5d aims to visualize the concept of "double materiality," which represents a sector's environmental impact versus its dependency on ecosystem services. The most important area to observe is the high impact, high dependency quadrant (top right of the figure). Sectors in this quadrant significantly impact the environment while being heavily dependent on it. This poses a risk, as further damage to the environment could adversely affect their operations and thus is an incentive to mitigate the impacts.

Other quadrants capture various combinations of impact and dependency. For example, sectors with low impact but high dependency might prioritize advocating for widespread environmental protection. Conversely, those with a high impact but low dependency should focus on minimizing their environmental footprint. Overall, the double materiality figure offers a nuanced view of the interplay between sectoral impacts on and dependencies upon the environment.

Figure 5e depicts the distribution of biodiversity impact across different regions, helping to identify potential biodiversity hotspots. As an illustration, a car sold in the United States might depend on various parts sourced globally, and the production of these parts can have diverse environmental impacts depending on where they are manufactured. The overall impact is typically influenced by two factors: the overall activity in the region (e.g., the extent of land or water use) and the specific impact on biodiversity in that region (e.g., using the same amount of water in the Middle East might affect biodiversity differently than in Northern Europe). In some cases, even minimal activity can lead to significant biodiversity loss. For example, we can observe that land use in Madagascar has a relatively high impact. Although the overall land use in Madagascar by companies in the ACWI index is relatively small, the impact per km^2 of land use is considerable due to the high number of endemic species in the region.

4 | DISCUSSION

In this study we demonstrate how EEMRIO and LCA techniques from the industrial ecology field can be used to assess biodiversity loss and assist in financial decision-making. While new tools are emerging to assess biodiversity loss, the EEMRIO and LCA methodologies offer several distinct benefits. These approaches have been available for several decades and have evolved with continuous enhancement of methods and data, so there is extensive scientific literature addressing various aspects of this topic (Hellweg et al., 2023). Additionally, many practitioners are already familiar with the EEMRIO/LCA methodologies from their use in GHG accounting, making their adaptation for biodiversity loss relatively straightforward. In finance, EEMRIO/LCA techniques can be used for screening investments, identifying engagement areas to mitigate risks, and monitoring the performance of portfolios over time. However, while these approaches constitute a powerful decision-making tool it is important to acknowledge that they may suffer from simplifications and uncertainties (Hellweg & Milà i Canals, 2014). Ideally to overcome these issues, they should be combined and enhanced with other biodiversity assessment options and company specific information.

Biodiversity impacts presented in this paper are based on a spatially explicit modeling approach which considers the fact that the same activity in different places might have different impact on biodiversity because of different species richness and vulnerability (Verones et al., 2020). This approach has been recommended by the UNEP-SETAC Life Cycle Initiative to assess biodiversity impacts of land use (Jolliet et al., 2018), and to the best of our knowledge this is a first attempt to apply it in the financial setting.

Results at the industry level demonstrate high variability between sectors and between countries. This implies that companies operating in similar sectors in different countries might have very different impacts and also different levels of physical risk which may arise from stronger dependency on ecosystem services in some regions. Land use stands out as the most impactful category, followed by climate change and water stress. This is broadly in line with previously reported findings by Koslowski et al. (2020).

The ACWI index results show that America has the highest impact, followed by Asia, while Europe has the lowest. Even though Asia represents only about 6% of the index's country weight (meaning only 6% of companies are registered there), it has a significant effect on the index. Several factors contribute to this. First, the model considers global supply chain interlinkages, thus a product sold in America might have components manufactured in different countries, impacting biodiversity in those regions. In a world with fragmented supply chains that span multiple countries, the ability to track impacts from the point of sale to the point of production is important. Another reason is that the impact a company causes can differ based on location. For example, using water in drier places typically leads to worse impacts on biodiversity. Thus, the same product can have different impacts depending on where it is made, and regions with more diverse and vulnerable ecosystems are likely to experience higher impacts. Given that these differences can be substantial it is important to take these aspects into account either by prioritizing companies with lower impacts or by working with companies to ensure that adequate practices are in place to minimize the impact. Overall this variation implies that mitigation strategies should be tailored to the specific challenges inherent to each industry.

The concept of double materiality displayed in Figure 5d aims to address both the influence a company exerts on biodiversity and the implications of biodiversity loss for the company through its dependency on ecosystem services. Compared to the primary and material sectors, services and manufacturing sectors display lower double materiality. Companies in the primary and material sectors tend to perform worse, which is anticipated given their closer ties to nature. Double materiality offers a risk profile for individual companies. It is important to note that high materiality does not automatically suggest avoiding such companies, nor does low materiality indicate they should be favored. While these risks cannot be completely eliminated, once identified, they can be addressed.

Knowing the geographic location of companies might improve estimates; however, such enhancements are likely to be marginal and affect mainly companies operating in the primary sectors. This is because production processes are highly fragmented, with each company focusing on a specific segment of the entire value chain (Baldwin & Lopez-Gonzalez, 2015). For example, a car manufacturer typically concentrates on car assembly rather than component production. Components like cables, tires, and other parts, which account for a significant portion of impact, are usually produced by other firms in the supply chain. Thus, knowing where the car is assembled does not significantly improve the assessment since the bulk of the impact associated with car production often falls outside the company's direct operations and is often concentrated in the few primary sectors. The further downstream a company is in the value chain, the less likely its location matters for impact estimation. This is visible in Figure 3d where only a few primary sectors are responsible for most of the direct impact, while sectors further downstream have no direct impact, and their impact occurs indirectly. While knowing the location of a company's operations is important, understanding their supply chain linkages is arguably even more crucial. This is important because most of the companies in the investable universe are operating in secondary and tertiary sectors (MSCI, 2023).

4.1 | Limitations

The methodology outlined in this study offers investors a broad perspective on biodiversity risks linked to their investments, however, it does not encompass the measures companies implement to tackle their biodiversity issues. In addition, several aspects that are known to have biodiversity impact have not been taken into account. For instance, IPBES lists invasive alien species as one of the important drivers for biodiversity loss (IPBES, 2019). However, these are generally not taken into account in LCA modeling (Crenna et al., 2020). Furthermore, we do not include ecotoxicity impacts because the required emission inventory is not available in the GLORIA database, and we do not account for ocean acidification because CFs are not available in the LC-IMPACT database.

One of the key limitations of using EEMRIO analysis is that it assumes the same technology and environmental impacts across companies operating in the same sector (Popescu et al., 2023). This implies that, under identical revenue streams, companies would have the same impact per dollar of sales. However, in practice, one company may employ more efficient processes or use different energy from different sources than the sector average. That said, companies usually have multiple revenue streams from different economic activities in different countries. Combining this information together often yields unique company profiles that are different from sector averages.

4.2 | Future research

A biodiversity impact assessment aims to capture the negative environmental impacts an organization has on the environment. However, biodiversity metrics might be insufficient to identify companies that contribute the most to reversing biodiversity loss and, in some cases, may lead to misleading signals. Kander et al. (2015) argues that to capture full impact of a product one must consider not only how a certain product/service was produced, but also what alternative production it replaces. These types of impacts are commonly referred to as "avoided impacts," "handprint," and/or "enabling effects." Measuring these "net impacts" is inherently complex and there are no defined standards. Given this general lack of knowledge and standards, it is important to develop a practical approach to estimate net impacts in future research. The work on GHG emissions by Kander et al. (2015) and Russell (2019) could provide valuable insights for the development of net impact measures for biodiversity.

The model outlined in this study can be further enhanced by incorporating additional impact categories and refining the existing ones. Scherer et al. (2023) introduced land use CFs that combine the benefits of two recent advancements in the field: the consideration of land use intensities and land fragmentation. These newly published CFs can be utilized to update the land use CFs currently available from LC-IMPACT.

The issue of invasive alien species, identified by IPBES (2019) as a driver of biodiversity loss, has been underexplored in LCA domain. Until very recently, only one case study had explored the introduction of alien species into freshwater systems (Hanafiah et al., 2013). To bridge this research gap, Borgelt et al. (2024) developed country-specific CFs that quantify the global or regional PDF due to alien species introductions per unit of goods transported between two countries. The CFs published by Borgelt et al. (2024) provide a good starting point for integrating invasive species within the EEMRIO/LCA domain.

Ecotoxicity can significantly contribute to overall biodiversity impacts in some LCA methods, as shown in a study on EU consumption (Sanyé-Mengual et al., 2023). We have not considered ecotoxicity impacts due to the absence of the required environmental inventory in the GLORIA database, this is the case for most other MRIO databases as well. Recently, Leclerc et al. (2023) proposed an integrative approach to assess toxicity impacts by combining multiple databases, inventory methods, and gap-filling/extrapolation techniques. This work can serve as a good basis for the comprehensive integration of toxicity impacts within the EEMRIO/LCA domain.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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