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Methodological insights into Biodiversity Impact Assessment and the *Nexus*-by-design approach in the European Green Deal

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Abstract

Biodiversity loss is a pressing challenge for developing a sustainable economy, yet this still represents a very low priority in corporate surveys. This study explores the emerging field of Biodiversity Management, proposing a comprehensive framework for managers to understand the reciprocal influence among businesses and biodiversity. A theoretical guideline grounded in Supply Chain practices enriches the understanding of effective biodiversity management. The work critically reviews Biodiversity Impact Assessment methods within the Life Cycle Assessment (LCA) context, identifying gaps, strengths and recommending improvements.

The omics revolution, spanning genomics, transcriptomics, proteomics, metabolomics and meta-omics, is proposed as a powerful tool for biodiversity impact assessment and conservation. Despite limitations, integrating omics tools into global biodiversity is deemed essential for effective policy and practice, explicating the interconnected nature of human and ecosystem health – One Health. Bold policy interventions are deemed necessary, with scrutiny on the Nexus-by-design approach in the European Green Deal (EGD), investigating its interconnections with climate change, biodiversity and circular economy policies. This work contributes to biodiversity management and corporate sustainability by underscoring the urgency for integrated biodiversity management, interdisciplinary collaborations and transformative policies to address the coupled climate and biodiversity crises and their societal impacts.

Key words: Biodiversity, Impact Assessment, Management, Circular Economy, Green Deal.

1 Introduction

1.1 Biodiversity, explained

1.1.1 What is Biodiversity?

"The variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species, and of ecosystems (United Nations, 2013)".

A prevailing viewpoint among scientists asserts that the evaluation and analysis of biodiversity ought to be conducted across three interrelated hierarchical tiers:

- **Genetic Diversity**: the overall diversity in the DNA between the individuals of a species. It is the foundation level, providing adaptive capacity and resilience to extinction when changes in (a)biotic conditions occur (Leigh et al., 2019).
- **Species Diversity**: it encompasses the number of different species in a particular area and their relative abundance – the former is referred to as *species richness,* the latter is known as *species evenness*. The area in question could be a habitat, a biome, or the entire biosphere (Ha and Schleiger, 2020). Healthy ecosystems contain a diversity of

species, each playing a role in Ecosystem Function[1]; therefore, species diversity as well as ecosystem diversity are essential to maintaining Ecosystem Services (ES)[2].

- **Ecosystem Diversity**: it is the variety of habitats, the communities found in a geographic location, the beneficial services they provide, and the processes that support the ecosystem. Earth is composed of terrestrial and aquatic environments. There are six main types of ecosystems: *forests, grasslands, tundras* and *deserts* are found on land; *freshwater* and *marine* ecosystems are found in the earth's waters. Each ecosystem is connected to the other because certain biotic and abiotic factors can move between ecosystems, like nutrients, organisms, water, and air. As a result, changes to one ecosystem can lead to changes in another (New England Primate Conservancy, 2023).

The three layers of diversity exhibit an inseparable and symbiotic relationship: genetic diversity serves as the fundamental basis for species diversity, thereby facilitating the emergence of ecosystem diversity. In turn,

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[1] Ecosystem Function is the capacity of natural processes and components to provide goods and services that satisfy human needs, either directly or indirectly (de Groot et al., 2002).

[2] Ecosystem Services are the benefits people obtain from ecosystems. These include *provisioning*, *regulating*, and *cultural* services that directly affect people and *supporting* services needed to maintain the other services (Millennium Ecosystem Assessment (MA), 2005).

the latter creates favourable conditions for the persistence of both species and genetic diversity. (Panwar et al., 2023).

Enterprises operating across a variety of sectors directly contribute to the **drivers** of biodiversity loss, namely: land use change, climate change, pollution, overexploitation and introduction of invasive species (Armenteras et al., 2012). Figure 1 schematically represents this conceptual framework (Panwar et al., 2023).

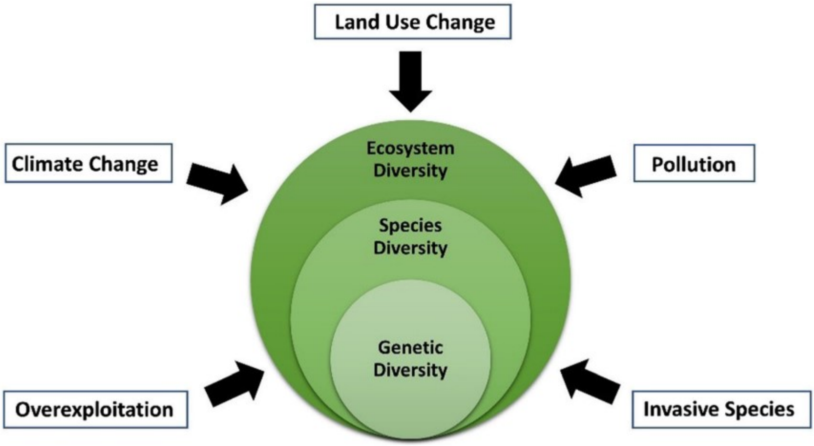

Figure 1 The three tiers of Biodiversity and the main challenges

Driving forces determinants of such decline are encompassed by broader **global mega trends**: excessive resource consumption, escalating standards of living, population expansion and unsustainable patterns of production and consumption. (Crist et al., 2017; IPBES, 2019).

While the discourse on biodiversity loss primarily centres on the loss of species, the concurrent decline in genetic diversity warrants attention. Human population expansion and extensive resource utilization have precipitated habitat reduction, leading to the fragmentation and diminishment of wild populations worldwide (Minter et al., 2021). This phenomenon has culminated in a discernible **global decline in genetic diversity**, estimated at up to **6%** since the advent of the Industrial Revolution (Leigh et al., 2019).

1.1.2 Relating Biodiversity with Ecosystem Services

Biodiversity strongly influences the provision of ES and therefore human well-being (Diaz et al., 2015; Minter et al., 2021).

Ecosystem processes frequently affected by global changes include pollination, seed dispersal, climate regulation, carbon sequestration, agricultural pest and disease control, and human health regulation. Furthermore, by affecting ecosystem processes such as primary production, nutrient and water cycling, soil formation and retention, biodiversity indirectly supports the production of food, fibres, potable water, shelter, and medicines (*see Fig. 2: dotted lines relating Global Changes to: (i) Ecosystem Processes; (ii) Biodiversity and (iii) Ecosystem Services*).

Global change drivers that indirectly affect biodiversity, further affect biodiversity-dependent ecosystem processes and services. Among these global change drivers, a major threat to biodiversity-dependent human wellbeing is large-scale land use change, especially the intensification and extensification associated with large-scale industrial agriculture (high certainty). This threat is most obvious for those human groups that are already vulnerable because their livelihoods rely strongly on the use of natural and seminatural ecosystems. These include subsistence farmers, the rural poor, and traditional societies (Diaz et al., 2015).

Species composition (a component of *Biodiversity box, in Fig. 2*) is often more important than the number of species in affecting ecosystem processes. Thus, conserving or restoring the composition of communities, rather than simply maximizing species numbers, is critical to maintaining **ecosystem services**. Notably, changes in species composition can occur directly by species introductions or removals, or indirectly by altered resource supply due to abiotic drivers (such as climate) or human drivers (such as irrigation, eutrophication, or pesticides).

In the ecological discourse, **functional traits** are defined as "morphological, biochemical, physiological, structural, phenological, or behavioural characteristics that are expressed in phenotypes of individual organisms and are considered relevant to the response of such organisms to the environment and/or their effects on ecosystem properties (Violle et al., 2007)". It is precisely the set of functional traits of species that determine their contribution in providing ecosystem services. That also justifies the central position assumed by functional traits in *Figure 2* (Diaz et al., 2015).

The **redundancy** among functionally homologous species, wherein one may partially replace another, is juxtaposed against the distinctive contributions of key species that uniquely influence and measurably impact ecosystem function (i.e.: **singularity**). The loss or gain of such species introduces a context-dependent, **idiosyncratic** and unpredictable dimension to the overall impact on ecosystem services that species render (Dal Grande, 2023), ultimately affecting human well-being (Diaz et al., 2015).

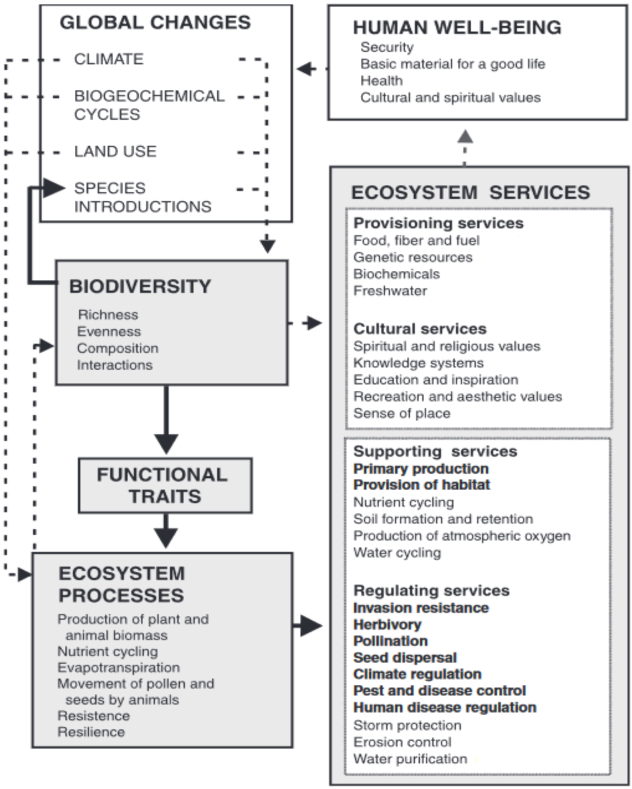

Figure 2 Biodiversity as a response variable

1.1.3 The contemporary Biodiversity Crisis

Intended or accidental changes in the composition of ecological communities can lead to disproportionately large, irreversible, and often negative alterations of ecosystem processes, causing large monetary and cultural losses (Diaz et al., 2015).

Numerous investigations have provided ample documentation of the continuous deterioration of the world's natural environment; this has been foremost highlighted in the recent discussion surrounding the concept of **Planetary Boundaries** (Richardson et al., 2023). The authors present a set of nine boundaries within which humanity can continue to develop and thrive for generations to come, namely: *(i) Novel entities; (ii) Stratospheric ozone depletion; (iii) Atmospheric aerosol loading; (iv) Ocean acidification; (v) Biogeochemical flows; (vi) Freshwater change; (vii) Land-system change; (viii) Biosphere integrity and (iv) Climate change.*
Richardson et al., (2023) reveal that six out of the nine have been transgressed, as illustrated in *Figure 3*.

Said boundaries represent interconnected processes within the intricate biophysical system of Earth. Therefore, addressing global sustainability necessitates more than solely focusing on climate change. Instead, comprehending the intricate interplay among various boundaries, including climate and biodiversity loss, is imperative both in scientific research and practical application.

Exceeding these boundaries heightens the likelihood of triggering significant and potentially irreversible environmental alterations on a large scale. While such changes may not manifest immediately, collectively, these boundaries signify a crucial threshold, amplifying risks to both human populations and the ecosystems we inhabit.

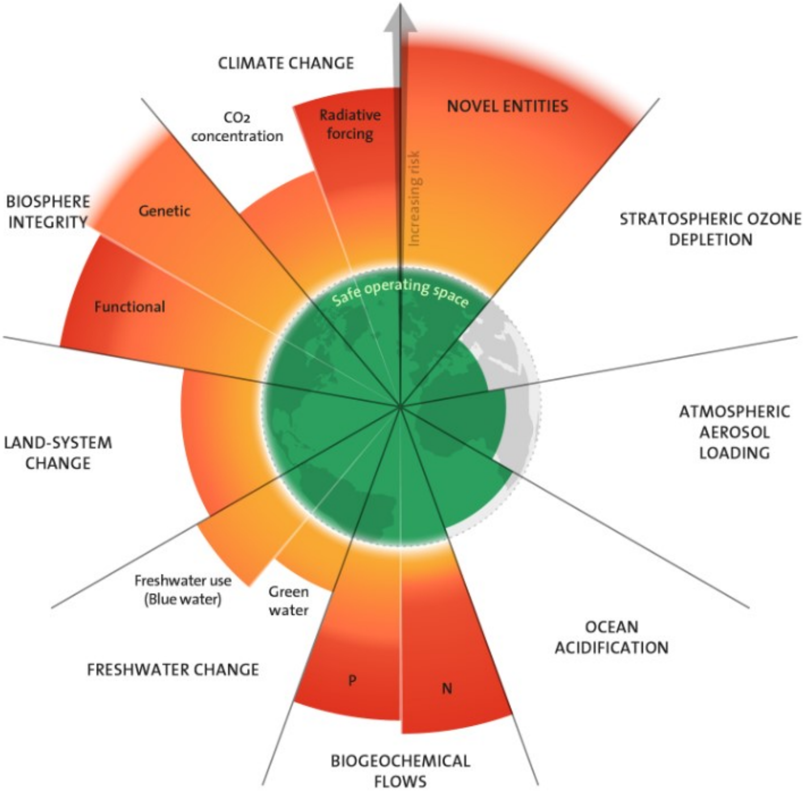

Figure 3 Earth is beyond six out of nine planetary boundaries

The two core dimensions of the planetary boundary *Biosphere integrity* are Genetic Diversity and Planetary Function – noteworthy, "integrity" does not imply an absence of biosphere change, rather a change that preserves the overall dynamic and adaptive character of the biosphere. Each dimension is measured through suitable proxies.

Genetic diversity is assessed via the maximum extinction rate compatible with preserving the genetic basis of the biosphere's ecological complexity (with boundary level of **< 10 E/MSY**, **extinctions per million species-years**); of an estimated 8 million plant and animal species, around 1 million are threatened with extinction, and over 10% of genetic diversity of plants and animals may have been lost over the past 150 years. Thus, the genetic component of the biosphere integrity boundary is markedly exceeded (Richardson et al., 2023).

The **Net Primary Production** (**NPP**) is a computable metric for photosynthetic energy and materials flow into the biosphere. The functional component of the biosphere integrity boundary is therefore defined as "a limit to the **Human Appropriation of the biosphere's NPP** (**HANPP**) as a fraction of its Holocene NPP" (Richardson et al., 2023). The authors determined the terrestrial biosphere's Holocene NPP to have been 55.9 Gt of C year^{-1} (2σ), varying by not more than ±1.1 Gt of C year^{-1}. Their model suggest that NPP still had a Holocene-like level in 1700 (56.2 Gt of C year^{-1} for *potential natural vegetation* and 54.7 Gt of C year^{-1} when *land use* is taken into account). By 2020, potential natural NPP would have risen to 71.4 Gt of C year^{-1} because of carbon fertilization, a disequilibrium response of terrestrial plant physiology to anthropogenically increasing CO_2 concentration in the atmosphere, whereas actual NPP was 65.8 Gt of C year^{-1} due to the NPP-reducing effects of global land-use.

HANPP designates both the harvesting and the elimination or alteration (mostly reduction) of potential natural NPP, mainly through agriculture, silviculture, and grazing. Terrestrial HANPP can be estimated both as a fraction of potential natural NPP (15.7% in 1950 and 23.5% in 2020) and of Holocene mean NPP (30% or 16.8 Gt of C year^{-1} in 2020). Richardson et al.,

(2023) argue that an NPP-based planetary boundary limiting HANPP should be set in relation to **preindustrial Holocene mean NPP** and not the current potential natural NPP. This is because the global increase in NPP due to anthropogenic carbon fertilization constitutes a resilience response of Earth system that dampens the magnitude of anthropogenic warming. Hence, the NPP contribution to a carbon sink associated with CO_2 fertilization should be protected and sustained rather than considered as being available for harvesting.

The contemporary era has witnessed a pronounced escalation in rates of species extinction, markedly evident over the preceding two centuries, coinciding with the ascendancy of industrial society. These current rates substantially surpass background extinction levels, underscoring a notable departure from historical ecological norms (*see Fig. 4 and Fig. 5:* Ceballos et al., 2015).

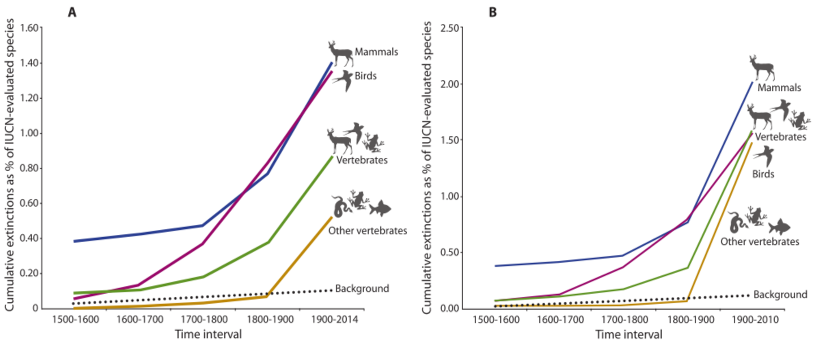

Figure 4 Cumulative vertebrate species recorded as extinct or extinct in the wild by the International Union for Conservation of Nature (IUCN, 2012)

Graphs show the percentage of the number of species evaluated among mammals (5513; 100% of those described), birds (10,425; 100%), reptiles (4414; 44%), amphibians (6414; 88%), fishes (12,457; 38%), and all vertebrates combined (39,223; 59%). Dashed black curve represents the number of extinctions expected under a constant standard background rate of 2 E/MSY, i.e.: two mammal extinctions per 10,000 species per 100 years. (A) Highly conservative estimate. (B) Conservative estimate.

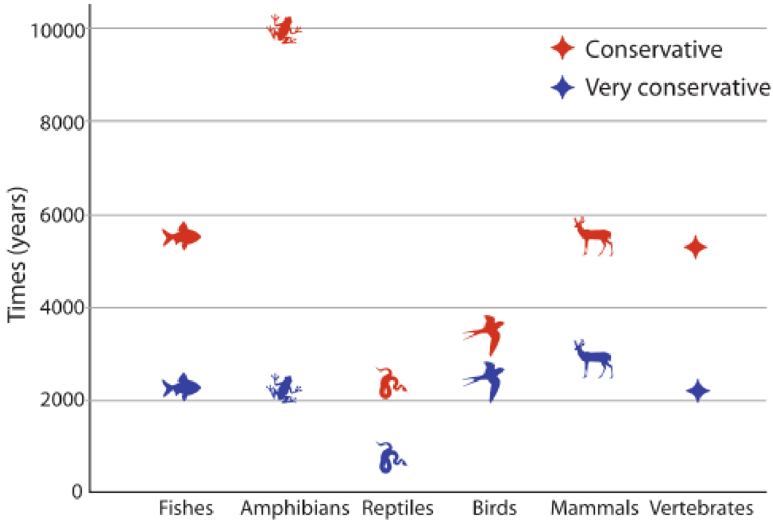

Figure 5 Number of years that would have been required for the observed vertebrate species extinctions in the last 114 years to occur under a background rate of 2 E/MSY

Red markers represent the highly conservative scenario; blue markers, the conservative one. Note that for all vertebrates, the observed extinctions would have taken between 800 to 10,000 years to disappear, assuming a standard background rate of 2 E/MSY. Different classes of vertebrates all show qualitatively similar trends.

Ceballos' (2015) analysis reveals that, even in cases where: (i) the background rate is assumed to be twice as high as earlier estimates and (ii) the data on recent vertebrate extinctions are handled as conservatively as possible, current extinction rates still significantly exceed natural average background rates.

The alarming decrease of biological diversity has the potential to exacerbate the impacts of climate change, threaten world food security, increase health risks, undermine the sociocultural integrity and survival of many rural and Indigenous communities. Moreover, this reduction carries considerable **economic consequences**, as biodiversity provides a foundation for numerous sectors and represents a source of occupational opportunities for billions of people (Gibassier et al., 2019; Panwar et al., 2023), posing a significant impediment to the attainment of virtually every **United Nations Sustainable Development Goals** (**UN SDGs**) (IPBES, 2019; Schaltegger et al., 2023).

With the onset of the **sixth mass extinction** currently underway, the timeframe for implementing effective measures is exceedingly limited, likely spanning only two or three decades at most (Ceballos et al., 2017, 2015).

1.1.4 The Double Materiality

Biodiversity loss has been identified as **the third most pressing risk** for the global economy and numerous countries in the next decade (WEF, 2022). **Half of the global economy** is at risk due to biodiversity decline, an unprecedented systemic portfolio risk for investors, with **$44 trillion** of economic value generation being moderately or highly dependent on nature and the services it provides (WEF, 2022).

The issue of biodiversity loss holds pertinence for all enterprises, with particular salience for those extensively utilizing land or marine territory, exhibiting pronounced dependence on natural resources or generating substantial emissions (Salmi et al., 2023).

The necessity of adopting a dual perspective in the context of adhering to planetary biodiversity boundaries has been brought to the fore as the basis for sustainability disclosures (*ESRS E4:* see EFRAG, 2022). This imperative entails conducting a thorough examination of both the influence exerted by biodiversity on corporations and the reciprocal impact of corporations on biodiversity, commonly referred to as "**Double Materiality**" (*Fig. 6,* Schaltegger et al., 2023).

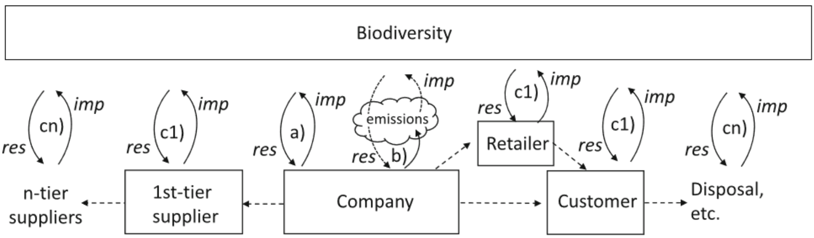

Figure 6 The Double Materiality is often indirect

Arrows (**a**) in Figure 6 represent direct links for *biodiversity resource consumption* (*res.*) and *impacts* (*imp.*) *on biodiversity*; **arrows** (**b**) stand for emission causing indirect impacts on biodiversity and biodiversity resources being impacted by emissions; **arrows** (**c1**) indirectly link a focal company with biodiversity, representing intermediate actors (e.g.: suppliers and customers); **arrows (cn)** regard far apart entities (e.g.: disposal firms, sub-contractors).

Owing to the often intricate and indirect nature characterizing the interface between companies and biodiversity, a systematic approach is required for its effective accounting and management. Said framework necessitates a comprehensive evaluation across diverse dimensions, encompassing aspects such as products, emissions and waste. Further, it mandates a consideration of impacts originating from both direct stakeholders (e.g.: customers) and indirect stakeholders situated within the intricate framework of the supply chain (Schaltegger et al., 2023).

Businesses possess noteworthy potential to mitigate both adverse and positive environmental impacts, via the adoption of sustainable and more biodiversity-centric business models and through the management of their supply chains (Salmi et al., 2023).

1.2 Barriers towards Biodiversity Management

In light of the alarming mass extinction that is currently taking place (Ceballos et al., 2017, 2015; De Vos et al., 2015), guidance on the appropriate management of biodiversity issues is greatly needed also for companies.

Despite the abundance of literature in the area of natural sciences, there is a conspicuous dearth of management and accounting studies that tackle biodiversity (Panwar et al., 2023; Schaltegger et al., 2023). The importance of this information has been highlighted recently (Kennedy et al., 2023) and the difficulties preventing more businesses from becoming involved with biodiversity preservation have been identified (Schaltegger et al., 2023):

- **Beliefs and mindset**: whilst some managers argue that biodiversity impacts and opportunities are adequately addressed by environmental management frameworks in place, others hold the view that biodiversity analyses transcend the company boundaries.
- **High complexity**: biodiversity is a highly dynamic, debated and systemic concept.
- **Diversity as such**: comprehension of the biodiversity status is always location-specific.
- **Lack of management and accounting approaches**: professional studies typically suggest preliminary methods and scholarly publications overlook the role of biodiversity in corporate management.
- **Not recognised relevance and opportunities**: executives often wait for shareholders or legislatures to exert pressure on them or to establish incentives to adjust.

The same authors developed a helpful framework to assist firms in weighing biodiversity and list valuable resources and referrals (Schaltegger et al., 2023):

I. **Identification and assessment of biodiversity exposure and impacts**: with the support of databases (IBAT Alliance, 2022; Natural Capital Finance Alliance. & UNEP-WCMC, 2022) and guidelines (*see ESRS E4*: EFRAG, 2022; TNFD, 2023).

II. **Priority setting for corporate biodiversity management**: as new standards take shape – notably the *TNFD* (2023) disclosure framework and the *ESRS E4* draft standard on Biodiversity and Ecosystems (EFRAG, 2022) – target setting is ever more essential.

III. **Monitoring and assessing the effectiveness and efficiency of management actions**: for this purpose, the Science Based Target Network (SBTN) has released a novel *Action Framework* (*see AR3T*: Science Based Targets Network, 2020) which extended the mitigation hierarchy notion to include proactive, positive steps for nature. It recognises five management actions: Avoid, Reduce, Regenerate, Restore and Transform.

While further operationalization and development of this model are necessary, it has the potential to inspire management academics to formulate more comprehensive strategies.

1.3 Corporate Biodiversity Strategies

The rationale underlying corporate endeavours in biodiversity strategies is grounded in three main reasons, encompassing compliance with **regulatory requirements** (i.e.: *Corporate Sustainability Reporting Directive, CSRD*), **market pressures** (e.g.: the framework developed by the *Taskforce on Nature-Related Financial Disclosures*, *TNFD;* the guideline by *Science Based Targets Network, SBTN*) and **voluntary commitments** (Brugger and Santos, 2022; Davis-Peccoud et al., 2023).

Every industry contributes to the direct drivers of biodiversity loss: (i) via *land use change* when building their facilities in previously undeveloped areas; (ii) by *polluting* the air, soil and water environments via their emissions; (iii) contributing to the *introduction of invasive species* through international trade; (iv) via the *overexploitation* of animal or plant resources and (v) contributing to *climate change* and ultimately reducing: (a) *genetic* *diversity*, because only the genes that are adaptive under new conditions will persist; (b) *species diversity*, that miss the resources they need to survive at the time of year those resources are required and (c) entire *ecosystems* may transition to new states, with unprecedented impacts on biodiversity (Panwar et al., 2023).

Four main corporate biodiversity strategies arise out of combining two types of **temporal** and **spatial** interventions – before or after loss; on-site or off-site (Panwar et al., 2023).

- **Conservation**: *a before-loss, on-site strategy*.
  Forest companies may adopt a **Forestry Stewardship Council** (**FSC**) certification; ùfood sector firms may opt for **Marine Stewardship Council** (**MSC**) certification or the **Roundtable on Sustainable Palm Oil** (**RSPO**) one, mostly because of market and/or regulatory pressures. Apparel companies are scrutinising the opportunities of more sustainable fibres (e.g.: **hemp** versus cotton) to reduce soil toxicity and/or **waterless dyeing techniques**, to diminish their water usage and contamination.
  Conservation strategies are clearly not feasible for industries that are highly dependent on resources present at specific locations, such as mining companies. For them, the conservation approach would significantly reduce their operational scale, hence their profit.

- **Restoration**: *an after-loss, on-site strategy.*
  Regulations may require for mining companies to restore extraction sites. In Europe, the *Environmental Impact Assessment Directive*, *The Waste Framework*, *Hazardous Waste* and *Landfill Directives* comprise the regulatory framework for restoration and reclamation

of soil and water streams, which ultimately aid biodiversity restoration. The **One Planet Business for Biodiversity** (**OP2B**) initiative aims to foster value-chain level collaborations for biodiversity restoration through regenerative practices. Companies of such size and scope as Danone, Kellogg's, Mars Wrigley, Nestlé, Symrise, and Unilever are OP2B participants.

Still being a necessary undertaking, it is impossible to fully restore ecosystems to their previous state and some form of biodiversity loss is unavoidable.

- **Compensation**: *a before-loss, off-site strategy.*

  The **Natura 2000** regulatory framework in the European Union is expanding biodiversity compensation initiatives; these are to be intended as **offsets**, allowing corporations to resolve the inherent trade-offs between biodiversity conservation and economic development. <u>In-kind</u> and <u>like-for-like offsets</u> occur in the same biogeographical region where biodiversity loss occurred; <u>out-of-a-kind offsets</u> are implemented in a different region and for a different species.

  Offsets are a convenient option for enterprises, allowing the continuation of the business-as-usual on site. Yet, their major weaknesses are: (i) *confusion* on what should count as offset; (ii) *ambiguity* regarding the weight of the offset; (iii) uncertainty about the *time period* over which the offset should operate and (iv) *how to manage the risk* in case it fails.

- **Reparation**: *an after-loss, off-site strategy.*
  Reparation is evident through **voluntary carbon offset initiatives**. These typically involve afforestation projects and have become popular particularly for airlines companies.
  Their attractiveness is greenwashed. Their ability to mitigate biodiversity loss is limited indeed, by the fact that restoration and damage to biodiversity occur in different temporal and spatial dimensions, which runs counter to the core concept of biodiversity always being location-specific.

Conservation, restoration, compensation and reparation strategies are to be intended as customisable for individual organizations targeting differentiation from their competitors. Notably, a consensus within the scientific community regarding the optimal methodologies for implementing a specific strategy is lacking (Panwar et al., 2023).

1.3.1 Biodiversity Reporting and Accounting

Biodiversity reporting refrains from adhering to a uniform template and, instead, takes a granular approach, based on the areas in which the company focuses its attention (Panwar et al., 2023). Firms additionally face obstacles when designing a biodiversity strategy, such as the infancy of biodiversity standards, changing reporting obligations and an inadequate amount of funding (Davis-Peccoud et al., 2023).

International initiatives, particularly the **Global Reporting Initiative** (**GRI**), have facilitated the advancement of more sustainable *Corporate Social Responsibility* (*CSR*) reporting initiatives. Nonetheless, these approaches might not be fully sufficient or suitable for certain biodiversity contexts (Sobkowiak et al., 2020).

While protecting biodiversity is a top priority globally, there are significant regional fluctuations in the solutions that must be applied. Assessing the impact of biodiversity conservation through the **Eco-Management and Audit Scheme** (**EMAS**) or **ISO 14001 certifiable standards** may provide significant perspectives on the matter (Blanco-Zaitegi et al., 2022).

In the endeavour to enhance, uphold, or rectify legitimacy, companies may opt for the expedient of **Impression Management** when voluntarily addressing biodiversity concerns – an option perceived as less arduous when contrasted with more comprehensive alternatives. Within this context, **neutralization-techniques** are commonly implemented: (i) statements of net positive or neutral impacts on biodiversity; (ii) negations of serious impacts; (iii) distancing behaviour from impacts; and (iv) dilution of accountability (Blanco-Zaitegi et al., 2022). Such strategic manoeuvres, while aiming to burnish the corporate image, can inadvertently contribute to increasing social scepticism, fortifying critical perspectives toward the corporation and ultimately eroding a firm credibility (Boiral, 2016).

The **subject** of biodiversity reports warrants a critical examination: asymmetrical attention is paid to threatened iconic species evoking emotional responses (Cuckston, 2018). Businesses are prompted to actively participate in fundraising for the conservation of mammals and birds (Atkins and Maroun, 2018), overshadowing less conspicuous entities such as insects, fungi and bacteria, despite their equal ecological importance (Almond et al., 2020). The efficacy of said approach in preserving biodiversity comprehensively is questioned (Blanco-Zaitegi et al., 2022).

This juncture marks a pertinent moment for the visualization of the aggregate biomass across Earth, specifically its delineation within the seven taxonomic Kingdoms of Life (*see Fig. 7*: adapted from Belan, M. & Ghosh A.I., 2021). With our planet sustaining a staggering array of over **8.7 million species**, humans constitute a mere **0.01%** of the total biomass on Earth (Bar-On et al., 2018).

The manifold contributions of microorganisms to ecosystem services and human sustenance underscore the importance of comprehending and preserving microbial diversity. Nevertheless, the elucidation of this diversity remains an endeavour for forthcoming research initiatives in the domain of microbial ecology. Numerous microorganisms exhibit resilience against conventional methodologies of isolation and cultivation, thereby complicating their investigational accessibility.

Historically, research emphasis has disproportionately favoured investigations into medically pertinent microorganisms, thereby relegating broader exploration of microbial taxa possessing ecological and biotechnological significance to a secondary status. Consequently, a substantial proportion of microbial species remains undiscovered, thereby constraining our grasp of their ecological functions and prospective applications. Their capacities are still latent for the benefit of both environmental integrity and societal welfare (Vitorino and Bessa, 2018).

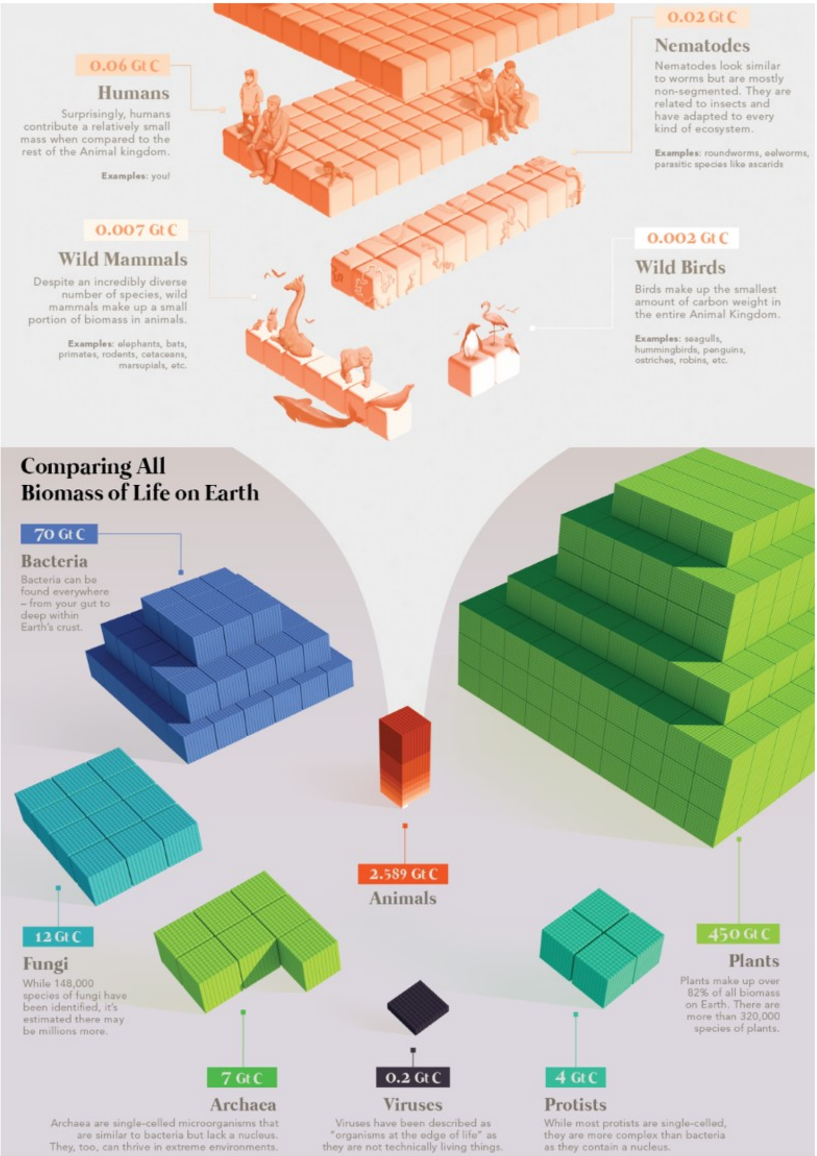

Figure 7 Visualising the Biomass on Earth

Biomass is measured by the amount of carbon an organism contains. Carbon is a primary component of all known life on Earth, used in complex biological molecules and compounds. One cube represents 1 million metric tons of carbon. One thousands cubes represent 1 Gigaton of Carbon (Gt C).

The domain of **Biodiversity Accounting** encompasses two primary perspectives, differing in the ethical approach: I) *anthropocentric* or II) *non-anthropocentric* (Blanco-Zaitegi et al., 2022).

The former stance postulates that biodiversity preservation should be driven by human interests. Its proponents argue that the direct consequences of species loss, such as diminishing vital resources (e.g.: food and materials), pose a tangible threat to humanity (Jones and Solomon, 2013).

The latter, often termed *Deep Ecology* (Naess, 1973), emphasizes an awareness of the intrinsic value inherent in biodiversity; all living beings possess an incalculable and irreplaceable intrinsic value in and of themselves (Maunders and Burritt, 1991).

In synthesizing these frames of mind, the discourse on biodiversity reporting stands at the intersection of ethical considerations, resource management, and the broader ecological landscape, suggesting that a holistic framework is imperative for its effective management (Samkin et al., 2014).

1.4 A Supply Chain perspective

The work by Salmi et al. (2023) delivers the most contemporary and exhaustive review pertaining to the domain of **Biodiversity Management** (**BM**) when viewed through the lens of a Supply Chain perspective.

For starters, BM functions as an umbrella concept encapsulating a spectrum of initiatives geared towards achieving one or more of the following **performance outcomes**:

I) *Reducing* negative biodiversity outcomes;

II) *Eliminating* negative biodiversity outcomes;

III) *Restoring* biodiversity;

IV) *Regenerating* biodiversity.

Within numerous industries, the preponderance of adverse effects on biodiversity is notably concentrated at the level of **sub-tier suppliers** where resources and raw materials are produced or extracted. This underscores the role that purchasing executives and managers assume in influencing biodiversity management practices and mitigating biodiversity impacts throughout their supply chains (Salmi et al., 2023).

Purchasing and Supply Chain Management (**PSCM**) **practices** are commonly broken down into:

- *Collaboration practices*: such as supplier training and education, exchanging expertise and knowledge, jointly solving sustainability problems and jointly developing innovative solutions.
- *Assessment practices*: include supplier audits, questionnaires, codes of conduct, environmental certifications and standards,

environmental management systems, performance monitoring, penalty clauses, rewards and incentives relating to sustainability performance.

To date, the conspicuous underrepresentation of biodiversity within the specified operations underscores the imperative for the development of a structured guide for corporations targeting positive biodiversity performance outcomes (Salmi et al., 2023).

Figure 8 reveals the data coding of BM practices: nine **first-order concepts** pertain to an equivalent number of **second-order themes**, subsequently consolidated within four **aggregate dimensions** (i.e.: set of practices). The inaugural objective of this thesis is dedicated to a comprehensive examination of the methods employed in Biodiversity Impact Assessments. Consequently, the study situates itself within the aggregate dimension of intra-organizational practices.

Figure 9 presents a theoretical model delineating Biodiversity Management within Purchasing and Supply Chain Management (PSCM). The model underscores that the firm's biodiversity management practices, targets and outcomes collectively shape the state of biodiversity, encompassing the three tiers of biological diversity.

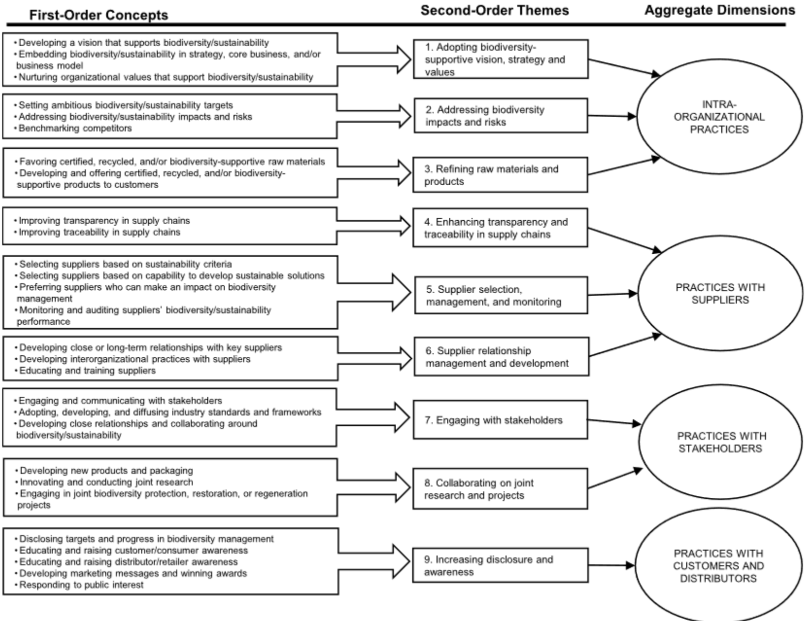

Figure 8 Data coding of biodiversity management practices

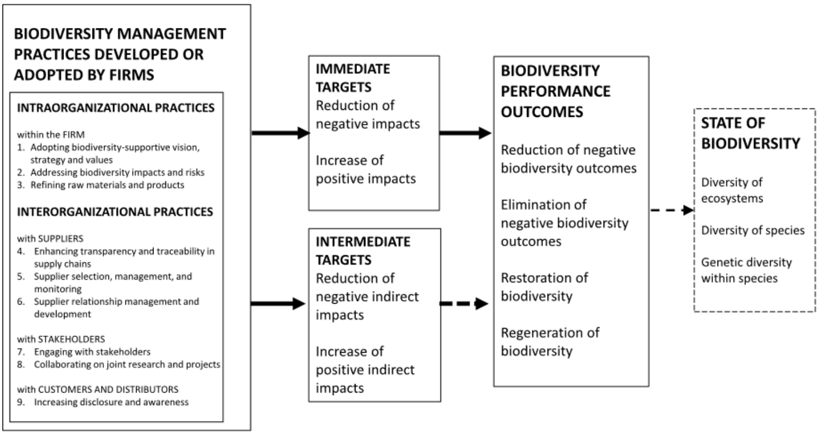

Figure 9 Model of biodiversity management in PSCM

Empirical findings (Salmi et al., 2023) stress the role of interorganizational practices with supply chain members, highlighting the inadequacy of relying solely on intraorganizational efforts.

Biodiversity performance outcomes vary, with some being *immediate* targets of the firm's activities, while others require *intermediate* goals.

Both immediate and intermediate targets span diverse locations and supply chain partners, potentially influencing biodiversity outcomes and its global state over time.

1.5 International Biodiversity undertakings

In response to the urgent biodiversity loss crisis, the United Nations (UN) initiated negotiations for an international biodiversity agreement in Rio de Janeiro in 1992, with the accord officially taking effect the following year, ratified by 196 parties. In 2010, the agreement was supplemented by the **Aichi targets**, a set of objectives aiming to halt global biodiversity loss by 2020 (CBD, 2020). With a palpable sense of displeasure, it must be highlighted that none of the 20 international targets were fully achieved by the specified deadline (Pörtner et al., 2023).

To refine and strengthen the implementation of the agreement, global attention turned to the UN Biodiversity Conference (**COP-15**), held in two stages in 2021 and 2022. The conclusive meeting in Montreal in December 2022 resulted in the adoption of a new global biodiversity agreement under the Convention on Biological Diversity (CBD), which sets ambitious goals to halt and reverse biodiversity loss by 2030 (UNEP, 2022).

1.5.1 The EU Biodiversity Strategy for 2030

The European Union (EU) and its Member States have undertaken substantial commitments and articulated explicit objectives to arrest biodiversity loss, both within the continent and on a global scale.

The pursuit of these objectives has been reinforced by **legal frameworks**, exemplified by the *Birds and Habitats Directives* and the *Marine Strategy Framework Directive*; strategic **policies**, as evidenced by the *EU Biodiversity Strategy*; and **financial instruments**, notably the *LIFE programme*. These initiatives have fostered an unparalleled, concerted effort, resulting in the establishment of the world's most extensive network of Protected Areas (PAs) known as the **Natura 2000 network** (**N2K**). Presently encompassing 18.5% of the European land area and nearly 10% of the entire EU marine expanse, the Natura 2000 network stands as a testament to the collective dedication and coordinated action undertaken on an unprecedented global scale (Hermoso et al., 2022).

The European Commission, as acknowledged in its **Green Deal**, recognizes the substantial contributions of nature and biodiversity to both our economy and health. The Green Deal represents a potential initial stride toward a paradigm shift within the EU, by prioritizing biodiversity conservation as a central concern and addressing the longstanding demand for more effective integration of biodiversity conservation within various sectoral policies.

The recently endorsed **Biodiversity Strategy for 2030** not only emphasizes the potential for biodiversity conservation and restoration but also aligns with the overarching goals of the Green Deal. With its central objective of "*Bringing nature back into our lives*," this strategy not only complements the

Green Deal, but also provides additional policy context by outlining specific objectives and financial mechanisms (Hermoso et al., 2022).

The Biodiversity Strategy for 2030 is organized based on three fundamental pillars: (i) protecting and restoring nature in the EU, by consolidating a coherent and effective network of Protected Area (PAs) and restoring degraded habitats; (ii) enabling a new governance framework to ensure co-responsibility and co-ownership by all relevant actors in meeting the biodiversity commitments, including setting up new financial opportunities; and (iii) adopting a global biodiversity agenda, to strengthen the contribution of the EU towards halting global biodiversity loss and minimizing externalities of EU use of resources and consumption on other biodiversity-rich areas of the planet.

1.5.2 An alphabet soup for companies: CSRD and ESRS

As part of the European Green Deal (EGD), the **Corporate Sustainability Reporting Directive** (**CSRD**) aims to enhance sustainability reporting and transparency by obligating companies to use **common standards**, making it easier for investors, civil society organizations, consumers and other stakeholders to evaluate companies' sustainability performance. The directive requires all large companies and listed companies — with the exception of listed micro-enterprises — to disclose information on the risks and opportunities for their business arising from social and environmental issues and on the impact of their activities on people and the environment.

The information needs to be reported following the **European Sustainability Reporting Standard** (**ESRS**), which have been adopted by the Commission through delegated acts that define the content and, if applicable, the structure for presenting the information (European Commission, 2023). The ESRS delegated act will be passed along to the EU Parliament and Council for a two-month scrutiny period, with implementation set to begin for some companies for the 2024 fiscal year.

The CSRD replaces and builds on the existing **Non-Financial Reporting Directive** (**NFRD**), to strengthen and streamline sustainability reporting requirements. The NFRD lacked crucial details for investors and stakeholders, making it challenging to compare company reports and creating uncertainty about their reliability and actionability. For the green investment market to be credible, investors need reliable information about companies' environmental impacts (and their strategies for reducing these impacts in the future) to appropriately direct funds toward sustainability-linked initiatives. The CSRD expands the scope of the NFRD, intending to reduce corporate greenwashing, as well as implements full and harmonized disclosure of ESG[3] topics. The CSRD also puts **sustainability reporting on the same level as financial reporting**, requiring that information about sustainability risks are more available to the general public.

The main **objective** of the CSRD is to provide relevant stakeholders, including investors, consumers and policymakers, with comparable non-financial information to assess company risks around climate change and other ESG issues. Since companies will have to report under one common

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[3] Environmental, social and governance (ESG) topics refers to a set of standards for a company's behaviour used by socially conscious investors to screen potential investments.

framework, stakeholders will have access to clearer, comparable and more reliable information.

Companies will have to start by disclosing an overview of their legal and policy structure before diving into their sustainability journey. However, certain ESG topics are more relevant to some companies and sectors more than others. When determining which ESG topics companies will need to report on, the ESRS takes a "**double materiality**" perspective. This is an approach that includes both how sustainability issues create financial risks and opportunities for a company (**financial materiality**) and a company's own impacts on people and the environment (**impact materiality**).

Financial Materiality: a sustainability issue has an impact on or could reasonably be expected to have an impact on (positive or negative) a company's business model, cash flow, revenue or enterprise value.

Impact Materiality: a business activity has an actual or potential impact (positive or negative) on people or the environment over the short-, medium- or long-term.

Reports should also include corporate strategies to **mitigate and adapt to ESG risks**, depending on the results of their double materiality assessment. The reported information should cover short-term, medium-term, and long-term perspectives, as appropriate. The report must be integrated within a company's management report, rather than published as a separate annual report, and it must be in a standardized digital format so it can be easily compared with other companies' ones.

Depending on the results of a company's materiality assessment, reporting under the CSRD will need to cover a range of environmental topics beyond climate, such as pollution, water, biodiversity and natural resource use, as well as social and governance topics.

In addition to double materiality, firms must disclose their strategies to **mitigate and adapt to sustainability-related risks**. Companies will need to outline their business model and strategy, a timeline of sustainability initiatives, governance, impacts, risks and KPIs. This information will enable investors and other relevant stakeholders to track the progress of corporate sustainability initiatives.

CSR Europe is the leading European business network for Corporate Sustainability and Responsibility: "with our corporate members, National Partner Organisations (NPOs), and Associated Partners, we unite, inspire & support over 10,000 enterprises at local, European and global level. We support businesses & industry sectors in their transformation and collaboration towards practical solutions and sustainable growth. We are for systemic change. Following the SDGs, we want to co-build with the European leaders and stakeholders an overarching strategy for a Sustainable Europe 2030."

Members of its *Collaborative Platform Biodiversity and Industry* encompass corporations such as BASF, GSK, Philip Morris International, Enel, Solvay, Ipsen, UnipolSai, Engie, Titan and Iberdrola.

CSR developed '**The Biodiversity Risk Scan**', a framework to prioritise risks in business projects: "the purpose of the Biodiversity Risk Scan is to help companies identifying and prioritizing the potential biodiversity impacts of a project. The assessed project may be a manufacturing activity, a product, or supply chain. It may also be a new development or an activity under way for which no biodiversity management has been set up so far.

The aim is to map all the key impacts and hotspots in order to implement the adequate measures. It is not about the detailed assessment of the real alterations to biodiversity itself."

The *Five Steps* of the Biodiversity Risk Scan are: (i) Scoping; (ii) Internal Assessment; (iii) External Stakeholder Engagement; (iv) Materiality Matrix and (v) Decision-Making Guidelines.

The CSRD requires sustainability information to be subject to **assurance**. Companies' statutory auditors will be required to carry out sustainability reporting assurance in partnership with another auditor or an independent assurance provider. Auditors' reports must be integrated into the company report and align with other global standard-setting initiatives, such as the *Sustainable Finance Disclosure Regulation* (*SFDR*) and *EU Taxonomy Regulation*.

Information on how or when the EU Commission will impose **sanctions for businesses that fail to comply** with the CSRD is not yet available. However, they are expected to be significant.

There are 12 reporting standards covering the full range of sustainability issues, in line with the *European Financial Reporting Advisory Group's* (*EFRAG*) proposal:

Group	Number	Subject
Cross-cutting	ESRS 1	General Requirements
Cross-cutting	ESRS 2	General Disclosures
Environment	ESRS E1	Climate
Environment	ESRS E2	Pollution
Environment	ESRS E3	Water and marine resources
Environment	ESRS E4	Biodiversity and ecosystems
Environment	ESRS E5	Resource use and circular economy
Social	ESRS S1	Own workforce
Social	ESRS S2	Workers in the value chain
Social	ESRS S3	Affected communities
Social	ESRS S4	Consumers and end users
Governance	ESRS G1	Business conduct

ESRS 1 (General Requirements) sets general principles to be applied when reporting and doesn't set specific disclosure requirements. ESRS 2 (General Disclosures) specifies essential information to disclose, irrespective of the sustainability matter being considered. ESRS 2 is also mandatory for all companies under the CSRD.

All the other standards and individual disclosure requirements — including the data points within them — are subject to a **materiality assessment**. Companies will only need to report relevant information and may omit information that isn't determined to be material to its business model and activities.

There are around **50,000 listed companies** that will eventually have to comply with the CSRD, although there are some exemptions to the initial implementation. All listed companies that are active in the EU will have to implement the CSRD by 2029. Companies will have to start reporting under ESRS according to the following timetable:

- **Financial Year 2024**: companies previously subject to the NFRD (large listed companies, large banks and large insurance undertakings that have more than 500 employees), as well as large non-EU listed companies with *more than 500 employees* will need to report on the 2024 fiscal year, with the first sustainability statement published in 2025, or *EUR 40 million turnover* and/or *EUR 20 million balance sheet value*.

  Financial Year 2025: other large companies, including other large non-EU listed companies, that meet two out of three criteria, including having in excess of *250 employees*, the *turnover greater than EUR 40 million* and/or *EUR 20 million balance sheet value*. They will need to report on the 2025 fiscal year, with the first sustainability statement published in 2026,.

- **Financial Year 2026**: listed SMEs, including non-EU-listed SMEs, will need to report on the 2026 fiscal year, with the first sustainability statements published in 2027. However, listed SMEs may decide to opt out of the reporting requirements for a further *two years*. The last possible date for a listed SME to start reporting is the 2028 fiscal year, with the first sustainability statement published in 2029.

- **Financial Year 2028**: in addition, non-EU companies that generate over *EUR 150 million* in the EU and that have, in the EU, one of the following: (a) a branch with a turnover exceeding €40 million; (b) a subsidiary that is a large company or (c) a listed SME – will have to report on the sustainability impacts at the group level of that non-EU company as from the 2028 fiscal year, with a first sustainability statement published in 2029. Separate standards will be adopted specifically for this case.

Three **phase-in provisions** have been developed: (i) during the first reporting year, companies are not obligated to report on anticipated financial effects from all climate and environmental-related impacts, risks and opportunities; (ii) for the first three years of reporting, the anticipated financial effects disclosures may be qualitative instead of quantitative; and (iii) for companies with fewer than 750 employees, ESRS E4 may be omitted for the first two reporting years.

The transition plan **for biodiversity and ecosystems** under the **European Sustainability Reporting Standard E4** (**ESRS E4**) is classified as a voluntary disclosure (Gavron, 2023).

ESRS E4 specifically addresses biodiversity and ecosystems and the related disclosure requirements. It is structured as follows:

- **General disclosure:**
  - *ESRS E4-1*: Transition plan on biodiversity and ecosystems

- **Impact, risk and opportunity management:**
  - *ESRS E4-2*: Policies related to biodiversity and ecosystems
  - *ESRS E4-3*: Actions and resources related to biodiversity and ecosystems

- **Metrics and targets:**
  - *ESRS E4-4*: Targets related to biodiversity and ecosystems
  - *ESRS E4-5*: Impact metrics related to biodiversity and ecosystems change
  - *ESRS E4-6*: Potential financial effects from biodiversity and ecosystem-related impacts, risks and opportunities

While the CSRD has been adopted by the European Commission, it will have global implications. Any listed company that is active in the EU, even if they are headquartered outside of the EU, will have to comply under CSRD, which hints at the start of globalizing sustainability reporting.

Many other countries have plans to create regulations in alignment with the CSRD or match its ambitions. For example, the UK is planning to create UK Sustainability Disclosure Standards (SDS) for corporate reporting on sustainability-related risks, setting the foundation for future legislation around sustainability topics. Switzerland has also announced plans to discuss alignment with the CSRD. The ultimate goal is to have a standardized global framework for sustainability reporting (Marelli et al., 2023).

1.5.3 The European Green Deal and the EU Taxonomy

With the escalating impact of the climate crisis, the EU has established the **European Green Deal** – a set of rules and guidelines with the overarching goal of transforming the EU into a modern, resource-efficient, and competitive economy.

The deal is structured to ensure that:

- There are no net emissions of greenhouse gases by 2050 – with an ambition to become the first climate-neutral continent.
- Economic growth is 'decoupled' from the use of resources.
- There are no people or places left behind.

As a component of the European Green Deal (*see Fig. 10:* Descio and Crabbendam, 2022), the *EU implemented the Action Plan on Sustainable Finance*, designed to facilitate financing for the transition toward a low-carbon, resource-efficient economy. Its objective is to channel increased funds from investors into sustainable projects, assets, and companies, thereby

Figure 10 The components of the European Green Deal

supporting environmentally friendly initiatives and contributing to the broader goals of sustainable development.

The **EU Taxonomy** facilitates the expansion of sustainable investments and counteract the phenomenon of *'greenwashing'* associated with purportedly *'sustainable'* financial products. To determine which investments qualify as sustainable, the EU has introduced the **green classification system** – economic activities labelled as 'green' or 'environmentally sustainable' are those that make a substantial contribution to at least one of the EU's climate and environmental objectives, while at the same time not significantly harming any of the six environmental objectives and meeting minimum safeguard standards.

The six climate and **environmental objectives** established by the EU are:

- **Climate change mitigation**
- **Climate change adaptation**
- **Sustainable protection of water and marine resources**
- **Transition to a Circular Economy**
- **Pollution prevention and control**
- **Protection and restoration of biodiversity and ecosystems**

An economic activity qualifies as green or *'environmentally sustainable'* only if it satisfies the three **performance thresholds** established by the EU:

- ***Contribute***: substantially contribute to at least one of the six environmental objectives.

- ***DNSH***: Do No Significant Harm (DNSH) to any of the other five environmental objectives.
- ***Social***: comply with minimum social safeguards.

This presents an opportunity for businesses to showcase their performance and advancements toward adopting more sustainable business models. By doing so, it allows financial markets to make more informed investment decisions, promoting transparency and accountability in the pursuit of sustainable practices.

It is important to distinguish between activities that are *'aligned'* with the European Green Deal and those that are *'eligible'* under the new rules. An activity is deemed **taxonomy-eligible if it is explicitly listed in the EU Taxonomy, regardless of whether it fulfils specific conditions**. Conversely, if the activity is not explicitly described in the regulation, it is considered non-eligible. This differentiation helps provide clarity on which activities are formally recognized and meet the established criteria outlined in the EU Taxonomy.

Figure 11 (Moro, B., 2023) summarises the parties involved in the just-described European legal landscape.

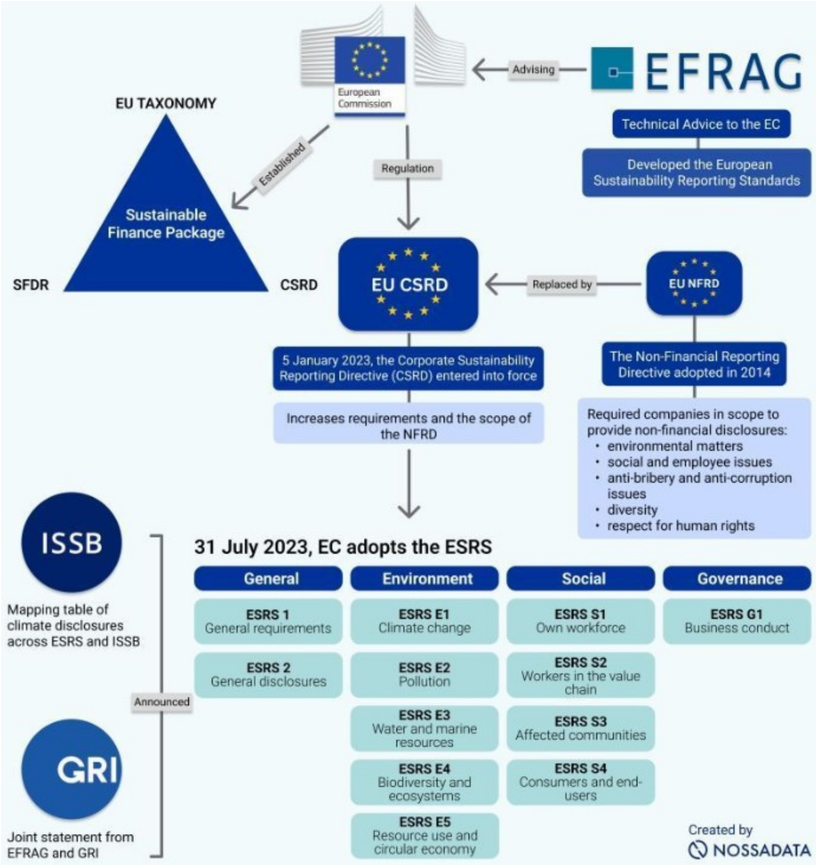

Figure 11 The alphabet soup, explained

2 Scope

In the contemporary era, the escalating global concern of Biodiversity Loss has taken notoriety in environmental discourse, demanding immediate attention and strategic interventions. Despite its paramount importance, the Biodiversity Management research field is still in its early stages of development.

The European Green Deal (EGD) marks a paradigm shift in the landscape of EU environmental policy. Envisioned as *Nexus*-by-design growth strategy, it integrates and attempts to equally consider the realms of Biodiversity, Climate Change and Circular Economy.

This thesis endeavours to review: (i) the current state of Biodiversity Management strategies, specifically delving into the methodologies employed for comprehensive Biodiversity Impact Assessment and (ii) the valorisation of the *Nexus thinking* approach in the EGD Strategic Framework.

Through these dual objectives, this research seeks to make a meaningful contribution to the ongoing discourse, fostering a deeper understanding of the subject and providing practical guidance for practitioners getting to grip with Biodiversity Impact Assessment and scrutinising Circular Economy opportunities.

3 Methodology

This thesis' methodology is based on a thorough analysis of the body of literature that currently exists in the fields where Business Strategies and Environmental Science and Policy meet.

The main body of information for study consists of critical reviews and expert opinions from prestigious and reputable journals and websites in a number of disciplines. The selection criteria for these resources included the scholarly significance of the publications, the reputation of the journals and the experience of the contributing writers in order to guarantee the highest degree of academic rigour.

A methodical review procedure was implemented, which comprised the identification, screening, and careful assessment of pertinent material.

This scheme of action has been tailored to make sure that significant perspectives and concepts related to Biodiversity Management are included in the context of Corporate Sustainability Reporting undertakings.

The objective was to gauge the range of Life Cycle Assessment (LCA) methods that can be applied when conducting a comprehensive Biodiversity Impact Assessment, while simultaneously investigating the dynamics, synergies and trade-offs that constitute the interactions between Biodiversity, Climate Change and the transition to a Circular Economy in the landscape of the European Green Deal.

Key insights, theoretical frameworks and empirical findings from the identified literature were synthetised to form the foundation for the subsequent discussion.

4 Results

4.1 LCA Methods for Biodiversity Impact Assessment

To evaluate the impact of products and organizations on biodiversity, it is crucial to create scientific methods and indicators that can comprehensively measure biodiversity effects throughout the entire value chain. Such approach would empower companies to identify the root causes of biodiversity loss, monitor shifts over time and formulate effective mitigation initiatives (Crenna et al., 2020).

The most recent and comprehensive critical review of methodologies for Biodiversity Impact Assessment (BIA) within the context of Life Cycle Assessment (LCA) is presented by Damiani et al., (2023), here illustrated in *Figure 12*.

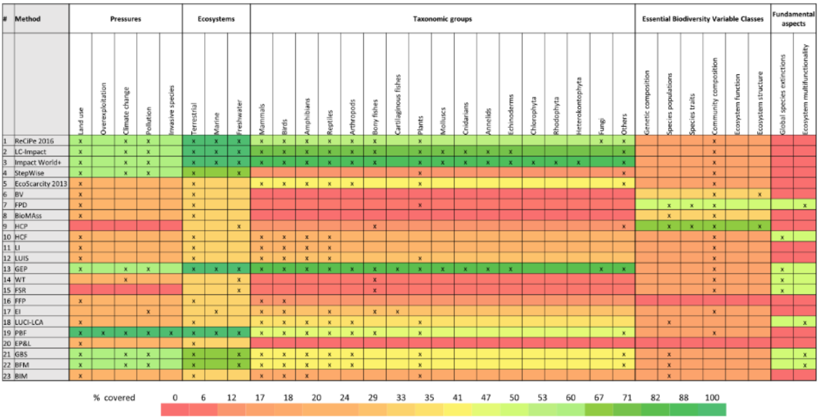

Figure 12 Categories covered by the methods for each criterion assessed

Their evaluation gauged the degree to which biodiversity is accounted for within diverse Biodiversity Impact Assessment (BIA) methodologies, employing a defined set of five criteria:

- **Pressures**: method *#19 PBF* performs best at capturing the five direct drivers of biodiversity loss, discussed in paragraph 1.1.
- **Ecosystems**: five methods equally perform best as they cover *Terrestrial*, *Marine* and *Freshwater* ecosystems: *#1 ReCiPe*, *#2 LC-Impact*, *#3 IW+*, *#13 GEP* and *#19 PBF*.
- **Taxonomic groups**: the best method is *#3 IW+*, with fifteen taxonomic groups covered, immediately followed by *#13 GEP* with fourteen groups covered. Note that the category "*other*" encompasses algae, macroinvertebrates and zooplankton.
- **Essential Biodiversity Variable (EBV) classes**: the best performing method is *#9 HCP* as the metric it uses (*Habitat Change Potential*) considers parameters referring to four distinct EBV classes. It is noteworthy that no method returns assessments related to *Genetic composition* and *Ecosystem function* subcategories.
- **Fundamental aspects**: the Potentially Disappeared Fraction (PDF) metric, when assessed on a global scale, serves as an approximation for *Global species extinctions*, addressed by four methods: *#10 HCF*, *#13 GEP*, *#14 WT* and *#15 FSR*. The Mean Species Abundance (MSA) metric serves as an approximation for the *Ecosystem multifunctionality* addressed by four methods: *#7 FDP*, *#18 LUCI-LCA*, *#19 GBS* and *#22 BFM*.

Methods ranging from #1 to #17 are referred to as LCA-based, while those from #18 to #23 are categorized as beyond-LCA methods, aligning with Life Cycle Thinking or employing Ecosystem Service Accounting approaches.

It is imperative to consider, in the interpretation of results, that the inclusion of a specific category by a method does **not necessarily indicate comprehensive coverage** of that particular category.

While the majority of the methods studies the impact of land use in terrestrial ecosystems, only method *#19 PBF* explicitly considers the pressures arising from **overexploitation** and **invasive alien species**.

Even the most comprehensive methods, in terms of the taxonomic groups considered, encompass only a limited fraction of both known and unknown biodiversity. Notably, certain vital terrestrial and marine taxa, such as **fungi** and **sponges**, **are entirely overlooked** within these methodologies.

The representation of other EBV classes than "*community composition*" - described by the indicator of species richness PDF - is comparatively limited, resulting in a substantial oversight of crucial biodiversity facets, including **genetic composition**, **species traits** and **ecosystem functioning**.

Presently, a comprehensive method capable of simultaneously assessing (i) Pressures on biodiversity; (ii) Ecosystems; (iii) Taxonomic groups; and (iv) EBV classes, has yet to be developed. Research perspectives aimed at addressing such gap involve two primary dimensions: (a) to increase the completeness of methods with regards to pressures and taxonomic groups covered and (b) to enhance the descriptive power of the methods on genetic diversity, community composition and structure, and ecosystem functionality (Damiani et al., 2023).

4.1.1 LCA and Biology run on a different scale

Biologists study biodiversity at **high resolution** (e.g.: specific ecoregions at a location), whereas LCA assesses impacts on the environment on a **global scale**. Consequently, the applicability of LCA methods for BIA appears limited compared to more generalized methods, such as those employed for climate change in typical LCA applications. Additionally, the precise measurement of biodiversity remains an unresolved challenge, further complicating the integration of biodiversity considerations into LCA methodologies (Winter et al., 2018).

A case-specific trade-off must be sought to reconcile the perspectives of biology and Life Cycle Assessment (LCA). The conceptual framework introduced by Winter et al., (2018) proposes such reconciliation at the **national level**, considering the compromise between available inventory data and the preferred spatial resolution for biodiversity assessment. It serves as a pioneering step toward an impact assessment methodology for biodiversity, covering genetic, species, and ecosystem diversity, applicable for all impact categories and seamlessly integrating into the LCA practice.

4.2 Genomic diversity for Biodiversity Conservation and ES Management

Genomic diversity, i.e.: the genetic diversity at the genome-wide level, is composed both of DNA variants that are mostly neutral to natural selection and of variants that can respond to selection, affecting individual fitness and population adaptation. Genomic diversity is responsible for the level of <u>adaptation</u> of populations to environmental change and increases their <u>resilience</u> to anthropogenic risks. However, the benefits of genomics applications to inform biodiversity conservation and ES management are underachieved (Heuertz et al., 2023).

The sustainable provision of ES depends on the persistence and continued performance of the species that provide the ES ('**ES species'**), which relies on the sustainability and adaptive evolution of biodiversity at all levels, as well as the ecosystem's stability (Hairston Jr et al., 2005). **Keystone species** are species that exert very large effects on other associated species in a community. Their adaptive potential is therefore particularly important to consider for management alongside that of the co-occurring ES species (Heuertz et al., 2023).

A cost-effective genomics-informed ES management requires the identification of keystone and ES species and populations, and a suitable study design, sampling strategy and choice of genomic markers to inform on evolutionary processes within species and, in some cases, in communities of co-occurring and/or interacting species (Heuertz et al., 2023).

The same authors developed a methodological framework on how to use genome-wide diversity in association with phenotypic and environmental data to guide management actions for biodiversity and ecosystem services (*see Fig. 13*).

Note that the column "**Data**" is divided into types of genomic diversity data (*left*) and complementary data (*right*).
GWAS, genome-wide association study; eDNA: environmental DNA; eRNA: environmental RNA.

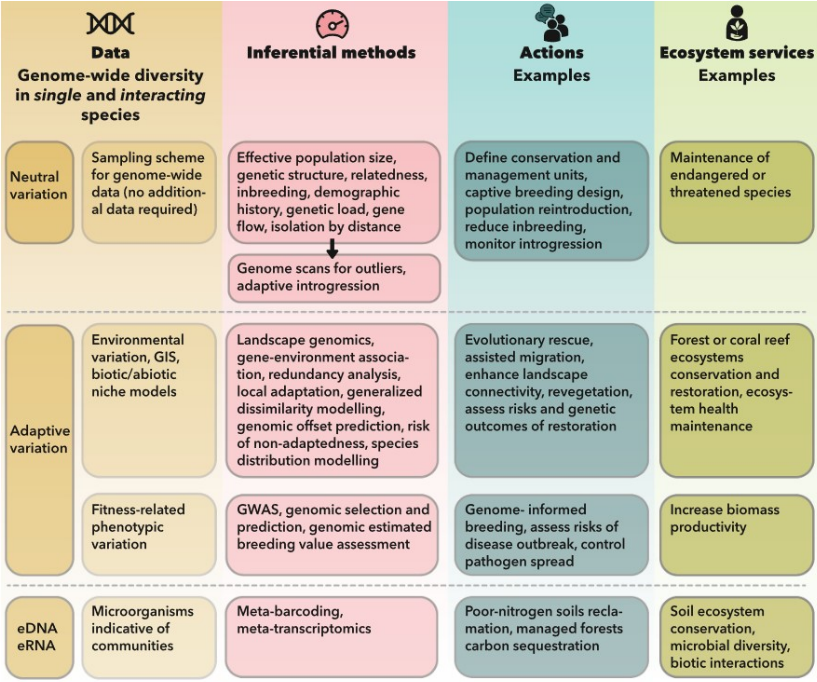

Figure 13 Genomic and other environmental data to guide management actions for Biodiveristy and ES

Different evolutionary processes affect biodiversity and thus ES provision: speciation and hybridization events shape *species diversity*; mutation, genetic drift, gene flow and selection shape the *genetic diversity* within species, with potential effects on species interactions (Whitham et al., 2006). Both these tiers of diversity are relevant for biodiversity conservation and ES provision.

High-throughput sequencing technologies have brought to the table their added value: they made it possible to study evolutionary processes at the genomic level in model and in non-model organisms (Formenti et al., 2022; Rajora, 2019), with a 100–10,000 fold increase in the number of genetic markers assessed (e.g.: single nucleotide polymorphisms, SNPs), which allows for more accurate estimation of evolutionary parameters and removes biases due to uneven genome sampling (Peterson et al., 2012).

Heuertz et al., (2023) distinguish the contributions of single species and interacting species genomic diversity data and relate these to two different sets of **Management Goals** in ecosystems, that derive from biodiversity (MG, in bold) and *Management Actions* for said MG that benefit from genomic data (MA, in italic).

Single species genomic diversity data:

I) **Conservation of threatened species**: *captive breeding (design), reduction of inbreeding, supplementation, assisted colonisation*.

II) **Sustainable productivity**: *define conservation or management units, breeding for productivity, genomics-informed breeding, assisted gene flow*.

III) **Facilitate adaptation to climate change**: *promote climate-adaptive variants, evolutionary rescue, enhance landscape connectivity, manage risk of non-adaptedness, assisted gene flow or migration.*

IV) **Restore and renew diversity**: *climate-adjusted provenancing, assess risks and monitor outcomes of management actions, reforestation.*

Interacting species genomic diversity data:

- **I)** **Manage invasive species and their effects on species interactions**: *prevent introduction or establishment, minimise spread and hybridisation of invaders, limit negative impact on native species, population control and eradication.*
- **II)** **Harness hybridisation**: *monitor hybridisation and its effects, use hybridisation for genetic rescue or adaptation / adaptive potential, manage disease risks in genetic rescue.*
- **III)** **Manage host-microorganism interactions**: *assess risk of disease outbreak, protect hosts from pathogens, prevent pathogen spillover, discontinuation of host cultivation, enhance beneficial associations.*
- **IV)** **Conserve and utilise microbial communities in water, soils and sediments**: *maximise carbon sequestration and nitrogen storage, soil reclamation, restore post-industrial ecosystems.*
- **V)** **Delineate areas for conservation and ES**: *prioritisation that maximises benefits of biodiversity and ES, delineate areas that maximise (multispecies) evolutionary potential.*
- **VI)** **Restore communities, habitats and ecosystems**: *multispecies regional admixture provenancing, monitor genetic diversity & specie composition and functions of restored communities, translocation of communities.*

As genomics applications allow to tackle ambitious Management Goals, natural resource managers are increasingly aware of the benefits provided by genomic monitoring tools. Genomic data acquisition and analysis workflow still need to be simplified and standardised, to bring down their cost and facilitate the practical deployment of genomics in Management Actions (Heuertz et al., 2023; Rossetto et al., 2021; von Thaden et al., 2020).

4.2.1 Omics-based Ecosurveillance for the assessment of Ecosystem Health

Ecosurveillance is defined as the systematic collection, analysis, and interpretation of information on ecosystem health. With the aim to support environmental management and policy decisions, it synthesises data from several sources (Beale et al., 2022). The capacity to gather and analyse data on ecosystems as well as inorganic and organic contaminants offers a potent instrument for environmental health management. Following that, ecosurveillance can also be used to quantitatively assess whether Management Actions were successful or unsuccessful (Beale et al., 2022).

Omics-based approaches could serve as monitoring tools. **Sequence-based environmental DNA (eDNA) data** detect the presence/absence and/or the relative abundance of indicator organisms and/or function-specific genes, from which the ecosystem health status is inferred – via taxonomic information when it is available or through bioinformatic functional inference approaches (Beale et al., 2022).

Microbial indicators make such assessment less straightforward: microbiome metabolic capabilities can be decoupled from their taxonomic identity, e.g.: because of gene loss or horizontal gene transfer (Martiny et al., 2013). Furthermore, environmental conditions influence their range of metabolic capabilities (Chen et al., 2021).

Transcriptomes, which are sequences of RNA from active genes, inform with regards to which organisms are active and which genetic pathways are being expressed. However, just because certain transcripts are present, this does not necessarily mean that the associated functions are actively happening: regulation can occur after the genes are expressed (Tsujimura et al., 1995). Many enzymes catalyse reactions both in the forward and in the backward directions, further complicating the understanding of the outcome of gene expression activity alone (Heuertz et al., 2023).

Proteomics and **metabolomics** – i.e.: the evidence of the protein activity, or the metabolitic content, is defined as *metabolome* – in the context of an integrated ecosurveillance framework, have the potential to improve our understanding of the realised ecosystem health and function that can be used to improve management outcomes (Geist et al., 2022). Nevertheless, while DNA and RNA approaches have been readily accessible due to advances in technology for sequencing, quantifying and comparing these data, until recently, proteomics and metabolomics lacked the depth and sensitivity to be useful except in very targeted experimental approaches (Heuertz et al., 2023).

As new technology and computational tools continue to advance, their applications are increasingly extending beyond the confines of laboratory settings.

The datasets, tools, and applications of omics-based eco-surveillance and the value of genomic diversity knowledge have been reviewed respectively by Beale et al., (2022); Heuertz et al., (2023).

4.2.2 Omics tools to address the biodiversity crisis

Conservation efforts often focus on large Protected Areas (PAs) such as national parks or marine reservations. Yet, the preservation status of individual species and populations within these vast areas is difficult to measure using traditional tools, and in some cases, protected areas may fail to prevent biodiversity loss (Appleton et al., 2022; Maxwell et al., 2020). Progress has been made with **genomics**, for instance in the design of a restoration program for the macroalga *Phyllospora comosa* in Australia (Wood et al., 2020). Genomic analysis quantity key population parameters (e.g.: genetic diversity, effective population size in endangered species) that have practical conservation value for a variety of animals (De León et al., 2023).

Environmental metagenomics (**eDNA**) purpose is to document the present or past presence of species at a location, hence being useful for monitoring invasive species (Dougherty et al., 2016) and for discovering microorganisms with potential for bioremediation (Sharma et al., 2022).

Assisted evolution can be used to increase the adaptability and persistence of populations in perturbed environments. This can be achieved via traditional methods like *controlled breeding* or via gene editing techniques such as *CRISPR/Cas9* (*Clustered Regularly Interspaced Short Palindromic Repeats and CRISPR-associated protein 9*). The latter gained interest in marine environments, to increase the heat tolerance of the coral reef (Cleves et al., 2020; Oppen and Coleman, 2022). It is unknown if such interventions will prevent species extinctions in the wild (De León et al., 2023). *Omics-guided de-extinctions* involve resurrecting extinct species (e.g.: the woolly mammoth). All these technologies face ethical and logistical concerns (McCauley et al., 2017).

Omics advances also permit to tackle the drivers of biodiversity loss (De León et al., 2023):

- **Climate change**: (*a*) *metagenomics* (*eDNA*) has been used to track populations of threatened sea turtles affected by rising temperatures; (*b*) *genomics and transcriptomics* have helped identify genetic variations associated with local adaptation to environmental stressors in multiple taxa; (*c*) *genomics and environmental modelling* combined permit to project corals' adaptive potential in response to future temperature scenarios and (*d*) *metabolomics and statistical modelling* have helped identify metabolites associated with climate resilience in plants.
- **Pollution**: ecotoxicological studies are increasingly using omics to monitor ethe ffects of pollution on populations: (*a*) *transcriptomics studies* have identified differential gene expression associated with pollutants such as heavy metals in the endangered freshwater mussel *Margaritifera margaritifera* herbicide glyphosate in the mussel *Mytilus galloprovincialis* and polycyclic aromatic hydrocarbons in the marbled crab *Pachygrapsus marmoratus*. (*b*) in applied work, *genomics* has facilitated evolutionary rescue of the Atlantic killifish (*Fundulus heteroclitus*) via introgression of pollutant-resistant genes from the Gulf killifish *Fundulus grandis* and (*c*) *metagenomics*, *metatranscriptomics* and *metabolomics* have helped characterize the response of microbial communities to

heavy metals, likewise their potential for bioremediation of oil spills.

- **Overwxploitaiton**: (*a*) *low-coverage whole-genome resequencing* was used to explore the genomic consequences of sizeselected fishing in Atlantic silversides in experimental conditions; (*b*) a combination of *whole-genome resequencing and SNP* (*single nucleotide polymorphisms*) *array genotyping* has been used to identify the presence of supergenes associated with persistence of the heavily fished Atlantic cod; (*c*) a target capture approach was used to characterize *historical genetic changes* associated with overexploitation in tiger sharks in Australia and (*d*) recent *High-Throughput Sequencing* (*HTS*) and associated *analytical tools* potentiate such demographic analyses by relying on a low number of individuals, and even on one single genome sequence. Moreover, this analysis has been used to characterize demographic changes associated with overexploitation in forest musk deer as well as in Atlantic cod.

- **Habitat loss and urbanisation**: (*a*) *genomics* has helped characterize population genetic structure in disturbed habitats in the tropical bee *Melipona subnitida*, as well as hybridization mediated by habitat disturbance in nontropical songbirds; (*b*) *transcriptomics* has helped reveal genes associated with heat tolerance in the neotropical lizard *Anolis cristatellus* adapted to urban environments; (*c*) *metagenomics* has also increasingly been used to changes in soil microbiome diversity associated with transition to monoculture in Indonesian rainforest, homogenization soil microbiome in urban environments and changes in the gut microbiome of urban-associated species such the ibis (*Eudocimus albus*) in southern Florida.

- **Invasive species**: (*a*) *metagenomics* is effective in the detection of both historical and ongoing invasions, such as in the case of the cane toad (*Rhinella marina*) in Australian islands, the rusty crayfish (*Orconectes rusticus*) in inland lakes in the United States and invasive gobies in Europe; (*b*) *Genome skimming using Oxford Nanopore Technologies (ONT)* has recently been used to discover hybridization between invasive and threatened marmoset species in Brazil; (*c*) *population genomics* have also been used to characterize the invasion history of the cane toad in North America and (*d*) *genomics* has helped assess the efficacy of lethal-control strategies campaigns for the black rat (*Rattus norvergicus*) invasion in Brasil.

Omics tools are revolutionizing our understanding about human impacts on biodiversity, by: (i) enhancing the **precision and standardization** of biodiversity metrics and their human-induced impacts; (ii) accelerating bioassessments through **data generation** within short timeframes and (iii) elucidating the **connections** between environmental disturbances and biodiversity responses. Their utilisation holds significance in anticipating how biodiversity will respond to environmental disturbances, enabling the formulation of strategies to effectively mitigate their impacts (De León et al., 2023).

Nevertheless, it is imperative to acknowledge and address significant challenges associated with their application: (i) **inaccessibility**: omics tools can be expensive for most biodiversity conservation programs, demanding specialized training, sophisticated algorithms and advanced computational infrastructure. This inaccessibility is particularly pronounced in economically disadvantaged, highly biodiverse regions; (ii) **biodiversity itself is a challenge**, underscored by the lag in species discovery compared to the accelerating rate of species loss; (iii) **integrated multi-omics approaches** hold potential, yet current studies tend to focus on single-omics approaches, limiting knowledge gains; (iv) **availability of historical data**, crucial for identifying biodiversity shifts, is often lacking in monitoring programs, especially in economically challenged tropical countries; and (v) **translation** of omics knowledge into effective policy and conservation practice remains extremely limited (De León et al., 2023).

4.2.3 The distance between genomic research and its practical translation in biodiversity conservation

Gaps exist in the translation of foundational genomic research to tangible applications in conservation. The scientific and policy-practitioner communities function within distinct spheres and the incorporation of genomics further widens this divide. Funding allocated to basic research institutions frequently diverges from the exigencies of frontline conservation efforts and proves efficacious for biodiversity preservation only when directed towards applied research initiatives (*see Fig. 14*: Shafer et al., 2015). Currently there are two largely separate spheres of applied and basic research.

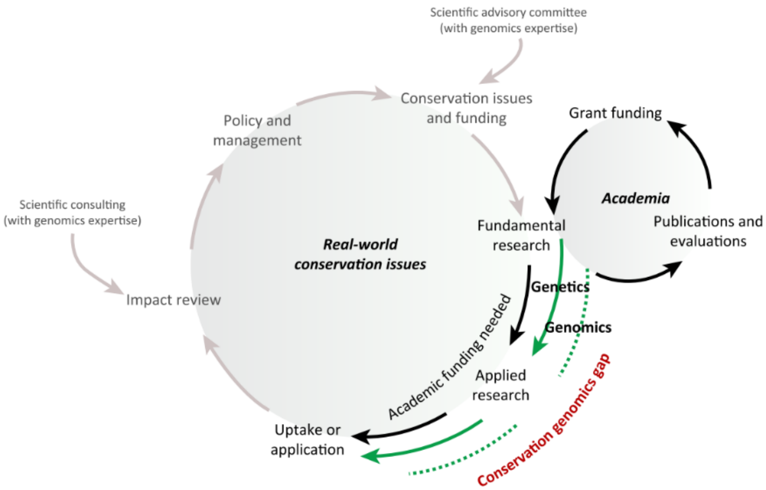

Figure 14 The challenging translation of conservation genomics research to conservation policy and action

The black lines represent basic research to applied workflow, with the green lines reflecting the extent to which conservation genetics and genomics currently fit into this scheme – note that conservation genetics has integrated into the applied sphere. The broken green line represents the gap we see between the academic groundwork readily embracing genomic technology and on-site conservation needs. The gray lines are reflective a larger emerging framework, where conservation questions directly fund conservation genomics research and feed into management and biodiversity policies.

4.3 Coupling Climate and Biodiversity Crises

Climate change, driven by anthropogenic activities like greenhouse gas emissions (including those from biodiversity loss), is causing temperatures to rise beyond levels seen in the era when human civilization first developed and spread globally. This leads to more frequent and severe extreme weather events, disrupting ecosystems, causing habitat loss for both humans and other species, and worsening the already significant biodiversity loss caused by human activities.

Both crises are coupled through dynamic interactions across scales. They diminish the benefits that nature provides to people, which are essential for maintaining well-being, supporting livelihoods, economies and development, as well as aiding in climate change adaptation and mitigation efforts.

Failing to act will make humans more vulnerable to problems like poverty, food shortages, displacement, political instability and conflict (Pörtner et al., 2023).

A paradigm shift towards a "**nexus approach**" in governance is advocated, shaping an elevated quality of life and supporting the juncture among human and ecosystem health. Such approach mandates the mainstreaming of biodiversity considerations into climate policy and conversely, the integration of climate-related facets into biodiversity policy (*see Figure 15*: Pörtner et al., 2023).

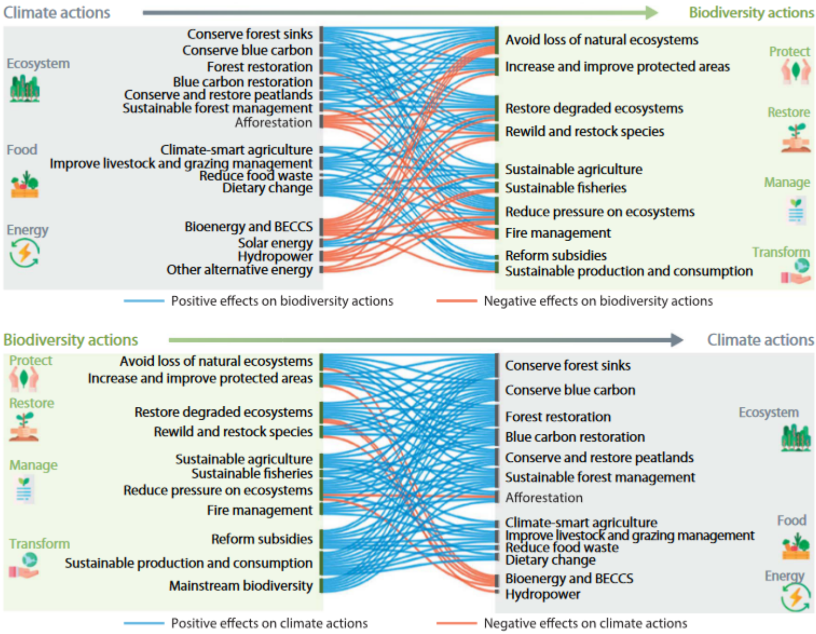

Figure 15 Positive and negative effects of the nexus approach

Biodiversity conservation and climate change mitigation actions that are well-managed and considered together tend to display more synergies than trade-offs (Pörtner et al., 2023). The most robust path to limiting climate change while safeguarding biodiversity depends on identifying the strongest win-win solutions by region and avoiding those with negative interactions (McElwee et al., 2020).

Although most actions to conserve biodiversity are positive or neutral for climate, some potential **climate mitigation and adaptation actions will have negative effects on biodiversity unless managed well**.

Devoting vast land areas globally to the production of biomass for bioenergy is integral to many mitigation scenarios, yet unintended negative side effects arise from their area requirements and competition for space, especially in terrestrial ecosystems, or from afforestation of natural grasslands. Projected CO_2 uptake rates through bioenergy or monoculture forest regrowth by 2050, which are similar in magnitude to double today's existing terrestrial carbon sink, are unrealistic. Relying on tree biomass for long-term carbon sequestration is risky, particularly in monocultures with high vulnerability to heat, drought, storms, fire, or pest outbreak (Pörtner et al., 2023).

Deployment of renewable energy infrastructure can substantially contribute to mitigation, but hydropower, solar and wind energy, and storage for these intermittent sources of energy can also have negative impacts on biodiversity if their scale and design are not carefully implemented (Pörtner et al., 2023).

Technological **mitigation**[4] measures can also exert harm to the environment and to biodiversity through the vast amount of materials required, such as metals or toxic waste products (Dhar et al., 2020).

Climate **adaptation**[5] policies can also incur large biodiversity impacts. For example, building sea walls to limit impacts of sea level rise on coastal

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[4] **Mitigation** actions aim to reduce emissions causing climate change (e.g.: sustainable transportation, clean energy supply, energy efficiency).

[5] **Adaptation** actions serve to manage the risk of climate change impacts (e.g.: upgrading infrastructures, building flood protection barriers).

infrastructure, adding irrigation capacity to reduce climate change impacts on agriculture, or introducing exotic tree species in anticipation of increasing climatic stress on forests impose substantial risks of large aggregate losses of biodiversity from these actions (Berry et al., 2015; Morecroft et al., 2019).

4.3.1 Circular Economy fitness to achieve Sustainability

Expanding circular economies are expected to reduce the net use of materials, enable reuse and avoid waste (OECD, 2019).

The implementation of Circular Economy approaches offers numerous opportunities (Stephenson and Damerell, 2022):

- Work, thinking and experience exist that can be built on.
- Sustainability is a topical, relevant and timely issue.
- Diverse and influential stakeholders are involved and engaged.
- Some indicators have been identified.
- The COVID-19 pandemic may create the stimulus for improving economic models.

Nonetheless, it faces some relevant difficulties (Stephenson and Damerell, 2022):

- Definitions are confused and unharmonized.
- Biodiversity is neglected in both models and proof of concept is lacking on how biodiversity will benefit.
- Many elements of society are excluded.

- Monitoring is weak with no use of biodiversity indicators.
- Inflated expectations of what each approach can achieve.
- Implementation is unharmonized and causes competition.
- Legal and organizational complexity across multiple sectors.
- Limited organizational and operational capacity for implementation.

The conceptualisation and realisation of sustainability is contingent upon the concerted efforts of the global community to delineate a more targeted agenda for Circular Economy, prioritising biodiversity and the well-being of local populations and marginalised communities (Stephenson and Damerell, 2022).

4.3 The Nexus thinking in the European Green Deal

Traditionally, the European Union (EU) has employed a compartmentalized or '**silo approach**' in addressing policy domains such as *Climate Change* (*CC*), *Biodiversity* (*BIO*) and the *Circular Economy* (*CE*). This strategy does not accurately capture the inherent interconnections among these diverse domains.

In contrast, the **European Green Deal** (**EGD**) stands out as an integrated growth strategy, making the EU environmental policy more consistent with the '**Nexus thinking**'.

The selected EGD documents scrutinised for checking their reciprocal synergies and trade-offs are presented in *Figure 16* (Paleari, 2024).

Policy domain	*EGD document*
CC	'Fit for 55' (EC, 2021a) Methane Emissions Reduction Strategy (EC, 2020a) REPower EU Plan (EC, 2022a) EU Save Energy Communication (EC, 2022b) EU Solar Strategy (EC, 2022c) Renovation Wave Initiative (EC, 2020b) Hydrogen Strategy (EC, 2020c) Strategy on offshore renewable energy (EC, 2020d) Strategy for Sustainable and Smart Mobility (EC, 2020e) Adaptation Strategy (EC, 2021b)
BIO	2030 Biodiversity Strategy (EC, 2020f) Soil Strategy (EC, 2021c) Forest Strategy (EC, 2021d) Action Plan for the development of organic farm production (EC, 2021e)
CE	Circular Economy Action Plan (EC, 2020g), Action Plan on sustainable and circular textiles (EC, 2022d)
Cross-cutting	Farm to Fork Strategy (EC, 2020i) Communication on the EU algae sector (EC, 2022k) Communication on a sustainable blue economy (EC, 2021i) Zero Pollution Action Plan (EC, 2021l) Chemicals strategy for sustainability (EC, 2020j) Communication on critical raw materials resilience (EC, 2020k)

Figure 16 Policy documents subject to the Nexus investigation

Synergies:

- **CC-BIO**
  - Carbon removals (by forests, soil, etc.) and carbon stock (wood).
  - Reducing methane emissions in agriculture and livestock (e.g. through increased recycling and biogas production).
  - Reducing the use of fertilizers.
  - Promoting organic farm production.
  - Implementing nature-based solutions.

- **CC-CE**
  - Higher circularity of carbon intensive sectors (e.g. food, textiles, construction).
  - Improving the recycling of critical raw materials.
  - Reducing the production of new vehicles (e.g. through shared mobility services).

- **BIO-CE**
  - Higher circularity of agriculture, the forest sector, and food systems.
  - Regenerative practices in agriculture, forestry and fishery.
  - Circular use of excavated soil and land.
  - Waste reduction measures (e.g. addressing food and plastic waste).

- **CC-BIO-CE**
  - Reducing resource extraction and processing (along with the related greenhouse gas emissions and impacts on biodiversity).
  - Improving water efficiency.
  - Fostering the production of RES/biofuels from biowaste and agriculture residues that cannot be recycled.

Trade-offs:

- **CC-BIO**
  - Biomass exploitation to produce renewable energy.
  - Development of certain innovative RES technologies (e.g. offshore renewable energy).

- Exploiting the potential of farmed seafood as an alternative source of protein (with a lower environmental footprint).

- **CC-CE**
  - ‘Substitution process’ triggered by boosting zero emission vehicles.
  - Impacts of buildings renovation on resource extraction and waste generation.

- **BIO-CE**
  - Extensive production/use of biomaterials and bioproducts from primary sources.

The obstacle to advancing the nexus approach lies significantly in *Governance*; it is crucial to perceive policy coherence not as an already finalised outcome, rather as an ongoing learning process (Paleari, 2024).

Committing to more profound transformative change necessitates: (i) the establishment of compelling incentives; (ii) comprehensive capacity building through widespread education and outreach initiatives; (iii) institutional modifications coupled with enhanced cooperation spanning sectors and jurisdictions and (iv) value realignments to uphold principles of intergenerational justice, equity and the inclusion of Indigenous peoples and local communities (Pörtner et al., 2023).

5 Conclusions and perspectives

This thesis addressed the urgent challenge of biodiversity loss within the broader context of corporate sustainability. The study commenced with a critical examination of the prevailing low prioritization of biodiversity in corporate surveys, highlighting the need for a comprehensive framework to elucidate the reciprocal influence between businesses and biodiversity. By grounding this framework in supply chain practices, the research contributed to a more complete understanding of effective biodiversity management.

The investigation further delved into the presently available BIA methods within the LCA context. The exploration of the omics revolution, spanning genomics, transcriptomics, proteomics, metabolomics and meta-omics, provided a forward-looking perspective on the potential of these tools for biodiversity impact assessment and conservation. Despite acknowledged limitations, integrating omics tools into global biodiversity was underscored as essential for informing policy and practice, elucidating the interconnected nature of human, ecosystem and planetary health. The recommendations for improvements in BIA methods should catalyse further research and development in this domain.

A critical juncture of the study involved an evaluation of bold policy interventions, specifically scrutinizing the Nexus-by-design approach within the European Green Deal (EGD). The integrated consideration of climate change, biodiversity and circular economy policies under this framework emerged as a focal point, with implications for transformative policies and interdisciplinary collaborations. Additionally, the study advocates for continued scrutiny and refinement of the Nexus-by-design approach in the

EGD, emphasizing the importance of adaptive governance in addressing the coupled biodiversity and climate crises.

It is hoped that the insights generated herein will contribute to a more sustainable future by fostering a deeper understanding of biodiversity management within the context of corporate sustainability.

Bibliography

Almond, R.E.A., Grooten, M., Peterson, T., 2020. Living Planet Report 2020 - Bending the curve of biodiversity loss. World Wildlife Fund, Gland, Switzerland.

Appleton, M.R., Courtiol, A., Emerton, L., Slade, J.L., Tilker, A., Warr, L.C., Malvido, M.Á., Barborak, J.R., de Bruin, L., Chapple, R., Daltry, J.C., Hadley, N.P., Jordan, C.A., Rousset, F., Singh, R., Sterling, E.J., Wessling, E.G., Long, B., 2022. Protected area personnel and ranger numbers are insufficient to deliver global expectations. Nat Sustain 5, 1100–1110. https://doi.org/10.1038/s41893-022-00970-0

Armenteras, D., Finlayson, M., Verschuuren, B., 2012. Chapter 5. Biodiversity. In UNEP. (Ed.), Global Environmental Outlook 5—Environment for the future we want. Progress Press Ltd.

Atkins, J., Maroun, W., 2018. Integrated extinction accounting and accountability: building an ark. Accounting, Auditing & Accountability Journal 31, 750–786. https://doi.org/10.1108/AAAJ-06-2017-2957

Bar-On, Y.M., Phillips, R., Milo, R., 2018. The biomass distribution on Earth. Proceedings of the National Academy of Sciences 115, 6506–6511. https://doi.org/10.1073/pnas.1711842115

Beale, D.J., Jones, O.A.H., Bose, U., Broadbent, J.A., Walsh, T.K., Van De Kamp, J., Bissett, A., 2022. Omics-based ecosurveillance for the assessment of ecosystem function, health, and resilience. Emerging Topics in Life Sciences 6, 185–199. https://doi.org/10.1042/ETLS20210261

Berry, P.M., Brown, S., Chen, M., Kontogianni, A., Rowlands, O., Simpson, G., Skourtos, M., 2015. Cross-sectoral interactions of adaptation and mitigation measures. Climatic Change 128, 381–393. https://doi.org/10.1007/s10584-014-1214-0

Blanco-Zaitegi, G., Álvarez Etxeberria, I., Moneva, J.M., 2022. Biodiversity accounting and reporting: A systematic literature review and bibliometric analysis. Journal of Cleaner Production 371, 133677. https://doi.org/10.1016/j.jclepro.2022.133677

Boiral, O., 2016. Accounting for the Unaccountable: Biodiversity Reporting and Impression Management. J Bus Ethics 135, 751–768. https://doi.org/10.1007/s10551-014-2497-9

CBD, 2020. Aichi Biodiversity Targets [WWW Document]. Convention on Biological Diversity, CBD. URL https://www.cbd.int/sp/targets/ (accessed 12.22.23).

Ceballos, G., Ehrlich, P.R., Barnosky, A.D., García, A., Pringle, R.M., Palmer, T.M., 2015. Accelerated modern human–induced species losses: Entering the sixth mass extinction. Sci. Adv. 1, e1400253. https://doi.org/10.1126/sciadv.1400253

Ceballos, G., Ehrlich, P.R., Dirzo, R., 2017. Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. Proceedings of the National Academy of Sciences 114, E6089–E6096. https://doi.org/10.1073/pnas.1704949114

Chen, Y.-J., Leung, P.M., Wood, J.L., Bay, S.K., Hugenholtz, P., Kessler, A.J., Shelley, G., Waite, D.W., Franks, A.E., Cook, P.L.M., Greening, C., 2021. Metabolic flexibility allows bacterial habitat generalists to become dominant in a frequently disturbed ecosystem. The ISME Journal 15, 2986–3004. https://doi.org/10.1038/s41396-021-00988-w

Cleves, P.A., Tinoco, A.I., Bradford, J., Perrin, D., Bay, L.K., Pringle, J.R., 2020. Reduced thermal tolerance in a coral carrying CRISPR-induced mutations in the gene for a heat-shock transcription factor. Proceedings of the National Academy of Sciences 117, 28899–28905. https://doi.org/10.1073/pnas.1920779117

Crenna, E., Marques, A., La Notte, A., Sala, S., 2020. Biodiversity Assessment of Value Chains: State of the Art and Emerging Challenges. Environ. Sci. Technol. 54, 9715–9728. https://doi.org/10.1021/acs.est.9b05153

Crist, E., Mora, C., Engelman, R., 2017. The interaction of human population, food production, and biodiversity protection. Science 356, 260–264. https://doi.org/10.1126/science.aal2011

Cuckston, T., 2018. Creating financial value for tropical forests by disentangling people from nature. Accounting Forum 42, 219–234. https://doi.org/10.1016/j.accfor.2018.07.001

Dal Grande, F., 2023. Introduction to Biodiversity [WWW Document]. URL https://stem.elearning.unipd.it/mod/kalvidres/view.php?id=294090 (accessed 12.18.23).

Damiani, M., Sinkko, T., Caldeira, C., Tosches, D., Robuchon, M., Sala, S., 2023. Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context. Environmental Impact Assessment Review 101, 107134. https://doi.org/10.1016/j.eiar.2023.107134

Davis-Peccoud, J., Murray, E., Morrison, A., Seemann, A., 2023. The Nature and Biodiversity Playbook for Business [WWW Document]. Bain.

URL https://www.bain.com/insights/the-nature-and-biodiversity-playbook-for-business/ (accessed 2.9.24).
de Groot, R.S., Wilson, M.A., Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecological Economics 41, 393–408. https://doi.org/10.1016/S0921-8009(02)00089-7
De León, L.F., Silva, B., Avilés-Rodríguez, K.J., Buitrago-Rosas, D., 2023. Harnessing the omics revolution to address the global biodiversity crisis. Current Opinion in Biotechnology 80, 102901. https://doi.org/10.1016/j.copbio.2023.102901
De Vos, J.M., Joppa, L.N., Gittleman, J.L., Stephens, P.R., Pimm, S.L., 2015. Estimating the normal background rate of species extinction. Conservation Biology 29, 452–462. https://doi.org/10.1111/cobi.12380
Descio, C., Crabbendam, N., 2022. The EU Taxonomy explained – Here's what it means for your company [WWW Document]. https://www.carbontrust.com/news-and-insights/insights/the-eu-taxonomy-explained-heres-what-it-means-for-your-company. URL https://www.carbontrust.com/news-and-insights/insights/the-eu-taxonomy-explained-heres-what-it-means-for-your-company (accessed 12.21.23).
Dhar, A., Naeth, M.A., Jennings, P.D., Gamal El-Din, M., 2020. Perspectives on environmental impacts and a land reclamation strategy for solar and wind energy systems. Science of The Total Environment 718, 134602. https://doi.org/10.1016/j.scitotenv.2019.134602
Diaz, S., Tilman, D., Fargione, J., Chapin III, F.S., Dirzo, R., Kitzberger, T., Gemmill-Herren, B., Zobel, M., Mitchell, C., Wilby, A., Daily, G., Galetti, M., 2015. Biodiversity Regulation of Ecosystem Services.
Dougherty, M.M., Larson, E.R., Renshaw, M.A., Gantz, C.A., Egan, S.P., Erickson, D.M., Lodge, D.M., 2016. Environmental DNA (eDNA) detects the invasive rusty crayfish Orconectes rusticus at low abundances. Journal of Applied Ecology 53, 722–732. https://doi.org/10.1111/1365-2664.12621
EFRAG (European Financial Reporting Advisory Group), 2022. First Set of draft ESRS - EFRAG [WWW Document]. URL https://www.efrag.org/lab6# (accessed 12.7.23).
European Commission, 2023. The Commission adopts the European Sustainability Reporting Standards - European Commission [WWW Document]. URL https://finance.ec.europa.eu/news/commission-adopts-european-sustainability-reporting-standards-2023-07-31_en (accessed 2.14.24).

Formenti, G., Theissinger, K., Fernandes, C., Bista, I., Bombarely, A., Bleidorn, C., Ciofi, C., Crottini, A., Godoy, J.A., Höglund, J., Malukiewicz, J., Mouton, A., Oomen, R.A., Paez, S., Palsbøll, P.J., Pampoulie, C., Ruiz-López, María J., Svardal, H., Theofanopoulou, C., de Vries, J., Waldvogel, A.-M., Zhang, Guojie, Mazzoni, C.J., Jarvis, E.D., Bálint, M., Formenti, G., Theissinger, K., Fernandes, C., Bista, I., Bombarely, A., Bleidorn, C., Čiampor, F., Ciofi, C., Crottini, A., Godoy, J.A., Hoglund, J., Malukiewicz, J., Mouton, A., Oomen, R.A., Paez, S., Palsbøll, P., Pampoulie, C., Ruiz-López, María José, Svardal, H., Theofanopoulou, C., de Vries, J., Waldvogel, A.-M., Zhang, Goujie, Mazzoni, C.J., Jarvis, E., Bálint, M., Aghayan, S.A., Alioto, T.S., Almudi, I., Alvarez, N., Alves, P.C., Amorim, I.R., Antunes, A., Arribas, P., Baldrian, P., Berg, P.R., Bertorelle, G., Böhne, A., Bonisoli-Alquati, A., Boštjančić, L.L., Boussau, B., Breton, C.M., Buzan, E., Campos, P.F., Carreras, C., Castro, L.Fi., Chueca, L.J., Conti, E., Cook-Deegan, R., Croll, D., Cunha, M.V., Delsuc, F., Dennis, A.B., Dimitrov, D., Faria, R., Favre, A., Fedrigo, O.D., Fernández, R., Ficetola, G.F., Flot, J.-F., Gabaldón, T., Galea Agius, D.R., Gallo, G.R., Giani, A.M., Gilbert, M.T.P., Grebenc, T., Guschanski, K., Guyot, R., Hausdorf, B., Hawlitschek, O., Heintzman, P.D., Heinze, B., Hiller, M., Husemann, M., Iannucci, A., Irisarri, I., Jakobsen, K.S., Jentoft, S., Klinga, P., Kloch, A., Kratochwil, C.F., Kusche, H., Layton, K.K.S., Leonard, J.A., Lerat, E., Liti, G., Manousaki, T., Marques-Bonet, T., Matos-Maraví, P., Matschiner, M., Maumus, F., Mc Cartney, A.M., Meiri, S., Melo-Ferreira, J., Mengual, X., Monaghan, M.T., Montagna, M., Mysłajek, R.W., Neiber, M.T., Nicolas, V., Novo, M., Ozretić, P., Palero, F., Pârvulescu, L., Pascual, M., Paulo, O.S., Pavlek, M., Pegueroles, C., Pellissier, L., Pesole, G., Primmer, C.R., Riesgo, A., Rüber, L., Rubolini, D., Salvi, D., Seehausen, O., Seidel, M., Secomandi, S., Studer, B., Theodoridis, S., Thines, M., Urban, L., Vasemägi, A., Vella, A., Vella, N., Vernes, S.C., Vernesi, C., Vieites, D.R., Waterhouse, R.M., Wheat, C.W., Wörheide, G., Wurm, Y., Zammit, G., 2022. The era of reference genomes in conservation genomics. Trends in Ecology & Evolution 37, 197–202. https://doi.org/10.1016/j.tree.2021.11.008

Gavron, S., 2023. Supporting ESRS E4 Requirements - Endangered Wildlife OÜ. URL https://endangeredwild.life/2023/09/19/supporting-esrs-e4-requirements/ (accessed 2.14.24).

Geist, J.A., Mancuso, J.L., Morin, M.M., Bommarito, K.P., Bovee, E.N., Wendell, D., Burroughs, B., Luttenton, M.R., Strayer, D.L., Tiegs, S.D., 2022. The New Zealand mud snail (Potamopyrgus antipodarum): autecology and management of a global invader. Biol Invasions 24, 905–938. https://doi.org/10.1007/s10530-021-02681-7

Gibassier, D., Maas, K., Schaltegger, S., 2019. Special issue of business, strategy, and the environment call for papers business, society, biodiversity, and natural capital deadline June 30, 2020 (see details of conference/workshop at the end of the call for paper). Business Strategy and the Environment 28, 921–924. https://doi.org/10.1002/bse.2348

Ha, M., Schleiger, R., 2020. ASCCC Open Educational Resources Initiative [WWW Document]. Biology LibreTexts. URL https://bio.libretexts.org/Bookshelves/Ecology/Environmental_Science_(Ha_and_Schleiger)/03%3A_Conservation/3.01%3A_The_Value_of_Biodiversity/3.1.02%3A_Species_Diversity (accessed 2.14.24).

Hairston Jr, N.G., Ellner, S.P., Geber, M.A., Yoshida, T., Fox, J.A., 2005. Rapid evolution and the convergence of ecological and evolutionary time. Ecology Letters 8, 1114–1127. https://doi.org/10.1111/j.1461-0248.2005.00812.x

Hermoso, V., Carvalho, S.B., Giakoumi, S., Goldsborough, D., Katsanevakis, S., Leontiou, S., Markantonatou, V., Rumes, B., Vogiatzakis, I.N., Yates, K.L., 2022. The EU Biodiversity Strategy for 2030: Opportunities and challenges on the path towards biodiversity recovery. Environmental Science & Policy 127, 263–271. https://doi.org/10.1016/j.envsci.2021.10.028

Heuertz, M., Carvalho, S.B., Galindo, J., Rinkevich, B., Robakowski, P., Aavik, T., Altinok, I., Barth, J.M.I., Cotrim, H., Goessen, R., González-Martínez, S.C., Grebenc, T., Hoban, S., Kopatz, A., McMahon, B.J., Porth, I., Raeymaekers, J.A.M., Träger, S., Valdecantos, A., Vella, A., Vernesi, C., Garnier-Géré, P., 2023. The application gap: Genomics for biodiversity and ecosystem service management. Biological Conservation 278, 109883. https://doi.org/10.1016/j.biocon.2022.109883

IBAT Alliance, 2022. Integrated Biodiversity Assessment Tool (IBAT) [WWW Document]. Integrated Biodiversity Assessment Tool (IBAT). URL https://www.ibat-alliance.org (accessed 12.7.23).

IPBES, 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Zenodo. https://doi.org/10.5281/zenodo.6417333

Jones, M.J., Solomon, J.F., 2013. Problematising accounting for biodiversity. Accounting, Auditing & Accountability Journal 26, 668–687. https://doi.org/10.1108/AAAJ-03-2013-1255
Kennedy, S., Fuchs, M., Van Ingen, W., Schoenmaker, D., 2023. A resilience approach to corporate biodiversity impact measurement. Bus Strat Env 32, 2567–2582. https://doi.org/10.1002/bse.3140
Leigh, D.M., Hendry, A.P., Vázquez-Domínguez, E., Friesen, V.L., 2019. Estimated six per cent loss of genetic variation in wild populations since the industrial revolution. Evolutionary Applications 12, 1505–1512. https://doi.org/10.1111/eva.12810
Marelli, A., Diener, A., Noe, G., 2023. Everything businesses need to know about the EU's Corporate Sustainability Reporting Directive (CSRD). Quantis. URL https://quantis.com/news/business-implications-eu-corporate-sustainability-reporting-directive-csrd/ (accessed 2.14.24).
Martiny, A.C., Treseder, K., Pusch, G., 2013. Phylogenetic conservatism of functional traits in microorganisms. The ISME Journal 7, 830–838. https://doi.org/10.1038/ismej.2012.160
Maunders, K.T., Burritt, R.L., 1991. Accounting and Ecological Crisis. Accounting, Auditing & Accountability Journal 4, 0–0. https://doi.org/10.1108/09513579110003277
Maxwell, S.L., Cazalis, V., Dudley, N., Hoffmann, M., Rodrigues, A.S.L., Stolton, S., Visconti, P., Woodley, S., Kingston, N., Lewis, E., Maron, M., Strassburg, B.B.N., Wenger, A., Jonas, H.D., Venter, O., Watson, J.E.M., 2020. Area-based conservation in the twenty-first century. Nature 586, 217–227. https://doi.org/10.1038/s41586-020-2773-z
McCauley, D.J., Hardesty-Moore, M., Halpern, B.S., Young, H.S., 2017. A mammoth undertaking: harnessing insight from functional ecology to shape de-extinction priority setting. Functional Ecology 31, 1003–1011. https://doi.org/10.1111/1365-2435.12728
McElwee, P., Calvin, K., Campbell, D., Cherubini, F., Grassi, G., Korotkov, V., Le Hoang, A., Lwasa, S., Nkem, J., Nkonya, E., Saigusa, N., Soussana, J.-F., Taboada, M.A., Manning, F., Nampanzira, D., Smith, P., 2020. The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN Sustainable Development Goals. Global Change Biology 26, 4691–4721. https://doi.org/10.1111/gcb.15219
Millennium Ecosystem Assessment (MA), 2005. Ecosystems and Human Well-being: A Framework for Assessment.

Minter, M., Nielsen, E., Blyth, C., Bertola, L.D., Kantar, M.B., Morales, H.E., Orland, C., Segelbacher, G., Leigh, D.M., 2021. What Is Genetic Diversity and Why Does it Matter? [WWW Document]. Frontiers for Young Minds. URL https://kids.frontiersin.org/articles/10.3389/frym.2021.656168 (accessed 2.14.24).
Morecroft, M.D., Duffield, S., Harley, M., Pearce-Higgins, J.W., Stevens, N., Watts, O., Whitaker, J., 2019. Measuring the success of climate change adaptation and mitigation in terrestrial ecosystems. Science 366, eaaw9256. https://doi.org/10.1126/science.aaw9256
Naess, A., 1973. The shallow and the deep, long-range ecology movement. A summary∗. Inquiry 16, 95–100. https://doi.org/10.1080/00201747308601682
Natural Capital Finance Alliance. & UNEP-WCMC, 2022. ENCORE [WWW Document]. ENCORE. URL https://encorenature.org/en (accessed 12.7.23).
New England Primate Conservancy, 2023. BIODIVERSITY: Ecosystem Diversity - New England Primate Conservancy [WWW Document]. URL https://neprimateconservancy.org/biodiversity-ecosystem-diversity/ (accessed 2.14.24).
OECD, 2019. Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences. Organisation for Economic Co-operation and Development, Paris.
Oppen, M.J.H. van, Coleman, M.A., 2022. Advancing the protection of marine life through genomics. PLOS Biology 20, e3001801. https://doi.org/10.1371/journal.pbio.3001801
Paleari, S., 2024. The EU policy on climate change, biodiversity and circular economy: Moving towards a Nexus approach. Environmental Science & Policy 151, 103603. https://doi.org/10.1016/j.envsci.2023.103603
Panwar, R., Ober, H., Pinkse, J., 2023. The uncomfortable relationship between business and biodiversity: Advancing research on business strategies for biodiversity protection. Bus Strat Env 32, 2554–2566. https://doi.org/10.1002/bse.3139
Peterson, B.K., Weber, J.N., Kay, E.H., Fisher, H.S., Hoekstra, H.E., 2012. Double Digest RADseq: An Inexpensive Method for De Novo SNP Discovery and Genotyping in Model and Non-Model Species. PLOS ONE 7, e37135. https://doi.org/10.1371/journal.pone.0037135
Pörtner, H.-O., Scholes, R.J., Arneth, A., Barnes, D.K.A., Burrows, M.T., Diamond, S.E., Duarte, C.M., Kiessling, W., Leadley, P., Managi, S., McElwee, P., Midgley, G., Ngo, H.T., Obura, D., Pascual, U.,

Sankaran, M., Shin, Y.J., Val, A.L., 2023. Overcoming the coupled climate and biodiversity crises and their societal impacts. Science 380, eabl4881. https://doi.org/10.1126/science.abl4881

Rajora, O.P. (Ed.), 2019. Population Genomics: Concepts, Approaches and Applications, Population Genomics. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-04589-0

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S.E., Donges, J.F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., Feulner, G., Fiedler, S., Gerten, D., Gleeson, T., Hofmann, M., Huiskamp, W., Kummu, M., Mohan, C., Nogués-Bravo, D., Petri, S., Porkka, M., Rahmstorf, S., Schaphoff, S., Thonicke, K., Tobian, A., Virkki, V., Wang-Erlandsson, L., Weber, L., Rockström, J., 2023. Earth beyond six of nine planetary boundaries. Science Advances 9, eadh2458. https://doi.org/10.1126/sciadv.adh2458

Rossetto, M., Yap, J.-Y.S., Lemmon, J., Bain, D., Bragg, J., Hogbin, P., Gallagher, R., Rutherford, S., Summerell, B., Wilson, T.C., 2021. A conservation genomics workflow to guide practical management actions. Global Ecology and Conservation 26, e01492. https://doi.org/10.1016/j.gecco.2021.e01492

Salmi, A., Quarshie, A.M., Scott-Kennel, J., Kähkönen, A.-K., 2023. Biodiversity management: A supply chain practice view. Journal of Purchasing and Supply Management 29, 100865. https://doi.org/10.1016/j.pursup.2023.100865

Samkin, G., Schneider, A., Tappin, D., 2014. Developing a reporting and evaluation framework for biodiversity. Accounting, Auditing & Accountability Journal 27, 527–562. https://doi.org/10.1108/AAAJ-10-2013-1496

SBTN (Science Based Targets Network), 2020. AR3T [WWW Document]. Science Based Targets Network. URL https://sciencebasedtargetsnetwork.org/how-it-works/act/ (accessed 12.7.23).

Schaltegger, S., Gibassier, D., Maas, K., 2023. Managing and accounting for corporate biodiversity contributions. Mapping the field. Bus Strat Env 32, 2544–2553. https://doi.org/10.1002/bse.3166

Shafer, A.B.A., Wolf, J.B.W., Alves, P.C., Bergström, L., Bruford, M.W., Brännström, I., Colling, G., Dalén, L., De Meester, L., Ekblom, R., Fawcett, K.D., Fior, S., Hajibabaei, M., Hill, J.A., Hoezel, A.R., Höglund, J., Jensen, E.L., Krause, J., Kristensen, T.N., Krützen, M., McKay, J.K., Norman, A.J., Ogden, R., Österling, E.M., Ouborg, N.J., Piccolo, J., Popović, D., Primmer, C.R., Reed, F.A., Roumet, M., Salmona, J., Schenekar, T., Schwartz, M.K., Segelbacher, G.,

Senn, H., Thaulow, J., Valtonen, M., Veale, A., Vergeer, P., Vijay, N., Vilà, C., Weissensteiner, M., Wennerström, L., Wheat, C.W., Zieliński, P., 2015. Genomics and the challenging translation into conservation practice. Trends in Ecology & Evolution 30, 78–87. https://doi.org/10.1016/j.tree.2014.11.009
Sharma, P., Singh, S.P., Iqbal, H.M.N., Tong, Y.W., 2022. Omics approaches in bioremediation of environmental contaminants: An integrated approach for environmental safety and sustainability. Environmental Research 211, 113102. https://doi.org/10.1016/j.envres.2022.113102
Sobkowiak, M., Cuckston, T., Thomson, I., 2020. Framing sustainable development challenges: accounting for SDG-15 in the UK. Accounting, Auditing & Accountability Journal 33, 1671–1703. https://doi.org/10.1108/AAAJ-01-2019-3810
Stephenson, P.J., Damerell, A., 2022. Bioeconomy and Circular Economy Approaches Need to Enhance the Focus on Biodiversity to Achieve Sustainability. Sustainability 14, 10643. https://doi.org/10.3390/su141710643
Taskforce on Nature-related Financial Disclosures (TNFD) Recommendations – TNFD [WWW Document], 2023. URL https://tnfd.global/publication/recommendations-of-the-taskforce-on-nature-related-financial-disclosures/ (accessed 12.7.23).
Tsujimura, A., Yasojima, K., Kuboki, Y., Suzuki, A., Ueno, N., Shiokawa, K., Hashimotogotoh, T., 1995. Developmental and Differential Regulations in Gene Expression of *Xenopus* Pleiotropic Factors-α and -β. Biochemical and Biophysical Research Communications 214, 432–439. https://doi.org/10.1006/bbrc.1995.2305
UNEP, U.N.E.P., 2022. UN Biodiversity Conference (COP 15) [WWW Document]. UNEP - UN Environment Programme. URL http://www.unep.org/un-biodiversity-conference-cop-15 (accessed 12.22.23).
United Nations, 2013. The Convention on Biological Diversity. Secretariat of the Convention on Biological Diversity.
Violle, C., Navas, M.-L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I., Garnier, E., 2007. Let the concept of trait be functional! Oikos 116, 882–892. https://doi.org/10.1111/j.0030-1299.2007.15559.x
Vitorino, L.C., Bessa, L.A., 2018. Microbial Diversity: The Gap between the Estimated and the Known. Diversity 10, 46. https://doi.org/10.3390/d10020046
von Thaden, A., Nowak, C., Tiesmeyer, A., Reiners, T.E., Alves, P.C., Lyons, L.A., Mattucci, F., Randi, E., Cragnolini, M., Galián, J., Hegyeli, Z.,

Kitchener, A.C., Lambinet, C., Lucas, J.M., Mölich, T., Ramos, L., Schockert, V., Cocchiararo, B., 2020. Applying genomic data in wildlife monitoring: Development guidelines for genotyping degraded samples with reduced single nucleotide polymorphism panels. Molecular Ecology Resources 20, 662–680. https://doi.org/10.1111/1755-0998.13136

WEF, 2022. Global Risks Report 2022 [WWW Document]. World Economic Forum. URL https://www.weforum.org/publications/global-risks-report-2022/ (accessed 12.13.23).

Whitham, T.G., Bailey, J.K., Schweitzer, J.A., Shuster, S.M., Bangert, R.K., LeRoy, C.J., Lonsdorf, E.V., Allan, G.J., DiFazio, S.P., Potts, B.M., Fischer, D.G., Gehring, C.A., Lindroth, R.L., Marks, J.C., Hart, S.C., Wimp, G.M., Wooley, S.C., 2006. A framework for community and ecosystem genetics: from genes to ecosystems. Nat Rev Genet 7, 510–523. https://doi.org/10.1038/nrg1877

Winter, L., Pflugmacher, S., Berger, M., Finkbeiner, M., 2018. Biodiversity impact assessment (BIA+) – methodological framework for screening biodiversity. Integr Envir Assess & Manag 14, 282–297. https://doi.org/10.1002/ieam.2006

Wood, G., Marzinelli, E.M., Vergés, A., Campbell, A.H., Steinberg, P.D., Coleman, M.A., 2020. Using genomics to design and evaluate the performance of underwater forest restoration. Journal of Applied Ecology 57, 1988–1998. https://doi.org/10.1111/1365-2664.13707

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