

A systemic model of the relationships between companies, biodiversity, and ecosystems to manage the environmental performance¹

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Abstract

Biodiversity loss and ecosystem collapse are major threats to humankind's well-being and companies are facing increasing attention – and normative pressure – to consider their impacts on and dependencies on biodiversity and ecosystems. However, it is not easy to understand the complex relationship occurring between business activities, biodiversity, and ecosystems. Therefore, this research constructs a systemic model to comprehend such a relationship and breaks it up into simpler and manageable components. The research adopts an interventionist methodology in which the researchers undertook a literature review followed by focus groups with experts and companies to co-develop the systemic model. The final model identifies and classifies sixteen types of impacts that companies have on biodiversity grouped into five main drivers: ecosystem use change, over-exploitation, invasive alien species, pollution, and climate change. Moreover, the model identifies and classifies twenty-four ecosystem services grouped into three main categories: provisioning services, maintaining and regulating services, and immaterial and cultural services. This research contributes to management control research and practice by proposing a model that could help companies value, manage, monitor, and account for a complex phenomenon – the relationship between companies, biodiversity, and ecosystems – by breaking it up into simpler, clearer, and more manageable components.

Keywords: biodiversity; ecosystem; impact; dependency; interventionist research; systemic model.

1. Introduction

Over the last twenty years, the relationship between companies and natural capital has become increasingly important importance from economic and social viewpoints. On the one hand, accounting research highlights how companies need to be vigilant and fast in adapting their activities towards sustainable production that meets changing customers' demands (Miolo Vitali, 1978; Coda, 2010; D' Onza, 2022; Mio, 2021), avoid communicating an environmental performance that is not backed up by reality (Lai et al., 2016; Melloni et al., 2016; Testa et al., 2020), and capture the potential deriving from technological and business model eco-innovations (Porter & van der Linde, 1995; Olivotto, 2022; Torelli & Balluchi, 2022). On the other hand, we observe growing institutional and

¹ Paper presented at MSAR 2024 - Manufacturing & Service Accounting Research Conference - Aarhus, Denmark, June 19-21, 2024

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regulatory pressure to measure, manage, and disclose a company's impacts on natural capital (Doni et al., 2020; Pigatto et al., 2022; Busco et al., 2024). In this context, companies are struggling to understand the relationship between their activities and the loss of biodiversity and ecosystem collapse (Corvino et al., 2021; Doni et al., 2022). Such a specific take on business sustainability and biodiversity loss is still in its infancy but is gaining traction among other sustainability perspectives (Bebbington et al., 2021; Laine et al., 2022).

In recent decades, there has been a deterioration of biodiversity and ecosystems at a global level symbolized by the increase in animal and plant species at risk of global extinction (IUCN, 2023; Atkins & Maroun, 2018) and the destruction of natural habitats (IPBES, 2019; Jaureguiberry et al., 2022). Such a deterioration – the sixth mass extinction (Laine et al., 2022) – is also a consequence of anthropic economic and corporate activities that lead to negative socio-economic repercussions (IPBES, 2019; Sun et al., 2022). In fact, the World Economic Forum ranks biodiversity loss and ecosystem collapse as the third most serious risk that businesses and society will face in the coming years (WEF, 2024). Furthermore, more than half of the world's economic output depends on ecosystems and their services and some sectors such as forestry and agri-food are highly dependent on such services (WEF, 2020, 2023; Vysna et al., 2021).

Understanding the relationship between companies, biodiversity, and ecosystems is a crucial issue since it addresses the possibility of the world's future life. On the one hand, companies affect biodiversity by exploiting natural resources or polluting therefore generating "impacts". On the other hand, companies receive "services" from biodiversity and ecosystems such as the service of supplying raw materials and fertile land therefore creating "dependencies" (Carvalho et al., 2022; Sun et al., 2022). From a business perspective, it is particularly complex to valorise and disclose the value of biodiversity and ecosystems as well as the impact on biodiversity, the functioning of ecosystems, and species extinctions (Corvino et al., 2021; Atkins & Maroun, 2018). However, these topics are essential for the development of corporate sustainability strategies and open up space for research on possible performance measurements that support the decisions, actions, and disclosure of the results obtained. To address such complexity, this paper proposes a systemic model to assess the relationship between a company, biodiversity, and ecosystems that identifies and classifies the impacts and dependencies that underlie said relationship (Houdet et al., 2012; Addison et al., 2020).

The impact-dependency model was developed in two phases. First, an initial literature review of mainly a non-academic nature (so-called *gray* literature) provides the state of the art of the impact-dependency relationship (Morgan, 1996). Second, focus groups with experts and companies detail the model and streamline it for adoption by companies.

The model is composed by a classification of sixteen types of corporate impacts on biodiversity and ecosystems grouped into five primary drivers: sea/land use change, overexploitation, introduction of invasive alien species, pollution, and climate change (IPBES, 2019; Jaureguiberry et al., 2022). Furthermore, the model comprises twenty-four types of ecosystem services grouped into three main categories: provisioning services, maintenance and regulating services, and immaterial and cultural services (Haines-Young & Potschin, 2018; Dasgupta, 2021).

Along with the model construction, which is the main aim of the research, we discuss how the model aligns with the double materiality concept as enunciated by the recent European Corporate Sustainability Reporting Directive - CSRD (European Parliament, 2022; Cooper & Michelon, 2022). Furthermore, we highlights the criticalities underlying the relationship between companies, biodiversity, and ecosystems such as the identification of corporate and extra-corporate responsibilities for the deterioration of ecosystems, and the temporal and geographical specificity of impacts and dependencies.

Despite such critical issues, the proposed model represents a starting point for a company that wants to begin evaluating, managing, monitoring, and reporting its “impacts on” and “dependencies from” natural capital. In fact, without a methodologically robust classification of what the impacts and dependencies of a company are, it is very complex to identify those to be measured and acted upon. Furthermore, the model may also be suitable for planning, measuring, and controlling those risks coming from the deterioration of dependencies on natural capital. Therefore, the model is helpful to expand the "internal-external" governance perspective to link external reporting with the information collected for internal management purposes (Raar et al., 2020).

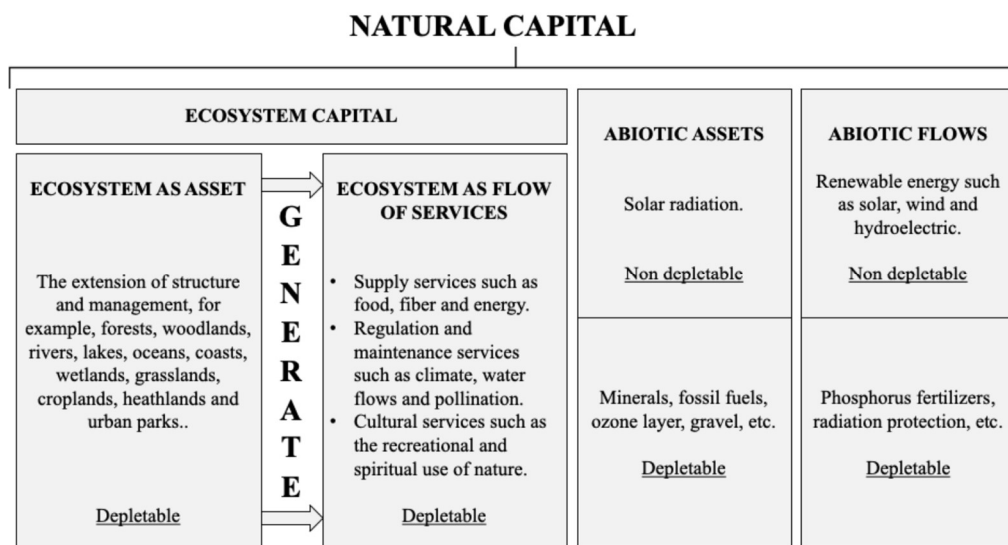
The paper is structured as follows. Section 2 illustrates the context from which the research originates and explains why issues related to biodiversity and ecosystems are relevant for businesses. Section 3 describes the steps followed by researchers to develop the systemic impact and dependencies model. Section 4 discusses the model and its main criticalities. Finally, Section 5 concludes the article delving into the contributions and limitations of the research.

2. Biodiversity, Ecosystem Services, and Businesses

Biodiversity is first and foremost an essential part of the so-called "natural capital" (Figure 1), which includes all living and non-living resources such as soil, vegetation, animals, and water (Fleming et al., 2022; Haines-Young & Potschin, 2018). In practical terms, biodiversity combines with non-living (abiotic) elements to form ecosystems such as forests, farmlands, coasts, oceans, and urban parks. Therefore, there is a causal relationship between the health status of biodiversity and the productivity - that is considered as the ability to generate biomass - of ecosystems and natural capital (Dasgupta,

2021; UN, 2021) which, through ecosystem services, are critical to ensuring a good quality of life for humans (IPBES, 2019). Ecosystems are functional to humans and provide various services to humans, businesses, and society at large: provisioning services such as food, clean water, and energy; regulating and maintaining services such as climate regulation, pollination, and soil fertility; and cultural services with spiritual, aesthetic, religious and recreational value (Dasgupta, 2021; Haines-Young & Potschin, 2018). In general, ecosystem services are "benefits that we receive from nature and that are the basis of our economies and well-being" (Maes et al., 2020, p. 360).

Figure 1 – Main components of Natural Capital



Source: Adapted from Haines-Young and Potschin (2018, p. 6)

Moreover, as highlighted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019), there is a reciprocal relationship between the development of anthropic activities and nature. In particular, the social (human) component and the ecological elements co-exist, co-evolve, and co-depend on each other. The interaction between humans and nature generates a feedback system (IPBES, 2019).

While ecosystems provide well-being for humankind through their services, anthropic activities also have the capacity to influence the state of biodiversity and ecosystems by determining their productivity in terms of services generated. In particular, human activities impact nature through five categories of direct drivers: ecosystem land-use change, over-exploitation of natural resources, pollution, climate change, and invasive alien species (IPBES, 2019).

The negative impact of human activities on biodiversity and ecosystems has suffered an acceleration with the spread of the Industrial Revolution in a way that we consider the historical period we are living through as the sixth mass extinction (Laine et al., 2022). This acceleration, which continued throughout the 20th century, has led to a dramatic situation of the present day in which some habitats

have lost more than 90% of their extension in Europe and North America (IPBES, 2019). Furthermore, the global rate of species extinction is accelerating, and estimated that already 1% of vertebrates have gone extinct in the last five hundred years which is undoubtedly underestimated (IPBES, 2019; IUCN, 2023). In addition, the average percentage of animal and plant species at risk of global extinction is around 28% (IUCN, 2023). As a result, the deterioration of biodiversity and ecosystems negatively affects the ability to generate services such as pollination, regulation of soil, water, and air quality, and maintenance of habitats (IPBES, 2019).

The deterioration of biodiversity and ecosystems - although not entirely dependent on human actions (IPBES, 2019) - has a strong connection with anthropic activities, which include the production activities carried out by companies. Therefore, the relationships between humans and nature constitute a complex reciprocal system of impacts-dependencies, in which human actions influence the state of ecosystems, which in turn define people's standard of living through the generation of ecosystem services.

Despite this complexity, many national and international institutions have started to require companies to consider their specific impacts on biodiversity and their exposure to ecosystem collapse (CBD, 2022; GAA, 2022; TNFD, 2023; UNEP-WCMC et al., 2022; Natural Capital Committee, 2022). Furthermore, it is reasonable to expect that legislative efforts on this issue will increase in the coming years especially in the Western world and in particular in Europe (see, for example, the Align community projects (UNEP-WCMC et al., 2022), the CSRD and the Nature Restoration Law).

Despite the growing awareness observed among citizens, companies, financial institutions, and policymakers on the mutual relationships between companies, biodiversity, and ecosystems, investigations on this relationship still need to be completed (UNEP-WCMC et al., 2022; NGFS, 2022). Hence, it is essential to develop a model that enucleates the relationship between business, biodiversity, and ecosystems to make this relationship clearer and ultimately manageable.

While this model of impacts-dependencies is acknowledged in the literature (Houdet et al., 2012; Addison et al., 2020) and by European institutions (UNEP-WCMC et al., 2022) at the conceptual level, it is not always clear how the relationships between the anthropogenic world and the natural world may also closely affect companies. Therefore, this paper aims to place companies within the abovementioned context, proposing a "systemic model of impacts and dependencies" that focuses on the relationships between companies, biodiversity, and ecosystems. Furthermore, several subcategories of impact drivers and ecosystem services will be enumerated, resulting from a careful analysis of existing gray literature on these issues .

It is important to point out that the topic of biodiversity (and natural capital more generally) is not absent from the Italian and international business economics literature. However, business economics

studies on the subject tend to focus on the external reporting that companies produce (Vola et al., 2021; Boiral, 2016), in part because of the complexity associated with integrating traditional internal control tools with sustainability-related issues (Hsiao et al., 2022). Therefore, this impacts-dependencies model aims to simplify and make the relationship between biodiversity, ecosystems, and the company more manageable at an internal company operational level, a prerequisite for its incorporation into company practices, routines, and communication (Raar et al., 2020).

3. Methodological approach to the building of systemic model

The structure of the impacts and dependencies model that would provide companies with a valuable tool to support managers and business actors in identifying the relationship between the company, biodiversity, and ecosystems, is part of a more comprehensive research project under the National Recovery and Resilience Plan (Piano Nazionale di Ripresa e Resilienza - PNRR), in which the National Research Council coordinates a project on biodiversity through the National Biodiversity Future Center (NBFC), which was established for this purpose ([https://www.nbfc .it](https://www.nbfc.it)), and of which the authors are part. The NBFC aims to aggregate national scientific research excellence and modern technologies to support operational interventions to monitor, preserve and restore biodiversity in marine, terrestrial and urban ecosystems of the Italian peninsula, as well as to enhance biodiversity and make it a central element on which to base sustainable development.

Considering the topic's novelty for research and business practice, the methodology is based on an already-tested interventionist approach (Pigatto et al., 2023). Interventionist research is suitable for studying emerging phenomena that are not extensively adopted in companies (Suomala & Lyly-Yrjänäinen, 2009). Furthermore, the research focuses on defining a solution to companies' practical problems (Dumay, 2010), by which possible solutions are sought and tested (Westin & Roberts, 2010).

During the research, the researchers frequently interacted with the participating companies in the expansion of the project and development of a model for measuring and evaluating the relationship between the company, biodiversity, and ecosystems, actively participating in solving the problem from an emic perspective, in which researchers study the topic from the inside (Jönsson & Lukka, 2007). Thus, researchers are “catalytic”, in that they play both a role as catalysts for action and as analytics in observing results on an ongoing basis (Dumay, 2010).

As regards the creation of the model, the research was structured into two main phases: the review of the existing literature and the definition and classification of the main elements that make up the model. In the first phase, the researchers explored the existing literature (Wohlin, 2014) that studied the relationship between the company, biodiversity, and ecosystems and identified the two main

components: the five drivers of biodiversity impacts and the three categories of ecosystem services that biodiversity and ecosystems generate. In the second phase, through focus groups with companies and experts (Morgan, 1996), these two main components identified in the first phase were further enucleated and classified into sixteen types of business impacts and twenty-four types of dependencies. Below, the process of identification and construction of the impacts-dependencies model is shown and divided into the two phases as mentioned above.

3.1. Phase 1: Literature review

The first phase of the impact-dependencies model building process involved the exploration and systematization of relevant documents of a primarily nonacademic nature. The relevant documents include regional, national, and international communities that deal with biodiversity and ecosystem services with business implications. Lacking a useful reference database for the purpose, the search for such institutions and documents was done through two mechanisms. Firstly, a targeted search was carried out using, individually or in combination, some keywords in Italian and English such as “biodiversity”, “ecosystem”, “ecosystem service”, “BES” (biodiversity-ecosystem service), “business”, and “accounting”. Secondly, further documents and institutions were identified through snowballing, a methodology that allows the identification of additional documents among citations of other previously selected documents (Wohlin, 2014).

Internationally, the initiatives identified as relevant, among others, are the Convention on Biological Diversity (CBD) of the United Nations (UN) and the standard for reporting on biodiversity no. 304 of the Global Reporting Initiative (GRI, 2016), the sectoral analyses of Business for Nature, the Capitals Coalition, the Common International Classification of Ecosystem Services (CICES), the Finance for Biodiversity, the Network for Greening the Financial System (NGFS), the IPBES, the Science Based Targets Network (SBTN), the System of Environmental-Economic Accounting (SEEA), the Economics of Ecosystems and Biodiversity (TEEB), the Taskforce on Nature-related Financial Disclosure (TNFD) and the Sustainable Development Goals – (SDGs) number 13, 14 and 15 (Marcellari et al., 2018).

At the EU level, the European Green Deal has given a strong impetus to the consideration of issues related to biodiversity and ecosystems, culminating in the formulation of the Biodiversity Strategy 2030 (European Parliament, 2021), in the adoption of the Nature Restoration Law (European Parliament, 2023) and in the issuing of the European Sustainability Reporting Standard (ESRS) E4 dedicated to reporting on biodiversity and ecosystems (EFRAG, 2022). Furthermore, the Align (UNEP-WCMC et al., 2022, 2023a, 2023b, 2023c) and EU Business and Biodiversity Platform (www.green-business.ec.europa.eu/business-and-biodiversity_en) projects are also of particular

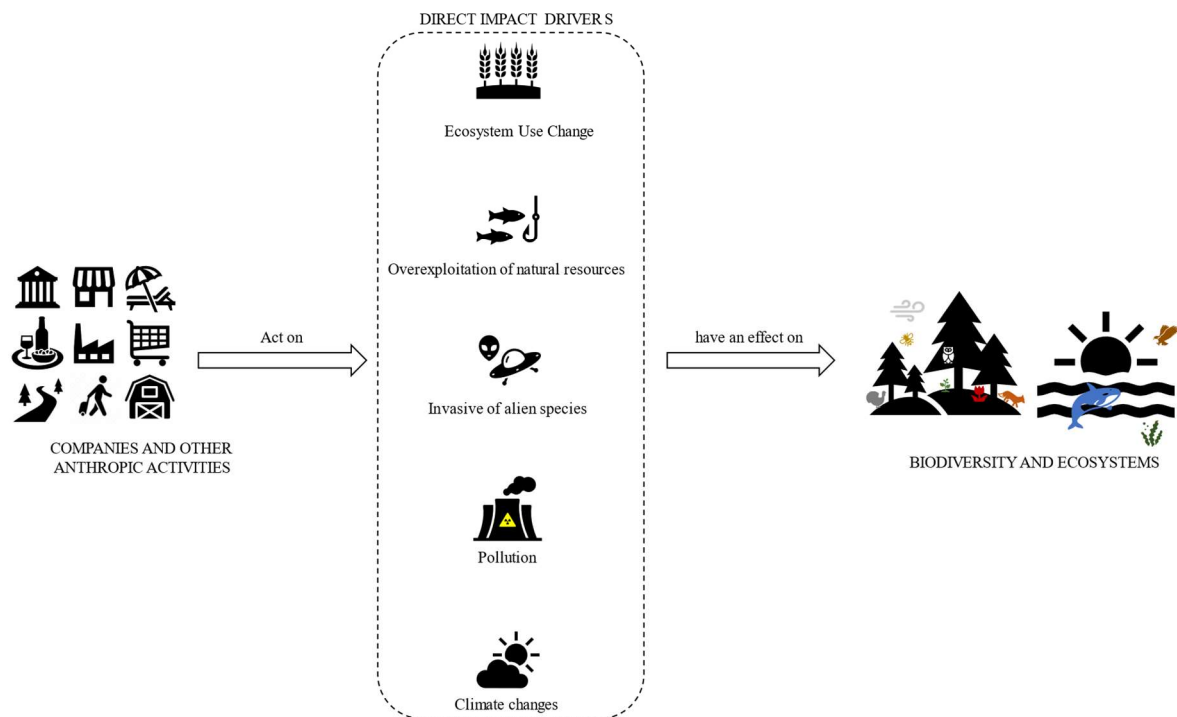
relevance, funded and supported by the European Commission. These EU initiatives strongly linked to biodiversity and ecosystem issues should be considered within the broader regulatory framework that is emerging in the European Green Deal framework, which sees the drafting of regulations such as the European Taxonomy of Sustainable Activities (so-called EU Taxonomy) and related delegated acts, the CSRD, the Corporate Sustainability Due Diligence Directive (CSDDD), the Deforestation Law and the Sustainable Finance Disclosures Regulation (SFDR).

At the Italian level, of note are the initiatives of the National Biodiversity Future Center (NBFC), an entity recently established within the PNRR to aggregate excellent national scientific research and modern technologies to support interventions on biodiversity and ecosystems and the initiatives of the Higher Institute for Environmental Protection and Research (Istituto Superiore per la Protezione e la Ricerca Ambientale - ISPRA). Outside the Italian borders, other relevant initiatives include the English Dasgupta Review (Dasgupta, 2021), the French CDC Biodiversité (2020), and the Irish Natural Capital Accounting for Sustainable Environments (Farrell et al., 2019).

The exploration and systematization of gray literature have led to identifying the primary international, community, or national documents that delve into the relationship between biodiversity, ecosystems, and companies. There are two main results obtained from the literature review phase.

The first result concerns the identification of the five drivers that directly impact human activities - including companies - have on biodiversity (IPBES, 2019; WEF, 2020; Jaureguiberry et al., 2022): ecosystem use change, over-exploitation of natural resources, invasive alien species, pollution, and climate change (Figure 2).

Figure 2 - The five drivers of companies' direct impact on biodiversity and ecosystems



Source: our elaboration from IPBES (2019) and Jaureguiberry et al. (2022)

The *ecosystems use change* is mainly caused by the expansion of agricultural land and fishing areas, the urbanization that has occurred in the last century due to the expansion of the world population, and the progressive depletion of land fertility (IPBES, 2018, 2019). In the business field, these changes affect the primary construction sectors and directly drive the ecosystem (IPBES, 2018).

The *overexploitation of natural resources* occurs when the human extraction of raw materials, whether abiotic, such as water, or biotic, such as plant life or animals, exceeds the capacity of an ecosystem to regenerate raw materials. Such overexploitation acts on the loss of biodiversity and collapse of ecosystems caused both by the removal of a particular species (e.g., due to poaching) and by the alteration of the balance in the ecosystem, which makes it impossible for function and determines the consequent collapse (e.g., overexploitation of water resources can lead to semi-desertification or desertification) (IPBES, 2019; Jaureguiberry et al., 2022).

In recent years, the number of *invasive alien species* has doubled, which not only results in an increasing threat to native species but also affects the ability of ecosystems to act (IPBES, 2019). Additionally, the exponential growth of international trade is one of the reasons that led to the spread of alien species by sea (e.g., in the ballast tanks of cargo ships), land, and air effects (Vysna et al., 2021). Globally, the economic cost resulting from the provisioning of alien species is estimated at 423 billion dollars, a value that quadruples every decade (IPBES, 2023).

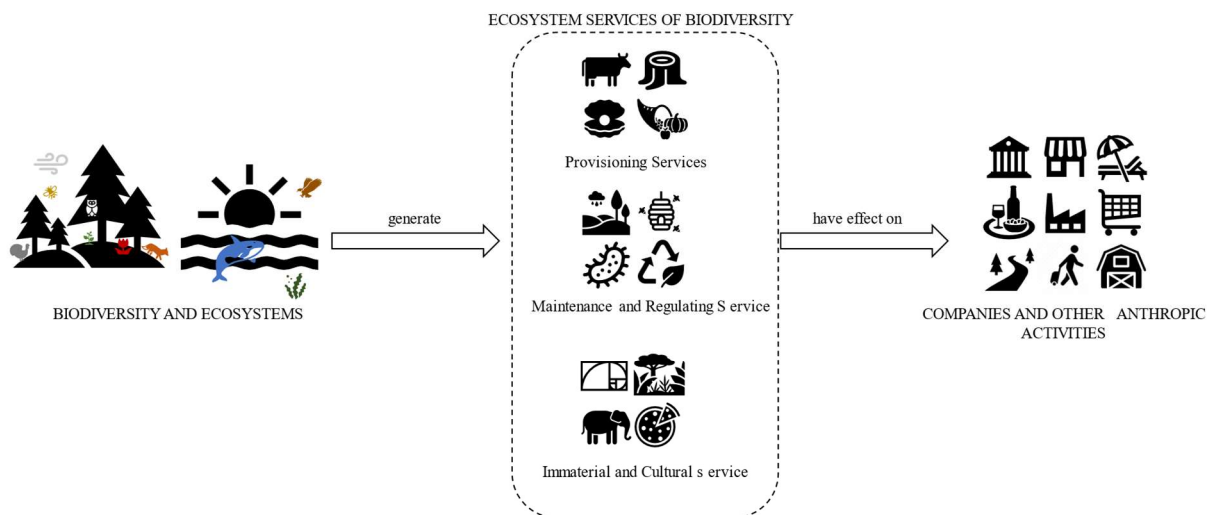
Pollution is a further driver of biodiversity loss. It is due to emissions into the atmosphere, contaminants dissolved in water or solid material and has consequences not only for human health

but also for the delicate balance between ecosystems' abiotic and biotic components (IPBES, 2019; Dasgupta, 2021). An example of the imbalance that can be generated due to pollution is the phenomenon known as eutrophication or an overabundance of nitrates and phosphates (used in many fertilizers) in aquatic environments. Eutrophication can lead to an uncontrolled proliferation of algae in waterways resulting in a decrease in water oxygenation to the detriment of fish and other animals and obvious damage to the fishing sector (IPBES, 2018).

Finally, *climate change* is a direct driver of impact on biodiversity. Global warming, rising sea levels, and ocean acidification are some of the effects of climate change that modify the composition and functioning of ecosystems, adding further pressure on the survival of some species (IPBES, 2019; Jaureguiberry et al., 2022).

The second result of the literature review concern the identification of the three types of ecosystem services: provisioning services, regulation and maintenance services, and cultural and intangible services (Haines-Young & Potschin, 2018; Dasgupta, 2021). These services represent the dependencies that companies have on ecosystems whose productivity depends significantly on the health of biodiversity (UNEP-WCMC et al., 2022) (Figure 3).

Figure 3 - Ecosystem services of biodiversity



Source: our elaboration from Dasgupta (2021), Haines-Young and Potschin (2018) and UN (2021)

Provisioning ecosystem services allows companies to source materials such as food, plant fibers, wood, biochemical components, genetic resources, and energy sources such as plant and animal fuels (Dasgupta, 2021; UN, 2021; Haines-Young & Potschin, 2018). These services represent the contribution of ecosystems to human well-being (UN, 2021). These provisioning services are the

basis of many primary and secondary sector industries, including the fishing and agri-food industries, paper, textile, and leather industries, and biopharmaceutical industries.

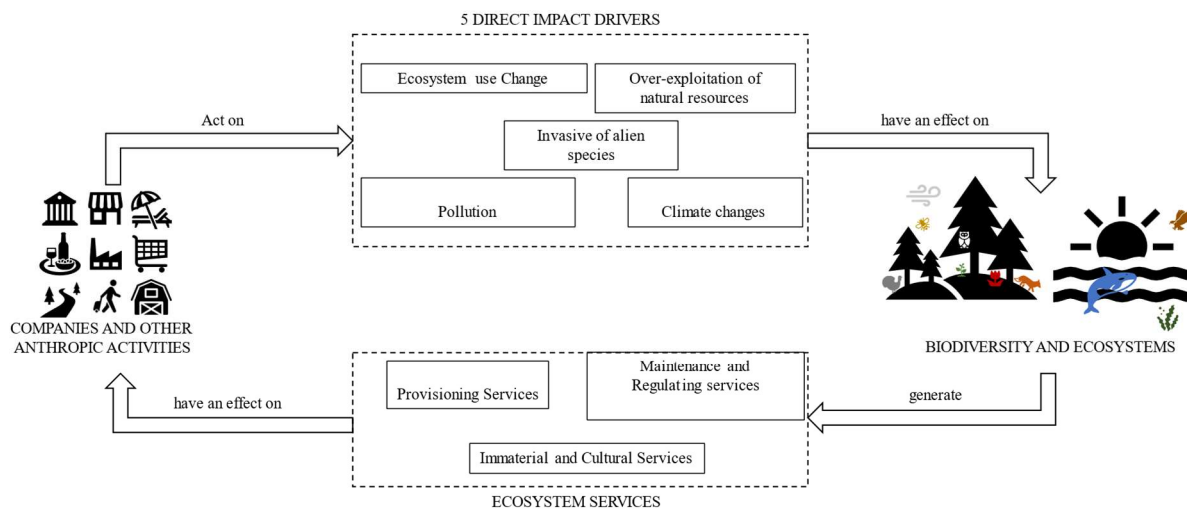
Regulation and maintenance ecosystem services are those services that regulate and maintain ecosystem processes, i.e., keep the ecosystem functioning. Through processes such as the chlorophyll photosynthesis, nitrogen fixation to the soil, and pollination process, this type of ecosystem service controls the productivity of the ecosystem over time and its ability to regenerate and produce biomass. Regulation and maintenance services, therefore, not only ensure that the ecosystem can continue to produce ecosystem services but also guarantee the breathability of the air, the drinkability of the water, and the mitigation of climate change through the absorption of CO₂ (Dasgupta, 2021; UN, 2021; Haines-Young & Potschin, 2018). These services originate "*from the ability of ecosystems to regulate biological processes and to influence climate, hydrological and biochemical cycles, and thereby maintain environmental conditions beneficial to individuals and society*" (UN, 2021, p. 130). Although some classifications distinguish regulatory ecosystem services from maintenance ecosystem services, more recent classifications combine them, signaling that there needs to be a more precise separation of what regulation is from what maintenance is (Dasgupta, 2021).

Finally, *cultural and intangible services* provide intangible benefits that pertain to the moral, spiritual, religious, and aesthetic spheres. In other words, cultural and immaterial services "*are experiential and intangible services related to the perceived or actual qualities of ecosystems whose existence and functioning contributes to a range of cultural benefits*" (UN, 2021, p. 130). Particularly affected by this type of service are the recreation, tourism, and scientific research sectors, which find in the experience and relationship between humans and nature a central resource for value creation (UN, 2021; Dasgupta, 2021).

3.2. Phase 2: First definition of a systemic impacts-dependencies model

At the end of the literature review phase, therefore, it was possible to draw an initial two-way relationship between biodiversity and farm. On one hand, companies generate five impact drivers that affect the strength of biodiversity and ecosystems (Figure 4). On the other hand, biodiversity, as a central element of an ecosystem, determines the ecosystem's ability to generate services on which companies depend.

Figure 4 - The basic relationship between company and biodiversity



An initial outline of the mutual relationship of impacts and dependencies between biodiversity and the company is then outlined for the construction of the systemic impacts-dependencies model developed in the next section.

3.3. Phase 3: Refining the definition of impacts, dependencies & model completion

Subsequently, a phase of creating the impacts-dependencies model was developed, which shows a further in-depth study of the direct impact drivers of ecosystem services to create a more precise and operational classification of impacts and dependencies.

This classification was discussed and validated through interaction with companies and academics who are experts on the subject. Specifically, the researchers prepared an initial classification based on the most relevant documents from Phase 1. Subsequently, to discuss and validate this classification, the researchers used the focus group method (Morgan, 1996) with the involvement of both biodiversity-sensitive companies and experts in sustainability management, biology, agronomy, and business economics. In these focus groups, researchers presented the classification of impacts and dependencies by describing the different elements that make up the classification. At the end of the presentation, the researchers stimulated discussion on the classification's clarity, comprehensiveness and usability. Through 17 iterative cycles of presentation and discussion involving 11 academics and 6 company managers over 12 months (of which 9 with companies and 8 with experts only), the researchers achieved a classification considered by the experts, the companies,

and the researchers themselves as sufficiently exhaustive, precise and operational. This classification is discussed in the next paragraphs.

3.3.1. Classification of impacts

With the direct impact classification, the researchers created a list of subcategories of impact drivers that could be practical and implementable in corporate contexts.

The first step in this direction was to compare different subcategories of impacts proposed by the reference gray literature. In particular, 11 impact subcategories from the Natural Capital Protocol (NCP) (Natural Capital Coalition, 2016) and 10 from the SBTN (2020) were selected and aligned. Additionally, while this first phase helped categorize the change in the use of ecosystems, pollution, and climate change, on the other hand, it left partially uncovered the two drivers related to the direct exploitation of resources and the introduction of invasive alien species.

For the direct exploitation of resources, for example, NCP and SBTN limited themselves to indicating the subcategory *use of water* with the addition of a generic category *use of other resources* in the case of NCP. Therefore, the researchers investigated this driver further by considering the CICES classification of ecosystem services provision (Haines-Young & Potschin, 2018), including a list of the primary materials ecosystems provide to humans. In this way, it was possible to introduce four further subcategories for the use of resources, which concern the exploitation of mineral substances, plants, animals, and genetic material.

Subsequently, the IPBES documents (2019) were analyzed to define two subcategories regarding the introduction of alien species: *voluntary and involuntary introduction*.

The categories of impact drivers and the respective subcategories were subsequently translated into Italian and presented to the companies and experts involved in the project. The advisors were asked about specific issues considering their backgrounds and areas of expertise, which included farming and plant sciences, sustainability management, and circular economy. Following the feedbacks received, the classification underwent two further refinements. The driver of direct exploitation of resources has been renamed *overexploitation of resources* to highlight the negative effect that the intensive use of natural resources causes on the humankind wellbeing of ecosystems and their ability to regenerate substances and materials. Furthermore, the *solid waste* subcategory has been changed to *waste* that includes solid waste and harmful liquid substances. The description of the 16 impact subcategories is reported in Appendix A.

3.3.2. Classification of dependencies

In order to classify dependencies (ecosystem services) on biodiversity in more detail, a similar work was made as for impact drivers.

First, the gray literature on the topic was analyzed, and the most globally recognized categorizations of ecosystem services were identified. The first reference source was the Common International Classification of Ecosystem Services, from which 34 classes of ecosystem services were extrapolated (belonging to the "group" heading of this international categorization).

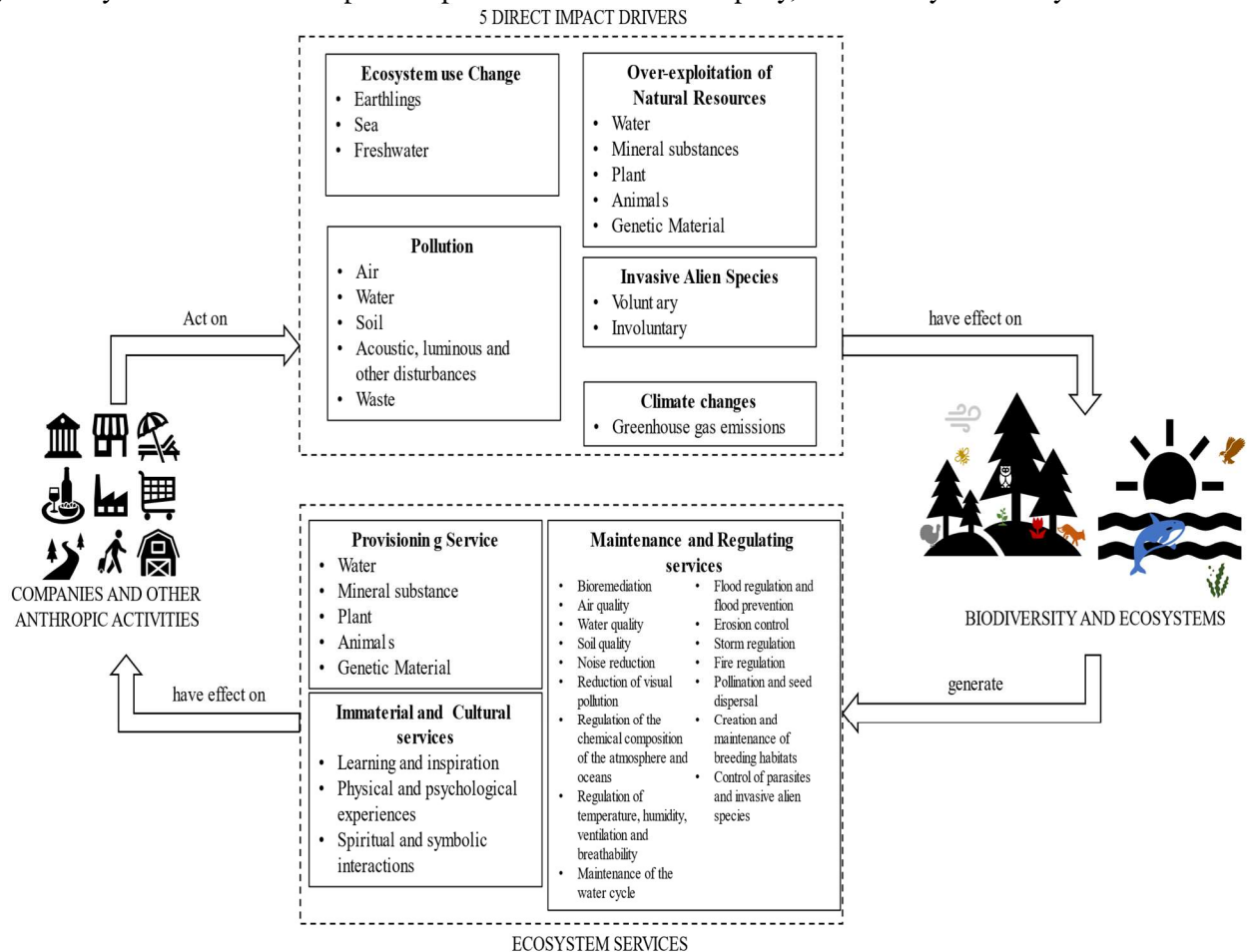
Subsequently, 21 categories from the Encore Partnership (ENCORE, 2024) and 18 categories from IPBES (2019) were taken into consideration, which were aligned with those of CICES (Haines-Young & Potschin, 2018). For example, as subcategories for plant provision services, the NCFE proposed *fibers and other materials*; the IPBES included *energy, food, and feed; materials and assistance; medicinal, biochemical, and genetic resources*; and CICES reported *aquatic plants grown for food; materials, or energy; land plants grown for food, materials, or energy*. In this case, the alignment generated the subcategory *collection and use of plants for nourishment, materials, and energy*.

This comparative work identified 15 dependencies deriving mainly from CICES and two IPBES categories for intangible ecosystem services. Furthermore, the four macro categories of services (maintenance and regulation service, immaterial, provisioning services) have been reduced to three recognitions for the grouping of maintenance and regulation services, which, being closely related and difficult to separate, can be considered together.

These categories were then translated into Italian and proposed to the companies and advisors involved in the project for feedback. The moment of comparison pushed the researchers to refine the subcategories relating to regulation and maintenance services, which were expanded from 7 to 16 considering 29 classes proposed by CICES and 22 "subtypes" proposed by SEEA (UN, 2021). The description of the 16 impact subcategories is reported in Appendix B.

At the end of the two phases of literature review and focus groups with companies and experts, the systemic model of the relationship of impacts and dependencies between biodiversity and the company appears as depicted in Figure 5. In detail, this systemic model develops the primary relationship that exists between biodiversity, ecosystems, and companies by the classification of five direct drivers impact (IPBES, 2019; Jaureguiberry et al., 2022) and of ecosystem services (Haines-Young & Potschin, 2018; UN, 2021).

Figure 5 - Systemic model of impacts-dependencies between company, biodiversity and ecosystems



The systemic nature of the model consists of the ability to represent and understand the complex interactions between different elements within the system and the holistic approach. The interconnections between the different parts of the system (impact drivers, ecosystems, ecosystem services) and their mutual influence are taken into account in the model, as well as a holistic approach that looks at the whole system rather than focusing only on isolated parts, an approach that allows interactions and consequences to be considered at the systemic level (Arbnor & Bjerke, 2009).

4. Discussion of the model

4.1. The underlying logic of “double materiality”

Upon closer observation, the concept of double materiality contained in recent European regulations is reflected and considered in the proposed model. According to the principle of double materiality (or double relevance), as set out in the CSRD, companies must “report both on the impact of the company's activities on society and the environment and on how sustainability issues impact the business. It is the so-called “double relevance” perspective, in which the risk that the company faces

and the impact represent a relevant perspective on each product” (European Parliament, 2022, art. 29). Double materiality includes a *financial materiality* part which requires the company to account for risks deriving from the environment - but also includes the socio-economic context - that could undermine the company's ability to create value and thrive over time. However, it also consists of a part of *impact materiality*, which requires the company to provide the information necessary to understand its impact on the environment and society more generally.

Regardless of the relationship between biodiversity, ecosystems, and companies, impact materiality underlies the relationship of impact that the company, through the five direct impact drivers, generates on the health status of biodiversity and ecosystems. On the contrary, the productivity of biodiversity and ecosystems to generate services has important implications in terms of financial materiality. An ecosystem's ability not only continues a value creation process but is also a source of exposure to the risk deriving from the collapse of the ecosystem and the inability to maintain the level of service necessary for the company value creation process (Carvalho et al., 2022). Consequently, while ecosystem services represent an opportunity for businesses and a source of value creation, they intrinsically contain the risk that these services cease when the state of well-being of the ecosystem and biodiversity deteriorates to the point of preventing regeneration.

The systemic model presented in Figure 5 fits into the logic of the double materiality between the company, ecosystems, and biodiversity, providing a level of detail that companies can use to identify specific ecosystem impacts and services for the value-creation process.

4.2. Allocation of responsibilities and decision support of the model

The systemic model of impacts and dependencies, as presented in Figure 5, has the limit to simplify the reality as every model in general, but it is worthy of further study. At first observation, the model seems to indicate a "closed" relationship between the company or anthropic activity being analysed, its impact on the humankind well ecosystem and the ecosystem's ability to return services to the company or anthropic activity being analysed that generates the impact. This reading, however, needs to be more accurate because it overlooks the change in the strength of biodiversity and ecosystems caused by other stakeholders and factors.

The health status of the ecosystem can suffer from alterations resulting from companies' external stakeholders, such as other companies' practices, institutions, individual actions, consumption decisions, urban development, and demographic, technological, and economic changes (IPBES, 2019). Furthermore, natural factors such as climate change, the spread of invasive alien species, natural disasters, and extreme weather events not necessarily completely linked to human actions (IPBES, 2019; WEF, 2023).

As mentioned above, it follows that the proposed systemic model should be viewed as one that fits into an "open" context, in which the health of the ecosystem functional to a given company is influenced by a number of actors and factors that are external to and different from the company itself. Therefore, a problem arises linked to allocating responsibility for the deterioration of a specific ecosystem - and its services - which could lie with the company being analysed or with different service areas.

The allocation of responsibility for the deterioration of a specific ecosystem is a prerequisite for the company to formulate actions to contain the risk posed by the possibility that the ecosystem is no longer able, in the future, to generate the services from which it draws value. On the one hand, if the responsibility for the deterioration lies with the company, the actions called upon to undertake must concern the cessation of those activities that, through the five drivers of direct impact, are causing damage to the ecosystem or regenerate actions. In this situation, the company actively reduces impacts, preserves, or restores the ecosystem, and produces services. If the responsibility for the deterioration does not lie with the company but with external stakeholders or factors, the company will tend to play a more passive role concerning the ecosystem. Company actions may be oriented towards mitigating the risk deriving from the possible cessation of the relevant ecosystem service and diversification. However, the possibility remains open for the company to adopt regenerative actions that can be effective if these lead to a regeneration of the ecosystem faster than its deterioration.

4.3. Standardization, territorial specificity, and the time factor

A further critical point underlying the relationship between the company and biodiversity is the necessity to compromise between standardizing the measurement of impact measures of dependence on biodiversity and ecosystems and the specificity of the relationship itself.

On the one hand, there are growing demands to develop standardized metrics to measure and evaluate corporate impacts and dependencies on biodiversity and ecosystems (UNEP-WCMC et al., 2022; GRI, 2016; EFRAG, 2022; CBD, 2022), while on the other these impacts and dependencies have an intrinsic territorial and temporal specificity (IPBES, 2019). Hence, placing a well-defined particular ecosystem at the center of the analysis required a specific time frame for the value creation process. This temporal and territorial specificity brings an additional level of complexity for the company in measuring and managing its impacts and dependencies.

Firstly, companies with similar impacts and dependencies but located in different places could be exposed to a different risk of degeneration of the ecosystems with which the company interacts, and generate different material impacts. For example, a bathing business located on the shores of Garda

Lake will not be affected by the spread of alien marine species, unlike a similar business situated on the upper Adriatic Sea.

Secondly, a company could generate impacts and have risk exposure in places very distant from own production sites, if considering its supply chain (UNEP-WCMC et al., 2023a, 2023b). For example, a coffee roaster from India will not be as affected by the Amazon fires as a coffee roaster from Brazil. Third, the materiality of an impact generated by the same company may vary over time. For example, a farm that uses massive amounts of water for irrigation could cause a significant effect in terms of over-exploitation of water - with consequent deterioration of the surrounding ecosystems - during periods of drought. The exact impact could become irrelevant in periods of heavy rainfall. These aspects linked to the territorial and temporal specificity of the relationship between company, biodiversity, and ecosystems represent a challenge to achieving complete standardization of models and metrics.

5. Conclusions, limitations and future developments

This research has developed a systemic impact-dependency model that enucleates and classifies the relationship between companies, biodiversity, and ecosystems. What makes this research relevant is, first, the growing awareness that the strength position of many ecosystems is deteriorating due, in many cases, to the negative impacts generated by the actions of businesses (Dasgupta, 2021; IPBES, 2019; Jaureguiberry et al., 2022; Atkins & Maroun, 2018). Secondly, research has observed that the capacity of biodiversity and ecosystems to create valuable services for humans is also deteriorating (UNEP-WCMC et al., 2022; IPBES, 2019; UN, 2021).

Giving further importance to the topic is the tendency of many national and international institutions to require companies to consider their impacts on – and dependencies from - biodiversity and ecosystems (TNFD, 2023; UNEP-WCMC et al., 2022). European Union has considered these initiatives, such as the CSRD, the Nature Restoration Law, and the Align project (UNEP-WCMC et al., 2022). Furthermore, this research is part of a larger project within the PNRR that is developed in a research center dedicated to biodiversity, the NBFC, of which the authors are members.

The objectives of the NBFC have a solid operational characteristic to support interventions aimed at monitoring, preserving, and restoring biodiversity, and enhancing and promoting sustainable development. Consequently, these objectives offer well-planned research experimentation developed through the interventionist research methodology (Suomala & Lyly-Yrjänäinen, 2009).

As defined in the previous sections, this interventionist research was divided into two phases, the first phase consists of an academic review and gray literature (Wohlin, 2014) and the second phase of

focus groups (Morgan, 1996). At the end of these two phases, a systemic model of impacts-dependencies between company, biodiversity, and ecosystems was proposed (Figure 5) in which sixteen types of company impacts and twenty-four types of ecosystem services were detailed and classified (IPBES, 2019; Jaureguiberry et al., 2022; Haines-Young & Potschin, 2018; UN, 2021).

The main contribution of this research is to create a systemic model that allows to understand and identify corporate impacts on biodiversity, ecosystem functioning, and extinctions (Corvino et al., 2021; Atkins & Maroun, 2018) and corporate dependencies on natural capital (Carvalho et al., 2022; Sun et al., 2022). The relevance from a managerial control perspective is given by the awareness not only to evaluate, manage, monitor, and report on a complex phenomenon such as the relationship between the company, biodiversity, and ecosystems but also by the possibility it gives to embed and understand the interaction between company and nature and break down into simpler units that are more understandable and ultimately manageable. This proposed model is a simple but methodologically robust classification of impacts and dependencies beneficial for internal risk management and external purposes of reporting effects on biodiversity. Consequently, when used as an analytical tool, it can create an expanded “internal-external” governance perspective that links information collected internally for management purposes (e.g., risk management and dependency assessment) with external reporting (e.g., measurement and management of impacts and mitigation actions) (Marchi, 2011; Raar et al., 2020).

The research and the proposed model have certain limitations. Firstly, the model suffers from the difficulties inherent in attempts to standardize the complex and detailed relationship between the company and biodiversity and, ultimately, between humans and nature. Furthermore, while the standardization of this relationship is essential to create a common language and homogeneous and comparable components, there is also a risk of losing relevant information on the spatial context and not adequately considering the temporal dimension in which this relationship takes shape (IPBES 2019). The trade-off between standardization and specificity is a potentially critical issue for any standardization initiative (e.g., GRI 304 & ESRS E4), including the present research. Therefore, this criticality offers a potentially useful starting point for future research.

A further limitation arising from the use of the systemic model to measure impacts and dependencies. Although numerical and financial measurement approaches for impacts and dependencies are more widespread (Laine et al., 2022), these approaches suffer from the complexities linked to the topic. Additionally, incorporating natural capital-related measures into management accounting systems can inform business decision-making in ways that are conducive to nature conservation and restoration (Cuckston et al., 2022). On the other hand, the financialization of biodiversity and conservation efforts risks reinforcing a neoliberal logic centered on the value of returns for investors, leaving open

the fundamental question of whether it is possible to reconcile nature's intrinsic value – often intangible, moral and spiritual (Dasgupta, 2021; IPBES, 2019) – to the value of natural capital as considered by investors: protecting nature implies cultivating the uniqueness of relationships between humans and ecosystems, while financialization implies the abstraction of nature to transform it into a “passive object” to be commodified, calculated and marketed (Arjaliès & Gibassier, 2023).

These limitations provide further stimuli to carry out research to validate the model components and experiment use in the corporate environment. Therefore, by continuing and expanding the interaction with companies and researchers from different disciplines, scientific research can be led towards strengthening the systemic model of impacts-dependencies both from a methodological and scientific, as well as operational and pragmatic, point of view.

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Acknowledgment

The European Union funding – Next Generation EU. However, the views and opinions expressed are solely those of the authors and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Appendices

Appendix A. Description of the subcategories of corporate impact drivers on biodiversity and ecosystems.

| Impact drivers | Impact driver subcategories | Subcategory description |
|---------------------------------------|--|---|
| Change the use of ecosystems | Change of use of terrestrial ecosystems | Concerning, such agricultural, forestry, mining, and extractive and urban planning activities that involve land consumption. |
| | Change of use of marine ecosystems | Concerning, such as aquaculture activities, and extraction from the seabed which involve the use of the sea and/or the seabed. |
| | Change of use of freshwater ecosystems | Concerning, such as wetlands, ponds, lakes, streams, rivers, or peatlands necessary to provide ecosystem services such as water purification and fish reproduction, areas of infrastructure necessary for the use of rivers and lakes as bridges, dams, and flood barriers. |
| Invasive alien species | Voluntary introduction | The introduction of invasive alien species may be voluntary. |
| | Involuntary introduction | The introduction of invasive alien species may be involuntary or accidental. |
| Overexploitation of natural resources | Direct overexploitation of water | Concerning, such as the volume of groundwater consumed, and the volume of surface water consumed. |
| | Direct overexploitation of mineral substances | Concerning, such as everything that is extracted from the subsoil (This category does not include the mere consumption of land from mining and extractive activities which are part of the change of use of terrestrial ecosystems item). |
| | Direct overexploitation of plants | Concerning, such as the collection of wild or cultivated plants (In these cases not all vegetation is removed, as in the case of deforestation under the heading change of intended use of terrestrial ecosystems). |
| | Direct overexploitation of animals | Concerning, such as hunting, fishing, and capturing wild or farmed animals. |
| | Direct overexploitation of genetic material | Removal of genetic material for, for example, research and genetic engineering. |
| Pollution | Air pollution (excluding greenhouse gases) | It includes, such as fine (PM2.5) and coarse (PM10) particulate matter, volatile organic compounds (VOC), mono-nitrogen oxides (NO and NO ₂ , commonly referred to as NO _x), sulfur dioxide (SO ₂), carbon monoxide (CO). |
| | Water pollution | It includes, such as the spillage of nutrients (e.g. nitrates and phosphates) or other substances (e.g. heavy metals and chemicals). |
| | Soil pollution | It includes, such as, the volume of waste material discharged and retained in the soil over a given period, and chemical compounds resulting from fertilizers and pesticides. |
| | Noise, light pollution, and other disturbances | It includes, such as the decibels and duration of the noise, the lumens, and duration of light, or other disturbances that alter the quiet of a given ecosystem. |
| | Waste pollution | It includes, such as non-hazardous, hazardous and radioactive waste, specific materials (e.g. lead and plastic) and their disposal (e.g. landfill, incineration, recycling, specialized treatment). |
| Climate changes | Greenhouse gas emissions | It includes, such as carbon dioxide (CO ₂), methane (CH ₄), nitrous oxide (N ₂ O), sulfur hexafluoride (SF ₆), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). |

Appendix B. Description of ecosystem service subcategories.

| Ecosystem services | Subcategories ecosystem services | Subcategory description |
|---|---|--|
| Supply of ecosystem services | Water withdrawal and use | Withdrawal and use of water for nutrition, materials, and energy. |
| | Withdrawal and use of mineral and non-mineral substances | Withdrawal and use of minerals (e.g. oil, uranium, gas) and non-minerals (e.g. sunlight, wind, geothermal water) for nourishment, materials, or energy. |
| | Collection and use of plants | Taking and using plants for food, materials, and energy. |
| | Collection and use of animals | Taking and using animals for food, materials, or energy. |
| | Collection and use of genetic material | Taking and using animals for food, materials, or energy. Taking and using genetic material from animals, organisms, plants, algae, or fungi. |
| Ecosystem regulation and maintenance services | Bioremediation | A process carried out by microorganisms, algae, plants, and animals and involves the decomposition of waste and pollutants. These solid waste remediation services are ecosystem contributions to the transformation of organic or inorganic substances, through the action of microorganisms, algae, plants and animals that mitigate their harmful effects. Examples of this service are the bioremediation of industrial waste through disposal on agricultural land or bacteria such as marine bacteria which can break down the oil into simple monomers |
| | Maintenance of air quality | It concerns regulation by processes of filtration, sequestration, storage and accumulation by microorganisms, algae, plants and animals. Maintaining air quality also includes reducing odors. Examples of these services are trees in urban settings that filter dust or birds and bacteria that remove decaying algae. |
| | Maintenance of water quality | It occurs by maintaining the chemical conditions of freshwater, including rivers, streams, lakes, groundwater sources, and saltwater, to ensure favorable living conditions for plants and animals. |
| | Maintenance of soil quality | It is ensured by atmospheric processes, which maintain soil biogeochemical conditions, including soil fertility and structure, and by decomposition and fixation processes, which allow nitrogen fixation, nitrification and mineralization of dead organic material. |
| | Noise reduction | Reduction of the impact of noise on people which mitigates its harmful or stressful effects. For example, vegetation belts on roadsides. |
| | Reduction of visual pollution | It provides for the screening of unpleasant views. For example, shielding production sites with trees and other natural elements. |
| | Regulation of the chemical composition of the atmosphere and oceans | Regulation of the chemical composition of the atmosphere and oceans influences global climate through the accumulation and retention of carbon and other greenhouse gases (e.g. methane) in ecosystems and the ability of ecosystems to remove (sequester) carbon from the atmosphere. |
| | Regulation of temperature, humidity, ventilation and breathability | It occurs through the use of vegetation that improves people's living conditions and supports economic production. Examples include the evaporative cooling provided by urban trees ("green space"), the role of urban water bodies ("blue space"), and the contribution of trees in providing shade for humans and livestock. |
| | Maintenance of the water cycle | It occurs through the ecosystem contribution of vegetation, in particular forests, to the maintenance of atmospheric precipitation through evapotranspiration. Forests and other vegetation provide moisture in the atmosphere for precipitation generation. Precipitation in the interior parts of the continents depends entirely on this process. These services contribute to the regulation of river flows and underground and lake aquifers and |

| | | |
|--|--|--|
| | | derive from the ability of ecosystems to absorb and store water and to gradually release it during the seasons or dry periods through evapotranspiration and therefore guarantee a regular flow of water. |
| | Flood regulation and flood prevention | It derives from the ability of ecosystems to absorb and store water, and therefore to mitigate the effects of floods and other extreme water-related events. River flood mitigation services are provided by riparian vegetation which provides structure and a physical barrier to high water levels and therefore mitigates the impact of flooding on local communities. Coastal flood mitigation services are provided by linear elements of the seascape, such as coral reefs, sandbars, dunes, or mangrove ecosystems along the coast. |
| | Erosion control | Land stabilization and erosion control are ensured by plant cover that protects and stabilizes terrestrial, coastal and marine ecosystems, coastal wetlands and dunes. The vegetation on the slopes also prevents avalanches and landslides, while mangroves, sea grasses and macroalgae protect the coasts and sediments from erosion. |
| | Storm regulation | It concerns the ecosystem contributions of vegetation in mitigating the impacts of wind, sand and other storms (other than water-related events) on local communities. |
| | Fire regulation | The ability of ecosystems to reduce the frequency, spread or magnitude of fires (e.g. wetlands between forests or fire zones in forests containing low-combustibility species). |
| | Pollination and seed dispersal | The contributions of wild animals to the fertilization of crops that maintain or increase the abundance and/or diversity of other species whose benefits economic units use or enjoy. Pollination and seed dispersal services are also provided by other mechanisms such as water and wind. |
| | Creation and maintenance of breeding habitats | Services necessary to support the reproduction of plant or animal species that economic units use or benefit from (e.g. coasts where turtles/migratory birds nest). |
| | Control of pests and diseases and management of invasive alien species | It can occur through the direct introduction and maintenance of predator populations of the pest or invasive species, landscaped areas to encourage pest reduction habitats, and the production of natural biocides (a family of substances that act against pests). Furthermore, ecosystems play an important role in regulating diseases for human populations and for wild and domestic flora and fauna. |
| Cultural and intangible ecosystem services | Intangible learning and inspiration services | It includes, such as opportunities to develop capabilities to thrive through education, knowledge acquisition, and inspiration for art and technological design (e.g., biomimicry). |
| | Intangible services based on physical and psychological experiences | It includes opportunities for physically, athletically and psychologically beneficial activities, healing, relaxation, recreation and aesthetic enjoyment based on close contact with nature. |
| | Intangible services based on spiritual, symbolic interactions, etc. with the natural environment | This includes religious, spiritual and social cohesion experiences; sense of place, purpose, belonging, rootedness, or connection, associated with different entities in the living world; narratives and myths, rituals and celebrations; satisfaction resulting from knowledge of the existence of a particular landscape, seascape, habitat or species. |