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A Systemic Model for Understanding Business Interactions With Biodiversity and Ecosystems

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ABSTRACT

Biodiversity loss and ecosystem degradation represent critical threats to human well-being and economic resilience, challenging businesses to understand and manage their interdependence with natural systems. This study develops a systemic framework—the BioModel—that elucidates the reciprocal relationship between businesses, biodiversity, and ecosystems. Adopting a mixed-methods design that combines an extensive review of academic and gray literature with a series of focus groups involving experts and practitioners, the research co-constructs a theoretically grounded yet practically applicable model. The BioModel identifies 16 types of corporate impacts and 24 ecosystem services, classifying them into coherent drivers and dependency categories. It demonstrates how these relationships can be modeled to capture both the “impacts on” and “dependencies from” natural capital, aligning with the principle of double materiality introduced by the EU Corporate Sustainability Reporting Directive. The discussion emphasizes the model's potential to bridge ecological science and corporate management by translating complex ecological interconnections into decision-relevant structures. Ultimately, the study concludes that BioModel provides a foundational tool for assessing, managing, and reporting biodiversity-related risks and opportunities, thereby potentially enabling businesses to integrate ecological considerations into strategic and operational decision-making.

1 | Introduction

> *The “need” for theories lies in the human behaviour of wanting to impose order on unordered experience. [...] The human mind has a “need” to see order in nature, or, more broadly, in all experience*
>
> (Dubin 1978, 6)

Understanding the relationship between businesses, biodiversity, and ecosystems is a crucial issue since it addresses the possibility of the world's present and future life. However, said relationship is complex and multifaceted because complex and multifaceted are ecological processes and organizations (Panwar et al. 2023; Testa et al. 2025). Therefore, this research is about finding “order in the booming, bustling confusion that is the realm of experience” (Dubin 1978, 5).

The topics of biodiversity and ecosystems are essential for the development of corporate sustainability strategies and open space for research on performance measurements that support the decisions, actions, and disclosure of the results obtained. From a business perspective, however, it is particularly complex to valorize 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 and Maroun 2018). Building on the long tradition of constructivist development of theoretical models in management and accounting studies (Kasanen et al. 1993; Whetten 1989), and consistent with the pragmatic constructivist approach that emphasizes the interplay between facts, possibilities, values, and communication in organizational theorizing (Nørreklit 2017), this paper proposes a method theory addressing a practical problem (Van de Ven and Johnson 2006; Lukka and Vinnari 2014), namely, how to make sense of the complex relationship between a business, biodiversity, and ecosystems. We do that by proposing a systemic model (hereafter, BioModel) that identifies and classifies the impacts and dependencies that underlie said relationship (Houdet et al. 2012; Addison et al. 2020).

The BioModel was developed in two phases. First, we reviewed academic and nonacademic literature (so-called *gray* literature) to understand the state of the art of the business–biodiversity relationship (Morgan 1996). In parallel, we employed focus groups with academics and businesses to construct and detail the BioModel and streamline it for adoption by businesses. The BioModel is composed of a classification of 16 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 BioModel comprises 24 types of ecosystem services grouped into three main categories: provisioning services, maintenance and regulating services, and immaterial and cultural services (Haines-Young and Potschin 2018; Dasgupta 2021).

The model is systemic by nature because it allows representing and understanding the complex interactions between different elements in a holistic manner. The interconnections between the different parts of the system (i.e., businesses, impact drivers, biodiversity and ecosystems, and 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 and Bjerke 2009). The BioModel's ambition therefore is to detail the different, separate units that underpin the business–biodiversity relationship without losing sight of the bigger, complex, and "systemic" reality of such relationship.

Along with the model construction, which is the main aim of the research, we discuss how BioModel aligns with the double materiality concept as enunciated by the recent European Corporate Sustainability Reporting Directive (CSRD) (European Parliament 2022; Cooper and Michelon 2022). In fact, we discuss how BioModel can be used in an "open" or "closed" modality to address the direct and indirect impacts and dependencies. Furthermore, we highlight the criticalities underlying the relationship between companies, biodiversity, and ecosystems such as the identification of corporate and beyond-corporate responsibilities for the deterioration of ecosystems, and the temporal and geographical specificity of impacts and dependencies.

Despite such critical issues, the proposed BioModel represents a starting point for a business that wants to begin evaluating, managing, monitoring, and reporting its "impacts on" and "dependencies from" natural capital. In fact, without a methodologically robust model able to detect what the impacts and dependencies of a business are, it is very complex to identify those to be measured and acted upon. Furthermore, BioModel offers a foundational, conceptual bridge between the deterioration of dependencies on natural capital and the business risks that might arise as a consequence of such deterioration. Therefore, BioModel 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 methodology followed by researchers to develop the theoretical model. Section 4 describes the main units and characteristics of BioModel, while Section 5 discusses its boundaries, application and linkages with the double materiality. Section 6 concludes the paper detailing its contributions to research and practice.

2 | Literature Review on Business and Biodiversity

2.1 | An Anthropocentric View of Biodiversity and Ecosystems

We are aware of the fundamental debate around ecocentric and anthropocentric worldviews. Before proceeding with the literature review and presenting the research problem, we want to point out such issue as it affects the business–biodiversity theorization. The first worldview, anthropocentrism, values ecosystem services based on their utility to humans and sees nature primarily as a resource for human benefit, often focusing on how environmental degradation affects humans or economic outcomes (O'Neill et al. 2008). Conversely, ecocentrism asserts that nature has an intrinsic ethical and moral value, which is independent of human use and utility. Moreover, the value of nature, in the ecocentric view, cannot be replaced with utilitarian, human-centric values (Dempsey 2016; Atkins et al. 2023).

Traditional environmental accounting typically reflects the anthropocentric worldview, aiming to quantify the negative environmental externalities that impact financial performance (Atkins et al. 2023) and make the values of ecosystem services more apparent since they are not captured by the market, even though they are essential for its functioning (Costanza et al. 1997). In fact, biodiversity and ecosystems do possess value, whether that be moral, spiritual, practical, or a mixture of these (Dasgupta 2021; Cuckston 2019; Sullivan and Hannis 2017). In a business context, the easiest type of value to grasp is a utilitarian/practical one. If biodiversity and ecosystems deteriorate too much, they risk posing a threat to the financial viability of businesses (O'Neill et al. 2008; Vysna et al. 2021).

Such an anthropocentric and business-centric view of biodiversity and ecosystems is not necessarily bad since it can make the effects of biodiversity loss and ecosystem collapse visible, and it can sound the alarm to businesses, pushing them to consider the gravity and urgency of the problem and motivating them to act accordingly (World Economic Forum 2020; Atkins et al. 2023).

However, we remain conscious that the anthropocentric worldview hides commodification and reductionist traps that risk oversimplifying the complexity of ecological processes into simplistic numbers that are not only easy to understand and communicate but also easy to manipulate as well. Therefore, considering biodiversity and ecosystems only in terms of business value implies problematic philosophical and ethical consequences that researchers and businesses need to keep in mind (Dempsey 2016; Dasgupta 2021; Sullivan and Hannis 2017).

That said, in the remainder of the paper we will explore the relationship between business and biodiversity. Therefore, we will take an anthropocentric view on the phenomenon while being cognizant of the pitfalls such a view entails.

2.2 | The Business–Biodiversity Relationship

Ecosystems are functional to humankind and provide various services: 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 (Daily 1997; Dasgupta 2021; Haines-Young and 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, 360).

Economics-based research on the dependencies from ecosystem services of entire sectors, regions, and economies is flourishing (O'Neill et al. 2008; World Economic Forum 2020; Vysna et al. 2021; UN 2021; Small et al. 2025). Specifically, the United Nations (UN) System of Environmental–Economic Accounting (SEEA) is often used to assess the value of ecosystems and their services. SEEA is "a spatially-based, integrated statistical framework for organising biophysical information about ecosystems, measuring ecosystem services, tracking changes in ecosystem extent and condition, valuing ecosystem services and assets and linking this information to measures of economic and human activity" (UN 2021, 1). This framework complements the exchange values from the System of National Accounts and uses accounting principles to integrate physical and monetary measures of the natural environment into the nation's accounts (UN 2021). Valuing the worth of an ecosystem's services often results in resorting to different methods, such as choice experiments (Scarpa et al. 2003), acquisition costs (Kim et al. 2014), or hedonic pricing (Belcher and Chisholm 2018), as a way of assigning an economic value to biodiversity and ecosystem services.

Whereas sectoral and regional ecosystem services are well established in academic research, business dependencies have received scant attention (Carvalho et al. 2022; Houdet et al. 2012; UNEP-WCMC et al. 2022; Ingram et al. 2024). Such a lack of research can be due to the complex ecological mechanisms governing ecosystem services that can lead to the unforeseen deterioration of some services while trying to improve the productivity of another ecosystem service. Moreover, several ecosystems and the services they generate may exist within a larger one with boundaries expanding and contracting over time in response to various drivers of change. Also, ecosystem services might be difficult to convert into economic and/or monetary terms, therefore making it difficult for businesses to understand their value (Houdet et al. 2012).

On the contrary, as noted by Carvalho et al. (2022), practice-oriented literature—also referred to gray literature—on business dependencies is flourishing. In fact, the gray literature and the institutions behind such literature (e.g., ACCA et al. 2012; Tin et al. 2024; UNEP-WCMC et al. 2022; UNEP-WCMC et al. 2023; Value Balancing Alliance 2023) are actively engaging in making biodiversity and ecosystem services understandable to businesses using risk language and metrics (Dempsey 2016). Ecosystems generate services on which businesses depend for their value creation processes (WEF 2020). Therefore, practice-oriented literature is focusing on helping businesses reflect on the risks that dependencies from biodiversity and ecosystem services pose to their operations (Carvalho et al. 2022).

Anthropic activities have the capacity to influence the state of biodiversity and ecosystems by altering the ecological processes on which ecosystem equilibria depend. Human activities impact biodiversity and ecosystems through five categories of direct drivers: sea/land-use change, overexploitation of natural resources, pollution, climate change, and invasive alien species (IPBES 2019).

The negative impact of human activities on biodiversity and ecosystems has accelerated with the spread of the Industrial Revolution in a way that we can 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 in which some habitats have lost more than 90% of their extension in Europe and North America (IPBES 2019). The global rate of species extinction has heightened, and it is estimated that already 1% of vertebrates have gone extinct in the last 500 years—undoubtedly an underestimated figure (IPBES 2019; IUCN 2025). In addition, the average percentage of animal and plant species at risk of global extinction is around 28% (IUCN 2025). 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 businesses (Panwar et al. 2023). 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.

2.3 | Research Aim and Research Questions

Despite the complexity of the business–biodiversity relationship, many national and international institutions have started to require businesses to consider their specific impacts on biodiversity and their exposure to ecosystem collapse (CBD 2022; GAA 2022; Taskforce on Nature-Related Financial Disclosure (TNFD) 2023; UNEP-WCMC et al. 2022; Comitato Capitale Naturale 2022; Ingram et al. 2024). Furthermore, it is reasonable to expect that legislative efforts on this issue will increase in the coming years, especially in the Western world, especially in Europe (see, for example, the EU CSRD and the EU Nature Restoration Law). Although the general relationship of impacts-dependencies is acknowledged in the literature (Houdet et al. 2012; Addison et al. 2020; Ingram et al. 2024) and by European institutions (UNEP-WCMC et al. 2022) at the conceptual level, it is not always clear how the relationships between the anthropic world and the natural world affect businesses. In fact, prior studies on the subject tend to focus on the external reporting that businesses produce (Boiral 2016), in part because of the complexity associated with integrating traditional internal control tools with sustainability-related issues (Hsiao et al. 2022).

Despite the growing awareness of citizens, businesses, financial institutions, and policymakers on the mutual relationships between businesses, 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 rigorous yet practical model that enucleates the relationship between business, biodiversity, and ecosystems to make this relationship clearer and ultimately manageable (Raar et al. 2020; Carvalho et al. 2022). Therefore, this paper aims to develop a theoretical model of impacts and dependencies that focuses on the relationships between businesses, biodiversity, and ecosystems. As any theoretical model should do, BioModel aims to provide some level of order and make the relationship between biodiversity, ecosystems, and the business more understandable and manageable at an internal business operational level (Dubin 1978). In sum, this paper will answer the following research questions:

RQ1: How can a systemic model be developed to explain business impacts and dependencies on biodiversity and ecosystems?

In the next section, we will describe how we resorted to a constructive approach to tackle these questions (Kasanen et al. 1993). Specifically, we undertook a literature review coupled with focus with academic experts and practitioners to ensure that BioModel could respond to a problem with practical relevance (Dubin 1978; Storberg-Walker 2003; Van de Ven and Johnson 2006; Lukka and Vinnari 2014).

3 | Methodology

3.1 | Theoretical Development of BioModel

According to Dubin (1978), to develop a theoretical model in social sciences, a theorist must start from defining the model's units. Units represent the building blocks, the concepts, the variables, the "things," and their properties on which the model rests (p. 40). Once the units constituting the subject matter of attention have been defined, the theorist describes the "laws of interaction" (p. 90). Laws of interaction are statements of relationship that specify how the units interact among each other. Without specifying the relationships among units, the model remains only a taxonomic model of units. It is worth mentioning that laws of interaction are not necessarily causal laws but can encompass categorical, sequential, and determinant interactions (Dubin 1978).

A third key element of a theoretical model—and particularly relevant for the business–biodiversity relationship—is boundary (Dubin 1978). Boundaries express the limited portion of the world within which the model is expected to hold. Therefore, clearly and transparently setting up the boundaries of the model gives the appropriate coordination for the generalizability of the results. The generality of a scientific model, in fact, depends only on the size of the domain it represents. Drawing boundaries and specifying boundary criteria are crucial to understanding what the model is about, and what it is not. Within the model's boundaries, different system states can exist. That is, the laws of interactions among units might behave differently under different system conditions.

Once clarified, the model's boundaries and system states, propositions can be developed. A proposition is a "truth statement of a special and limited kind" (Dubin 1978, 160). Simply put, propositions are the logical consequences that can be drawn from the model once units, laws of interactions, boundaries, and system states have been defined. Therefore, propositional statements reflect the predictions that can be expected to be seen from the model in operation. Once propositions are defined, the model is developed and the model testing can commence.

The approach we use to develop the theoretical BioModel is constructive (Kasanen et al. 1993). A constructive approach to theory and model development means starting from a managerial problem with practical relevance (and research potential) and construct a solution by showing the theoretical connections through models, diagrams, plans, etc. (Kasanen et al. 1993; Lynham 2002). Such a model construction therefore helps advance knowledge in a given domain and bridges the theory–practice gap (Lukka and Vinnari 2014; Van de Ven and Johnson 2006). Given that the managerial problem has practical relevance and the theoretical model needs to function in practice (Kasanen et al. 1993), practitioners (i.e., the people expected to use some outcomes of the model) can play a crucial role in the model development (Dubin 1978; Storberg-Walker 2003; Van de Ven and Johnson 2006).

Such a constructive approach has been further refined in the principles of pragmatic constructivism (Nørreklit 2017), which emphasizes that valid knowledge in the social sciences emerges from the actors' co-construction of pragmatic truths, which ensure that the models developed are not only conceptually robust but also actionable and meaningful for practitioners. Within this perspective, the BioModel can be viewed as a pragmatic construction that translates theoretical understanding of business–biodiversity relationships into a form that practitioners can apply and validate in real-world settings.

As presented in the next section, the developed BioModel followed the constructive approach to address a practically relevant problem: helping a business make sense of, measure, and manage its relationship with biodiversity and ecosystems.

3.2 | Methods

The BioModel building process involved the exploration and systematization of relevant documents of a primarily nonacademic nature (cd., gray literature). The relevant documents originate from regional, national, and international institutions 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. First, 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." Second, 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 of the UN and the standard for reporting on biodiversity No. 304 of the Global Reporting Initiative updated to GRI 101: Biodiversity in 2024 (GRI 2016, 2024), 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 SEEA, the Economics of Ecosystems and Biodiversity, the TNFD, and Sustainable Development Goals 13, 14, and 15.

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 Standards (ESRS) E4 dedicated to reporting on biodiversity and ecosystems (EFRAG 2022). Furthermore, the Align (UNEP-WCMC et al. 2022; UNEP-WCMC et al. 2023), the Transparent (Heller, Gough, and Bakker 2023; Heller, Gough, Bakker, Verheye, et al. 2023), and EU Business and Biodiversity Platform (www.green-business.ec.europa.eu/business-and-biodiversity_en) projects are also of 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, the EU Deforestation Regulation, and the Sustainable Finance Disclosures Regulation.

At the national level, of note are the initiatives of the Italian National Biodiversity Future Center (NBFC), an entity recently established within the Next Generation EU 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 on a country level include the English Dasgupta Review (Dasgupta 2021), the French CDC Biodiversité (2020), and the Irish Natural Capital Accounting for Sustainable Environments (Farrell and Stout 2019).

We downloaded and read several documents issued by the national and international institutions listed above looking for information on the impact–dependency relationship between businesses, biodiversity, and ecosystems. For example, we reviewed the documents to collect different classifications of business impacts on biodiversity, types of dependencies, and indicators used to measure impacts and/or dependencies. Moreover, we integrated the information obtained from the gray literature with the academic articles (e.g., Carvalho et al. 2022; Jaureguiberry et al. 2022) on the topic until we reached a point of saturation in which any additional article, report, or document provided information already found in the ones already analyzed.

Along with the literature search, we organized focus groups with businesses and experts to corroborate the results emerging from the literature review (Morgan 1996). The focus groups involved both biodiversity-sensitive businesses and experts in sustainability management, biology, agronomy, and business economics. In these focus groups, researchers presented the results of the literature reviews in terms of the business–biodiversity relationship, the classifications of impacts and dependencies, and the indicators for measuring impacts and dependencies, which ultimately detail the BioModel. At the end of the presentation, the researchers stimulated discussion on the BioModel's clarity, comprehensiveness, and usability. Through 16 iterative cycles of presentation and discussion involving 11 academics and 3 businesses (of which 8 with businesses and 8 with experts only for a total of 24 h of data collection) between November 2022 and September 2023, the researchers drafted the BioModel considered by the experts, the businesses, and the researchers themselves as sufficiently exhaustive, precise, and operational (Table 1).

We chose the businesses and the experts to involve in the study through theoretical sampling (Patton 2014). Ultimately, the study involved three Italian organizations that (a) already had some familiarity with the topic of biodiversity and ecosystem services and (b) expressed their willingness to provide their practical knowledge to the researchers (Dubin 1978; Kasanen et al. 1993). Specifically, we discussed the BioModel in focus groups with three Italian businesses belonging to the agri-food sector: AgriBio, SocioBio, and PetBio (Table 2).

Founded in the 1970s in Central Italy as a cooperative, AgriBio is a limited business specializing in the production of organic food products. AgriBio coordinates an almost completely integrated supply chain, involving 10 large members and over a 1000 farmers and beekeepers. Production exceeds 300 types of organic foods, including pasta, rice, tomato puree, drinks, cocoa, sugar, and honey, exported to 52 countries. AgriBio is committed to sustainable and environmentally friendly practices, ensuring that all its products are free from synthetic chemicals and genetically modified organisms (GMOs). In 2023, AgriBio employed around 100 people, presented an operating turnover of about €70 million and €50 million in assets.[1]

SocioBio is a prominent Italian fair-trade organization, established in the 1980s and headquartered in Northern Italy. The business operates as a consortium, promoting fair trade practices and sustainable development. SocioBio collaborates with more than 150 producer organizations across more than 45 countries, ensuring fair wages and working conditions for

TABLE 1 | List of plenary sessions and corresponding code.

Phase	Plenary session date	Participants other than the researchers	Code
1 - Model definition	2022.11.23	PetBio	PS1.1
	2022.12.07	PetBio	PS1.2
	2023.01.18	PetBio	PS1.3
	2023.02.13	PetBio	PS1.4
	2023.02.23	Professor of Sustainability Management (Italy)	EXP1.1
	2023.04.13	PetBio	PS1.5
	2023.04.26	Professor of Agronomy and Plant Science (Italy)	EXP1.2
	2023.06.05	PetBio	PS1.6
	2023.06.05	Professor of Accounting (Italy)	EXP1.3
	2023.06.06	Professor of Sustainability and Biodiversity Accounting (the UK)	EXP1.4
	2023.06.16	Professor of Agronomy and Plant Science (Italy)	EXP1.5
	2023.06.26	Professor of Accounting (Denmark)	EXP1.6
	2023.07.10	PetBio, SocioBio, AgriBio	PS1.7
	2023.07.13	3 Professors of Sustainability Management (Italy)	EXP1.7
	2023.09.12	Professor of Accounting and Corporate Governance (Australia)	EXP1.8
	2023.09.25	PetBio, SocioBio, AgriBio	PS1.8

TABLE 2 | Businesses participating in the study.

Code name[a]	Main business activities	Actors involved
AgriBio	AgriBio is a limited business that grows and sells organic food	Agronomist, sustainability team
SocioBio	SocioBio is a social cooperative that sells agricultural products adopting a fair-trade approach	Sustainability manager
PetBio	PetBio is a foundation-owned business that sells pet food	Project manager, scientific responsible

[a]Code names are fictitious to preserve the anonymity of the businesses.

artisans and farmers. The business offers a diverse range of products, including food items, handicrafts, and personal care products, all sourced through a transparent and traceable supply chain. In 2024, SocioBio employed around 70 people, presented an operating turnover of about €35 million, and €27 million in assets.

PetBio was founded in the early 2000s in Northern Italy and specializes in high-quality pet food for cats and dogs. PetBio is renowned for its commitment to using 100% HFC (Human Food Chain) ingredients, which are originally fit for human consumption. PetBio's product range includes wet and dry food, as well as plant-based, compostable cat litter, sold in more than 50 countries. The business operates under a peculiar economic model, where all profits are reinvested into nature conservation projects through FoundBio. In fact, in 2018, PetBio was donated to FoundBio, a nonprofit organization dedicated to biodiversity protection and combating climate change. This transition marked a significant shift in the business's mission, aligning its commercial success with environmental sustainability. FoundBio's initiatives are funded entirely by PetBio's profits, ensuring that the business's growth directly benefits ecological projects. In 2023, PetBio employed around 45 people and presented an operating turnover of about €115 million and €74 million in assets.

4 | The BioModel

The BioModel is composed of four main units: business, biodiversity and ecosystems, impacts, and dependencies. In the following sections, we deepen the nature of the last three:

4.1 | Biodiversity and Ecosystems

Biodiversity is an essential dimension of the so-called "natural capital" (Figure 1), which includes all living and nonliving resources such as soil, vegetation, animals, and water (Fleming et al. 2022; Haines-Young and Potschin 2018). In practical terms, biodiversity combines with nonliving (abiotic) elements to form ecosystems such as forests, farmlands, coasts, oceans, and urban parks. The health status of biodiversity directly affects ecosystems and natural capital's productivity, which is the

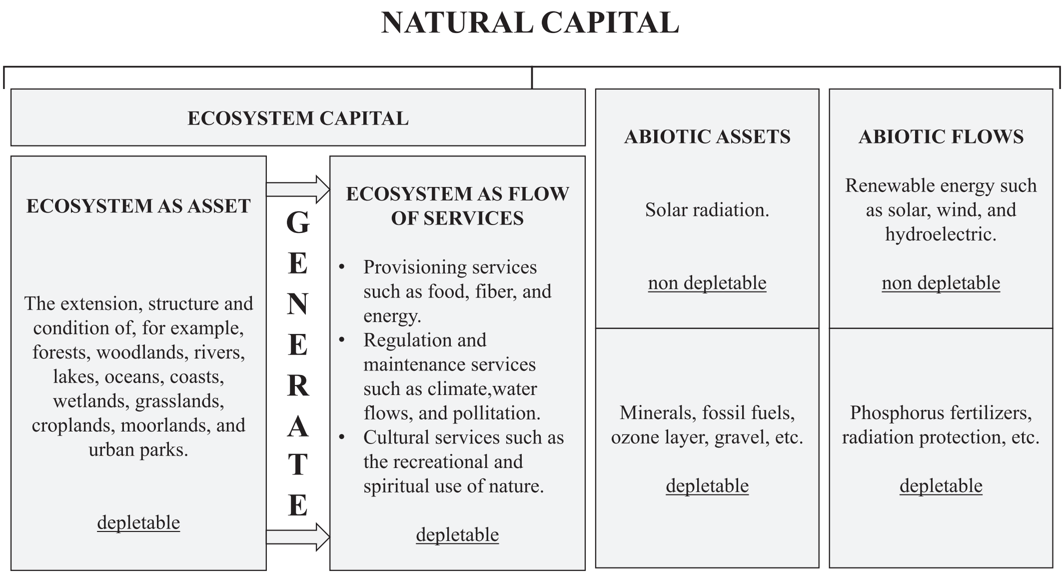

FIGURE 1 | Main components of natural capital. *Source:* Adapted from Haines-Young and Potschin (2018, 6).

ability to generate biomass (Dasgupta 2021; UN 2021). Moreover, ecosystems generate ecosystem services that are critical both to preserve all life on the planet and ensure a good quality of life for humans (IPBES 2019).

4.2 | Impacts

Businesses affect biodiversity by exploiting natural capital resources or polluting, therefore generating "impacts." Human activities—including businesses—have a direct impact on biodiversity through five drivers: ecosystem use change, overexploitation of natural resources, invasive alien species, pollution, and climate change (IPBES 2019; WEF 2020; Jaureguiberry et al. 2022; Panwar et al. 2023).

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).

After presenting the five drivers of direct impact in the plenary session (PS1.2), it emerged immediately the need to further refine the drivers into more manageable subdrivers that a business can act on. Therefore, the researchers created a list of subcategories of impact drivers that could be practical and implementable in corporate contexts. This process was strongly informed by the iterative interaction with businesses, whose feedback was essential in translating the conceptual structure into a usable framework. The dialogue with practitioners thus represented not only a source of empirical insight but also a constitutive element of the constructive methodology adopted (Kasanen et al. 1993), consistent with the pragmatic constructivist view that knowledge emerges from the integration of facts, possibilities, values, and communication (Nørreklit 2017).

The first step in this direction was to compare different subcategories of impacts proposed by the reference gray literature. Eleven impact subcategories from the Natural Capital Protocol (NCP) (Natural Capital Coalition 2016) and 10 from the SBTN (2020) were selected and aligned. Additionally, although 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 and 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 businesses and experts involved in the project (PS1.3 to PS1.7; EXP1.1 to 1.8). Specifically, the experts were asked about specific issues considering their backgrounds and areas of expertise, which included agronomy and plant sciences, sustainability management, accounting, and circular economy. Following the feedback 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 ecosystems and their ability to regenerate (EXP1.1, 1.2, 1.5, 1.7). Furthermore, the *solid waste* subcategory was changed to *waste* that includes solid waste and harmful liquid substances (EXP1.1). The description of the 16 impact subcategories is reported in Table 3.

4.3 | Dependencies

Businesses 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; Small et al. 2025). Business dependencies from biodiversity and ecosystems fall within one of three types of ecosystem services: provisioning services, regulation and maintenance services, and cultural and intangible services (Haines-Young and Potschin 2018; Dasgupta 2021). These services represent the dependencies that businesses have on ecosystems whose productivity depends significantly on the health of biodiversity (UNEP-WCMC et al. 2022).

Provisioning ecosystem services allow businesses 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 and 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, 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 CO_2 (Dasgupta 2021; UN 2021; Haines-Young and 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, 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, 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).

As it happened in the case of impacts, after presenting the three types of ecosystem services in the plenary session (PS1.2), it emerged immediately the need to further refine the ecosystem services into more manageable dependencies from biodiversity and ecosystems that a business can monitor.

The discussion with participating companies proved particularly valuable in this phase, as the multifaceted and interrelated nature of ecosystem dependencies made it difficult to model them without practitioner input. The interaction with businesses enabled the researchers to translate complex ecological interconnections into categories meaningful for management purposes. Also, this process exemplifies the constructive and pragmatic constructivist approach underpinning the study (Kasanen et al. 1993; Nørreklit 2017), where theory development is shaped through the integration of practical experience, contextual understanding, and conceptual reasoning.

TABLE 3 | 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 such 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 that 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), mononitrogen oxides (NO and NO_2, commonly referred to as NOx), 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 nonhazardous, 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_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

Source: Translated and adapted from Cinquini et al. (2024).

First, the gray literature on the topic was analyzed, and the most globally recognized categorizations of ecosystem services were identified. The most relevant source was the CICES, 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 (NCFA, UN Environment WCMC 2018; ENCORE 2024) and 18 categories from IPBES (2019) were taken into consideration, which were aligned with those of CICES (Haines-Young and Potschin 2018). For example, as subcategories for plant provision services, the Natural Capital Finance Alliance (NCFA) 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*, and *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 resulted in the identification of 15 dependencies deriving mainly from CICES and two IPBES categories for intangible ecosystem services. Furthermore, the four macro categories of services (maintenance, regulation, immaterial, and provisioning services) have been reduced to three by grouping 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 businesses and experts (PS1.3 to PS1.7; EXP1.1 to 1.8). The feedback from businesses and experts pushed the researchers to further refine and split 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 final 24 ecosystem services is reported in Table 4.

4.4 | BioModel Representation and Characteristics

At the end of the literature search and focus groups with businesses and experts, the systemic model of the relationship of impacts and dependencies between biodiversity and the business appears as depicted in Figure 2. This systemic model develops the primary relationship that exists between biodiversity, ecosystems, and businesses by detailing the 16 subcategories of impact grouped into the five direct drivers of impact (IPBES 2019; Jaureguiberry et al. 2022) and the 24 subcategories of dependencies grouped into the three ecosystem services (Haines-Young and Potschin 2018; UN 2021).

The laws of interaction among BioModel's units are represented by the arrows. From left to right, businesses act on one or more direct impact drivers that, in turn, alter the state of biodiversity and ecosystems. For example, the conversion of peatland and bogs into arable land (i.e., terrestrial ecosystem use change) has a direct impact on wild flora and fauna and can lead to the destruction of the ecosystem (Cuckston 2017; Puspitaloka et al. 2021). Business impacts on biodiversity and ecosystems are not necessarily always negative. For example, converting intensive agricultural land to agroforestry (i.e., terrestrial ecosystem use change) can lead to the return of wild fauna (Hübel and Wenzig 2025), or the conversion of a dumpsite into a closed landfill with the creation of an urban green space can help reducing pollution by waste, promote afforestation, and restore vegetated areas (Pinto et al. 2024).

From right to left, the relationship interaction between biodiversity and businesses is less straightforward than it is for impacts (Carvalho et al. 2022; Sobkowiak et al. 2025). The health of biodiversity and ecosystems is at the basis of functioning ecosystem services. And ecosystem services underpin many economic activities—and human life, if nothing else (Dasgupta 2021). A classic example is that of pollinators (Vysna et al. 2021). A population of pollinators in good health is crucial for ensuring crop yields. When the ecosystem becomes unbalanced, for example, by introducing invasive alien species, business dependencies become more apparent. Vysna et al. (2021) estimate that the diffusion of the Asian hornet in Europe can lead to an effect in fruit and vegetable production between −9% and −20% in countries such as Belgium, the Netherlands, the United Kingdom, and Germany. In fact, the Asian hornet predates bees, which are important pollinators. As bee populations dwindle because of Asian hornets' diffusion, the regulating and maintenance ecosystem service of "pollination" gets compromised and agricultural crop yield suffer, consequentially. Although it is easier to grasp business dependences from biodiversity in the primary sectors (e.g., agriculture, fishery, silviculture), dependencies exist in the manufacturing and service sectors, as well (Dasgupta 2021; Vysna et al. 2021). For example, (eco)tourism depends on the immaterial aesthetic value of natural landscapes offering physical and psychological experiences; production sites in areas under hydrogeological risks depend on the local flora for erosion control; pharmaceutical companies depend on the discovery of new molecules from plants, fungi, lichens, and microorganisms (Caparrós et al. 2017; Dietrich et al. 2025; Erwin et al. 2010).

One way to better explain why dependencies are relevant to a business context is conceptually linking them to business risks (Ingram et al. 2024; La Notte et al. 2025; Bach et al. 2025; Fu et al. 2025). In fact, the ability of an ecosystem to continue to generate useful services—if not essential—for a business is also a source of exposure to risk deriving from the collapse of that ecosystem or its inability to maintain the level of service necessary for the business over time (Carvalho et al. 2022; TNFD 2022; Bach et al. 2025). Therefore, on the one hand, ecosystem services represent an opportunity for businesses and a source of value creation; on the other, they intrinsically contain the risk that such services cease when the health of the ecosystem and biodiversity deteriorates to the point of preventing their regeneration. Therefore, reasoning in terms of dependence as "risk" can provide businesses with coordinates with which to orient themselves in mapping their exposure to the risk that certain ecosystem services, and therefore dependencies, deteriorate or collapse entirely. It is worth clarifying that the BioModel is not a risk assessment model since it does not provide risk measurements (e.g., likelihood, magnitude, exposure) necessary to support a risk-based approach to dependencies from ecosystem services. However, we believe that eliciting business dependencies from ecosystems as sources of business risks can provide a conceptual bridge for future risk assessment tools.

At this point, the issue of time and space can no longer be overlooked. In fact, if BioModel is by design a static representation that inevitably models the business–biodiversity relationship at a certain point in time, impacts and dependencies have an inherent spatial and temporal specificity (IPBES 2019). In other words, impacts and dependencies occur in a specific space and

TABLE 4 | 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 nonmineral substances	Withdrawal and use of minerals (e.g., oil, uranium, gas) and nonminerals (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 with 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.

(Continues)

TABLE 4 | (Continued)

Ecosystem services	Subcategories ecosystem services	Subcategory description
Ecosystem regulation and maintenance services	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, whereas 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 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.

Source: Translated and adapted from Cinquini et al. (2024).

time, not abstractly and acronical. Businesses with similar impacts and dependencies, but located in different places, may have a different exposure to risk, and therefore dependency, from degeneration of the ecosystems with which the business interacts. For example, a bathing establishment located on the shores of Lake Garda will not be affected by the spread of marine allochthonous species, unlike a similar establishment located on the upper Adriatic Sea. Furthermore, an impact generated by the same farm may vary over time. For example, a farm with a massive use of water for irrigation could generate a major impact in terms of overexploitation of water—with consequent deterioration of surrounding ecosystems—during periods of drought.

The same impact could become insignificant during periods of abundant rainfall.

Therefore, it is necessary to preserve a balanced equilibrium between the need to standardize the modeling of business impacts and dependencies using theoretical models of the likes of BioModel with the need not to lose important geographical and temporal contextual information that the business knows as it operates in a specific place and time.

5 | Discussion

5.1 | BioModel Boundaries and Application

From BioModel's representation in Figure 2, it might appear that the theoretical model is a closed model in which impacts and dependencies of a single business on biodiversity and ecosystem exist in a feedback loop. It is not. Different businesses can impact on a/or depend on the same ecosystem (Figure 3). Moreover, other anthropic actors such as cities, consumers, institutions, and not-for-profit organizations can impact on the biodiversity and ecosystems a business relies on.

Such an “open” representation of the business and biodiversity relationship implies a broader consideration of externalities (Martinet and Blanchard 2009; Bebbington and Larrinaga 2014; Unerman et al. 2018). In fact, impacts on biodiversity are often borne by actors that are different from the actors generating them. Similarly, positive effects coming from conservation, re-wilding, and nature-positive activities often extend to adjacent neighborhoods. An “open” version of BioModel should account for and manage the negative and positive effects that business externalities have on biodiversity and ecosystems.

It is worth underlining that negative or positive externalities tend to be localized upstream in the supply chain. In fact, according to the SBTN (2024) and UNEP-WCMC et al. (2023), businesses should assume that sourcing activities (extraction/growing/harvesting) are the ones with the highest impact on biodiversity and ecosystems unless there is evidence to prove otherwise. Therefore, downstream businesses necessarily need to assess, trace, measure, and manage their impacts along the supply chain if they truly want to help solve the biodiversity crisis (UNEP-WCMC et al. 2023). Direct impacts are easier for businesses to identify and measure. However, indirect impacts, which often occur upstream in supply chains, remain a significant challenge due to limited data availability and the difficulty of tracing responsibility across complex global networks (UNEP-WCMC et al. 2022; UNEP-WCMC et al. 2023). It follows that, to obtain an in-depth analysis of the real impact of a business or its dependencies on natural capital, it is necessary to broaden the scope of analysis to the value chain. As pointed out by UNEP-WCMC et al. (2023), the extraction phases of raw materials, whether living or nonliving, are the ones to be considered primarily because it is there that most impacts tend to occur.

Take, for example, the large-scale retail sector. The main impacts of such businesses are related to greenhouse gas emissions, refrigerant gases, energy consumption, and waste generation. However, the choice of which products to display on the shelf and the choices of their own branded products have an upstream

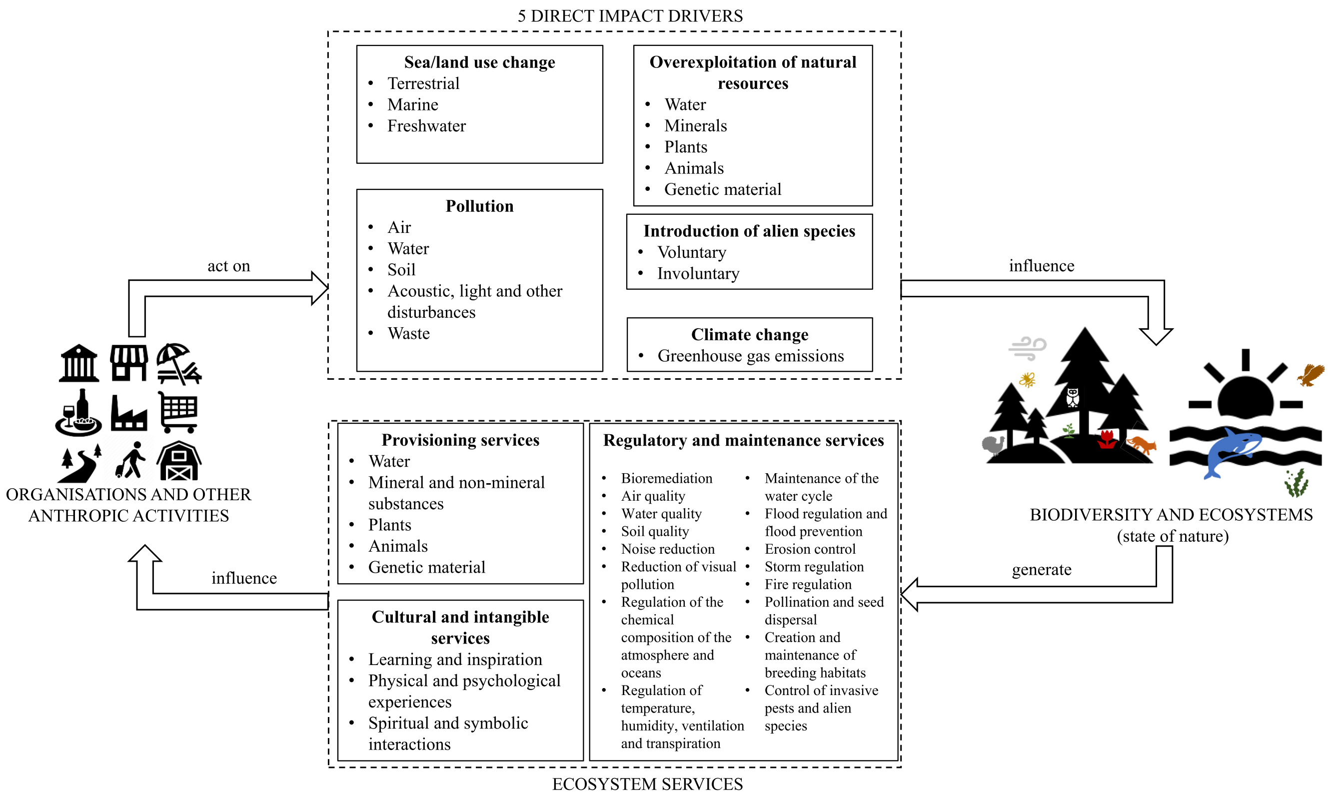

FIGURE 2 | Representation of the impact–dependency relationships underpinning the BioModel. *Source:* Adapted from Cinquini et al. (2024).

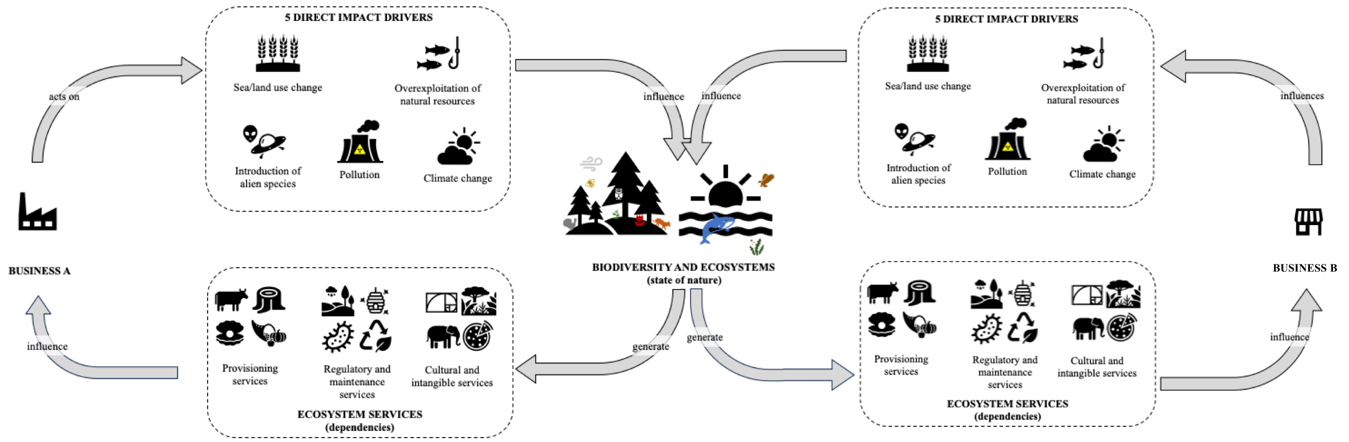

FIGURE 3 | BioModel in its "open" version.

impact on the raw material extraction stages, agriculture, and animal husbandry, primarily. Farms upstream in the agri-food chain, unlike those downstream, are much more exposed to dependencies on natural capital and have different impacts such as soil and water pollution (e.g., fertilizers and pesticides), water consumption (irrigation), and change of use of terrestrial ecosystems. Also, within the same agri-food chain, the transport of goods can be a vector for invasive alien species as well as the generation of greenhouse gases (Business for Nature 2023).

Taking an "open" or "closed" approach to the BioModel has practical implications. The "closed" BioModel implies that a business considers only its direct impacts and dependencies—the impacts and dependencies that are within the business' boundaries and over which it exerts control. On the contrary, an "open" BioModel asks businesses to consider their indirect impacts and dependencies that might be "further away" from the business' boundaries and well beyond its control (Schaltegger et al. 2022).

5.2 | BioModel and Double Materiality

One of the most significant regulatory innovations in the European sustainability landscape is the CSRD, which enshrines the principle of double materiality (Pigatto 2025). Unlike traditional materiality, which emphasizes issues that are financially material to the reporting entity, double materiality requires firms to report on both how sustainability issues affect the company's financial performance (outside-in perspective) and how the company's operations affect society and the environment (inside-out perspective) (European Parliament 2022; Pigatto 2025). This conceptual framework resonates strongly with the systemic logic of the BioModel, which explicitly disentangles impacts (how businesses alter biodiversity and ecosystems) and dependencies (how businesses rely on ecosystem services). In essence, the BioModel reflects double materiality for biodiversity: impacts align with the "inside-out" dimension, whereas dependencies mirror the "outside-in" dimension of materiality.

The interplay between BioModel and double materiality can be seen in three critical ways. First, the model offers firms a structured taxonomy for identifying and categorizing their material impacts on biodiversity, which the CSRD requires to be disclosed through the ESRS (EFRAG 2022). For instance, subdrivers such as overexploitation of resources, pollution, and ecosystem use change provide granular entry points for evaluating how firms contribute to biodiversity loss. This classification prevents superficial or selective reporting and enables comparability across firms and sectors (Boiral 2016). In doing so, the BioModel strengthens the impact–materiality perspective by guiding firms beyond generic statements toward evidence-based disclosures.

Second, the BioModel can advance the financial–materiality perspective by providing a foundational, conceptual bridge between dependencies from ecosystem services and sources of business risks and opportunities. Dependencies on pollination, water quality, or soil fertility are not just ecological realities but potential financial exposures when ecosystem functions degrade (Carvalho et al. 2022; Ingram et al. 2024). By aligning dependencies with ecosystem services, the model allows managers to articulate how external ecological shifts—such as species decline or climate-driven changes in ecosystem regulation—might propagate into strategic and financial risks (Bach et al. 2025; Fu et al. 2025). This echoes the rationale behind the TNFD (2023), which emphasizes the need to map dependencies as nature-related risks. Thus, BioModel serves as a conceptual foundation for future operational tools aiming to implement the outside-in dimension of double materiality in practice.

Last, the systemic nature of BioModel enriches the double materiality principle by highlighting interdependencies and spillover effects across value chains. Although the CSRD recognizes the importance of upstream and downstream impacts, operationalizing this requirement remains a significant challenge for many firms (Schaltegger et al. 2022). The BioModel's "open" version explicitly encourages businesses to extend their analysis beyond direct operations to indirect impacts embedded in supply chains and to consider the collective dependencies that multiple actors place on the same ecosystems (Schaltegger et al. 2022; UNEP-WCMC et al. 2023). By doing so, it not only strengthens compliance but also promotes a more holistic understanding of corporate responsibilities and exposures, consistent with the EU's broader ambition to integrate ecological boundaries into financial and nonfinancial reporting.

6 | Conclusion

In this research, we have adopted a constructive approach to theory and model development developed to articulate the BioModel, a systemic framework that explicates the complex relationship between businesses, biodiversity, and ecosystems (Kasanen et al. 1993). By disentangling the multifaceted web of impacts and dependencies, the model provides both researchers and practitioners with a structured approach to understanding how firms both rely on and influence ecological processes. The BioModel responds to the increasing recognition that biodiversity loss is not only an environmental crisis but also a material risk to business continuity, competitiveness, and legitimacy (IPBES 2019; Addison et al. 2020; WEF 2025).

Our analysis takes its premises from considering that without methodologically robust models capable of capturing interdependencies between business operations and natural capital, it is challenging to translate sustainability aspirations into measurable strategies and actionable interventions (Dubin 1978). The BioModel thus provides a conceptual bridge between ecological science and business decision-making, aligning with emerging frameworks such as the CSRD (European Parliament 2022) and the TNFD. By integrating ecological complexity into the language of businesses, it offers firms an entry point for both strategic reflection and operational practice.

Moreover, the development of the BioModel demonstrates internal coherence with the theoretical and methodological foundations underpinning the study. Consistent with Dubin's (1978) framework for theory building, the model defines its units, laws of interaction, boundaries, and propositions in a transparent and systematic way. The constructive research process (Kasanen et al. 1993) ensures that the model emerges from a practically relevant problem, whereas iterative engagement with businesses supports its validity. At the same time, the pragmatic constructivist perspective reinforces the epistemological soundness of this approach (Nørreklit 2017). In this sense, the BioModel is not only a descriptive tool but also a theoretically informed construct that bridges empirical observations and conceptual reasoning. Its conceptual validity thus rests on the coherence between methodological rigor, theoretical consistency, and practical applicability—a triad that reflects the essence of constructivist research.

At a broader level, the study highlights the necessity of embracing an "open" systems perspective when analyzing business–biodiversity relations. Restricting the analysis to direct corporate impacts risks ignoring the more substantial indirect effects embedded in value chains (Schaltegger et al. 2022). This extension is not only conceptually significant but also ethically and practically essential, as it forces recognition of how corporate choices reverberate across ecosystems and communities far beyond immediate organizational boundaries (Unerman et al. 2018).

6.1 | Limitations and Future Research

The limitations of the BioModel are a consequence of its boundaries discussed in Section 5.1. First, the model is conceptual and categorization focused. Therefore, even if the BioModel could be useful for breaking down and understanding a business' relationship with biodiversity and ecosystems, it does not provide operational tools, metrics, or procedures to measure, quantify, or manage that relationship. Second, the model is static by design, as it represents impacts and dependencies at a given point in time. Although the paper explicitly recognizes that impacts and dependencies are spatially and temporally specific, the BioModel does not model their evolution over time, nor does it simulate dynamic feedback loops, nonlinear ecological responses, or threshold effects. Third, the systemic nature of the BioModel should be interpreted in analytical rather than dynamic or predictive terms. The model is systemic insofar as it explicitly links businesses, impact drivers, biodiversity and ecosystems, and ecosystem services within a coherent relational structure that captures both "impacts on" and "dependencies from" natural capital. However, consistent with its positioning in Sections 4.4 and 5.2, although the BioModel is not a risk assessment model and does not operationalize double materiality, it provides a conceptual foundation and a classificatory structure that can support the design and implementation of operational tools, dynamic analyses, and risk-based or double-materiality assessments.

The development of the BioModel opens several promising avenues for future inquiry. First, empirical validation of the model across industries and geographies is necessary to refine its categories and test its applicability under different institutional and ecological contexts. Comparative studies could explore how sectoral characteristics—such as resource intensity, supply chain complexity, or regulatory exposure—shape the configuration of impacts and dependencies (Carvalho et al. 2022). Second, more work is required to connect the BioModel to performance measurement and accounting practices. Although prior research has critiqued the limitations of biodiversity reporting (Boiral 2016; Atkins and Maroun 2018), there remains a need for robust assessment frameworks and indicators that can be embedded into management control systems and used for both internal decision-making and external accountability (Raar et al. 2020; Sobkowiak et al. 2025). Interventionist research (Suomala et al. 2017) represents a promising methodological path, enabling scholars to codevelop tools with practitioners and observe how biodiversity considerations reshape governance and strategy. Third, future research should address the philosophical and ethical tensions inherent in translating biodiversity into business terms. As noted in ecological accounting debates (Sullivan and Hannis 2017; Dempsey 2016), reducing ecological value to quantifiable indicators risks commodification and oversimplification. Researchers must therefore investigate alternative forms of representation that capture both anthropocentric dependencies and ecocentric values, potentially integrating qualitative and narrative approaches alongside metrics. Finally, research should more explicitly explore the role of finance and capital markets in shaping biodiversity strategies (Hadji-Lazaro et al. 2024). Recent contributions on financialization and nature suggest that investor expectations and risk logics may powerfully influence how businesses internalize ecological considerations (Arjaliès and Gibassier 2023; La Notte et al. 2025). The BioModel could thus be extended to analyze how financial actors mediate the translation of ecological dependencies into business risks and opportunities.

For practitioners, the BioModel offers a structured and actionable pathway to embed biodiversity within corporate sustainability strategies. Managers can use the model to support the mapping of direct and indirect impacts, identify dependencies critical to long-term resilience, and prioritize interventions. This is particularly relevant given the acceleration of regulatory requirements such as the CSRD and the EU Nature Restoration Law (European Parliament 2022, 2023). By employing the BioModel, firms can align compliance efforts with strategic foresight, turning regulatory challenges into opportunities for innovation and differentiation. Moreover, the model underscores the importance of integrating biodiversity considerations into supply chain management. In practice, this means that procurement policies, supplier audits, and collaborative initiatives must explicitly address ecological impacts and dependencies (UNEP-WCMC et al. 2023). Companies adopting an "open" version of the BioModel can better anticipate systemic risks—such as disruptions in pollination services or freshwater scarcity—that cascade across value networks. The BioModel also provides a foundation for enhancing stakeholder dialogue. By clarifying the categories of impacts and dependencies, it can help managers communicate with investors, regulators, NGOs, and local communities in ways that are both scientifically grounded and business-relevant (Addison et al. 2020). This transparency is essential for building trust and legitimacy in an era where nature-related risks are increasingly viewed as strategic concerns (Busco et al. 2024).

As biodiversity loss intensifies and regulatory landscapes evolve, the integration of ecological considerations into business decision-making will become not only desirable but indispensable. By bridging ecological science with management and accounting perspectives, we believe that the proposed BioModel represents a step toward reconciling economic activity with the ecological limits upon which all businesses—and societies—ultimately depend. Future developments should continue to test and refine the BioModel across contexts, thereby contributing to the ongoing dialogue between theory and practice that lies at the heart of constructivist research. Moreover, we do believe a fruitful line of research would be to operationalize the conceptual BioModel by constructing and testing methods, metrics, and processes for the operational deployment of the model. Furthermore, future research should provide case applications of BioModel in practice and how BioModel could be used—if at all—to inform and operationalize double materiality and risk assessment.

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Endnotes

[1] Data on employees and financial statements of the three businesses are sourced from Moody's ORBIS database.

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