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Biodiversity and chemical regulation: Status quo, data gaps, and recommendations for future action

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Conflicts of interest

ECETOC is a not-for-profit scientific organisation that provides a collaborative space for scientists from industry, academia and regulatory bodies to develop and promote trusted and practical scientific solutions to chemical safety assessments. The twenty participants to the Task Force

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comprised fourteen from companies who manufacture or use of chemicals or are involved in the applied research of their impact on the environment, three from academia or research institutes, two from EU policy support institution and regulatory agency and one from ECETOC. The chemical sectors represented included industrial chemicals, consumer products and plant protection products.

ECETOC Task Force members aim to provide an objective, scientific assessment of the topic. Some members of this Task Force work for companies that produce chemicals and assessing the risks of chemicals to biodiversity may affect substances that are of commercial importance to these companies. The potential conflict of interest does not apply to the Task Force members from academia and regulatory bodies.

This manuscript was subjected to internal peer-review from participating companies/organisations, as needed, and only minimal changes were requested. This manuscript was also reviewed by the ECETOC Scientific Committee consisting of representatives of academia and industry (<http://www.ecetoc.org/about-ecetoc/scientific-committee/>). This review yielded very few and only minor comments.

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The coauthors of this manuscript consist of ECETOC Task Force members (comprising members from industry, academia and regulatory bodies) and Stewards from the ECETOC Scientific Committee. The views expressed in this article are solely those of the coauthors and may not represent those of their organisations.

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Biodiversity and chemical regulation: Status quo, data gaps, and recommendations for future action

Abstract

Global biodiversity is declining, driven by multiple, interacting pressures including the 5 most prominent of resource use, habitat loss, invasive species, climate change, and chemical pollution. While chemical exposure is recognised as a potential driver of biodiversity loss, quantitative links and its relative impact compared to other stressors remains poorly understood. The European Union (EU) has intensified efforts to reduce pollution and restore biodiversity through strategic frameworks such as the Biodiversity Strategy, Farm to Fork Strategy, Zero Pollution Action Plan, and Chemical Strategy for Sustainability. Key chemicals regulations like REACH and the Plant Protection Products Regulation aim to protect ecosystems, however, due to the complexity of ecosystems and the range of impacting stressors it is difficult to measure their direct impact on maintaining or improving biodiversity objectives. This review, conducted by a multidisciplinary Task Force brought together by ECETOC, evaluates the current state of biodiversity research efforts and its integration within EU chemical regulation. We examined EU legislation, strategy documents, EU-funded research, and peer-reviewed literature to identify biodiversity definitions, metrics, and methodologies, and to highlight gaps in linking chemical exposure to biodiversity outcomes. Findings indicate that: current chemical regulations reference biodiversity mainly qualitatively, biodiversity research often lacks a focus on chemical impacts, and research outcomes are not clearly linked to regulatory frameworks. The relationship between biodiversity and chemical impacts is further complicated by diverse definitions and metrics of biodiversity in the academic literature, with limited consistency across biomes and minimal alignment with chemical risk assessment practices. To strengthen biodiversity considerations in chemical regulation, we recommend: developing operational definitions of biodiversity applicable across regulatory contexts; standardising metrics and indicators; establishing a centralised data platform for biodiversity research; and leveraging existing data, methodologies, tools and new technologies (e.g. machine learning). Bridging knowledge gaps between policy objectives and available approaches, whilst aligning biodiversity considerations across both chemical regulation and other regulations which can impact biodiversity such as habitat loss, will promote coherence and cooperation. Continued multistakeholder engagement and alignment is critical in achieving these recommendations.

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Keywords: Biodiversity, Chemicals, Regulation, Chemicals Management,
Environmental Risk Assessment

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Introduction

There is now widespread evidence that biodiversity is globally declining, although location-specific trends depend largely on scale, habitat, and region (Dornelas et al., 2023). Mounting evidence for the negative impacts of biodiversity loss (IPBES, 2019) has led the UN to prioritise a halt to biodiversity loss in the UN sustainable development goals (Goal 15, <https://www.un.org/en/exhibits/page/sdgs-17-goals-transform-world>). Pollution, including chemical exposure, is cited as one of the key drivers of biodiversity loss in the 2022 Kunming-Montreal Global Biodiversity Framework, which aims to halve and reverse biodiversity loss by 2030 (CBD, 2022). Other key drivers listed as having an impact on biodiversity include habitat loss, invasive species, overexploitation of resources, and climate change (CBD, 2022). The EU and European Commission are increasingly focused on pollution reduction to restore and preserve biodiversity. This shift is evidenced by several new strategic documents, such as the EU Biodiversity Strategy (European Commission, 2020c), Farm to Fork Strategy (European Commission, 2020a), Zero Pollution Action Plan (European Commission, 2021), Chemical Strategy for Sustainability (European Commission, 2020b) and One Health approach (European Commission, 2024). These strategy documents explicitly target chemical inputs as one of the main drivers of biodiversity decline and set ambitious goals for reducing their entry into the environment. In addition, researchers highlight the role of chemicals in biodiversity declines (Groh et al., 2022), and call for stricter, more holistic assessment of risks from exposure to chemicals (Axelman et al., 2024; Brühl & Zaller, 2019; Topping et al., 2020). However, quantitative links between biodiversity loss and chemical exposure for different groups of organisms and systems are yet to be fully understood. Moreover, the effects of chemical exposure on biodiversity relative to other pressures (e.g., habitat loss) have yet to be quantified (Semenchuk et al., 2022; Tilman et al., 2017). To bridge these knowledge gaps, there is a need to develop clear definitions, identify the state and trajectory of existing research, interpret how that research is integrated with chemicals legislation, and explore existing tools that can facilitate quantitative linkages between measurement and assessment endpoints (Forbes & Galic, 2016; Maltby et al., 2021).

Chemical industries in the EU are subject to strict regulation, with specific requirements to assess and demonstrate acceptable risk to the environment from chemical exposure before a substance enters the market (e.g. the REACH Regulation (EC) No 1907/2006 (European Parliament and Council, 2006b), the Plant Protection Products Regulation (EC) No 1107/2009 (European Parliament and Council, 2006a)). Environmental risk assessments, carried out in line with the relevant regulatory guidance and internationally agreed practice under OECD, determine the risk to a set of standard representative species using conservative predicted exposure estimates and margins of safety. This process is intended to ensure that other species within the same ecosystem are also protected. Studies have been conducted with the aim to link risk assessment methodology to biodiversity metrics, including the alignment between species sensitivity to chemical toxicity with species abundance in aquatic systems (Hoeks et al. 2020) and effect of chemical mixtures with environmental stressors, on biodiversity in surface waters (Posthuma et al. 2019). However, significant work is still needed to establish if these and any additional approaches effectively address ambitious targets set by recent EU biodiversity strategies.

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This issue was recently highlighted in a Joint Research Centre of the European Commission (JRC) report which examined how standard ecotoxicological studies address each class of Essential Biodiversity Variables (EBVs) - a set of descriptors that capture key aspects of biodiversity. The report highlighted how the potential misalignment between ecotoxicological endpoints and EBVs can hinder establishing a causal link between chemical pollution and biodiversity effects (Baccaro et al., 2025). The European Food Safety Authority (EFSA) proposes defining Specific Protection Goals (SPGs) within the ecosystem services context to better assess and manage risks to biodiversity (EFSA Scientific Committee, 2016). This approach acknowledges that biodiversity is crucial for the functioning of ecosystems and the services they provide. The European Food Safety Authority's framework for developing SPGs involves identifying relevant ecosystem services, the units providing those services, and the levels of protection needed for those units. However, operationalising SPGs has been challenging due to limited specific definitions and scales of biodiversity. In addition, corporate reporting requirements, such as those mandated by the Corporate Sustainability Reporting Directive (CSRD) (European Parliament and Council, 2022) and the EU Taxonomy (EU No 2020/852) include biodiversity considerations, but it is unclear whether these reporting frameworks are aligned with biodiversity definitions and metrics used in other regulatory contexts and academic research, further complicating coordinated efforts to monitor and manage biodiversity risks related to chemical exposure.

To address these challenges and knowledge gaps, the European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) initiated a Task Force at the end of 2023.

The Task Force reviewed the status quo with respect to three key objectives:

- 1) To evaluate existing EU legislation and strategic documents to clarify how the term biodiversity is used and defined, including the metrics and methods employed in these high-level documents;
- 2) To compile an overview of recent and ongoing EU-funded research projects related to chemical impact on biodiversity to identify how new scientific knowledge can inform regulatory frameworks and to highlight future research needs;
- 3) To evaluate the landscape of biodiversity definitions and metrics across biomes, with the goal of offering insight into potential frameworks for standardization across global regions.

The aim of this paper is to present the outcomes of this review, integrating these insights to highlight critical knowledge gaps and misalignments. By doing so, this paper contributes to advancing a discussion on the link between chemical exposure and biodiversity loss, including aspects of biodiversity metrics as well as research needs. This emphasises the need for continued stakeholder engagement to advance the scientific understanding required for robust and ecologically relevant risk assessments.

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Biodiversity considerations in EU legislation and strategic documents [Objective 1]

Aim:

By reviewing existing high-level EU legislation and strategic documents, we aimed to evaluate how the term ‘biodiversity’ is defined and considered within the context of EU chemical regulation, including the metrics and methods employed. The analysis focused specifically on EU chemical regulatory frameworks, which establish the legal scope, overarching protection goals and risk assessment paradigms. In addition, some more conservation-focused documents were also considered for a broadened perspective. The review did not assume that EU legislation should include detailed quantitative specifications; instead, it examines whether biodiversity is explicitly represented within the regulatory baseline. The identification of specific species, habitats, or systems, and their treatment in detailed annexes or technical guidance, and national implementation, was considered out of scope. While this downstream guidance for implementation provides quantitative details (e.g. habitat quality criteria or species lists), the focus of this review was on chemical regulation and legislation specifically and how effects on biodiversity are defined. Assessing this legislative level was essential to identify systemic gaps and differences rather than implementation variability.

Methods:

Initially, 41 legislative and strategy documents were identified by expert judgement as being potentially relevant for this evaluation based on the broad expertise of the Task Force with chemical regulations in the EU. The EUR-Lex website was searched (<https://eur-lex.europa.eu/advanced-search-form.html>). Search criteria: Domain: All, Type of act: Regulation, Directive, Results containing: biodiversity In title and text, Results containing: chemical In title and text, Search language: English), and key documents from different chemical sectors were selected. This was not necessarily comprehensive, but the evaluation focused on the most widely used regulations from different chemical sectors within chemical risk assessments. These comprised: 15 European regulations; 12 European Directives; 6 policy strategies from the European Commission (ECHA’s Key Areas of Regulatory challenge document was included here); 6 frameworks (4 from the EU, 2 transnational agreements); 1 national law; and 1 other type of document. Of the 41 documents reviewed 28 stated biodiversity with a notable increase in prominence since the 1990s, potentially due to the 1992 Rio Convention on Biodiversity (Figure 1).

As a first step, the 41 documents were screened for several aspects (Table 1), the two most important criteria being: a) ‘Biodiversity explicitly stated’ or ‘Biodiversity addressed via a generic surrogate e.g. nature, environmental, wildlife’; or b) presence of a specific focus on chemicals impact on the environment OR the mitigation of chemical impacts on the environment. If either a) or b) were fulfilled, the documents were taken to the next step of the evaluation. The resulting list was further condensed by excluding documents where biodiversity was referred to very few times

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or in a general manner, and therefore not considered useful for further evaluation. This included the strategy documents as well as some directives and frameworks including the EU Habitat conservation Directive, EU CS3D ([Corporate Sustainability Due Diligence Directive](#)), EU WEEE (Waste Electrical and Electronic Equipment) Directive, EU Pollinators initiative and EU SSbD (Safe and Sustainable by Design) framework. In addition, two regulations linked to the data requirements for plant protection products (PPPs) were excluded as they were considered as being under the main PPP regulation 2009/1107. From the initial list of 41, 25 documents remained for a further evaluation on how biodiversity is currently defined and considered for regulatory purposes.

Outcomes:

The main findings from the 25 legislative and strategy documents identified for further evaluation can be summarised as follows:

- Definitions for biodiversity are rarely provided, and, where provided, largely follow the Convention on Biological Diversity (CBD) 1992 definition of biological diversity (total: 5)
- Metrics for biodiversity in relation to chemical risk are rarely reported in legislative and strategy documents (although noted that downstream national regulations will contain more specific details for biodiversity these are not apparent in the legislative documents) (total: 8) and where provided are often qualitative (habitat conditions, political indices, 'good conditions') but become more specific (e.g., populations of surrogate species) for regulations relating to chemicals intended for use in the environment or where their release is anticipated. Examples for the latter are the regulations for plant protection and biocidal products.
- Methodology to assess the chemical impact on (a proxy of) biodiversity are considered only in few documents (total: 3)

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The technical guidance documents associated with the legislative documents were not evaluated as these were out of scope of the focus of the evaluation, even though some of these documents may provide more precise metrics than the main legal text of regulations and directives. For instance, subject-specific documents supporting the PPP Regulation (EC No 1107/2009) include guidance on conducting environmental risk assessments for birds and mammals (EFSA, 2023). Here, the operational protection goal focuses on ‘no visible mortality’ and ‘no long-term repercussions for abundance and biodiversity’ of birds and mammals in agricultural areas, and biodiversity definition is in line with the one from CBD 1992. The focus of risk assessment in the birds and mammals guidance is on species that typically occur in or adjacent to agricultural landscapes, and on the protection of potentially sensitive species or vulnerable populations. The recently published proposed strategy for the definition of SPGs for terrestrial organisms for pesticide environmental risk assessment (ERA) addresses several taxonomic groups occurring in agricultural landscapes, including non-target plants, non-target arthropods, and soil organisms (micro- and mesofauna as well as microorganisms) (EFSA et al., 2025). Nevertheless, some potentially important components of biodiversity may still be underrepresented or only indirectly covered in current schemes (e.g. fungi, protists; noting that aspects of soil microbial functioning are considered via soil microflora tests such as nitrogen transformation). A systematic evaluation of coverage across all taxa and functions was beyond the scope of the present analysis and would require a dedicated assessment.. It should also be noted that while the EU Habitats Directive (Council Directive 92/43/EEC) includes annexes of species lists to determine habitat quality, the directive does not have a specific focus on chemicals impact on the environment.

The mechanisms for regulation and risk management of chemicals across the 25 legislative and strategy documents were also reviewed. It can be summarised that each document generally states several mechanisms, with hazard/risk assessments and use restrictions and limitations being the most common. The choice and combination of the mechanisms applied is linked to the purpose and scope of the document. For example, in cases where a release into the environment is not intended, the focus is on mechanisms safeguarding that the risks from releases are controlled, e.g. by use instructions/use limitations. For chemicals where release to the environment is intended or unavoidable, hazard and risk assessment are more in focus, e.g., PPP and biocides. In more recent legislation, including the EU Regulation on Taxonomy for sustainable activities (EU No 2020/852) and the EU Directive on corporate sustainability reporting (CSRD; EU No 2022/2464), monitoring and financial mechanisms are incorporated as part of the EU’s sustainable finance initiatives (https://finance.ec.europa.eu/news/sustainable-finance-2025-05-21_en). The latter include payments, reporting obligations and due diligence for sustainability and impacts on biodiversity.

Conclusion – Objective 1:

In the 25 high level legislative and strategy documents reviewed, a limited number include definitions for biodiversity, and generally where it is mentioned the CBD 1992 definition is used.

Metrics for biodiversity are currently variable in availability and application and are often qualitative rather than fully standardised and quantitative. However, they tend to be more clearly defined in regulatory frameworks for chemicals intended for environmental use or with anticipated release (e.g., plant protection and biocidal products), where assessment typically centers on focal species representing potentially affected communities.

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Mechanisms for regulation and risk management of chemicals vary depending on the scope. Often hazard and risk assessment form the basis, followed up with obligations for appropriate risk management measures when a risk is indicated or suspected. More recent legislation includes payments, reporting obligations and due diligence for sustainability and impacts on biodiversity.

While it is acknowledged that downstream guidance documents and national laws for habitat protection include specific details for determining biodiversity and habitat quality, these aspects are not explicitly stated in chemical regulation and risk assessment and so there is an opportunity for future coordination.

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EU-funded research projects relating to biodiversity

[Objective 2]

Aim:

We aimed to overview the recent and ongoing EU-funded research projects related to chemical impact on biodiversity with two objectives: to identify how new scientific knowledge can better inform regulatory frameworks; and to highlight future research needs in the field.

Methods:

As a first step, we considered which databases to leverage to inform the question about European Commission funded research projects related to biodiversity and chemicals. We identified the CORDIS (Community Research and Development Information Service) database as the one with the most comprehensive and up-to-date information. The Community Research and Development Information Service is the European Commission's primary source of results from the projects funded by the EU's framework programmes for research and innovation, from framework programme 1 (FP1) to Horizon 2020 (2014-2020) and Horizon Europe (2021 – 2027). The review thus extracted the information from the (CORDIS) database (<https://cordis.europa.eu/search> - data extracted on 21 December 2023). We acknowledge that European Commission-funded research on biodiversity may fall under programmes other than these framework programmes, and these are not captured in this review.

The objective of the review was to map all potentially relevant projects and was set-up to be inclusive of all chemical groups, environmental compartments, and species taxa. Keyword searches were performed using the CORDIS standard search interface, which applies terms simultaneously to both the project title and objective (abstract) fields as searchable in the CORDIS database. The "objective" field contains the project summary/abstract as submitted by the project consortium at the time of registration; this field is referred to as "project description" in some CORDIS interface views but corresponds to the "objective" column in the exported data (SI1). The search was initially tailored to identify projects started since 2017 using the keyword 'biodiversity', which resulted in 1251 projects. These projects were then categorised based on their potential to be informative for regulatory frameworks assessing effects of chemicals on biodiversity as follows:

- Projects considered directly relevant. These were projects in which the project objective indicated that both chemical exposure and biological or ecological outcomes were being studied within an environmental risk assessment (ERA)-relevant environmental compartment. European Union chemical ERA under key legislative instruments reviewed in Chapter 2 - notably REACH (EC No 1907/2006), the PPP Regulation (EC No 1107/2009), and the Biocides Regulation (EU No 528/2012) - is structured around specific environmental compartments: aquatic (freshwater and marine), terrestrial (including soil and agricultural land), and sediment. The keywords set used to identify projects addressing

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these compartments were therefore: 'environmental', 'ecological systems', 'soil (health)', 'freshwater', 'marine', or 'agricultural ecosystems', applied in combination with both 'biodiversity' and 'chemicals'. These compartment-based keywords served as a regulatory proxy - projects using this vocabulary in combination with both biodiversity and chemicals were considered likely to generate the empirical exposure-effects data most applicable to ERA frameworks.

Following keyword pre-screening, expert validation confirmed 34 projects (~3%) as directly relevant.

- Projects considered indirectly or potentially relevant were those whose objective addressed frameworks, concepts, metrics, or policies that could support how ERA for biodiversity is designed or operationalised — such as protection goals, biodiversity indicators, risk management options, or policy instruments — without themselves generating direct chemical-biodiversity effect data. These projects were identified where the objective mentioned 'metrics', 'indirect effects', 'system level', 'protection goals', 'risk management', or 'policies', in the absence of the direct compartment-chemical-biodiversity co-occurrence required for direct relevance. While these keywords can in principle co-occur with those of the directly relevant category, the distinction is one of primary research purpose: directly relevant projects aim to characterise chemical effects on biodiversity empirically; indirectly relevant projects aim to inform the conceptual or policy infrastructure within which such effects would be assessed. 234 projects (~19%) were identified as indirectly relevant based on these criteria.
- Projects considered not relevant. These were projects whose descriptions mentioned 'biodiversity' but, based on the project description, related rather to topics such as climate change, astronomy, law, language and literature, history or clinical medicine; 983 projects (~78%) were identified as not relevant based on these criteria.

The directly relevant projects were checked for additional available information in the respective project related websites. As direct links to project website were only available for a few in the CORDIS database, the project names were entered into a search engine to look for additional details. To evaluate the EU investment into this research area, we searched for the funding information in terms of "EU contribution" to total costs within the CORDIS info. We also added the information on participating institutions in each project.

Outcomes:

EU-funded research spending on biodiversity and chemicals increased sharply after 2019, as shown by total and average costs per project (Figure 2; Supplemental Information (SI) 1, columns M–AH of tab 'summary 2017-2023_cordis-search'). While not all biodiversity-related research projects focus on chemical exposure or inputs, the impact of chemicals on biodiversity is mentioned in many of them. Of these, 34 projects were identified as directly relevant projects (green-highlighted rows in SI1, tab 'summary 2017-2023_cordis-search'), however, none focused specifically on developing methodologies or research outputs for direct implementation in chemical regulation to assess impacts on biodiversity.

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Instead, they tended to address biodiversity within broader studies of specific habitats (soil, marine, agricultural) or chemical groups (plant protection products, pharmaceuticals), often focusing narrowly on individual chemicals or species.

Taxonomic representation was uneven: vertebrates (fish, birds), insects (primarily pollinators), and plants (wild and crop) were prominently represented, while fungi and protists received comparatively less coverage. Determining the precise extent of this disparity requires a more thorough database analysis to identify key research gaps. As a result, while most of these projects demonstrated a range of applicable methods, their findings were not always directly actionable for policymakers or regulatory decision-making. In more recent projects, researchers have begun examining system- and landscape-level questions more relevant to chemical regulation — for example, the effects of plant protection products on non-target organisms across terrestrial landscapes.

A consistent challenge is represented by the fact that detailed content information on EU-funded projects is difficult to retrieve, consolidate, and analyse due to the absence of a centralised and FAIR (Findable, accessible, interoperable, and reusable; <https://www.go-fair.org/fair-principles/>) data source. While CORDIS contains substantial information (e.g., involved institutions, funding, timelines), direct links to full proposal texts, current status, and importantly, outputs and findings, are not systematically captured. The platform often lacks direct links to project webpages, and there is very limited archiving of past projects.

Conclusion – Objective 2:

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2019) and the United Nations Environment Programme (UNEP) identify five key direct drivers of biodiversity loss: land use change, overexploitation of organisms, climate change, pollution (including chemical exposure), and invasive alien species. These drivers rarely act in isolation — the majority of species under threat worldwide face two or more of these pressures simultaneously, and their interactions can be synergistic or antagonistic in ways that single-driver studies cannot detect.

The analysis of EU research activities demonstrates that the need of implementable tools, knowledge and data regarding the impact of chemicals on biodiversity is not yet clearly reflected in EU-funded research projects. In the context of assessing chemical risks to biodiversity, actionable regulatory recommendations are a crucial factor. A more detailed analysis of this aspect in the projects considered directly relevant could yield valuable input for effective chemical regulation and biodiversity protection.

Given the scale of EU investment in biodiversity-related research there is a compelling case for conducting meta-analyses across projects to synthesise existing findings, rather than relying on isolated project outputs. Such cross-project meta-analyses could, for the first time, enable quantitative attribution of biodiversity change to individual and combined drivers, and reveal where chemical exposure interacts most critically with other pressures. However, our review confirmed that conducting such analyses is currently not feasible in a consistent and systematic way.

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The core obstacle is the absence of a centralised and FAIR data source. The Community Research and Development Information Service provides basic project metadata (institutions, funding, timelines), but full proposals, outputs, and underlying datasets are not systematically captured, and archiving of past projects is limited. Under Horizon Europe, open science and FAIR data management are legal obligations, and the Horizon 2020 Guidelines on FAIR Data Management explicitly state that ‘Good research data management is not a goal in itself, but rather the key conduit leading to knowledge discovery and innovation, and to subsequent data and knowledge integration and reuse’ (https://ec.europa.eu/research/participants/docs/h2020-funding-guide/cross-cutting-issues/open-access-data-management/data-management_en.htm#:~:text=This%20document%20helps%20Horizon%202020%20beneficiaries%20make%20their,reusable%20%28FAIR%29%20to%20ensure%20it%20is%20soundly%20managed). Nevertheless, the gap between formal requirements and practical implementation remains substantial. Harmonised data reporting standards, agreed metadata schemas, and accessible long-term repositories are prerequisites for cross-project synthesis — and these are currently far from consistently applied across EU-funded biodiversity research.

Several opportunities exist to make future research more impactful. Progressive projects that explicitly build on prior work would support more informed regulatory frameworks and enable feedback on their effectiveness. Early collaboration between researchers and regulators is essential to ensure research addresses genuine policy gaps and that outputs align with decision-making needs. Actionable, standardised, and transparent results increase applicability in regulatory contexts, as does grounding research in real-world evidence — such as integrated biological and chemical monitoring data — with a clear understanding of existing regulatory frameworks. We recommend that future scientific efforts include meta-analyses across projects to consolidate the state of knowledge, identify gaps and clarify emerging research needs.

Finally, analysing the cross-links between regional regulatory frameworks and their global implications represents an important additional focus for Horizon Europe projects. Effectively addressing biodiversity loss requires coordinated global action, and such analysis would help ensure that regulatory interventions do not unintentionally export environmental footprints.

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Definitions, metrics, and tools for biodiversity in scientific literature [Objective 3]

Aim:

We evaluated peer-reviewed literature to generate an overview of biodiversity definitions across biomes and the myriad metrics and methods used to assess and quantify biodiversity. The proximate goal of our review is to reveal the landscape of these definitions and metrics, whereas the ultimate goal was to provide a stepping stone towards consistent frameworks for biodiversity assessment that can be used in legislation. To capture the broadest sweep of information, the primary focus of our search was on review papers, perspectives, and meta-analyses.

Methods:

Text-mining analytics were employed to assess the definitions and metrics for biodiversity in academic literature. Of specific interest was how definitions and metrics vary across major biomes, including both aquatic and terrestrial (Table S1 in SI2). For consistency and reproducibility, separate searches were conducted in Google Scholar (on 18 April 2024) for each biome using the search phrase:

[ecosystem] biodiversity review* OR perspective* OR synthesi* OR “meta-analysis” OR “meta analysis” monitor* OR measur*

The term [ecosystem] was replaced with a search phrase that included associated habitats for each biome, as well as alternative names for that biome (Table S1). For example, the grassland biome has several common names across the world; all were included within the search. The time range of the search was limited from 2014 to 2024, and the search was restricted to titles, abstracts, and metadata (e.g. keywords, key highlight statements). The top 100 citations were extracted from the search algorithm. Following the removal of any citations focused only on case studies, most biomes were represented by 30-50 papers. The top 25 papers for each biome, in terms of relevance, were then identified. This paper selection per biome generally aligned with the top-ranked papers according to number of citations. The 25 papers selected for each biome are provided in SI3 (yellow highlighted rows). Some papers overlapped between biomes; a total of 205 papers were identified.

Following selection of papers, the entire corpus of each selected text (i.e. title, abstract, keywords, and body) was downloaded into a single text file for each biome. The *tm* (Ingo 2013) and *SnowballC* (Bouchet-Valat 2020) packages in R were used for stopword removal and stemming, respectively. The JMP statistical software text-mining toolkit was used to identify the relative differences between sets of biome-relevant literature by conducting singular value decomposition (SVD) across all biomes. For this analysis, the maximum number of words per phrase was set to 4, the minimum characters per word was set to 2, and terms were weighted by frequency.

The first analysis assessed the association between the biome-specific corpora from the literature and GEOBON's six Essential Biodiversity Variables classes (EBVs; Balvanera et al. (2022);

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Pereira et al. (2013)), which are a set of descriptors that capture key aspects of biodiversity. The document-term matrix (DTM) of each biome was mined for keywords associated with each EBV name (i.e., subcategories; Table S2 in SI2). Because the previous analysis already stemmed every word, stemmed names of each EBV class were also used. The total number of instances for all EBV names was summed within an EBV class.

To identify the dominant types of organisms studied within biomes, additional text-mining analyses for biological keywords associated with EuropaBON's EBVs was conducted (Junker et al., 2023). Whereas GEOBON's EBVs describe ecosystem-agnostic and scalable variables, EuropaBON's EBVs identify target species within marine, terrestrial, or freshwater ecosystems. A similar DTM mining exercise was conducted to identify the associations between biome literature and EuropaBON's suggested target species.

All analyses were performed using R Statistical Software (v4.5.2; R Core Team 2021).

Outcomes:

The first three singular vectors of the SVD analysis accounted for 19.1%, 14.2%, and 11.6% of the total variation, respectively (cumulative variation = 44.9%). A k-means clustering analysis (using the *stats* R package) with all three vectors indicated that 87.5% and 94.1% of between sum of squares variation was accounted for with five and six clusters, respectively. The only difference in clustering between the five- and six-cluster analyses was the separation of the "urban" biome as an independent cluster in the latter analysis. The five-cluster representation is displayed in Figure 3. Major clusters included 1) "grassland" and "forest," 2) "soil," 3) "urban," "tundra," and "desert," 4) "freshwater" and "coral," and 5) "coastal" and "marine" biomes.

The GEOBON EBV class representation for each biome is shown in Figure 4. The most represented EBV class across biomes was "species traits," followed by "ecosystem function." In contrast, EBV classes "community composition" and "ecosystem structure" were the least represented. Representation of individual EBV classes between biomes was not always consistent. Notably, the prevalence of terms related to the "genetic composition" class was lower in strictly terrestrial biomes (i.e. soils/croplands, deserts, forests, and grasslands). The prevalence of terms related to the "ecosystem function" class was lower in tundra, desert, and urban biomes. Terms related to "community composition" were generally lacking except for coral, freshwater, forest, and grassland. Terms related to "ecosystem structure" were present at low levels except in coastal/marine, soil, grassland and forest biomes.

The frequency of major organism groups in the corpora for each biome, as identified in the EuropaBON EBVs target organisms, is displayed in the form of word clouds in Figure 5 and as percentages of total mentions of organismal keywords in Table S3 in SI2. As indicated by the target species with the highest percentage in each biome, papers discussing terrestrial biomes (i.e. grasslands, forests, croplands, desert, tundra, and urban systems) tended to emphasise "plants", whereas papers discussing aquatic biomes (i.e. freshwater, coral, coastal, and marine system) tended to emphasise "fish". Grassland papers had a secondary focus on "herbivores" whereas desert and tundra papers tended to focus on "mammals"; likely reflecting differences in available primary production between biomes. However, there is little focus on either "herbivores" or "mammals" in forest papers, suggesting a possible bias in the choice of organisms studied that does not fully reflect the ecological species present. "Birds" were a secondary focus of several

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biomes including forest, desert, tundra, and urban biomes. “Microbes” were also mentioned in cropland research and to a lesser extent in desert research. “Invertebrates” was a secondary focus in both tundra and freshwater biomes. “Plankton” was primarily mentioned among marine biome papers and “algae” was primarily mentioned among freshwater biome papers. Keywords related to “invasive species” were found in every corpus, but papers on freshwater biodiversity had more than double the frequency of mentions than any other biome. Overall, despite fungi being a fundamental eukaryotic group, being foundational in forests as decayers of wood, symbionts (mycorrhiza), and pathogens, they are scarcely addressed, indicating a major research gap. Also, notably absent were mentions of macroinvertebrates, despite their cosmopolitan role in nearly all terrestrial (e.g. pollinators), freshwater (e.g., detrital grazers), and marine (e.g. crustaceans) ecosystems. In general, the collection of studies in our analysis tended to be underrepresented by research on organisms that have been historically challenging to observe because of their small size (e.g., fungi, plankton) or cryptic habits (e.g., bats).

Conclusion – Objective 3:

We found distinct patterns in the discussion of biodiversity definitions, metrics, and methods across biomes. While many ecosystems tended to discuss these topics with similar language, distinct clusters of biomes were also found. The reasons for this clustering likely occur due to differences in food web structure between terrestrial and aquatic biomes, species density, variation in the physical nature of the biome (e.g., aquatic vs. terrestrial), and degree of disturbance. We discuss each of these factors below.

The absolute density of species often determines the method for describing and enumerating biodiversity. This is exemplified in the distinct clustering of coral and freshwater biomes, apart from marine and coastal biomes. Both coral and freshwater systems typically have relatively higher biodiversity per unit area than marine and coastal systems (Miller, 2021). A higher density of all distinct units allows for statistically less variable and more accurate estimations of biodiversity using nearly any method in a shorter timeframe. This also permits both temporal and spatial estimates of biodiversity. In contrast, the lower biodiversity per unit area of marine and coastal systems (Wu et al., 2023) necessitates more frequent use of techniques with greater data intensity (Mora et al., 2011), such as eDNA and acoustic monitoring. Moreover, the expense and time-intensity of these techniques limit the ability of researchers to gain a more temporal understanding of biodiversity.

Diversity in terrestrial systems is generally higher than in aquatic systems (Mora et al., 2011), but terrestrial and aquatic systems have well-known physical and chemical differences that impart unique ecological patterns (Shurin et al., 2006). Terrestrial ecosystems typically have shorter food chain lengths, lower rates of energy transfer, and a plant-dominated biomass pyramid. In contrast, the smaller size and greater edibility of primary producers in aquatic systems usually leads to an inverse biomass pyramid with the inclusion of secondary predators (Chase, 2000; Shurin et al., 2006). In line with the general perception, the main organisms of aquatic interest in our analysis were fish, whereas the main organisms of terrestrial interest were plants. Given the vastly different logistical challenges associated with measuring and monitoring sedentary plants in contrast to mobile consumers, it is reasonable to expect that research on these systems would be associated with different syntax. In any case, there is a striking imbalance between the key organismic components of the ecosystems studied and those considered in current research efforts.

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The distinctiveness of cropland biodiversity research relative to research in all other biomes is likely attributed to intensity of management and disturbance frequency. In general, terrestrial systems are more sensitive to small-scale perturbations than aquatic systems (Carr et al., 2003). Most agricultural ecosystems, by definition, are intensely and frequently disturbed environments that, as a result, continually return to the earliest stages of ecological succession.

Diversity assessments in cropland systems often focus on microorganisms (Figure 5) and associated biodiversity metrics (e.g., operational taxonomic units and functional diversity). This is likely due to large focus on soil health and its role in productivity. While the importance of microorganisms for agricultural ecosystems has long been recognised, their appreciation in other ecosystems is lower. However, even in agricultural systems, microbial risk assessment remains relatively narrow with a focus on functional assessments. In pesticide risk assessment, a soil nitrogen transformation study is required, reflecting the importance of nitrogen cycling to agriculture. However, broader species level assessments or other microbial functions are not generally considered.

Overall, our analysis points to real differences in the way that the academic literature defines, identifies, and measures diversity across biomes. The strength of our analysis lies in its ability to agnostically assess diverse literature for trends. This strength is bolstered by limiting our analysis to meta-analyses, reviews, and perspective papers. However, this approach also excludes more empirical work that often defines new waves of emerging science and might also exclude older literature that is not included in contemporary reviews. According to Chow et al. (2023), 70% of references in the literature are from the past ten years, and papers in conservation science often have a publication delay of approximately three years (Christie et al., 2021). In addition, there is often substantial lag between research publication and legislative consideration or adoption (Hocherman et al., 2025; Suazo-Galdames et al., 2025). Such lag times are often the result of fragmented advisory systems and unstructured communication between researchers and policymakers. Such limitations remain an unfortunate yet fundamental part of global communication and activity.

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Conclusions and recommendations

By reviewing EU chemical legislation and strategic documents (objective 1), EU-funded research (objective 2), and peer reviewed literature on biodiversity assessment methods and metrics (objective 3), we aimed to evaluate the current status of biodiversity research and its connection to chemical regulation. This review also sought to identify key needs for advancing the evaluation of chemical impacts on biodiversity and to highlight critical knowledge gaps requiring attention.

Key insights from this review include:

- 1) Current EU chemical legislation considers biodiversity more explicitly when chemicals are intended to be released into the environment. However, definitions of biodiversity within chemical risk assessment and overarching legislation guidance remain mostly qualitative, generally referencing the CBD definition. Downstream documents of legislations (annexes and technical guidance documents), not in scope of this review, may provide examples where attempts have been made to better operationalise definitions.
- 2) EU-funded biodiversity research has increased since 2019, but few projects explicitly address chemical exposure as a driver of biodiversity change, and linkages between research outputs and regulatory frameworks remain weak. The absence of a centralised, FAIR-compliant data platform for EU biodiversity research severely restricts cross-project synthesis and regulatory uptake.
- 3) A wide variety of biodiversity definitions, metrics and methodologies are currently employed in academic research. Although there are likely explanations for differences among ecosystems, our analysis suggests that a one-size-fits-all approach to biodiversity assessment may not lead to effective and actionable legislation. This will be particularly true when legislation targets physically and biologically different biomes.

This review highlights significant gaps that need to be addressed to strengthen the explicit consideration of biodiversity within chemical regulation. Most notably, limited access to relevant biodiversity research outcomes and the lack of standardised, applicable definitions and metrics for regulatory contexts are major barriers to progress. Critically, these gaps cannot be resolved within individual research projects or a single regulatory review — they require sustained, long-term, multistakeholder engagement and coordinated investment, ideally through dedicated research initiatives driven by the European Commission.

Based on these insights, we recommend the following actions:

- Develop operational definitions of biodiversity applicable across chemical regulatory frameworks, compatible with the CBD 1992 definition currently referenced in most EU legislation.
- Identify appropriate biodiversity metrics and indicators - including spatial and temporal scales and relevant entities (e.g., ecosystem services, focal species and indicator species) - relevant to chemical risk assessment.

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- Identify relevant databases, tools and methodologies, including mechanistic effect modelling and AI approaches, that correspond to these metrics/indicators and can be leveraged to support assessments of potential impacts of chemicals on biodiversity.
 - Fill gaps in our knowledge of biodiversity, particularly for organisms that have been historically challenging to quantify (e.g., fungi, invertebrates, and plankton).
 - Design research questions that are explicitly multi-factorial and systematically capture data on all five IPBES drivers for biodiversity decline. This will enable the quantification of the relative contribution of chemicals in context and inform the derivation of impactful regulatory actions.
 - Establish a centralised, FAIR-compliant data platform to collate and share EU-funded (biodiversity) research outputs — including underlying datasets, methodological documentation, and project deliverables — enabling cross-project meta-analyses and informing regulatory decision-making and research prioritisation.
 - Match policy objectives against available knowledge and tools, and identify knowledge gaps to better direct future research, including by evaluating the full hierarchy of regulatory instruments (framing legislation, technical guidance, and member state transpositions) rather than high-level documents alone.
- It is noted that biodiversity research is part of the three key priority areas of the new Horizon Europe strategic plan (2025-2027) with 10% of the total Horizon Europe budget dedicated to this topic (https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/strategic-plan_en).
- Explore further the alignment and discrepancies between biodiversity definitions and metrics used in chemical regulation and those applied in sustainable finance initiatives.

The breadth of these recommendations underscores the need for continued multistakeholder engagement and a global perspective. Organisations such as SETAC and ECETOC play crucial roles in facilitating this dialogue. Reflecting its mission to develop practical, science-based tools and solutions for advancing chemical safety assessment, ECETOC has identified biodiversity as a priority area. ECETOC organised a multistakeholder workshop on 4-6 May 2026, bringing together over 40 experts from industry, regulatory, policy and academic arenas, to start to advance some of the above recommendations. The workshop aimed to: explore available and developing biodiversity definitions, metrics and methodologies relevant to chemical risk assessment; understanding the landscape of biodiversity metrics used in sustainable finance initiatives and their relationship to chemical safety assessment, and; align tools and methodologies to achieve the biodiversity policy objectives. A workshop synthesis is being drafted and will be made publicly available.

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Figure 1: Number of chemical regulations and strategy documents, out of the 41 identified as potentially relevant, which state and do not state 'biodiversity'.
 Alt text: Figure 1 shows the number of chemical regulations and strategy documents, from a set of 41 reviewed documents, that either state or do not state the term "biodiversity." The figure compares document categories to illustrate how explicitly biodiversity is referenced across potentially relevant EU and related policy documents.

Table 1: 41 legislative and strategy documents identified by expert judgement as being potentially relevant for this review, and screening for further evaluation based on relevance criteria
 * EU Regulation Data requirements PPP actives 283/2013 and EU Regulation Data requirements PPP products 284/2013 were not further evaluated as they were considered as being under the main PPP regulation 2009/1107

Figure 2: Total and average contribution of EU funding towards research projects on biodiversity and chemicals [based on data extracted from the CORDIS database, which includes projects under framework programme 1 (FP1), Horizon 2020 (2014-2020) and Horizon Europe (2021 – 2027)].

Alt text: Figure 2 shows the total and average EU funding contribution to research projects on biodiversity and chemicals, based on CORDIS database records covering projects from FP1, Horizon 2020, and Horizon Europe. The figure illustrates an increase in EU-funded research activity in this area, particularly after 2019.

Figure 3: Singular value decomposition (SVD) of document-term matrix associated with the 10 biomes explored in this study. Only SVD 1 and SVD 2, which account for 33.3% of the total variation. Ellipses represent clusters determined by k-means clustering analysis, and account for 87.5% of total sum of squares.
 Alt text: Figure 3 shows a singular value decomposition analysis of document-term matrices for literature associated with 10 biomes. The plot groups biomes into clusters based on similarity in biodiversity-related terminology, with SVD 1 and SVD 2 together explaining 33.3% of the total variation.

Figure 4: Instances of keywords related to GEOBON's (Group on Earth Observations Biodiversity Observation Network) Essential Biodiversity Variables (EBVs) across biomes (panel A) and within biomes (panel B). A single instance of a keyword represents a detection of a stemmed word or phrase associated with any EBV subcategory for a given EBV class (Table S2 in SI2). Brackets next to biomes in panel B represent clusters detected following singular value decomposition (Figure 3).
 Alt text: Figure 4 shows the number of keyword instances related to GEOBON Essential Biodiversity Variable classes across different biomes. The figure compares overall representation across biomes and representation within each biome, showing that "species traits" and "ecosystem function" are generally the most frequently represented EBV classes, while "community composition" and "ecosystem structure" are less consistently represented.

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Figure 5: Bar graphs displaying the number of instances (i.e. mentions) that organismal groups appear in the literature for each biome analysed. Only the top ten words are shown for each biome. Organismal groups were identified as EuropaBON EBVs target species, and analysed in the corpora for each biome. Alt text: Figure 5 shows bar graphs of the most frequently mentioned organismal groups in the biodiversity literature for each biome analysed. The figure compares the top ten organismal groups per biome, based on EuropaBON Essential Biodiversity Variable target species, showing that terrestrial biome literature most often emphasises plants, while aquatic biome literature most often emphasises fish, with other groups such as birds, mammals, microbes, invertebrates, plankton, and algae varying by biome.

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	Legislation or Strategy document	Biodiversity stated, addressed via surrogate or specific focus on chemical impacts on environment	Biodiversity stated, addressed via surrogate or specific focus on chemical impacts on environment, but not yet in force	Biodiversity not stated nor addressed via a surrogate nor specific focus on chemical impacts, or biodiversity stated only few times or only in vague terms
Regulations	EU Reg: Taxonomy for sustainable activities 2020/852	x		
	EU Reg: PPP 1107/2009	x		
	EU Reg: Data requirements PPP actives 283/2013	x (*)		
	EU Reg: Data requirements PPP products 284/2013	x (*)		
	EU Reg: CLP 1272/2008	x		
	EU Reg: REACH 1907/2006	x		
	EU Reg: POPs 2019/1021	x		
	EU Reg: Vet med products 2019/6	x		
	EU Reg: Fertilising products 2019/1009	x		
	EU Reg: Biocides 528/2012	x		
	EU Reg: Batteries 2023/1542	x		
	EU Reg: Commodities/products associated with Deforestation 2023/1115			x
	EU Reg: 1229/2009 Cosmetic products			x
	EU Reg: Nature restoration 2024/1991		x	
	Proposed EU Reg: Sustainable use PPP (2022)		x	
Directives	EU Dir: Water framework 2000/60	x		
	EU Dir: Soil monitoring 2023/0232		x	
	EU Dir: Urban Waste Water Treatment 98/15	x		
	EU Dir: CSRD 2022/2464	x		
	EU Dir: Industrial Emissions 2010/75	x		
	EU Dir: PPP Sustainable Use 2009/128	x		
	EU Dir: Conservation wild birds 2009/147	x		

	Legislation or Strategy document	Biodiversity stated, addressed via surrogate or specific focus on chemical impacts on environment	Biodiversity stated, addressed via surrogate or specific focus on chemical impacts on environment, but not yet in force	Biodiversity not stated nor addressed via a surrogate nor specific focus on chemical impacts, or biodiversity stated only few times or only in vague terms
	EU Dir: Habitat conservation 92/43			x
	EU Dir: Marine strategy framework 2008/56	x		
	EU Dir: CS3D 2024/1760			x
	EU Dir: WEEE 2012/19/EU			x
	EU Dir: Med products 2001/83	x		
Strategies	EU strategy: Green Deal (2019)			x
	EU strategy: Biodiversity (2020)			x
	EU Com: Farm to Fork Strategy 2020/381			x
	EU Com: Chemicals Strategy for Sustainability 2020/667			x
	EU Com: Zero Pollution Action Plan 2021/400			x
Frameworks	ECHA key areas of regulatory challenge (KARC) (2023)			x
	EU Com: Circular Economy Action Plan 2020/98			x
	EU Com: Pollinators Initiative 2018/395			x
	EU Policy: Common Agricultural (1962)	x		
	EU Rec: SSbD framework (2022)			x
	Int Framework: KM Biodiversity (2022)	x		
National laws	Int Convention: OSPAR (1992)	x		
	Nat Act: German Supply Chain (2021)	x		

	Legislation or Strategy document	Biodiversity stated, addressed via surrogate or specific focus on chemical impacts on environment	Biodiversity stated, addressed via surrogate or specific focus on chemical impacts on environment, but not yet in force	Biodiversity not stated nor addressed via a surrogate nor specific focus on chemical impacts, or biodiversity stated only few times or only in vague terms
Other	Int Manufacturing Standard: AMR industry alliance (2022)	x		

PPP (Plant Protection Products)

CLP (Classification, Labelling, and Packaging)

REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals)

POPs (Persistent Organic Pollutants)

CSRD (Corporate Sustainability Reporting Directive)

CS3D (Corporate Sustainability Due Diligence Directive)

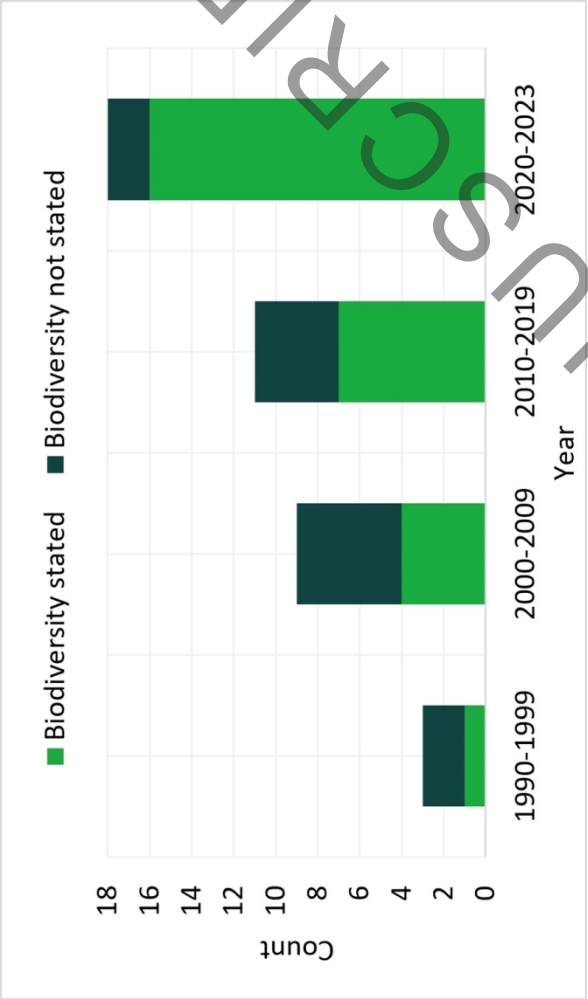
WEEE (Waste Electrical and Electronic Equipment)

SSbD (Safe and Sustainable by Design)

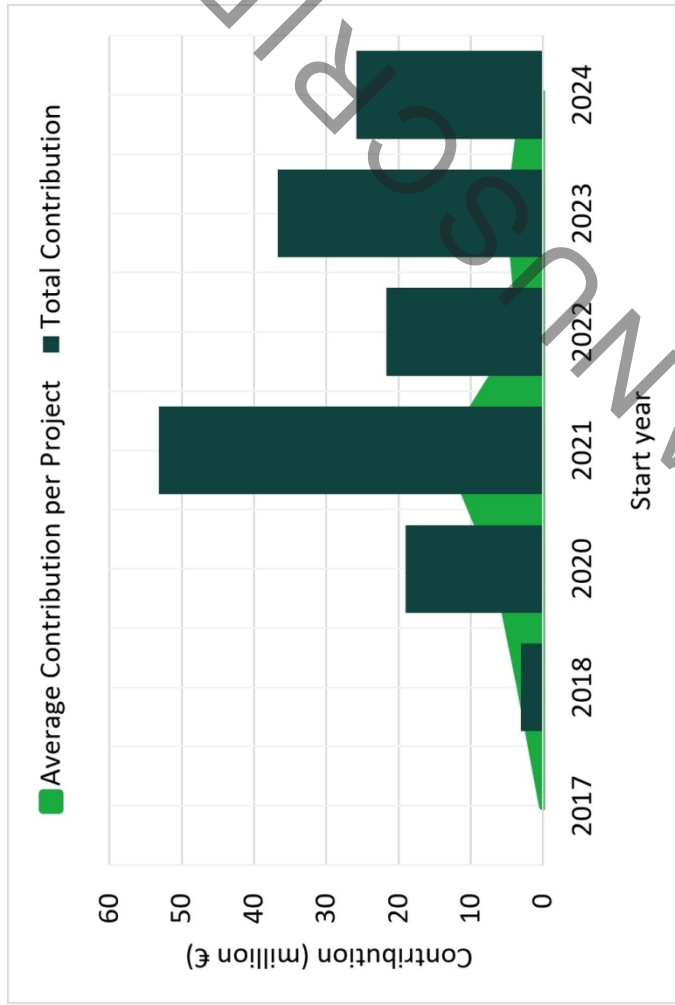
KM (Kunming-Montreal)

OSPAR (Oslo and Paris Conventions)

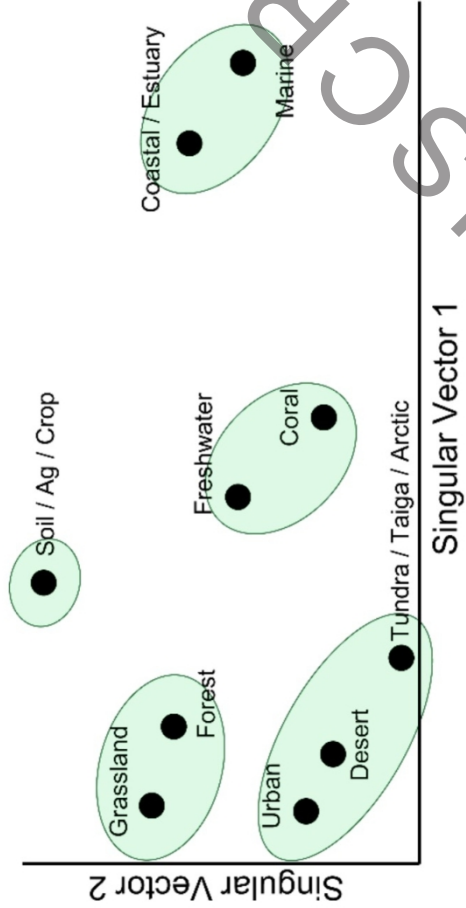
AMR (Antimicrobial Resistance)



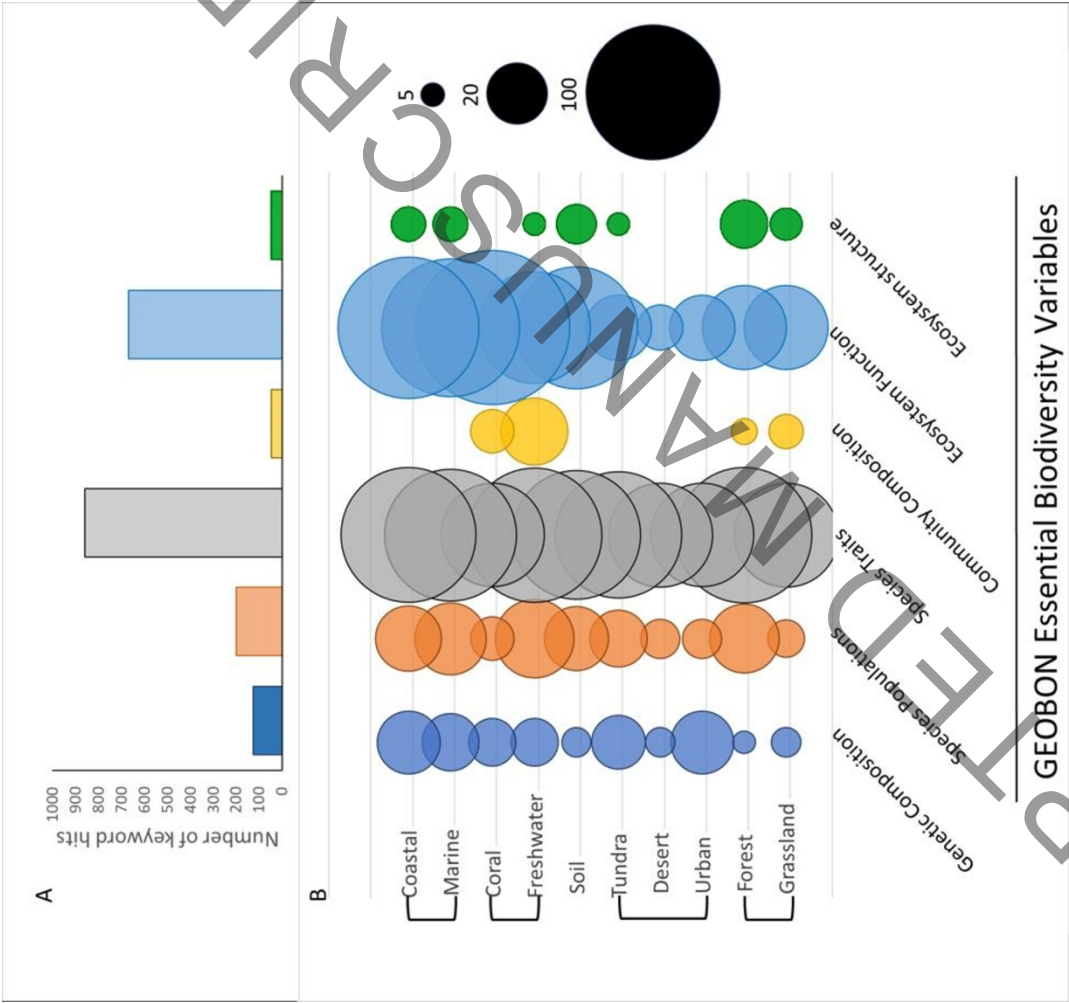
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128x86mm (300 x 300 DPI)

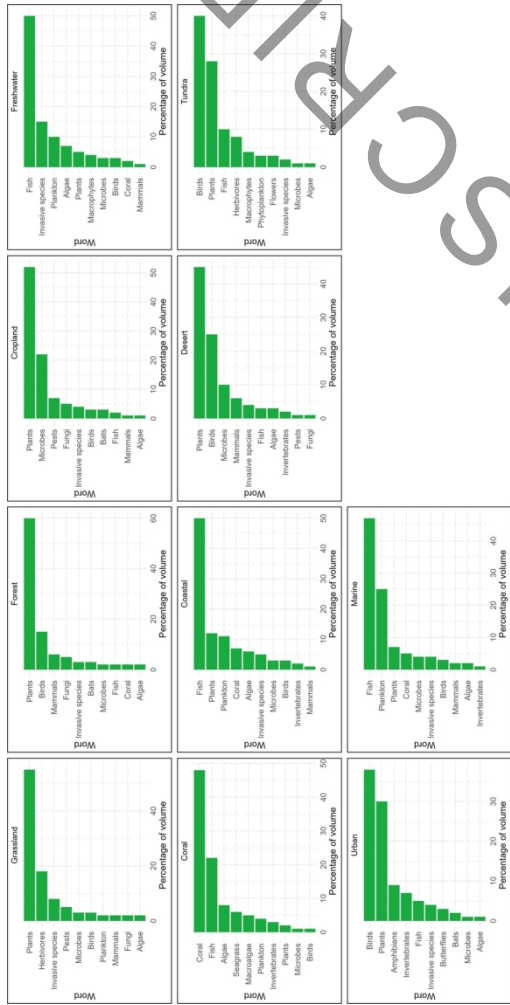


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GEOBON Essential Biodiversity Variables

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165x83mm (300 x 300 DPI)