Translational biodiversity beyond genomics: toward systemic action

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Abstract:

Biodiversity science faces the urgent challenge of being effectively connected to real-world action in the context of climate change and accelerating biodiversity loss. The concept of "translational biodiversity," which we define as the process of translating biodiversity knowledge into practical applications across science, policy, society, and economy, has largely remained confined to genomics, despite the growing urgency to bridge biodiversity science and real-world action across broader domains. In this review, we draw on interdisciplinary literature, diverse case studies, and global policy frameworks to identify key pathways and persistent bottlenecks in translating biodiversity knowledge, such as ecosystem services, monitoring data, and conservation innovations, into policy, health, economic, and juridical applications in the Anthropocene. We also give particular attention to the enabling conditions for effective translation, including equity, institutional coordination, and scalable monitoring systems. Rather than offering a singular blueprint, this article proposes a conceptual framework intended to support context-sensitive implementation and more responsive conservation practice. By articulating a vision for translational biodiversity that is systemic, inclusive, and action-oriented, this review aims to stimulate critical dialogue within and between disciplines and to attract sustained attention toward advancing this emerging agenda through future research and practice.

Keywords:

Translational biodiversity, biodiversity policy, ecosystem services, conservation science, Anthropocene

1. Introduction

The term translation has long held a pivotal role in the biomedical sciences, where the imperative to bridge laboratory discovery and clinical application gave rise to the field of translational medicine (Hegyi et al., 2021). In recent years, a similar concept has been increasingly invoked within biodiversity science, most notably in the context of genomic applications aimed at enhancing conservation outcomes (Hogg, 2023). While valuable advances have indeed been realized through approaches such as environmental DNA (eDNA), barcoding, and population genomics (Breed et al., 2019; Supple and Shapiro, 2018; Theissinger et al., 2023; Veilleux et al., 2021), the broader potential of translational biodiversity has remained largely underexplored. It has often been framed narrowly in terms of molecular tools, with limited attention given to the multidimensional nature of biodiversity knowledge and its application across societal domains.

In this review, the notion of translational biodiversity is envisioned not merely as the movement of genetic data into applied contexts, but as a systemic process by which diverse forms of ecological, social, and biocultural knowledge are mobilized to inform decision-making, institutional practice, and behavioral change (Enquist et al., 2017). This reframing is necessitated by the growing complexity of biodiversity challenges in the Anthropocene, where planetary-scale pressures like climate change, land-use conversion, pollution, and biological invasions, interact with deep social inequalities, economic dependencies, and governance failures (Davison et al., 2021; Kedward et al., 2020; Moore and Milkoreit, 2020; Woolley and Harrington, 2022). Within this context, translation must be understood not simply as a technical step but as a multidirectional process of negotiation, co-production, stakeholder education, and context-sensitive adaptation that builds decision-making capacity.

The value of broadening the translational framework has been increasingly recognized in parallel fields such as sustainability science, environmental health, and ecosystem services research (Hernández-Blanco et al., 2022; Hua et al., 2022; Luke et al., 2018; Spangenberg, 2011). There, the integration of knowledge across disciplines and sectors has been shown to increase the likelihood of uptake and impact. Yet in biodiversity science, translation remains often incidental rather than intentional, and success is rarely assessed through policy relevance, social uptake, or long-term system change. It has been observed that while data generation has accelerated, especially through remote sensing (Kerry et al., 2022), citizen science (McKinley et al., 2017), and big biodiversity informatics (Gadelha et al., 2021), mechanisms for turning this knowledge into actionable strategies have lagged behind (Lanzas et al., 2024). What has been missing is a conceptual framework to theorize and operationalize translation in ways that extend beyond genomics and take full account of the institutional, ethical, and political dimensions of conservation practice.

This section, therefore, sets the conceptual foundation for the review by outlining a more inclusive and pragmatic understanding of translation in biodiversity science. A brief account is provided of how the concept evolved within the biomedical field, followed by a critical reflection on how its application within conservation genomics has both illuminated and limited the translational agenda. The need for a more systemic and pluralistic model of translation is then established, one capable of linking biodiversity research to diverse forms of action, from policy design and economic valuation to health interventions and social justice outcomes. In doing so, a new basis is laid for the integrative framework proposed in the sections that follow.

2. Genomic foundations and their limits

The use of genomic tools in biodiversity science has expanded rapidly over the past two decades, transforming the way species are detected, classified, and monitored across ecosystems (Formenti et al., 2022; Hunter et al., 2018; Theissinger et al., 2023). Techniques such as DNA barcoding, environmental

DNA (eDNA) analysis, and whole-genome sequencing have made it possible to survey organisms at unprecedented scales and resolutions (Banerjee et al., 2022)(Yates et al., 2023). These advances have been particularly impactful in hard-to-access habitats, cryptic taxa, and degraded environments where traditional field-based methods may falter (Kanthaswamy, 2024; Ota et al., 2020). From tracking illegal wildlife trade in mammals (Tinsman et al., 2023) to characterizing microbial diversity in deep-sea vents (Zhou et al., 2022), genomics has unlocked new capacities for detection and surveillance. Nevertheless, despite these achievements, substantial conceptual and operational limits remain, especially when it comes to translating genomic outputs into conservation action, policy design, or landscape management (Shafer et al., 2015).

One of the core challenges lies in the dependency of all genomic approaches on robust and well-curated reference databases, including ML-ready databases with proper metadata that facilitate the straightforward application of predictive models (Mc Cartney et al., 2024). DNA barcoding, for example, is only as effective as the completeness and taxonomic accuracy of its underlying sequence libraries (Duarte et al., 2020). While the Barcode of Life Data Systems (BOLD) (Ratnasingham et al., 2024) and GenBank (Sayers et al., 2024) have grown significantly, large gaps persist, particularly for tropical fungi (Nilsson et al., 2018), soil protists (Geisen et al., 2018), understudied invertebrates (Chen, 2021), and endemic plants (Rattray et al., 2024). In many cases, even when sequences are available, metadata accompanying them are sparse or inconsistently annotated, limiting the utility of these records for ecological modeling or decision-support systems. The issue of metadata curation extends beyond taxonomy. Genomic data often lack standardized descriptors for ecological context, geographic coordinates, sampling methods, or host associations. The absence of formal ontologies and structured metadata vocabularies, such as those used in biomedical fields like MeSH (Medical Subject Headings) (Tamine and Goeuriot, 2021), makes cross-study synthesis laborious and error-prone. Without clear data provenance, comparative analyses across landscapes or taxa become unreliable, and integration with non-genomic datasets (e.g., habitat mapping, climate models, trait databases) remains difficult. These gaps significantly hinder the potential of genomics to inform conservation strategies that require multisource evidence, such as protected area design (Maxwell et al., 2020) or population viability analysis (Lacy, 2019).

Environmental DNA (eDNA) technologies have been particularly celebrated for their ability to detect species presence from environmental samples such as water, soil, or air (Banerjee et al., 2022; Beng and Corlett, 2020). This method has gained traction across taxa, from amphibians and fish in aquatic habitats to airborne pollen and fungal spores in terrestrial systems (Banchi et al., 2020; Berelson et al., 2025; Yates et al., 2023). However, eDNA also illustrates some of the systemic limitations of genomic biodiversity monitoring. Signals can be temporally unstable, degraded by UV exposure, and confounded by indirect DNA input into the study system (without actual species presence) or sample contamination, due to the high sensitivity of the method (Joseph et al., 2022). Moreover, without quantitative calibration, it remains difficult to infer abundance or ecological function from sequence counts alone (Mathieu et al., 2020). In microbial systems, the detection of genes does not necessarily translate into ecological relevance, especially when functional redundancy or dormancy obscures the community's actual dynamics (Louca et al., 2018; Mandal and Das, 2025).

Another underexamined limitation concerns what may be termed "genomic overreach": the implicit assumption that increased resolution in molecular data will directly translate into conservation outcomes (Garner et al., 2016; Hogg, 2023). While whole-genome sequencing can elucidate adaptive variation, inbreeding levels, or hybridization events (Fuentes-Pardo and Ruzzante, 2017; Kardos et al., 2016; Taylor and Larson, 2019), the practical application of such findings requires contextual interpretation and institutional support. In many conservation agencies and environmental ministries, technical expertise, budget constraints, and legal frameworks are insufficiently aligned with the demands of genomic implementation (Shafer et al., 2015)(Shaw et al., 2024). For example, while genomic assessments of genetic rescue potential have been conducted for endangered mammals such as the Florida panther (Pimm et al., 2006) and Ethiopian wolf (Mooney et al., 2023), actual policy responses have been slow or nonexistent, often stymied by political, cultural, or logistical barriers (Kreye and Pienaar, 2015; Marino et al., 2024). In the case of plants, genomic tools have provided valuable insights into seed provenance, genetic bottlenecks, and phylogeographic patterns, all of which are critical for restoration planning (Aronne, 2017; Médail and Baumel, 2018; Prakash et al., 2024). Yet few restoration projects globally incorporate genomic screening into practice, partly due to cost, but also due to lack of training and institutional guidelines (Schiebelhut et al., 2024). Similarly, although fungal DNA barcoding has helped uncover cryptic diversity and ecosystem specificity, fungal conservation remains one of the most neglected areas in biodiversity governance (Lücking et al., 2020). For microbes, the surge in metagenomic studies has produced massive inventories of genes and taxa across soils, oceans, and host-associated niches (Malard and Guisan, 2023). However, the translation of these insights into policy, for instance, in agricultural management or soil restoration, is only beginning to take shape, hindered by unclear regulatory frameworks and a lack of functional interpretation of many microbial genes (Jagadesh et al., 2024; Robinson et al., 2023). Overall, while the genomic revolution has undeniably enriched biodiversity science, its translation into conservation and policy action remains highly uneven. The effectiveness of genomics in biodiversity governance will ultimately depend not just on technological progress, but on better data mobilization, curated reference standards, and stronger institutional pathways for uptake.

3. Molecular approaches beyond genomics in biodiversity translation

Proteomics: Proteomic analyses have increasingly been applied to conservation biology, owing to their ability to reveal functional phenotypes and stress responses that cannot be inferred from genetic data alone (Gotelli et al., 2012; H. Guo et al., 2021). For instance, shifts in the abundance of heat-shock proteins and oxidative enzymes have been used as early-warning biomarkers of thermal stress in corals and freshwater fishes, enabling rapid assessment of organismal health under climate extremes (Ricaurte et al., 2016; Timmins-Schiffman et al., 2025). Such biomarkers can inform restoration efforts by identifying resilient populations or guiding selection of stock for assisted translocation. Moreover, proteomic profiling of invasive species has provided insights into physiological adaptations that underpin ecological success, aiding in the development of monitoring tools or novel management strategies (Qi et al., 2023). Beyond single-species applications, proteomics has been applied to ecosystem-level monitoring (Li and Figeys, 2020; Peters et al., 2023). The analysis of community-wide protein expression patterns from environmental samples can offer a dynamic portrayal of ecosystem status, complementing static measures such as biodiversity indices (Northrop et al., 2017; Trindade et al., 2021). This approach has proven fruitful in freshwater systems, where seasonal protein signatures in microbial and macro-invertebrate assemblages reflect water quality changes, pollutant exposure, and trophic dynamics (Gajahin Gamage et al., 2022). Proteomics also holds promise when integrated with ecogenomic workflows: linking gene variant data to protein expression profiles and downstream traits creates a more mechanistic narrative of organismal adaptation (Romanov et al., 2019). Such multi-omics strategies can be highly informative in biodiversity hotspots, where understanding adaptive potential is essential for effective management (De León et al., 2023). Although proteomic methods remain relatively costly and technically sophisticated, the development of field-deployable protocols, such as paper-based immunoassays (Sritong et al., 2023) or targeted mass spectrometry (Manes and Nita-Lazar, 2018), presents a near-term path for scaling their translational impact.

Metabolomics: Metabolomics, the comprehensive profiling of small-molecule metabolites in biological systems, has emerged as a sensitive and functionally rich approach for detecting physiological responses to environmental conditions (R. W. Brown et al., 2024; Matich et al., 2019; Pomfret et al., 2019; Zhang et al., 2021). Unlike genomics and proteomics, which indicate potential or ongoing biological processes, metabolomic data capture the immediate biochemical state of an organism, providing a snapshot of its interactions with the environment (Walker et al., 2022). This immediacy renders metabolomics particularly valuable in biodiversity research aimed at identifying early stress responses to pollution, nutrient shifts, or climate-related disturbances (Danczak et al., 2020; Shen et al., 2023). In aquatic ecosystems, metabolomic techniques have been employed to detect sublethal responses in species exposed to pollutants such as heavy metals, endocrine disruptors, and microplastics, well before changes in behavior or population dynamics become visible (Pomfret et al., 2019). For example, altered metabolite profiles in sentinel organisms such as mussels or amphibians have been linked to disrupted energy metabolism and immune function (Legrand et al., 2023; Snyder et al., 2022). These findings offer decision-makers a more responsive, biochemical basis for environmental monitoring and risk assessment, especially where traditional indicators lag or prove inconclusive. In plant ecology, metabolomics has illuminated how secondary metabolites, such as alkaloids, flavonoids, and terpenes (mediate species interactions), herbivory, and pathogen resistance (Elateeq et al., 2023; Sardans et al., 2021). This knowledge has been instrumental in guiding species selection for ecological restoration and agroecological design, as metabolite diversity has been associated with ecosystem resilience (Choudhury et al., 2021)(Raza, 2022). Moreover, metabolomics has facilitated the identification of "chemical phenotypes" among closely related taxa, refining biodiversity inventories and conservation prioritization where morphological or genetic differentiation is limited (Uthe et al., 2021; Welling et al., 2021). Though the field remains technically demanding, innovations in portable instrumentation and metabolite databases are steadily enhancing its accessibility. Future efforts should prioritize cross-taxa standardization, integration with metabolomic-environmental models, and the exploration of temporal dynamics to better understand how metabolic flexibility supports biodiversity under stress.

Environmental RNA: eRNA, the collection of extracellular RNA molecules shed by organisms into their environment, represents an emerging molecular tool with significant potential for biodiversity assessment and functional ecological monitoring (Cristescu, 2019; Stevens and Parsley, 2023). Unlike environmental DNA (eDNA), which provides information on species presence only with low temporal resolution, eRNA reflects actively transcribed genes and thus offers insight into a more recent snapshot of biodiversity and the current physiological state or activity of organisms *in situ* (Ahi and Schenekar, 2025; Yates et al., 2021). This temporal sensitivity makes eRNA a compelling complement to genomic tools in translational biodiversity science (Stevens and Parsley, 2023). Recent studies have demonstrated that eRNA can detect changes in community activity in response to environmental stressors such as hypoxia, temperature fluctuations, and chemical pollutants (Ahi and Schenekar, 2025; Greco et al., 2022; Hechler et al., 2023). For instance, shifts in eRNA profiles in aquatic microbial assemblages have been correlated with nutrient cycling efficiency, enabling early detection of eutrophication events (Giroux et al., 2022; Zilius et al., 2021). Similarly, the detection of specific stress-related transcripts in fish or invertebrate eRNA samples has allowed for fine-scale monitoring of sublethal ecosystem disturbances, information that can inform immediate conservation interventions or management adjustments (Giroux et al., 2022; Miyata et al., 2021). One of the principal advantages of eRNA is its potential to link biodiversity monitoring directly to ecosystem function (Glover et al., 2025; Pochon et al., 2025). Because eRNA captures gene expression patterns, it enables researchers to track not only which species are present, but what they are doing metabolically or behaviorally. This dynamic quality aligns well with the goals of adaptive management frameworks, where feedback-informed action is key (Pochon et al., 2025; Stevens and Parsley, 2023). However, technical challenges remain. RNA is inherently more fragile than DNA, and methods for capture, concentration, stabilization, extraction, and bioinformatic interpretation are still being refined (Ahi and Schenekar, 2025). Nevertheless, advances in sequencing technologies and eRNA capture are rapidly closing these gaps, bringing eRNA closer to operational use in conservation programs.

Microbiome profiling: The characterization of microbiomes, the complex microbial communities associated with organisms or environments, has opened new frontiers in biodiversity science (Peixoto et al., 2022). Once overlooked as ecological background, microbial assemblages are now understood to play central roles in species fitness, disease resistance, nutrient cycling, and habitat stability (van Bruggen et al., 2019). As such, microbiome profiling has emerged as a valuable translational tool for assessing ecosystem health and guiding conservation action (Ribas et al., 2023). In terrestrial and aquatic systems alike, microbial community composition has been shown to respond sensitively to environmental perturbations (Dodds et al., 2020). For instance, shifts in soil microbiomes have been correlated with land degradation, pesticide use, and altered precipitation patterns (Bei et al., 2023; Louisson et al., 2023; Ribas et al., 2023). These changes can precede visible vegetation loss, allowing for preemptive restoration or land-use interventions. In coral reef ecosystems, microbial dysbiosis is increasingly used as an early indicator of bleaching stress or pathogenic outbreaks, providing a diagnostic window into reef vulnerability that is not available through macrofaunal surveys alone (Boilard et al., 2020; Glasl et al., 2019). Microbiome data are particularly powerful when linked to host organisms. In wildlife conservation, for example, gut microbiome composition has been used to assess the nutritional status and health of endangered mammals, informing translocation strategies and dietary interventions in captive breeding programs (Chong et al., 2019; van Leeuwen et al., 2024). In agriculture and restoration ecology, rhizosphere microbial profiling has helped identify keystone symbionts that facilitate plant establishment in degraded soils, contributing to more resilient revegetation efforts (Benitez et al., 2021; Coban et al., 2022; Li et al., 2025). The translational value of microbiome science lies in its ability to serve as both a bioindicator and an intervention method (Rodriguez et al., 2024). Microbiome manipulation, through inoculation, rewilding, or habitat conditioning, has already been piloted in contexts ranging from amphibian disease mitigation to crop resilience enhancement, demonstrating that microbial diversity is not merely diagnostic but actionable (Rebollar et al., 2020; Singh and Kumar, 2024). Despite methodological challenges related to taxonomic resolution and ecological interpretation, rapid advances in metagenomics, metatranscriptomics, and statistical modeling continue to improve the utility of microbiome data (Blanco-Míguez et al., 2023; Meyer et al., 2022). As frameworks for ecosystem health assessment evolve, microbiome profiling will likely occupy an increasingly central position in translational biodiversity strategies, offering fine-scale, functional, and scalable insights into ecological condition and resilience.

Biochemical markers: Biochemical markers such as lipids, stable isotopes, and secondary metabolites provide precise, quantifiable insights into ecological interactions, environmental stress, and food web dynamics (Ohkouchi et al., 2015; Ruess and Müller-Navarra, 2019; Soman et al., 2024). Unlike genetic or proteomic data, which typically reflect organismal traits or molecular mechanisms, biochemical markers often act as integrators of environmental history and trophic relationships (Pethybridge et al., 2018; Wall et al., 2024). Their value in translational biodiversity science lies in their ability to bridge organismal physiology with ecosystem-level processes in a non-invasive, cost-efficient, and highly interpretable manner. Stable isotope analysis, for example, has become a cornerstone method for reconstructing food webs and tracking species movements across terrestrial, freshwater, and marine ecosystems (Eglite et al., 2022; McCue et al., 2020). Isotopic ratios of carbon and nitrogen (e.g., $\delta^{13}C$ and $\delta^{15}N$) have been widely used to infer dietary shifts, migration pathways, and exposure to anthropogenic inputs such as fertilizers or sewage (Guiry, 2019; Hobson, 2023; Nikolenko et al., 2018; Stephens et al., 2023). In conservation contexts, such data have informed protected area design, identified critical feeding grounds, and revealed cryptic anthropogenic pressures on endangered species (Gelippi et al., 2022; Naddafi et al., 2021). Similarly, lipid biomarkers, particularly in planktonic and benthic communities, have been used to assess ecosystem productivity, energy transfer efficiency, and contamination levels (Chen et al., 2019; Guo et al., 2020; Soman et al., 2024; Wall et al., 2024). The presence of specific fatty acids, for example, can signal the dominance of particular primary producers or the accumulation of pollutants through biofilms and detrital pathways (DeForest et al., 2016; Lau et al., 2023). These insights contribute to monitoring programs focused on climate impacts, eutrophication, and ecosystem tipping points (Dal'Olio Gomes et al., 2021; Derrien et al., 2017; Strandberg et al., 2022). Pigment analysis, including chlorophyll and carotenoids, has also been employed in remote and in situ biodiversity assessments to estimate photosynthetic activity and community structure in aquatic systems (Beamish et al., 2018; El Hourany et al., 2019; Molner et al., 2024). These markers are particularly valuable in detecting early ecological shifts not yet visible through taxonomic surveys. Though often treated as ancillary, biochemical markers offer direct, functional indicators that are highly compatible with other molecular tools. Their integration into biodiversity monitoring frameworks enhances both the resolution and actionability of assessments, providing a tangible link between ecological processes and management-relevant outcomes.

4. Other technologies for biodiversity translation beyond genomics

As the volume and resolution of biodiversity data continue to expand, so too does the demand for tools that can transform that information into actionable insights. Beyond the realm of genomics, a growing suite of technologies, ranging from artificial intelligence (AI) and remote sensing to bioacoustics, training networks and citizen science platforms, has emerged to support monitoring, assessment, and decision-making in conservation and ecological governance. These technologies hold significant promise for translating biodiversity knowledge into policy, management, and public engagement. Yet, their practical integration into institutional workflows remains uneven and often constrained by technical, social, and political barriers.

Remote sensing has become a cornerstone of large-scale ecological monitoring (Wang et al., 2010, 2024). Satellite imagery (Rocchini et al., 2016), unmanned aerial vehicles (UAVs) (Lyu et al., 2022), and LiDAR systems (Q. Guo et al., 2021) have been employed to map habitat structure (Pygas et al., 2020), track deforestation (Gao et al., 2020), assess species distributions (Wang et al., 2025), and quantify ecosystem service flows (De Araujo Barbosa et al., 2015). For example, forest cover dynamics in tropical regions can now be monitored in near-real time using high-resolution satellite data from platforms like Sentinel (Phiri et al., 2020) or PlanetScope (Frazier and Hemingway, 2021). These insights have been used to enforce anti-logging regulations, prioritize conservation corridors, and assess restoration outcomes. However, translating remotely sensed data into actionable management decisions requires robust ground-truthing, well-trained analysts, and local governance structures that can absorb and respond to the information. Without these, high-resolution maps may inform reports but fail to trigger enforcement or policy shifts.

Artificial intelligence (AI) has rapidly enhanced the analytical power of biodiversity monitoring tools (Ullah et al., 2024). Deep learning algorithms are now used to automate species identification from camera trap images (Norouzzadeh et al., 2021), analyze patterns in large-scale biodiversity datasets (Cornford et al., 2021), and model species responses to environmental change (Pichler and Hartig, 2023). In marine systems, AI-assisted image recognition has enabled automated coral reef assessments (González-Rivero et al., 2020), while in urban environments (Anwar and Sakti, 2024), AI has supported real-time tracking of invasive plant species using smartphone apps (Javed et al., 2025) and geotagged photos (Vanegas et al., 2024). Nevertheless, these technologies depend on extensive training datasets that are often taxonomically biased, favoring charismatic vertebrates over invertebrates, plants, or fungi (Guénard et al., 2025; Pollock et al., 2025). Moreover, their implementation may raise equity concerns, as the infrastructure and technical expertise required for machine learning remain concentrated in high-income countries and well-resourced institutions (Khan et al., 2024).

Bioacoustics has emerged as a powerful tool for non-invasive biodiversity monitoring, particularly for vocal taxa such as birds, bats, amphibians, and some insects (Kohlberg et al., 2024; Sugai et al., 2019). Autonomous recording units (ARUs) deployed in remote or sensitive habitats can capture rich acoustic datasets that reflect species presence, activity patterns, and even ecosystem-level dynamics (Darras et al., 2019; Vallee, 2025). Spectral analysis and automated call recognition tools allow for efficient processing of these datasets, supporting the identification of temporal trends, seasonal phenology, or habitat degradation (Chhaya et al., 2021; Mcloughlin et al., 2019; Sethi et al., 2020). Yet, challenges persist in distinguishing between acoustically similar species, especially in biodiverse tropical systems, and in linking acoustic activity with demographic or behavioral parameters (Gibb et al., 2019).

Citizen science platforms such as eBird (Sullivan et al., 2014), iNaturalist (Niemiller et al., 2021), and Pl@ntNet (van der Velde et al., 2023) have mobilized massive public participation in biodiversity documentation, generating millions of species occurrence records globally (Fraisl et al., 2022). These platforms have proven especially valuable in filling geographic and taxonomic gaps, democratizing biodiversity knowledge, and fostering conservation awareness (Feldman et al., 2021; Peter et al., 2019; Peters, 2020). In some cases, citizen science data have directly informed land-use planning (Todd et al., 2016), protected area designation (Cheung et al., 2022), and species status assessments (Gallagher et al., 2025). However, the integration of these datasets into formal conservation frameworks is not always straightforward. Issues of data quality, spatial bias, and uneven taxonomic coverage limit their direct applicability unless accompanied by robust validation protocols and contextual interpretation (Johnston et al., 2023).

While each of these technologies offers unique strengths, none serves as a panacea. Translational effectiveness depends not only on technical sophistication but on how tools are embedded in governance, planning, and participatory processes. For instance, real-time monitoring systems will have limited value if regulatory agencies lack the authority or resources to respond to alerts (Eicken et al., 2021). Likewise, AI tools can only influence conservation outcomes if their outputs are accessible to, and trusted by, the communities and institutions that manage biodiversity on the ground (Atalay et al., 2025; Ullah et al., 2024). Future research and development should prioritize interoperability across platforms, open data standards, and user-centered design that supports application by practitioners, not just researchers. Furthermore, fostering co-development with local communities, particularly in biodiversity-rich but resource-constrained regions, will be essential to ensure that technological solutions are not only innovative but also equitable and enduring.

5. Policy interfaces: from data-driven knowledge to institutional practice

The persistent gap between biodiversity science and environmental policy has long been recognized, yet it remains one of the most formidable barriers to effective conservation (Sabo et al., 2024). Despite the exponential growth in ecological data and biodiversity monitoring tools, including genomics, remote sensing, and citizen science, translation into institutional practice has lagged, often due to structural, political, and epistemic disconnects (De Donà and Linke, 2023). This science–policy divide is not merely a matter of communication; it is embedded in deeper mismatches between knowledge systems (Tengö et al., 2017), spatial scale mismatches in policy making (Falco et al., 2021), and incentive structures (Evans, 2021).

One core limitation arises from the way biodiversity knowledge is produced and disseminated. Much of it remains inaccessible to policymakers due to technical complexity, disciplinary jargon, or lack of relevance to on-the-ground decision-making (Cvitanovic et al., 2015; Sabo et al., 2024). Scientific outputs are frequently shaped by academic publishing norms rather than policy priorities, leading to a situation in which information exists but is not configured in a usable form. Furthermore, the absence of sustained interaction between researchers and policy actors means that research agendas often fail to reflect pressing societal needs, particularly at subnational and regional scales where implementation typically occurs (Akbaritabar, 2021; Cvitanovic et al., 2015; Ferraro and Failler, 2024). The fragmentation of governance further compounds this problem (Dallimer and Strange, 2015). Biodiversity policy is rarely the mandate of a single institution. Instead, responsibility is distributed across multiple ministries, agencies, and jurisdictions, each with their own goals, timelines, and regulatory frameworks (Berry, 2021; Petersson and Stoett, 2022). This separated system of responsibilities inhibits coherent action, especially in landscapes that span administrative boundaries or sectors, such as agricultural mosaics (Leventon et al., 2017), river basins (Bréthaut and Turley, 2020), or indigenous territories (Schroeder and González P., 2019). Fragmentation also leads to duplication of efforts, incompatible datasets, and policy incoherence (Bayraktarov et al., 2019; Pröbstl et al., 2025; Rogalla von Bieberstein et al., 2019). As a result, even well-established scientific recommendations may struggle to gain traction within institutional systems. International frameworks such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Turnhout et al., 2014) and the Convention on Biological Diversity (CBD) (Tsioumani, 2020) have sought to bridge this gap by developing mechanisms for knowledge synthesis, stakeholder consultation, and policy guidance. The IPBES Global Assessment, in particular, has played a critical role in drawing attention to systemic biodiversity loss, highlighting the role of indirect drivers such as consumption patterns, economic growth models, and institutional inertia (Ruckelshaus et al., 2020). Likewise, the CBD's Kunming–Montreal Global Biodiversity Framework (GBF) sets ambitious goals to integrate biodiversity into all sectors of planning and development (Joly and Joly, 2023). However, the translation of these frameworks into national policies has been uneven, often hindered by lack of technical capacity, insufficient funding, and weak political will.

Stakeholder inclusivity remains another major challenge (Sterling et al., 2017). While citizen science has emerged as a powerful mechanism for data generation and public engagement, it often operates in isolation from formal policy channels (Bowser et al., 2020). Large-scale projects such as eBird or iNaturalist have mobilized millions of observations, but their outputs are seldom incorporated systematically into national biodiversity strategies or protected area monitoring (Della Rocca et al., 2024; Pocock et al., 2018). The problem is not merely technical; it reflects a deeper lack of institutional frameworks for incorporating lay knowledge, local priorities, and community-derived data (Armitage et al., 2020). Without such structures, citizen science risks remaining a parallel track, rich in data but disconnected from decision-making authority. Moreover, misaligned incentives between the scientific community, policymakers, and stakeholders further hinder effective translation. Academic institutions reward novelty and peer-reviewed publication, whereas policymakers require actionable, context-specific evidence delivered within short decision cycles. Conservation NGOs and practitioners, meanwhile, often seek flexible tools and participatory processes, which may not align with the technical depth of scientific outputs (Cvitanovic et al., 2019). These divergent logics create friction at the interface, slowing the pace and reducing the efficacy of knowledge integration. Importantly, biodiversity decisions are rarely made on ecological grounds alone. Political feasibility, legal constraints, and economic trade-offs shape what gets implemented (Araújo, 2025; King et al., 2015). Even when compelling evidence is available, for instance, on the value of intact wetlands for flood mitigation (Endter-Wada et al., 2020) or pollinator services in agroecosystems (Gemmill-Herren et al., 2021), implementation may be blocked by short-term political interests or conflicting land-use incentives. Addressing these barriers requires more than better communication. It demands institutional innovations that embed science, policy engagement into governance structures from the outset. This includes the creation of boundary organizations (Gustafsson and Lidskog, 2018), long-term funding for translational roles (Cvitanovic et al., 2025), and co-production platforms that bring scientists, policymakers, communities, and private sector actors into shared dialogue (Naugle et al., 2020). Only through such sustained, multi-actor interfaces can biodiversity knowledge be rendered institutionally actionable and socially legitimate.

6. Ecosystem services and economic valuation

The concept of ecosystem services has become a dominant framework for articulating the value of biodiversity to human societies (Fischer and Eastwood, 2016; Lele et al., 2013). By identifying and classifying the benefits that nature provides, such as pollination (Porto et al., 2020), water purification (Piaggio and Siikamäki, 2021), climate regulation (Scholes, 2016), and cultural enrichment (Goodness et al., 2016), this approach aims to render ecological functions visible to policy and economic systems that have historically disregarded them. In principle, the ecosystem services paradigm serves as a translational bridge between ecological knowledge and practical decision-making. However, its application has revealed both opportunities and persistent tensions, especially regarding how valuation is framed and acted upon across sectors and scales (Hein et al., 2016; Kull et al., 2015). Efforts to incorporate ecological insights into economic valuation have produced a diverse array of tools, including cost–benefit analyses (Meraj et al., 2022), payment for ecosystem services (PES) schemes (Salzman et al., 2018), natural capital accounting (Hein et al., 2020), and biodiversity offsetting (Sonter et al., 2020).

These instruments are intended to inform land-use planning, development permitting, and conservation financing by assigning measurable value to ecosystem functions (Tammi et al., 2017). For example, in agricultural landscapes, pollination services provided by wild insects have been quantified to support policies that limit pesticide use and promote habitat heterogeneity (Raitif et al., 2019). Similarly, mangrove forests have been evaluated for their coastal protection services, influencing infrastructure investment decisions in cyclone-prone regions (Marois and Mitsch, 2015). Nevertheless, the translation of ecosystem knowledge into economic frameworks is not without pitfalls. One major concern lies in the oversimplification of complex ecological processes. Many valuation models rely on static assumptions about species–function relationships or spatial boundaries, overlooking the dynamic, nonlinear, and interdependent nature of ecosystems (Evans, 2019). In the case of soil biodiversity, for instance, microbial communities contribute to nutrient cycling and carbon sequestration, yet their roles are often undervalued or omitted entirely due to limited data or methodological constraints (Akter et al., 2025; Guerra et al., 2020). Similarly, in forest ecosystems, the contributions of fungi to decomposition and nutrient turnover are difficult to price, leading to their exclusion from conventional valuation models (Camenzind et al., 2024; Niego et al., 2023).

The use of natural capital frameworks has also sparked debates about the commodification of nature (Maechler and Boisvert, 2024; Martin-Ortega et al., 2019). While proponents argue that assigning value to ecosystem functions helps internalize environmental costs and inform more sustainable choices, critics caution that monetization can obscure ethical and intrinsic dimensions of biodiversity, especially in indigenous and culturally diverse contexts. The risk is that once nature is framed strictly in economic terms, its protection becomes contingent on market logic rather than ecological integrity or justice-based principles. This has been particularly evident in biodiversity offset schemes, where developers compensate for habitat destruction by investing in conservation elsewhere (Karlsson and Edvardsson Björnberg, 2021). Although such offsets are designed to achieve “no net loss,” in practice they often fail to account for ecological uniqueness, time lags in restoration, and uneven social impacts (zu Ermgassen et al., 2019). Importantly, the ecosystem services framework can mislead if used without attention to distributional effects. Who benefits from services, and who bears the costs of their loss or restoration, is rarely addressed in standard valuation models (Olander et al., 2018). For instance, upstream deforestation that affects water quality may impose burdens on downstream communities with limited political leverage (Hommes et al., 2020). Similarly, efforts to monetize ecotourism potential in biodiverse regions can result in exclusion of local populations or the commodification of sacred landscapes (Kaiser et al., 2023a).

Despite these challenges, the strategic use of valuation tools remains essential for embedding biodiversity considerations into mainstream economic and policy decisions. When applied thoughtfully, ecosystem service assessments can help justify investments in green infrastructure, inform subsidy reforms, and support multi-functional land-use planning (Jato-Espino et al., 2023; Zoppi, 2020). Success depends on integrating valuation with robust ecological data, participatory processes, and transparent assumptions (Hein et al., 2020). Methodological advances in spatial modeling, scenario analysis, and ecosystem accounting frameworks, such as those supported by the UN System of Environmental-Economic Accounting (SEEA) (King et al., 2024), are helping to address these gaps. Ultimately, economic valuation should be seen not as an end in itself, but as one pathway among many for translating ecological understanding into societal relevance. Its effectiveness depends on how well it is embedded in governance structures that recognize ecological complexity, social equity, and the plural values of nature. As interest in natural capital continues to rise, the challenge will be to ensure that valuation tools serve not as reductive mechanisms, but as instruments for more informed, accountable, and inclusive decision-making.

7. Biodiversity and human health: a One Health perspective

The interdependence of ecological and human health is becoming increasingly evident, especially in the context of global health crises, climate change, and biodiversity loss (Abbasi et al., 2024). The One Health framework, which recognizes the interconnections between the health of people, animals, plants, and their shared environments, offers a compelling lens for translational biodiversity science (H. L. Brown et al., 2024; Mwangi et al., 2016). Yet despite rhetorical commitment across many international organizations, biodiversity remains marginal in most public health strategies. This disconnect limits both proactive prevention and the co-benefits that nature-based approaches could offer to health systems.

One of the most urgent and well-documented links between biodiversity and human health lies in the domain of zoonotic disease (Shaheen, 2022). A growing body of research has shown that biodiversity loss, habitat fragmentation, and wildlife trade increase the risk of pathogen spillover from animals to humans (Cunningham et al., 2017; Tajudeen et al., 2022). Ecological degradation alters host and vector dynamics, often increasing the abundance or behavior of species that serve as reservoirs for infectious agents (Saba Villarroel et al., 2023). For instance, deforestation in tropical regions has been linked to elevated risks of diseases such as malaria, Ebola, and Lassa fever (Capps and Lederman, 2015; David, 2024; Scott, 2020; Zhang et al., 2024). Biodiverse ecosystems, by contrast, often support a regulatory effect, sometimes referred to as the “dilution effect”, in which a wider variety of host species reduces the transmission efficiency of pathogens (Arnal et al., 2025; Roberts and Heesterbeek, 2018). While the universality of this effect remains debated, it underscores the potential of biodiversity conservation as a preventive public health measure.

Beyond infectious diseases, biodiversity contributes to human well-being in more diffuse but equally important ways. Contact with biodiverse green spaces has been associated with lower levels of stress, improved cognitive function, and reduced incidence of depression and anxiety (Astell-Burt and Feng, 2019; Buxton et al., 2024; Jimenez et al., 2021). These mental health benefits have been observed across age groups and socio-economic contexts, and are believed to be mediated by a combination of sensory exposure, physical activity, and microbial interactions (Methorst et al., 2021; Oh et al., 2021; Wong and Osborne, 2022). Emerging evidence also suggests that exposure to diverse environmental microbiota may help calibrate immune systems (Wong and Osborne, 2022), potentially reducing the prevalence of allergies and autoimmune disorders, a concept known as the “old friends” hypothesis (Rook, 2023).

In the realm of biomedicine, biodiversity remains an invaluable resource for drug discovery (Davis and Choisy, 2024). Many modern pharmaceuticals, including antibiotics, antivirals, and anticancer compounds, originate from natural products derived from plants, fungi, and microbes (Halder and Jha, 2023; Patil and Selvaraj, 2025; Woo et al., 2023). The rainforest ecosystems as well as marine environments such as coral reefs and deep-sea vents, continue to yield novel bioactive compounds (Ahmed et al., 2022; Akhtar et al., 2019; Braga, 2021; Calado et al., 2025; Saide et al., 2021). However, as these habitats degrade, so too does the reservoir of untapped chemical diversity. Furthermore, bioprospecting often occurs without adequate benefit-sharing arrangements, raising ethical and legal concerns about access and equity under the Convention on Biological Diversity and the Nagoya Protocol (Colella et al., 2023; Nelliyat et al., 2024).

Despite these well-established connections, the integration of biodiversity considerations into public health frameworks remains uneven and underdeveloped. Health impact assessments rarely include biodiversity metrics. National health plans seldom incorporate conservation strategies, and funding streams for biodiversity, health research remain fragmented (Willetts et al., 2023). While international initiatives such as the Tripartite Alliance (WHO, FAO, and WOAH) (De La Rocque et al., 2023) and the Quadripartite One Health Framework (which also includes UNEP) (Lawson and Wessel, 2025) have made progress in linking environmental and health agendas, biodiversity is often treated as a background variable rather than a central determinant. To address this gap, more deliberate mechanisms are needed to operationalize One Health principles within both biodiversity and health governance. This includes shared surveillance systems, cross-sectoral policy instruments, and integrated training programs for ecologists, veterinarians, epidemiologists, and land-use planners (Pepin et al., 2024) (Oltean et al., 2025). Spatial planning tools that incorporate ecological risk indicators into disease mapping and public infrastructure development also hold promise.

Biodiversity and human health are not merely co-occurring concerns, they are deeply intertwined. Failing to reflect this interconnection in institutional design, research funding, and policy execution represents a missed opportunity for both sectors. By embracing a One Health perspective, translational biodiversity science can extend its relevance to public health, offering both a rationale for conservation and a toolkit for prevention and resilience in an era of escalating health and environmental crises.

8. Place, participation, and biocultural knowledge

Efforts to translate biodiversity knowledge into effective conservation practice must contend not only with ecological complexity, but with cultural, social, and historical context. In recent decades, a growing body of scholarship and practice has emphasized the critical role of indigenous, local, and place-based knowledge systems in sustaining biodiversity (Dawson et al., 2021; Wickham et al., 2022). These knowledge systems, often referred to as biocultural, do not merely supplement scientific understanding; they represent alternative epistemologies rooted in long-term interaction with specific ecosystems (Deroy et al., 2019; Turner et al., 2022). Recognizing, respecting, and meaningfully integrating this knowledge is not only a matter of justice, but a strategic imperative for translational biodiversity science.

Indigenous and local knowledge (ILK) has long guided landscape management, species stewardship, and ecosystem resilience across biomes, from rotational agriculture and water harvesting in drylands (Leal Filho et al., 2022; Melash et al., 2023) to fire regimes in savannahs and ethno-forestry in tropical forests (Akalibey et al., 2024; Bardsley et al., 2019; McKemey et al., 2020). Empirical studies have shown that areas managed by Indigenous peoples often exhibit equal or higher levels of biodiversity than adjacent lands under state or commercial management (Corrigan et al., 2018; Schuster et al., 2019; Zhang et al., 2023). For example, Indigenous Protected and Conserved Areas (IPCAs) in Canada (Mansuy et al., 2023) and Indigenous territories in the Amazon basin (Esbach et al., 2025) have demonstrated strong conservation outcomes despite limited formal state investment. Despite this, the integration of ILK into biodiversity policy and practice remains limited. Legal frameworks, conservation funding, and research methodologies often default to dominant science-centric paradigms, marginalizing non-quantitative, oral, or place-specific knowledge forms (Nemogá et al., 2022). Where inclusion does occur, it is often tokenistic, knowledge is extracted rather than co-produced, and community agency is restricted to consultation rather than decision-making (Moyo, 2023). This imbalance not only undermines ethical standards, but weakens the potential for effective conservation, particularly in culturally diverse or contested landscapes.

The concept of co-production has emerged as a promising corrective (Locatelli et al., 2024). In biodiversity contexts, co-production refers to the collaborative generation of knowledge, policy, or management strategies through equitable partnerships between scientists, Indigenous knowledge holders, practitioners, and other stakeholders (Buschman, 2022). Successful co-production requires more than stakeholder inclusion; it demands shared authority, mutual learning, and institutional flexibility. Examples include participatory mapping of culturally significant species (Morariu et al., 2023), community-led monitoring using both biological and cultural indicators (Fabre et al., 2021), and joint management of protected areas through plural governance arrangements (Rohe et al., 2019). In the coastal mangrove systems via Kenya–Tanzania transboundary conservation area (TBCA) (Kamau et al., 2024) and New Zealand's Māori land restoration initiatives (Peters et al., 2015), such approaches have led to tangible ecological gains and strengthened community cohesion.

Place-based monitoring is another pathway through which biocultural knowledge contributes to translational outcomes (Rayne et al., 2022; Wickham et al., 2022). Long-term observations rooted in specific landscapes often capture subtle shifts in phenology, species interactions, or ecological thresholds that may elude short-term scientific assessments (Alessa et al., 2016). For example, fishers in Brazil and the Solomon Islands have applied detailed ecological knowledge of spawning periods to manage harvest timing, insights that were subsequently validated by scientific studies (Renck et al., 2023). Similarly, herders in Central Asia have long used plant phenology and animal behavior as indicators of rangeland health, guiding rotational grazing and water use without the aid of satellite data or ecological models (Sharifian et al., 2023).

Beyond technical insights, biocultural frameworks support behavioral change and social learning, two elements critical to biodiversity translation (Gavin et al., 2015). Conservation initiatives that are culturally resonant and locally grounded are more likely to inspire sustained stewardship and collective action (Armitage et al., 2020). Rituals, stories, and communal practices often encode environmental norms, creating informal institutions that guide behavior in the absence of formal regulation. Recognizing these dimensions enhances the legitimacy and durability of conservation measures, especially in regions where state enforcement capacity is weak. However, integrating biocultural knowledge is not without challenges. Issues of intellectual property (Golan et al., 2019), knowledge sovereignty (Latulippe and Klenk, 2020), and historical trauma complicate collaborations (Reed and Diver, 2023). Ethical engagement requires time, trust-building, and attention to power dynamics. Protocols for free, prior, and informed consent (FPIC) must be respected not as procedural formalities, but as foundational to equitable partnerships (Mitchell et al., 2019). Ultimately, place, participation, and biocultural knowledge are not peripheral to biodiversity translation, they are central to its legitimacy, effectiveness, and resilience. By embracing multiple ways of knowing and fostering genuine co-creation, conservation science can become more context-aware, culturally rooted, and capable of responding to the complex realities of the Anthropocene.

9. Justice, equity, and the ethics of translation

As biodiversity science becomes increasingly data-rich, technologically advanced, and globally networked, questions of justice, equity, and ethical responsibility have moved to the center of translational practice (Pritchard et al., 2022). Who benefits from the translation of biodiversity knowledge into action, and who is left out, are not peripheral questions. They determine the legitimacy, sustainability, and social relevance of conservation efforts. While biodiversity loss is a global concern, its burdens and opportunities are unevenly distributed. Translational processes that ignore these asymmetries risk reinforcing historical injustices and undermining the very goals they seek to advance.

One of the most visible and contested arenas of inequity concerns access to and control over genetic and genomic data (Skye Miner et al., 2024). Digital sequence information (DSI), the digitized genetic material of organisms, is now a cornerstone of biodiversity research, bioprospecting, and synthetic biology (Akpoviri et al., 2023). Yet most DSI is generated from species and ecosystems located in the Global South, while the majority of sequencing infrastructure, data storage, and patent applications remain concentrated in high-income countries (Scholz et al., 2022). This geographic and institutional imbalance has sparked ongoing debates under the Convention on Biological Diversity (CBD) and the Nagoya Protocol about fair and equitable benefit-sharing (Silvestri and Mason, 2023). Many low- and middle-income countries have called for binding mechanisms to ensure that the economic and scientific value derived from DSI contributes meaningfully to local communities and biodiversity stewardship (Ljungqvist et al., 2025).

Beyond formal policy instruments, broader concerns around decolonial practice have gained traction (Corbera et al., 2024). Indigenous and local communities often hold deep knowledge about biodiversity, derived from long-standing relationships with land and species (Jessen et al., 2022). Yet these knowledges are frequently mined for data or incorporated into conservation projects without adequate consent, recognition, or compensation. This has led to growing calls for research protocols that respect data sovereignty, uphold the principle of Free, Prior, and Informed Consent (FPIC), and ensure that communities have both voice and agency in translational processes (Williamson et al., 2023). Ethical translation requires moving beyond extractive models of science toward reciprocal and trust-based partnerships that recognize multiple ways of knowing. Issues of justice also arise in the realm of digital infrastructure. The movement toward open science and data sharing, while commendable in principle, may inadvertently exacerbate inequities if it assumes equal capacity to produce, manage, or interpret digital data (Pritchard et al., 2022; Ross-Hellauer et al., 2022). For example, the FAIR principles (Findable, Accessible, Interoperable, Reusable) have become widely adopted as a framework for data stewardship in biodiversity science (Lannom et al., 2020). However, FAIR-ification requires technical resources, stable internet access, and trained personnel, resources that remain unevenly distributed across countries and institutions (Brett, 2022; Ross-Hellauer et al., 2022). Without deliberate investment in capacity-building and infrastructure, efforts to open and standardize biodiversity data may reinforce epistemic exclusion (Nyssa et al., 2024).

The translation of biodiversity science also intersects with broader political and economic structures that shape environmental governance (Coolsaet et al., 2020; Otero et al., 2020). Policies derived from global assessments or scientific consensus may fail to resonate locally if they conflict with livelihood needs, tenure arrangements, or cultural values. For instance, the establishment of protected areas, guided by biodiversity metrics or species distribution models, can lead to displacement or restricted access for Indigenous and rural communities if not grounded in participatory planning (Bray and Velázquez, 2009; Cebrián-Piqueras et al., 2023). Similarly, the implementation of ecosystem service valuation tools may commodify landscapes in ways that benefit large-scale actors while marginalizing smallholders or customary users (Kaiser et al., 2023b; Lliso et al., 2021). The Global Biodiversity Framework (GBF), adopted in 2022 under the CBD, attempts to address these concerns by embedding equity across its goals and targets (Ekardt et al., 2023). Notably, Target 20 calls for the equitable sharing of benefits from the use of genetic resources, while Target 22 emphasizes full and effective participation of Indigenous Peoples and local communities in decision-making (Stephens, 2023). However, these commitments remain aspirational unless accompanied by legal recognition, funding mechanisms, and institutional reform at national and subnational levels (Hughes, 2023). Translational biodiversity science must therefore take ethics and equity not as downstream considerations, but as foundational principles. This includes critically examining whose knowledge counts, who sets research priorities, who controls data flows, and who participates in implementation. By embedding justice into the architecture of translational processes, through inclusive design, transparent governance, and equitable access to benefits, biodiversity science can support not only ecological resilience but social dignity and planetary fairness.

10. From fragmentation to integration: barriers and enablers

Despite progress in biodiversity research, translating knowledge into action is hindered by structural fragmentation across disciplines, institutions, and policies. This leads to duplicated efforts, missed collaborations, and weak evidence–policy alignment. Overcoming these barriers is key to unlocking the potential of translational biodiversity science in the Anthropocene. One of the most persistent challenges is the compartmentalization of knowledge production. Biodiversity research remains deeply segmented across biological subfields (e.g., taxonomy, ecology, molecular biology), as well as between natural and social sciences (Hortal et al., 2022). Interdisciplinary collaboration is often constrained by incompatible methodologies, diverging epistemologies, and mismatched timelines or incentives (De Donà, 2023; MacLeod and Nagatsu, 2018). Conservation practitioners may prioritize rapid, scalable solutions, while academic researchers focus on theoretical generalizability or methodological novelty (Kharouba, 2024; Pienkowski et al., 2024). These tensions limit the development of integrative frameworks that could align biodiversity knowledge with complex, real-world problems. Institutional silos further exacerbate this problem (Lah, 2025). Within governments, responsibilities for biodiversity policy are typically spread across multiple ministries, such as environment, agriculture, health, and finance, each operating with its own mandates, data systems, and regulatory constraints (Runhaar et al., 2024). This fragmentation inhibits the coordination required to implement landscape-scale conservation, integrate biodiversity into national accounting systems, or link ecological planning to climate adaptation and public health strategies (Newell et al., 2025). The absence of interoperable data infrastructures and shared reporting frameworks only deepens this disconnection (Hardisty et al., 2019).

A related barrier is the limited capacity to bridge the data-to-policy gap (Geijzendorffer et al., 2016). Despite the proliferation of biodiversity monitoring technologies, ranging from remote sensing and eDNA to participatory mapping and AI-enhanced modeling, there remains a scarcity of institutional mechanisms to translate this data into usable formats for policy actors (Sarkki et al., 2024). Data are often delivered too late, , without the proper metadata (ML-ready datasets), or without clear relevance to regulatory mandates. This disconnect is further compounded by funding systems that prioritize innovation in research but underfund long-term monitoring, data curation, and boundary-spanning roles (Safford et al., 2017). Yet fragmentation is not inevitable. Several enabling conditions have been identified that support more integrated, actionable biodiversity science. One key enabler is interdisciplinary training (Byrne et al., 2025; Gardner, 2021). Programs that combine ecological, computational, social science, and policy analysis skills are beginning to produce a new generation of researchers fluent in both scientific rigor and applied relevance (Byrne et al., 2025; Ling et al., 2024; Slater et al., 2024). These profiles are particularly valuable for roles that demand translation across sectors, such as conservation planning, sustainability consulting, or international biodiversity negotiations (Miralles et al., 2021; Posner and Cvitanovic, 2019; Rodgers et al., 2025).

Boundary organizations, entities that operate at the interface of science, policy, and practice, have also emerged as important integrators (Cvitanovic et al., 2018). These organizations facilitate the co-production of knowledge, mediate between stakeholder groups, and translate complex findings into actionable insights. Examples include the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Wiegleb and Bruns, 2023), the Belmont Forum (Contreras and Reichman, 2015), and regionally anchored platforms such as the Europa Biodiversity Observation Network (Moersberger et al., 2022). By maintaining credibility with both scientific and policy communities, boundary organizations help institutionalize long-term collaboration and build mutual trust.

Adaptive governance offers another critical pathway for overcoming fragmentation (Wyborn, 2015). Unlike traditional top-down policy models, adaptive governance is characterized by flexibility, learning, and participatory decision-making (Butler et al., 2021). It emphasizes iterative feedback between knowledge and action, allowing policies to evolve as new data and stakeholder perspectives emerge. Case studies from water basin management, urban biodiversity planning, and community-led conservation have shown how adaptive governance can reconcile ecological complexity with social legitimacy (Butler et al., 2021; Green et al., 2016; Gunderson et al., 2016; Olivier et al., 2022; Pacoma et al., 2025; Schultz et al., 2015). Importantly, it requires institutional support for monitoring, deliberation, and revision, capacities that remain underdeveloped in many biodiversity governance systems.

Finally, technological interoperability and data standardization are increasingly important. Adopting FAIR principles and common metadata standards enables different sectors and disciplines to use and integrate biodiversity data more effectively (Güntsch et al., 2025; Lannom et al., 2020). Initiatives that promote open science, version-controlled workflows, and multilingual knowledge platforms also help democratize access to biodiversity information, especially for stakeholders in low-resource or non-English-speaking contexts. In sum, the barriers to translational biodiversity are real but not insurmountable. By investing in people, institutions, and practices that foster integration, the biodiversity community can move beyond fragmentation toward systems capable of learning, adapting, and responding to the ecological and societal challenges of the 21st century.

11. Conclusion

This review has made the case for a broader, more inclusive model of translational biodiversity, one that extends beyond genomics to encompass ecological function, policy systems, public health, and social equity. In the face of accelerating biodiversity loss in the Anthropocene, traditional pathways from research to action have proven insufficient. A more systemic approach is needed: one that recognizes translation as an ongoing, co-produced, and ethically informed process. Throughout the review, diverse pathways of translation have been examined, from the use of molecular tools like proteomics and metabolomics, to innovations in AI and remote sensing, to the vital role of Indigenous and local knowledge in shaping place-based conservation. Each pathway highlights both the potential and the limitations of current practices. What emerges is a need for a deeper integration of knowledge systems, governance mechanisms, and participatory frameworks. Realizing this vision will require change on multiple fronts. Transdisciplinary research must become standard practice, supported by institutions, funders, and journals that value relevance alongside rigor. Cross-sectoral partnerships, among scientists, policymakers, communities, and private actors, must be strengthened through formal collaboration platforms. Equally important, funding models should evolve to support the long-term, adaptive nature of translational work, including co-design, community engagement, and implementation. This article does not offer a single solution, but aims to stimulate dialogue and reflection. The future of biodiversity depends not only on the quality of data produced but on how that data is interpreted, shared, and acted upon. Translational biodiversity must be responsive to local contexts, rooted in justice, and adaptable to change. As the Global Biodiversity Framework enters its implementation phase, the challenge is clear: to ensure that scientific insight leads to tangible, equitable outcomes for ecosystems and communities alike. The task ahead is not merely technical, but political, ethical, and relational. It is, ultimately, a shared societal responsibility.

Box 1 | Key concepts in translational biodiversity

Translational biodiversity: The process of turning biodiversity knowledge into actionable strategies across science, policy, health, and society.

Anthropocene: A proposed epoch marked by significant human impact on Earth's ecosystems, biodiversity, and climate systems.

Genomic overreach: The assumption that genomic tools alone can address complex ecological and conservation problems.

Environmental DNA (eDNA): Genetic material collected from environmental samples (e.g., water, soil) to detect species presence.

Proteomics: The large-scale study of proteins, often used to assess organismal stress, function, and adaptation.

Metabolomics: Analysis of small molecules produced by organisms to understand physiological responses to environmental conditions.

Environmental RNA (eRNA): RNA shed by organisms into the environment, used to detect real-time gene activity and ecosystem function.

Microbiome profiling: Characterization of microbial communities associated with hosts or habitats to assess ecological health.

Bioacoustics: Use of sound recordings to monitor species presence, behavior, or habitat condition, especially for vocal taxa.

Remote sensing: Acquisition of ecological data via satellites, drones, or airborne sensors to monitor landscapes and ecosystems.

Artificial intelligence (AI): Algorithms that analyze large, complex datasets to model species distributions, threats, or patterns.

Citizen science: Public participation in biodiversity data collection, often through mobile apps and open-access platforms.

Ecosystem services: Benefits humans derive from ecosystems, including provisioning, regulating, cultural, and supporting services.

Natural capital accounting: A method to measure and value ecosystem assets within national economic frameworks.

Biodiversity offsets: Conservation actions intended to compensate for biodiversity loss caused by development projects.

One Health: A framework recognizing the interconnection of human, animal, and ecosystem health in addressing global threats.

Zoonotic spillover: The transmission of pathogens from animals to humans, often driven by biodiversity loss or habitat change.

Bioprospecting: The exploration of biodiversity for bioactive compounds with pharmaceutical, agricultural, or industrial value.

Digital sequence information (DSI): Digitized genetic data derived from biological samples, central to benefit-sharing debates.

FAIR principles: Guidelines for data management ensuring that datasets are Findable, Accessible, Interoperable, and Reusable.

Co-production: Collaborative creation of knowledge between scientists, communities, and policymakers with shared authority.

Biocultural knowledge: Integrated understanding of ecosystems based on cultural practices, traditions, and Indigenous stewardship.

Free, Prior, and Informed Consent (FPIC): The right of communities to approve or reject external activities affecting their territories.

Boundary organizations: Institutions that operate between science and policy to mediate, translate, and coordinate knowledge exchange.

Adaptive governance: Flexible, participatory, and learning-oriented approaches to environmental decision-making and policy.

Transdisciplinary research: Inquiry that integrates academic disciplines with non-academic knowledge to solve real-world problems.

Science–policy interface: The space where scientific evidence informs policy decisions, often mediated by expert platforms.

Equity in conservation: The fair distribution of costs, benefits, and participation in biodiversity decision-making and outcomes.

Global Biodiversity Framework (GBF): A strategic plan under the Convention on Biological Diversity to halt and reverse biodiversity loss by 2030.

Biodiversity observatories: Institutions or platforms that monitor ecological change and support evidence-based conservation.

Place-based monitoring: Long-term ecological observation tied to specific landscapes, often involving local or Indigenous communities.

Translational ecology: A field promoting the timely, actionable integration of ecological knowledge into decision-making.

Commodification of nature: The process of assigning economic value to ecosystems, which may risk simplifying their ethical and cultural significance.

Institutional silos: Lack of coordination between organizations or sectors, leading to fragmented biodiversity governance.

Knowledge justice: The principle that diverse forms of knowledge, especially from marginalized groups, should inform and benefit decision-making.

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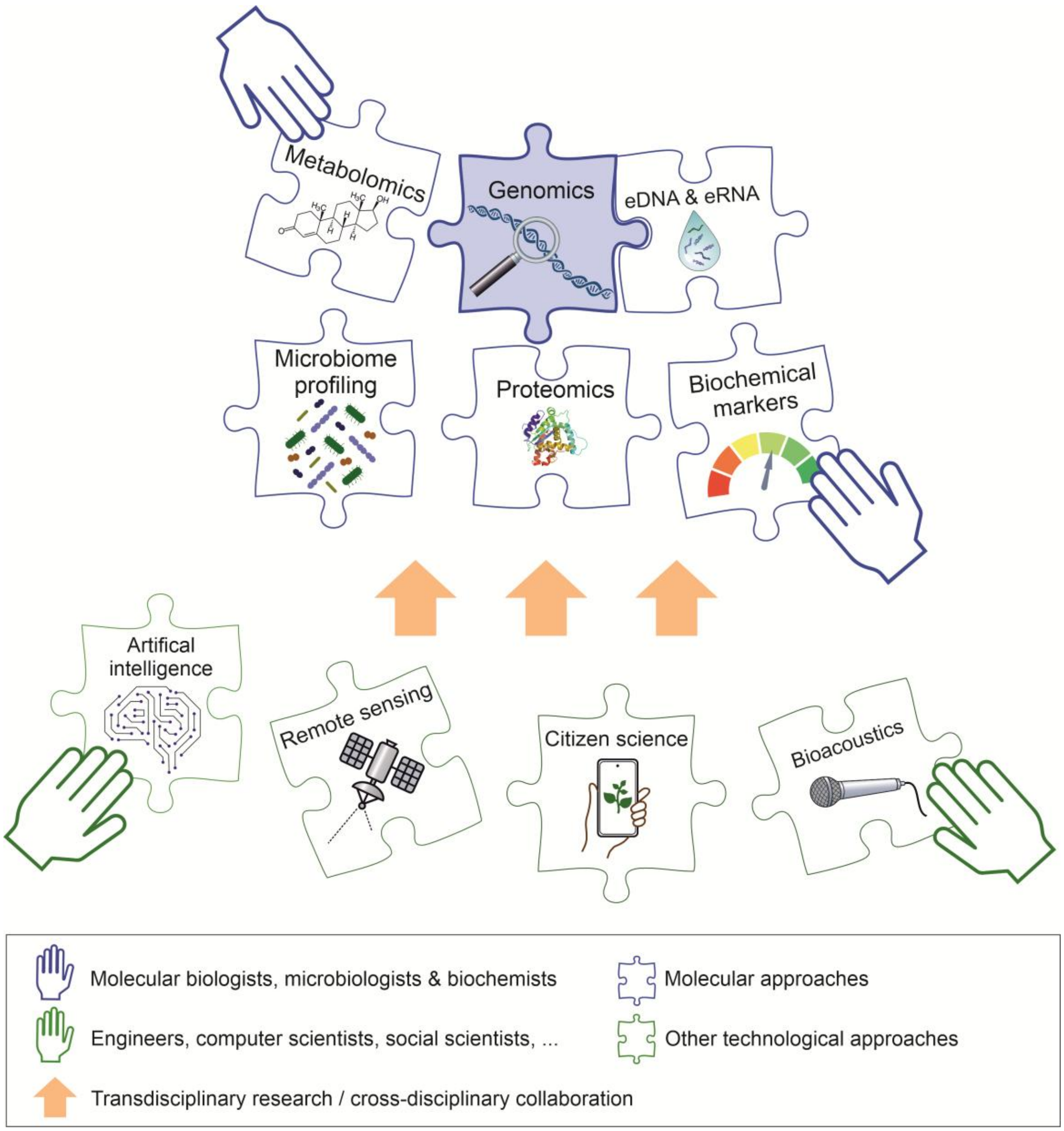

Figure 1. Translational biodiversity beyond genomics and at science interface.

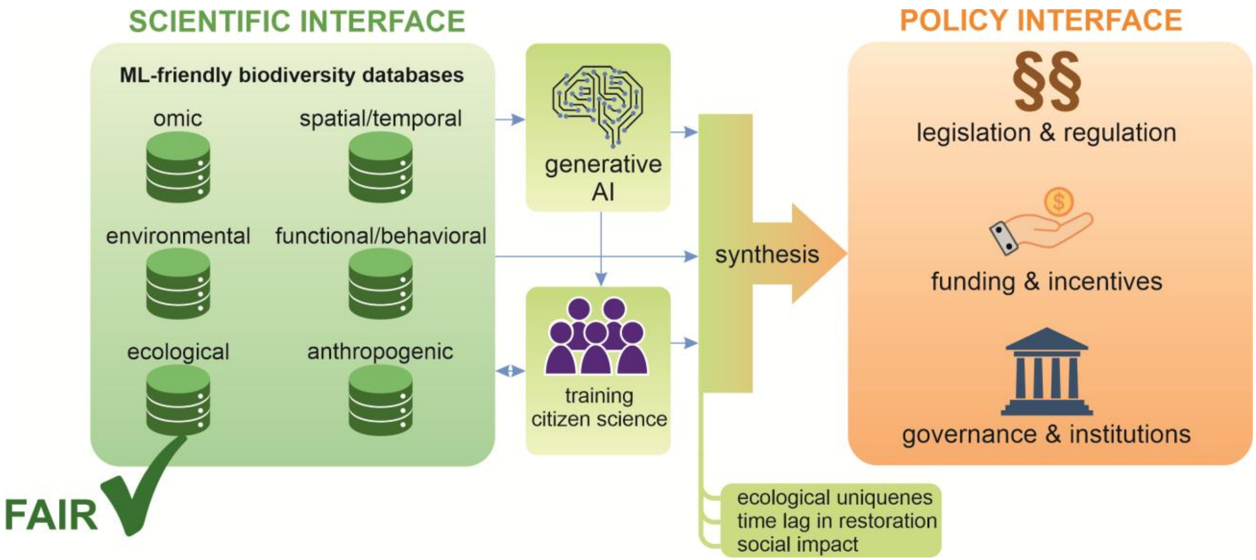

Figure 2. Conceptual framework for translational biodiversity. Biodiversity knowledge, systematically organized into ML-ready databases that integrate multi-level metadata (omic, spatial/temporal, environmental, functional/behavioral, ecological, and anthropogenic), can be harnessed to train generative AI models and to engage early-career and citizen scientists in raising awareness. This synthesis informs governance structures, enabling evidence-based legislation, regulation, and funding mobilization, thereby translating foundational knowledge into tangible societal outcomes.

Table 1. Translational tools and pathways in biodiversity science. This table synthesizes diverse tools and approaches relevant to translational biodiversity science, linking them to their knowledge domains, application scales, implementation pathways, enabling conditions, and present challenges. The examples span molecular, ecological, participatory, and institutional innovations drawn from across the review.

Tool or Approach	Knowledge Domain	Scale of Application	Translational Pathway	Key Enablers	Current Limitations
Environmental DNA (eDNA)	Molecular ecology/genomics	Species & habitat monitoring	Detection → Status assessment → Regulation	Reference libraries, taxonomic expertise	Degraded signals, incomplete databases
Remote sensing	Landscape ecology	Regional to global	Mapping → Trend analysis → Land-use policy	Satellite access, AI integration	Data processing burden, policy mismatch
Citizen science (e.g. eBird)	Public knowledge	Local to national	Observation → Data aggregation → Management inputs	Community engagement, digital platforms	Spatial bias, uneven data quality
Biocultural indicators	Indigenous/local knowledge	Site-specific	Cultural valuation → Co-management frameworks	FPIC, legal recognition	Tokenism, lack of institutional support
Natural capital accounting	Ecological economics	National planning	Valuation → Investment prioritization	Integration into finance policy	Oversimplification, equity concerns
Multi-omics (e.g. proteomics + genomics)	Functional ecology	Population and ecosystem	Mechanism → Prediction → Adaptive action	Interdisciplinary capacity, data sharing	Cost, technical complexity
FAIR data infrastructures	Data governance	Cross-scalar	Open access → Interoperability → Evidence synthesis	Metadata standards, repositories	Capacity gaps, uneven infrastructure
Environmental RNA (eRNA)	Molecular ecology	Community-level activity	Gene expression → Real-time monitoring → Ecosystem response	RNA preservation tech, sequencing platforms	Instability, lack of field protocols
Bioacoustics monitoring	Conservation tech	Site-specific to regional	Sound data → Species detection → Temporal trend analysis	ARUs, acoustic libraries	Signal overlap, species ID ambiguity
Zoonotic risk mapping	One Health	Regional to global	Habitat change → Host-pathogen models →	Cross-sector surveillance, spatial data	Data sharing limits, uncertainty in models

			Disease prevention		
Restoration co-design	Participatory conservation	Local to landscape	Community priorities → Ecosystem planning → Adaptive management	Inclusive governance, local capacity	Power asymmetries, time/resource constraints
Science-policy boundary platforms	Policy interface	National to global	Assessment → Synthesis → Policy adoption	IPBES-like structures, liaison roles	Slow uptake, misaligned incentives
Ethical DSI governance	Biodiversity law/ethics	Global	Digital access → Benefit-sharing → Compliance frameworks	Nagoya Protocol, equitable IP rules	Lack of consensus, enforcement issues