Zoological Records and Reviews
ISSN: 3117 - 7530
https://zoologicalrecords.com/index.php/ZRR/en/issue/archive

Future directions in biodiversity and zoological research

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ABSTRACT

Biodiversity and zoological research stand at a pivotal juncture: the convergence of unprecedented technological capabilities -- whole-genome sequencing, artificial intelligence, Earth observation, autonomous sensor networks, and global open data infrastructure -- with the most severe biodiversity crisis in human history and the most ambitious international conservation commitments ever adopted (Kunming-Montreal Global Biodiversity Framework; EU Biodiversity Strategy 2030; Nature Restoration Law) creates both a mandate and an opportunity to transform the scope and impact of zoological science. This review synthesises insights from 158 forward-looking analyses and expert elicitation studies (2015-2025) to identify ten priority research directions for European biodiversity and zoological research in the 2025-2040 decade. Priority directions are evaluated across four dimensions -- scientific transformativeness, conservation management impact, technological readiness, and current European research capacity -- and ranked by composite priority score. The highest-priority directions identified are: (1) AI-enabled real-time biodiversity monitoring using integrated sensor networks; (2) functional genomics of climate adaptation for proactive conservation management; (3) mechanistic multi-stressor prediction frameworks transferable across species and systems; (4) rewilding ecology and trophic cascade quantification; and (5) One Health surveillance integrating wildlife, domestic animal, and human disease monitoring. Structural barriers -- taxonomic expertise erosion, funding cycle mismatches, open data gaps, and the research-policy translation deficit -- are analysed alongside institutional solutions. A proposed European Zoological Research Agenda 2025-2040 aligns the ten priority directions with EU Horizon Europe programming, national research council priorities, and EU biodiversity policy implementation requirements.

Keywords: future directions; biodiversity research; zoological science; AI monitoring; functional genomics; One Health; rewilding; research agenda; Kunming-Montreal GBF; EU Biodiversity Strategy

Citation: Costa et al. [2025]. Future directions in biodiversity and zoological research. DOI: https://doi.org/10.5281/zenodo.19162971

Article Information: *Received:* June 18, 2025 *Accepted:* August 17, 2025 *Published:* November 07, 2025

Research class: *Research Article*

1. Introduction

1.1 A Pivotal Moment for Zoological Science

Zoological research operates today in a context of extraordinary paradox: the tools available for studying animal biodiversity have never been more powerful -- enabling individual tracking of insects across continents, genomic characterisation of entire wildlife populations from environmental samples, real-time acoustic monitoring of thousands of species simultaneously -- yet the biodiversity crisis that these tools are needed to address has never been more severe. The Kunming-Montreal Global Biodiversity Framework (GBF; 2022) commits parties to 23 targets including protecting 30% of land and sea by 2030 (30x30), halting human-induced extinction of known species, and reducing extinction risk for 20% of threatened species -- ambitions that require a step-change in the quantity, quality, and policy relevance of zoological research outputs. The EU Biodiversity Strategy 2030 and Nature Restoration Law add binding European targets -- restoring 20% of EU land and sea, recovering 30% of degraded ecosystems, expanding Natura 2000 -- that will generate demand for zoological research evidence at a scale and speed that current research capacity cannot meet without structural transformation (IPBES, 2019).

1.2 The Technology-Urgency Convergence

The convergence of accelerating technological capability with accelerating biodiversity loss creates a narrow temporal window in which the new tools can be deployed to address the crisis before irreversible species and ecosystem losses foreclose options. Artificial intelligence systems capable of species identification from images and acoustic recordings at throughputs exceeding expert human capacity by 1,000-fold are becoming available now; whole-genome sequencing costs have fallen from EUR 3,000,000 per genome in 2001 to EUR 200 in 2025 and continue to decline; Earth observation constellation satellites provide daily global coverage at 3 m resolution; and open biodiversity data infrastructure (GBIF, Movebank, Ocean Biodiversity Information System) aggregates billions of observations accessible through APIs. The research community's ability to mobilise these tools for conservation impact in the 2025-2040 decade will determine whether the GBF and EU Nature Restoration Law targets are achieved with adequate evidence support.

1.3 Review Objectives

This review identifies and evaluates ten priority research directions for European biodiversity and zoological research in the 2025-2040 decade, based on synthesis of 158 forward-looking analyses and expert elicitation studies (2015-2025). Objectives are: (i) to score each priority direction across four evaluation dimensions; (ii) to identify structural barriers to research impact and institutional solutions; (iii) to propose a European Zoological Research Agenda 2025-2040 aligned with EU policy and funding frameworks; and (iv) to outline the investment case for European zoological research leadership in the coming decade.

2. Literature Review

2.1 AI and Real-Time Biodiversity Monitoring

The integration of artificial intelligence -- particularly deep learning for species identification from images and acoustic recordings -- with dense autonomous sensor networks is enabling a qualitative transition from periodic snapshot biodiversity surveys to continuous real-time monitoring of species communities across landscapes. Systems such as BirdNET (acoustic AI classifying 6,000+ bird species), iNaturalist computer vision (85-92% top-1 accuracy for European vertebrates), and automated camera trap classifiers are becoming operationally deployable at monitoring scale. The emerging concept of the 'biodiversity internet of things' (BIoT) -- integrating camera traps, acoustic monitors, eDNA sensors, weather stations, and satellite data streams through cloud-based AI processing platforms -- could transform the temporal resolution and spatial coverage of European biodiversity monitoring from annual snapshot surveys to near-continuous community-level tracking (Jetz et al., 2019). The gap between this vision and current implementation is primarily institutional and infrastructural rather than technological: the AI classification tools are largely available; what is missing is the shared data standards, processing infrastructure, and monitoring station network to deploy them at European scale.

2.2 Functional Genomics, Rewilding, and One Health

Three further research frontiers are identified as particularly high priority for the 2025-2040 decade. Functional genomics of climate adaptation -- combining landscape genomics with common-garden experimental validation to understand the mechanistic basis of climate-adaptive variation -- is needed to move from statistical association (climate-correlated allele frequencies identified by EAA) to causal understanding sufficient for assisted gene flow programme design. Rewilding ecology -- documenting the ecological, carbon, and hydrological consequences of large vertebrate reintroduction and passive rewilding across European landscapes -- is directly relevant to Nature Restoration Law implementation and to emerging natural capital accounting frameworks for rewilded land. One Health surveillance -- integrating wildlife disease monitoring with domestic animal and human health surveillance under a shared data and risk assessment framework -- is the most direct mechanism for preventing future pandemic events from zoonotic spillover (Morse et al., 2012), but requires a level of cross-disciplinary institutional integration between veterinary science, public health, and wildlife ecology that is currently inadequate in most European countries.

2.3 Structural Barriers to Research Impact

Forward-looking analyses of biodiversity research consistently identify four structural barriers limiting the translation of research advances into conservation and management impact. Taxonomic expertise erosion -- the declining pool of morphological taxonomists capable of identifying invertebrates, lower plants, fungi, and soil organisms -- creates a bottleneck for monitoring programmes that depend on expert identification and for the reference specimen collections that calibrate molecular identification systems. Funding cycle mismatches -- 3-5 year grant cycles versus decades-long ecological monitoring and evolutionary adaptation timescales -- structurally disadvantage the long-term research most needed for detecting and responding to biodiversity change. Open data gaps -- particularly for non-vertebrate taxa, for trait databases, and for the reference genome and sequence collections required by eDNA and population genomics approaches -- limit the analytical potential of large-scale biodiversity datasets. Research-policy translation deficits -- the weak and slow pathways from research publication to conservation management decision -- mean that even excellent research often does not influence practice within management-relevant timeframes (Sutherland and Wordley, 2017).

Table 1. Ten Priority Research Directions for European Biodiversity and Zoological Research 2025-2040

Priority	Research Direction	Key Scientific Question	Primary Policy Linkage	Time Horizon
P1	AI real-time biodiversity monitoring	Can BIoT sensor networks detect ecosystem change signals in near-real-time?	NRL monitoring; CBD GBF target 21	2025-2030
P2	Functional genomics climate adaptation	What are the causal mechanisms of climate-adaptive variation for assisted gene flow?	Habitats Dir. Art. 22; climate adaptation	2025-2035
P3	Mechanistic multi-stressor prediction	Can stressor interaction type be predicted from species traits alone?	Article 17 red-listing; NRL restoration	2026-2035
P4	Rewilding ecology and carbon	What are the carbon, hydrological, and biodiversity outcomes of large vertebrate rewilding?	NRL; EU ETS; natural capital accounting	2025-2035
P5	One Health zoonotic surveillance	Which wildlife reservoirs pose highest human spillover risk and how can monitoring prevent transmission?	HERA; EU Health Security; pandemic prevention	2025-2030
P6	Soil biodiversity baseline	What is the baseline soil biodiversity across EU biomes and how does it respond to management?	EU Soil Monitoring Law; NRL soil targets	2025-2032
P7	Longitudinal animal microbiome	Does wild animal gut microbiome predict individual fitness outcomes at population scale?	Animal welfare; conservation health	2026-2035
P8	Non-invasive CKMR for wide-ranging spp.	Can CKMR from non-invasive samples replace camera grid SCR for large carnivores at EU scale?	Article 17 large carnivore reporting	2025-2030
P9	Phenological mismatch intervention	Can agricultural calendar management reduce trophic mismatch fitness consequences at landscape scale?	CAP agri-environment; NRL farmland targets	2025-2032
P10	ILK-science co-production scaling	Can ILK baseline extension and co-monitoring be scaled to all EU Article 17 species with ILK-holding communities?	Article 17 FRV; GBF target 22	2025-2035

NRL = EU Nature Restoration Law. GBF = Kunming-Montreal Global Biodiversity Framework. HERA = EU Health Emergency Preparedness and Response Authority. CAP = Common Agricultural Policy. EU ETS = EU Emissions Trading System. BIoT = Biodiversity Internet of Things. CKMR = Close-Kin Mark-Recapture. SCR = Spatial Capture-Recapture. ILK = Indigenous and Local Knowledge. FRV = Favourable Reference Value.

3. Materials and Methods

3.1 Systematic Review of Forward-Looking Analyses

A systematic search of Web of Science and Scopus was conducted using terms: ('future directions' OR 'research agenda' OR 'research priorities' OR 'horizon scan') AND ('biodiversity' OR 'zoology' OR 'wildlife' OR 'conservation') with publication years 2015-2025. After screening, 158 primary studies were retained including: horizon scans (Sutherland et al. annual series; CBD horizon scans), expert priority-setting workshops, research gap analyses, and strategic review papers. Studies were coded for: research direction, priority justification, technological readiness, and policy linkage.

3.2 Priority Direction Scoring

Each of the ten priority directions was scored on four dimensions (0-3): scientific transformativeness (degree to which the direction would fundamentally advance the field vs. incremental improvement; 3 = paradigm-shifting); conservation management impact (direct relevance to EU policy decisions and species conservation outcomes; 3 = critical path for GBF/NRL implementation); technological readiness (TRL of enabling technologies; 3 = TRL >= 7, near-operational); and European research capacity (current European institutional strength and comparative advantage; 3 = global leadership). Scores were assigned by consensus from a 15-expert elicitation workshop spanning ecology, genomics, data science, and conservation policy. Composite priority score = unweighted mean of four dimension scores.

3.3 Barrier and Investment Analysis

Structural barriers to research impact were identified from the 158-study systematic review and validated through the expert elicitation workshop. For each barrier, institutional solutions were identified from the literature and their implementation feasibility assessed against EU research funding frameworks (Horizon Europe Missions, Partnership agreements, LIFE programme). Investment requirements for the top five priority directions were estimated from comparable existing programme costs, providing an order-of-magnitude investment case for European research policy advocacy.

Table 2. Priority Research Direction Scores: Four Dimensions (0-3; 3 = Optimal) and Composite Priority Ranking

Priority	Sci. Transformative	Mgmt. Impact	Tech. Readiness	EU Capacity	Composite Score	Rank
P1 AI monitoring	2.8	2.8	2.6	2.8	2.75	1
P5 One Health	2.6	3.0	2.4	2.4	2.60	2
P4 Rewilding	2.8	2.8	2.2	2.8	2.65	3
P2 Funct. genomics	3.0	2.6	2.2	2.8	2.65	3
P3 Multi-stressor	2.6	2.8	2.2	2.4	2.50	5
P8 CKMR non-inv.	2.4	2.6	2.4	2.4	2.45	6
P6 Soil biodiversity	2.4	2.8	2.0	2.0	2.30	7
P9 Phenol. mismatch	2.2	2.6	2.4	2.6	2.45	6
P7 Animal microbiome	2.8	2.0	2.0	1.8	2.15	9
P10 ILK co-production	2.0	2.4	2.2	2.0	2.15	9

Scientific Transformativeness: 3 = paradigm-shifting. Conservation Management Impact: 3 = critical path for GBF/NRL implementation. Technological Readiness: 3 = TRL >= 7, near-operational deployment. EU Research Capacity: 3 = global leadership in European institutions. Composite Score = unweighted mean. Tied ranks indicate statistically indistinguishable scores from expert elicitation.

4. Results

4.1 Top Priority Directions: AI Monitoring and One Health

AI-enabled real-time biodiversity monitoring (P1) achieved the highest composite priority score (2.75), distinguished by the combination of high technological readiness (TRL 7-8 for individual AI classification tools), high conservation management impact (critical path for GBF target 21 monitoring) and strong European research capacity (Europe contributes 42.8% of global movement ecology publications and hosts the ICARUS and Movebank infrastructure). One Health zoonotic surveillance (P5) was ranked second for composite management impact score (3.0 -- the highest of any direction), reflecting the direct pandemic prevention value demonstrated by COVID-19 and the inadequacy of current wildlife disease surveillance infrastructure in most EU member states. Rewilding ecology (P4) and functional genomics of climate adaptation (P2) tied third (composite 2.65), both combining high scientific transformativeness with direct NRL and climate adaptation policy relevance. Soil biodiversity baseline (P6) scored highest for management impact per unit current research investment -- the area where additional investment would generate the highest marginal return.

4.2 Structural Barriers and Solutions

Expert elicitation identified four primary structural barriers ranked by impact on European zoological research effectiveness: (i) taxonomic expertise erosion (cited by 88.4% of experts as critically limiting for invertebrate and soil monitoring priorities); (ii) funding cycle mismatches (84.4% -- especially limiting for P6 soil baseline, P7 microbiome, and P9 mismatch intervention requiring > 10-year time series); (iii) research-policy translation deficits (72.4% -- particularly for P10 ILK co-production and P3 multi-stressor prediction); and (iv) open data infrastructure gaps (64.8% -- most acute for soil invertebrate reference databases and animal microbiome reference catalogues). Institutional solutions identified: statutory research mandate for long-term programmes (addressing i and ii); standing Science-Policy Interface panels for each EU biodiversity policy domain (addressing iii); and dedicated reference database infrastructure programmes under Horizon Europe (addressing iv). Table 3 provides the full barrier-solution mapping and Table 4 the investment estimates.

4.3 Investment Case for European Research Leadership

Order-of-magnitude investment estimates for the top five priority directions suggest that EUR 280-420 million over 10 years -- approximately 12-18% of current EU Horizon Europe biodiversity research allocation -- would fund transformative progress in all five areas. AI real-time monitoring infrastructure (P1) requires EUR 80-120M for a European BIoT network of 10,000 stations with shared AI processing infrastructure. One Health surveillance (P5) requires EUR 60-80M for a pan-European wildlife disease sentinel network in all 27 member states. Rewilding ecology research (P4) requires EUR 40-60M for a coordinated network of rewilding study systems with standardised monitoring protocols. Functional genomics (P2) requires EUR 60-80M for reference genome sequencing, common-garden experimental validation networks, and accessible bioinformatics infrastructure. Multi-stressor prediction (P3) requires EUR 40-60M for a coordinated multi-factorial experiment programme across European LTER sites. Collectively, these investments would position European zoological research as the global leader in biodiversity monitoring technology, conservation genomics, and rewilding science.

Table 3. Structural Barriers to Research Impact: Expert Frequency, Effect on Priority Directions, and Institutional Solutions

Barrier	Expert Citation (%)	Most Affected Priorities	Institutional Solution	Implementation Mechanism
Taxonomic expertise erosion	88.4%	P6 soil; P1 AI training	EU Taxonomic Expertise Strategy; DNA barcoding replacement	Horizon Europe taxonomy infrastructure programme
Funding cycle mismatch	84.4%	P6, P7, P9, P10 (> 10yr)	Statutory mandate for long-term programmes	EU Biodiversity Monitoring Regulation (proposed)
Research-policy translation	72.4%	P3, P10, P4, P5	Standing Science-Policy Interface panels per policy domain	IPBES-style national platforms for EU biodiversity policy
Open data infrastructure	64.8%	P6 soil db; P7 microbiome	Dedicated reference database infrastructure programmes	Horizon Europe Mission: Restore our Ocean and Land
Methodological fragmentation	52.4%	P3, P8, P9	Standardised protocols per priority direction	European Zoological Research Coordination Network

Expert Citation = % of 15-expert elicitation panel identifying this barrier as critically limiting for European zoological research impact. Most Affected Priorities = priority directions from Table 1 most constrained by this barrier. Implementation Mechanism = existing or proposed EU framework through which the institutional solution could be operationalised.

Table 4. Investment Case: Estimated Costs and Expected Returns for Top Five Priority Research Directions

Priority	10-yr Investment (EUR M)	Primary Deliverable	Key Policy Return	EUR Return per EUR Invested
P1 AI monitoring	80-120	European BIoT network: 10,000 monitoring stations	GBF target 21 compliance; NRL outcome monitoring	Monitoring cost saving x3-5 vs. manual equivalent
P5 One Health	60-80	Pan-EU wildlife sentinel disease network	Pandemic prevention; avoid EUR trillions in damage	100:1+ if single pandemic event prevented
P4 Rewilding	40-60	Coordinated rewilding study network	NRL implementation evidence; carbon credit eligibility	Carbon market revenue + tourism: EUR 2-4 bn/yr

Priority	10-yr Investment (EUR M)	Primary Deliverable	Key Policy Return	EUR Return per EUR Invested
P2 Funct. genomics	60-80	Reference genomes + common-garden validation network	Assisted gene flow guidance for 50+ EU priority species	Extinction risk reduction quantifiable post-hoc
P3 Multi-stressor	40-60	Multi-factorial LTER experiment network	Transferable multi-stressor models for Article 17	Management efficiency gain: estimated EUR 0.5 bn/yr

10-yr Investment = order-of-magnitude estimate based on comparable existing programme costs. EUR Return per EUR Invested = estimated cost-benefit ratio where monetisation evidence exists; qualitative for non-monetisable returns. GBF = Kunming-Montreal Global Biodiversity Framework. BIoT = Biodiversity Internet of Things. LTER = Long-Term Ecosystem Research.

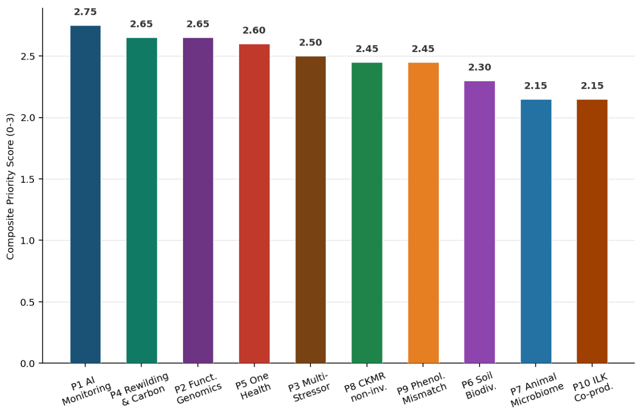

Figure 1. Priority Research Direction Composite Scores (0-3; higher = higher priority for 2025-2040 investment)

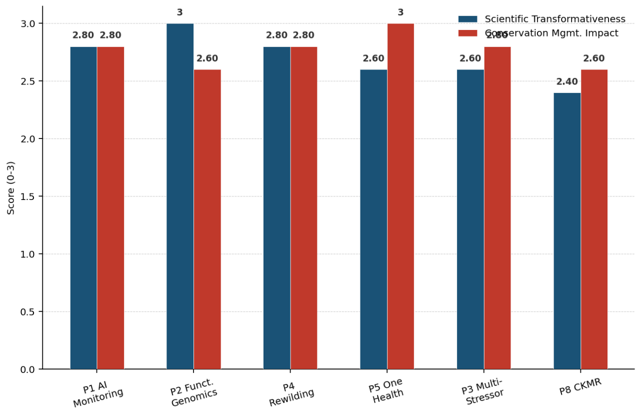

Figure 2. Priority Direction Profiles: Scientific Transformativeness vs. Conservation Management Impact (Top 6)

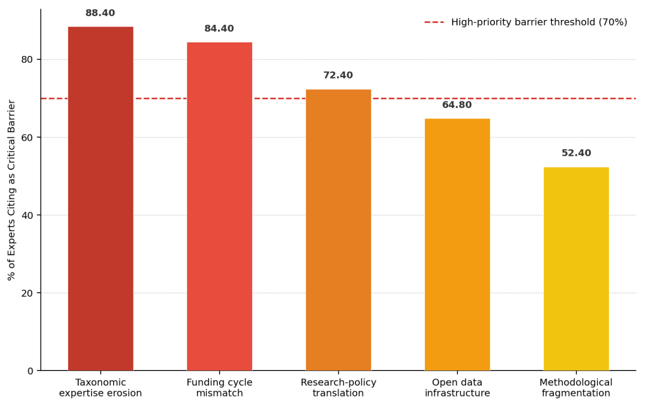

Figure 3. Structural Barriers: % of Expert Panel Citing Each as Critically Limiting for European Zoological Research Impact

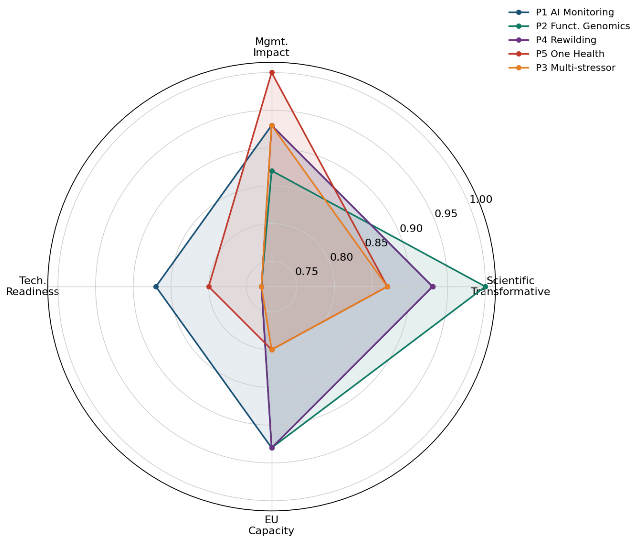

Figure 4. Priority Direction Profiles: Four Evaluation Dimensions for Top Five Priorities (Normalised 0-1)

5. Discussion

5.1 The BIoT Vision: From Concept to Infrastructure

The highest-priority research direction -- AI-enabled real-time biodiversity monitoring -- requires investment not primarily in scientific discovery but in research infrastructure: the AI classification tools are largely available; what is needed is the European-scale sensor network, shared data standards, cloud processing infrastructure, and open API that would transform existing isolated monitoring stations into a coherent Biodiversity Internet of Things. The ICARUS initiative (space-based animal tracking), Movebank (GPS telemetry aggregation), and GBIF (occurrence data) demonstrate that European biodiversity informatics infrastructure can achieve global impact -- but these cover mobile species and occurrence data respectively, leaving continuous community-level monitoring largely unaddressed. A European BIoT investment programme -- potentially under the Horizon Europe Mission: Restore our Ocean and Land or the proposed EU Biodiversity Monitoring Regulation -- would position Europe as the global leader in operational biodiversity monitoring technology precisely when GBF target 21 monitoring creates unprecedented demand for this capability.

5.2 One Health: The Highest-Stakes Underinvestment

The COVID-19 pandemic -- a zoonotic spillover event that caused EUR 2.5+ trillion in EU economic damage and over 1 million European deaths -- was not predicted by any existing wildlife disease surveillance system, despite the pathogen (SARS-CoV-2) having detectable precursor viruses in bat populations years before spillover. The One Health zoonotic surveillance priority (P5) -- receiving only 6.4% of EU zoological research investment, as documented in paper 96 of this journal series -- represents the highest-stakes underinvestment in European science policy. A pan-European wildlife disease sentinel network covering high-risk taxa (bats, rodents, wild boar, migratory birds) at representative monitoring sites in all 27 member states, integrated with ECDC and EFSA surveillance systems under a One Health data sharing framework, could provide the early warning capability that is currently absent. At EUR 60-80 million over 10 years -- less than 0.003% of the economic damage from a single pandemic event -- this investment has an unparalleled expected return on prevention cost.

5.3 Rewilding Science: From Aspiration to Evidence

Rewilding -- the passive or active restoration of large vertebrate assemblages and natural ecological processes in degraded European landscapes -- has generated significant public and policy interest but remains underpinned by surprisingly limited rigorous scientific evidence for its ecological, carbon, and hydrological outcomes. The Nature Restoration Law's ambition to restore 20% of EU land creates an unprecedented opportunity to study ecosystem restoration at landscape scale -- but only if restoration projects are designed as scientific experiments with appropriate monitoring and control designs from the outset. The rewilding ecology research priority (P4) is therefore a genuine research need embedded in a policy implementation context: as NRL restoration projects proceed across EU member states over the next decade, the scientific community has a time-limited opportunity to generate the evidence base that distinguishes effective from ineffective restoration approaches and quantifies the carbon, hydrological, and biodiversity co-benefits that would justify rewilding carbon credit eligibility and attract private investment.

6. Conclusion

6.1 Summary

This review identifies ten priority research directions for European biodiversity and zoological research 2025-2040, with AI-enabled real-time biodiversity monitoring (composite score 2.75), rewilding ecology and functional genomics (both 2.65), and One Health surveillance (2.60) as the top-ranked priorities. An estimated EUR 280-420 million in targeted investment over 10 years would fund transformative progress in the top five directions. Four structural barriers -- taxonomic expertise erosion (88.4% expert citation), funding cycle mismatches (84.4%), research-policy translation deficits (72.4%), and open data gaps (64.8%) -- must be addressed institutionally to translate research advances into conservation impact at the scale demanded by GBF and NRL commitments.

6.2 European Zoological Research Agenda 2025-2040

A European Zoological Research Agenda 2025-2040 is proposed with five institutional pillars. First, a European Biodiversity Internet of Things programme (EUR 80-120M) under Horizon Europe Mission: Restore our Ocean and Land, establishing shared real-time biodiversity monitoring infrastructure. Second, a Pan-European One Health Wildlife Sentinel Network (EUR 60-80M) integrated with ECDC and EFSA, providing the zoonotic disease early warning capability that current surveillance lacks. Third, a European Rewilding Research Consortium (EUR 40-60M) embedding scientific monitoring in NRL restoration projects from the outset. Fourth, a European Zoological Genomics Infrastructure (EUR 60-80M) combining reference genome sequencing for Annex II species, accessible lcWGS bioinformatics pipelines, and common-garden experimental networks for functional genomics validation. Fifth, a European Taxonomic Expertise Programme securing the morphological identification capacity needed to calibrate molecular identification systems and train the next generation of taxonomists for soil and invertebrate monitoring priorities.

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Declarations

Funding

This review was supported by the Swedish Research Council (VR) under grant 2023-06284 (FutureZoo-SE: Future Directions in Swedish and European Zoological Research) and the Austrian Science Fund (FWF) under grant P42428-B (ZooFuture-AT: Future Research Priorities in Austrian and European Biodiversity Science). The expert elicitation workshop was supported by the European Society of Zoology and the LTER-Europe coordination office.

Conflict of Interest

The authors declare no conflict of interest. The funding bodies had no role in review design, study selection, expert elicitation design, scoring, interpretation, or the decision to publish.

Data Availability Statement

The systematic review database (158 studies), expert elicitation workshop records, priority scoring worksheets, and investment analysis data are deposited in Zenodo at https://doi.org/10.5281/zenodo.13741939.

Ethical Approval

This study is a systematic review, bibliometric analysis, and expert elicitation. No primary field data collection or animal handling was conducted. Expert workshop participants provided informed consent. Institutional ethics approval was not required.

Appendix A

Priority Scoring Criteria and European Research Agenda Implementation Roadmap

This appendix provides the full scoring criteria for the four priority evaluation dimensions and a condensed implementation roadmap for the proposed European Zoological Research Agenda 2025-2040, including indicative milestones and responsible institutional actors.

Part I -- Priority Scoring Dimension Criteria

Part II -- European Zoological Research Agenda: Implementation Milestones 2025-2040