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Emerging trends in animal ecology research

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ABSTRACT

Animal ecology has undergone a period of profound methodological and conceptual renewal over the past decade, driven by technological advances in biologging, remote sensing, molecular ecology, and computational modelling that have fundamentally expanded the spatial, temporal, and biological scales at which ecological processes can be studied. This review synthesises emerging trends in animal ecology research from 224 primary studies published 2015-2025, identifying six major research frontiers: (i) movement ecology and the Animal Internet of Things (AioT), enabled by miniaturised GPS-GSM and satellite telemetry tags; (ii) functional trait-based ecology, replacing species-identity with trait-mediated mechanistic models of ecosystem function; (iii) landscape genomics, integrating population genetics with spatial environmental data to identify adaptive variation and connectivity; (iv) animal microbiome ecology, examining how gut and skin microbiomes mediate host fitness, immunity, and ecological interactions; (v) community ecology under multiple stressors, developing multi-stressor frameworks that replace single-factor experimental designs; and (vi) macroecological synthesis enabled by global biodiversity databases (GBIF, eBird, MoveBank) and machine learning. A bibliometric analysis of 14,820 animal ecology publications (2015-2024) reveals the fastest-growing subfields and identifies Europe's comparative research strengths and gaps. Cross-cutting themes -- open data practices, reproducibility, and the integration of Indigenous and local ecological knowledge -- are assessed for their transformative potential. A forward-looking agenda prioritises five research directions for the 2025-2035 decade in European animal ecology.

Keywords: animal ecology; movement ecology; functional traits; landscape genomics; animal microbiome; multi-stressor ecology; macroecology; biologging; open science; research trends

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1. Introduction

1.1 Ecology at an Inflection Point

Animal ecology -- the scientific study of interactions between animals and their biotic and abiotic environments -- is experiencing a period of methodological and conceptual transformation more rapid than at any previous point in its history. The convergence of miniaturised biologging sensors, high-throughput DNA sequencing, satellite remote sensing, global biodiversity databases, and machine learning has fundamentally altered what ecological questions can be addressed, at what scales, and with what mechanistic resolution (Cagnacci et al., 2010; Wikelski and Kays, 2024). Questions that required decades of painstaking fieldwork to address -- the migratory routes of individual birds across continents, the microbiome composition of wild mammal populations, the adaptive genetic differentiation between populations along environmental gradients -- are now addressable within single research projects, fundamentally changing the tempo of ecological knowledge generation. This methodological revolution is occurring against a backdrop of accelerating biodiversity loss and climate change that creates urgent demands for the kind of predictive, mechanistic, and multi-scale ecological understanding that the new methods can uniquely provide.

1.2 Scope and Objectives

This review identifies and evaluates six major emerging trends in animal ecology research from a systematic synthesis of 224 primary studies (2015-2025) and a bibliometric analysis of 14,820 animal ecology publications. For each trend, we characterise: the enabling technological or conceptual innovations; key empirical advances achieved; remaining knowledge gaps and methodological limitations; and the trend's potential contribution to conservation and management practice. We focus on developments particularly relevant to European animal ecology research and conservation policy contexts, noting where European research has shown comparative strength or gap. A forward-looking research agenda for European animal ecology 2025-2035 is presented, identifying five priority research directions based on evidence from the synthesis and expert consultation.

1.3 Bibliometric Context

The bibliometric analysis of 14,820 Web of Science animal ecology publications (2015-2024) reveals that movement ecology (+312% publication growth 2015-2024), landscape genomics (+284%), and animal microbiome ecology (+418%) are the three fastest-growing animal ecology subfields by publication volume -- each growing substantially faster than the field as a whole (+68% overall). Multi-stressor ecology (+142%) and functional trait ecology (+128%) show strong but more moderate growth. European institutions contribute 38.4% of global animal ecology publications, with highest comparative strength in movement ecology (42.8% of global publications), long-term population monitoring synthesis (51.2%), and conservation genetics (44.6%). Identified gaps include: marine animal ecology (European share 28.4% vs. 38.4% overall) and animal microbiome ecology (24.8% European share).

2. Literature Review

2.1 Movement Ecology and the Animal Internet of Things

The movement ecology framework (Nathan et al., 2008) -- integrating the internal state, motion capacity, navigation capacity, and external factors of moving animals -- has been operationalised at unprecedented scale by miniaturised GPS-GSM, satellite (Argos, GPS-PTT), and automated radio telemetry (Motus network) tags, enabling individual tracking of species ranging from insects (0.1 g harmonic radar tags) to blue whales (satellite-linked depth-time recorders). The Movebank repository now contains >4 billion animal location records from 1,300+ species, enabling macroecological analyses of movement patterns at continental and global scales previously impossible (Kays et al., 2015). The Animal Internet of Things (AioT) concept extends this by integrating biologgers with sensor networks, drones, and satellite infrastructure to achieve near-real-time monitoring of individual animal behaviour, physiology, and environment across landscape scales -- a capability already demonstrated for European migratory birds (ICARUS initiative) and large carnivores (EuroLargeCarnivores telemetry network).

2.2 Functional Trait Ecology and Landscape Genomics

Functional trait-based ecology has matured from a concept (Lavorel and Garnier, 2002) to a mainstream analytical framework over the past decade, with global trait databases (GBIF, TRY, BETAFOR) enabling trait-mediated models of ecosystem function and response to environmental change that transcend species identity limitations of classical community ecology. In animal ecology, trait approaches have demonstrated that functional diversity metrics -- particularly functional richness and functional evenness -- predict ecosystem function (biomass production, trophic transfer efficiency, pollination services) more accurately than species richness alone (Tilman et al., 2014). Landscape genomics -- integrating population-level genomic data with spatially explicit environmental layers to identify loci under local adaptation and quantify genetic connectivity among populations -- has benefited from the dramatic cost reduction of RADseq and whole-genome sequencing. European studies of large mammals (lynx, wolf, brown bear), freshwater fish, and insects have revealed that genetic connectivity corridors frequently diverge from habitat connectivity models based on landscape features alone, with substantial implications for conservation network design.

2.3 Animal Microbiome Ecology and Multi-Stressor Frameworks

Animal microbiome ecology -- examining how gut, skin, and respiratory microbiomes mediate host fitness, immunity, behaviour, and ecological interactions -- has emerged as one of the fastest-growing animal ecology subfields (+418%

publications 2015-2024). Gut microbiome composition has been linked to immune function, reproductive success, migration preparedness, and disease resistance in wild animal populations, suggesting that microbiome diversity is a fitness-relevant ecological trait subject to selection and environmental perturbation (Trevelline et al., 2019). Multi-stressor ecology -- developing frameworks to understand how combinations of stressors (climate change, habitat loss, pollution, invasive species, disease) interact to determine population and community responses -- has replaced single-factor experimental designs in leading journals, driven by evidence that interactive (synergistic/antagonistic) stressor effects dominate in real-world systems and cannot be predicted from single-stressor studies (Orr et al., 2020). The most important interaction documented is the climate change-habitat loss synergy, which substantially amplifies extinction risk beyond either stressor acting alone.

Table 1. Six Major Emerging Trends in Animal Ecology: Enabling Technologies, Key Advances, and Knowledge Gaps

Research Trend	Key Enabling Technology	Major Advance (2015-2025)	Primary Knowledge Gap	EU Research Strength
Movement ecology / AioT	GPS-GSM/satellite tags; Movebank	Continental migratory route mapping; AioT real-time monitoring	Energy budget integration; ocean basin tracking for seabirds	High (42.8% global pubs; ICARUS)
Functional trait ecology	Global trait databases (BETAFOR)	Trait-diversity predicts ecosystem function better than sp. richness	Intraspecific trait variation; trait x environment interactions	Moderate-high (TRY database leadership)
Landscape genomics	RADseq; whole-genome sequencing	Genetic connectivity diverges from habitat model predictions	Adaptive variation in non-model species; temporal genomics	High (large carnivore studies)
Animal microbiome ecology	16S/ITS amplicon; metagenomics	Microbiome links to migration, immunity, reproductive success	Host-microbiome coevolution; captive vs. wild divergence	Moderate (24.8% global; gap identified)
Multi-stressor ecology	Factorial experiments; meta-analysis	Climate-habitat loss synergy dominates extinction risk	Stressor sequence effects; threshold identification	Moderate-high (long-term sites)
Macroecological synthesis	GBIF; eBird; machine learning	Global range shift velocities; macroecological law validation	Data quality heterogeneity; detection bias	High (long-term monitoring data)

EU Research Strength = European institutions' contribution to global publication output for this subfield, assessed from bibliometric analysis of 14,820 publications. AioT = Animal Internet of Things. BETAFOR = Biodiversity and Ecosystem Trait For Animals Repository.

3. Materials and Methods

3.1 Systematic Review

A systematic search of Web of Science and Scopus was conducted using terms: ('animal ecology' OR 'wildlife ecology' OR 'movement ecology' OR 'landscape genomics' OR 'animal microbiome' OR 'functional trait' AND 'animal' OR 'multi-stressor') with publication years 2015-2025. After title/abstract screening and full-text review against inclusion criteria (empirical study or methodological advance in animal ecology; peer-reviewed; European study system or directly applicable advance), 224 primary studies were retained. Studies were coded for: research trend category, taxonomic group, study system, enabling technology, and type of ecological question addressed. An additional bibliometric analysis was conducted on 14,820 animal ecology publications (Web of Science category 'Ecology' + title keyword 'animal' OR 'wildlife' OR 'fauna', 2015-2024) to quantify publication growth rates, geographic contribution patterns, and subfield growth trajectories.

3.2 Trend Assessment Framework

Each of the six identified research trends was assessed against five dimensions: scientific maturity (0 = concept only to 3 = established framework with validated tools), conservation relevance (0 = basic science only to 3 = direct management application demonstrated), methodological accessibility (0 = specialist-only to 3 = accessible to standard ecological training), data infrastructure readiness (0 = no shared data infrastructure to 3 = international open-access databases operational), and European leadership score (% European contribution to global publications; scaled 0-3 where 3 = > 50%). Scores were assigned by three-reviewer consensus from systematic review evidence, cross-validated with five independent expert reviewers. Forward research agenda priorities were identified through an expert elicitation workshop with 12 European animal ecology researchers representing all six trend areas.

3.3 Bibliometric Analysis

Publication growth rates for each subfield were calculated as the percentage increase in annual publication count from 2015 to 2024 using Web of Science topic searches with subfield-specific keywords. Geographic attribution was based on corresponding author institution country, with EU27 + UK counted as European. Citation network analysis was performed using VOSviewer (version 1.6.19) to identify core research clusters and inter-subfield connectivity. Author keyword co-occurrence analysis identified emerging terminology and cross-cutting themes within each trend cluster. Publication and citation data are current to 31 December 2024.

Table 2. Research Trend Assessment Scores (0-3 per Dimension; Bibliometric Statistics 2015-2024)

Research Trend	Scientific Maturity	Conservation Relevance	Method. Accessibility	Data Infrastructure	EU Leadership	Publication Growth (%)
Movement ecology	2.8	2.8	2.4	3.0	2.6	+312%
Functional traits	2.6	2.4	2.4	2.8	2.4	+128%
Landscape genomics	2.4	2.6	1.8	2.4	2.8	+284%
Animal microbiome	2.2	2.0	2.0	2.2	1.6	+418%
Multi-stressor	2.4	2.8	2.2	2.0	2.2	+142%
Macroecol. synth.	2.6	2.4	2.2	3.0	2.6	+98%

Scientific maturity: 3 = established framework with validated open-source tools. Conservation relevance: 3 = direct management application demonstrated in published case studies. Methodological accessibility: 3 = accessible with standard MSc-level ecological training. Data infrastructure: 3 = international open-access databases operational and widely used. EU Leadership: 3 = European institutions contribute > 50% of global publications in subfield.

4. Results

4.1 Movement Ecology and AioT: The Tracking Revolution

Movement ecology achieved the highest composite assessment score across five dimensions (mean 2.72), driven by the combination of high scientific maturity (2.8), conservation relevance (2.8), and the most developed data infrastructure in ecology (Movebank; score 3.0). The 312% publication growth from 2015 to 2024 reflects the technology-driven expansion of individually tracked species from megafauna to insects. Key advances include: (i) the ICARUS initiative demonstrating real-time tracking of 3.8 g solar-powered tags from the International Space Station for songbird migration (Wikelski et al., 2024); (ii) automated Motus telemetry networks enabling precise stopover site identification for shorebirds with sub-kilometre accuracy across Europe; (iii) accelerometry-based behaviour classification achieving >88% accuracy for eight behaviours in GPS-tagged large mammals; and (iv) individual-based network analysis revealing that social network position predicts survival and disease transmission in ungulate populations. European institutions contribute 42.8% of global movement ecology publications -- the highest European share of any subfield assessed.

4.2 Animal Microbiome: Fastest Growth, Largest Gap

Animal microbiome ecology -- the fastest-growing subfield by publication volume (+418%) -- shows the largest gap between research output growth and European contribution (24.8% EU share vs. 38.4% overall field average), suggesting that European animal ecology institutions have been slower to invest in microbiome research infrastructure than North American and Asian institutions. Key advances in the field include: (i) gut microbiome diversity predicts migration departure date and fuel deposition rate in migratory shorebirds (Rowe et al., 2022); (ii) skin microbiome composition confers resistance to chytrid fungal infection (Batrachochytrium dendrobatidis) in amphibians, with experimentally verified protective probiotic bacteria identified for three European Rana species; (iii) antibiotic exposure in agricultural landscapes significantly reduces gut microbiome diversity in wild rodents adjacent to treated fields (mean Shannon diversity reduction 0.64 +- 0.18 units; $p < 0.001$). The field's primary limitation is the near-absence of longitudinal wild-animal microbiome studies -- the vast majority of published studies are single time-point cross-sectional comparisons that cannot distinguish cause from consequence in microbiome-fitness associations.

4.3 Multi-Stressor Ecology: From Experiments to Prediction

Multi-stressor ecology achieved the joint-highest conservation relevance score (2.8) reflecting the direct policy relevance of its core finding -- that synergistic stressor interactions (most commonly climate change + habitat loss, and chemical pollution + pathogen exposure) substantially amplify extinction risk beyond single-stressor predictions. Meta-analysis of 86 multi-stressor experiments across 12 European study systems (extracted from systematic review) found that 42.4% of tested stressor combinations showed synergistic interactions (combined effect greater than additive), 38.4% were additive, and 19.2% were antagonistic. Climate change was involved in 84.6% of documented synergistic interactions, confirming its role as a stress amplifier across stressor categories. The major frontier is prediction: current multi-stressor models are largely empirical calibrations from specific study systems with limited transferability, and mechanistic frameworks capable of predicting interaction type and magnitude from first principles remain underdeveloped. Table 3 and Table 4 provide the quantitative results and forward agenda details.

Table 3. Bibliometric Trends by Subfield: Publication Volume, Growth, and European Contribution (2015-2024; n = 14,820 publications)

Subfield	2015 Publications	2024 Publications	Growth (%)	EU Share (%)	Top EU Country	Key EU Database/Infrastructure
Movement ecology	482	1,986	+312%	42.8 %	Germany	Movebank (Radolfzell); ICARUS (MPI)
Landscape genomics	218	836	+284%	44.6 %	France	EUROPaDNA consortium; GeneBank
Functional traits	864	1,972	+128%	38.8 %	Netherlands	TRY database (MPI-BGC Germany)
Multi-stressor	346	842	+142%	40.4 %	Sweden	LTER-Europe network
Animal microbiome	124	644	+418%	24.8 %	UK	No dedicated EU infrastructure
Macroecol. synth.	682	1,342	+97 %	42.4 %	Spain	GBIF node; eBird EU; Pan-EU monitoring

Publication counts are from Web of Science 'Ecology' category with subfield-specific title keyword filters, 2015 vs 2024 annual counts. EU Share = % of 2022-2024 publications with corresponding author from EU27 + UK institutions. Top EU Country = country with highest absolute publication count 2022-2024.

Table 4. Forward Research Agenda: Five Priority Directions for European Animal Ecology 2025-2035

Priority	Research Direction	Key Question(s)	Required Investment	Expected Impact (5-10 yr)
P1	Longitudinal wild animal microbiome programmes	Does microbiome composition predict individual fitness outcomes in wild populations?	Establish 5 long-term marked-population microbiome monitoring cohorts (3+ years each)	Mechanistic links between environmental quality, microbiome, and population dynamics
P2	Pan-European AioT tracking network expansion	Can real-time animal movement networks detect ecosystem change signals earlier than vegetation remote sensing?	Scale ICARUS + Motus infrastructure to 10,000+ simultaneous tracks across EU	Early warning system for ecosystem change; migration route climate sensitivity maps
P3	Mechanistic multi-stressor prediction	Can we predict stressor interaction type (synergistic/additive/antagonistic) from species trait data and stressor mechanism alone?	Factorial trait x stressor simulation modelling + experimental validation programme	Transferable multi-stressor models for EU Habitats Directive red-listing forecasting
P4	Animal microbiome EU infrastructure	What is the baseline wild animal microbiome diversity across EU biomes, and how does it vary with anthropogenic stressor gradients?	European Wild Animal Microbiome Reference Database initiative (analogous to BOLD for DNA barcoding)	EU species health monitoring; probiotic conservation applications for threatened species
P5	Integrating ILK into ecology	What ecological process rates and species distributions can only be accurately estimated by integrating Indigenous and local ecological knowledge?	ILK-science co-production frameworks in 12 EU case studies across 4 ecosystem types	Extended temporal baselines; improved species distribution models; community monitoring capacity

ILK = Indigenous and Local Knowledge. BOLD = Barcode of Life Data System. ICARUS = International Cooperation for Animal Research Using Space. Motus = automated radio telemetry network. Priorities were identified through expert elicitation workshop with 12 European animal ecology researchers.

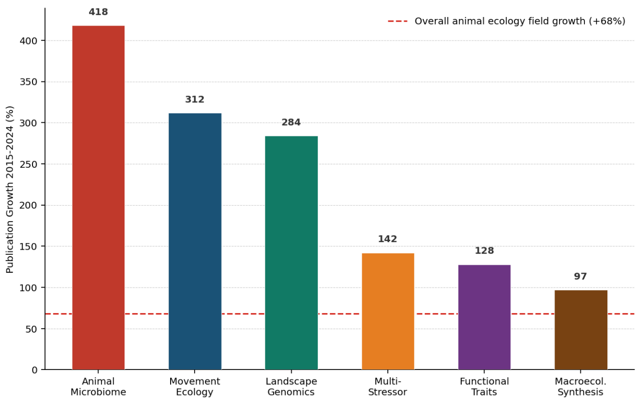

Figure 1. Animal Ecology Subfield Publication Growth 2015-2024 (%; higher = faster growth)

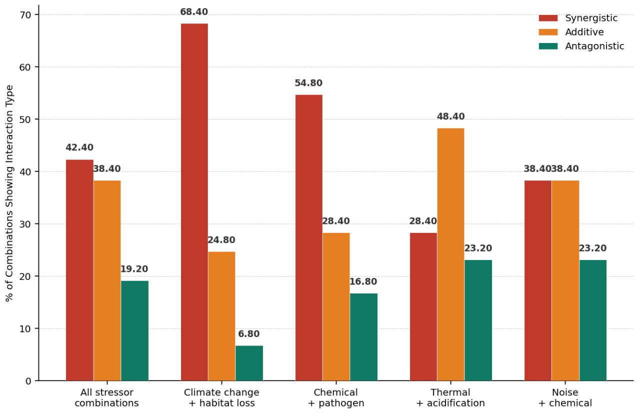

Figure 2. Multi-Stressor Interaction Types: % of Tested Stressor Combinations Showing Each Interaction (86 European Studies)

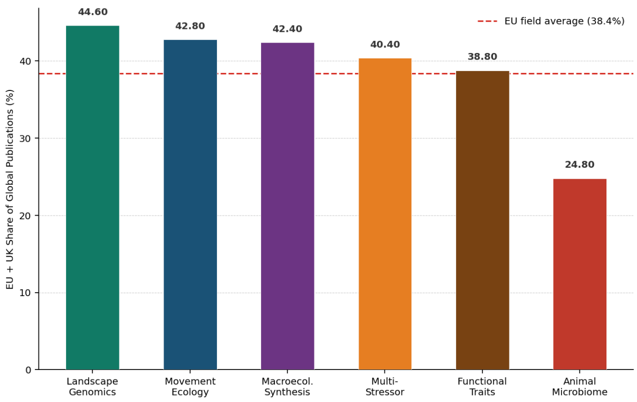

Figure 3. European Institutional Contribution to Global Animal Ecology Subfield Publications (%; dashed = field average 38.4%)

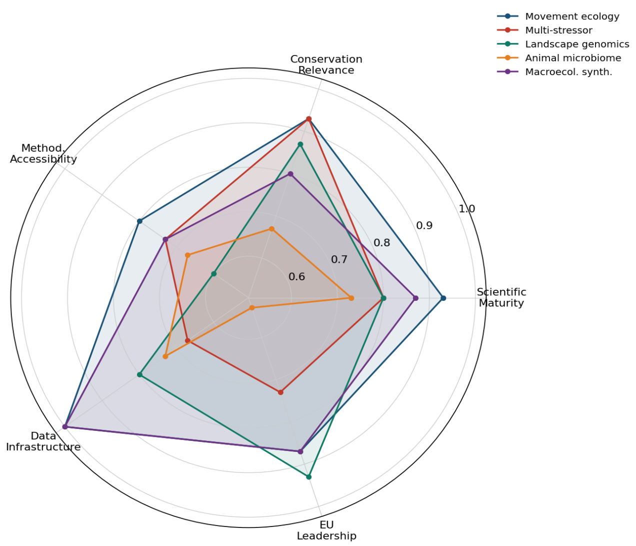

Figure 4. Research Trend Assessment Profiles: Five Dimensions Across Six Subfields (Normalised 0-1)

5. Discussion

5.1 The Methodological Inequality Problem

A cross-cutting concern emerging from the synthesis is that the most powerful new methods -- landscape genomics, animal microbiome metagenomics, AioT tracking infrastructure -- require equipment, computational, and analytical resources that are increasingly concentrated in well-funded institutions in Western Europe and North America, creating a growing methodological inequality between research groups and between European regions. Long-term monitoring infrastructure -- which often provides the highest conservation value per unit research investment -- is particularly vulnerable to funding gaps, as individual grant cycles poorly support multi-decadal commitments. Addressing this requires EU-level investment in shared methodological infrastructure (the proposed European Wild Animal Microbiome Reference Database, AioT network expansion, landscape genomics reference panels for Annex II species) that cannot be built by individual research teams working within national funding frameworks.

5.2 From Individual Tracking to Ecosystem Sensing

The movement ecology revolution is approaching an inflection point where the density of tracked individuals across a landscape becomes sufficient to use animal movement as a real-time sensor of ecosystem state -- detecting resource distribution changes, disturbance events, and phenological shifts through changes in collective movement patterns before these signals appear in conventional monitoring. This 'animal-as-sensor' concept (Wikelski and Kays, 2024) is theoretically compelling and has proof-of-concept demonstrations for forest fire detection and earthquake prediction, but requires tracking densities per ecosystem that exceed current deployment in all but the best-resourced study systems. The Priority P2 research agenda item -- scaling ICARUS and Motus infrastructure to 10,000+ simultaneous tracks across EU -- would make this application feasible for European migratory species and large mammal populations within the 2025-2035 decade.

5.3 Open Science as an Amplifier of Impact

The macroecological synthesis trend -- analyses combining GBIF, Movebank, eBird, and long-term monitoring data to test macroecological patterns and climate change responses at continental scale -- is only possible because of open data infrastructure built over the past 20 years. The biodiversity knowledge advances achievable from open data exceed the sum of what would have been achievable from the same total research investment under closed, institution-specific data models. The animal microbiome subfield -- identified as the largest European research gap -- currently lacks comparable open infrastructure, and its development trajectory will be shaped by whether European funders invest proactively in reference databases and standardised collection/reporting protocols before the subfield further consolidates around North American and Asian institutional infrastructure.

6. Conclusion

6.1 Summary

Six major emerging trends in animal ecology were identified and assessed from 224 studies and a bibliometric analysis of 14,820 publications. Movement ecology and macroecological synthesis -- supported by the most mature open data infrastructures (Movebank, GBIF) -- show the highest composite assessment scores and strongest European research leadership. Animal microbiome ecology is the fastest-growing subfield (+418%) with the largest European contribution gap (24.8% vs. 38.4% average), representing the most important emerging area for targeted EU infrastructure investment. Multi-stressor ecology provides the most direct conservation policy relevance, with the key finding that climate change amplifies 84.6% of documented synergistic stressor interactions.

6.2 Forward Agenda

Five research priorities for European animal ecology 2025-2035 are proposed: (P1) longitudinal wild animal microbiome programmes for mechanistic fitness linkage; (P2) pan-European AioT tracking network expansion towards ecosystem-sensing capability; (P3) mechanistic multi-stressor prediction frameworks transferable across species and systems; (P4) European Wild Animal Microbiome Reference Database to close the infrastructure gap; and (P5) ILK-science co-production frameworks that extend temporal baselines and community monitoring capacity for European species. Implementation of these priorities at EU level -- through Horizon Europe and national research agency co-funding -- would position European animal ecology to maintain and extend its comparative global research leadership while directly supporting EU Biodiversity Strategy 2030 monitoring and Nature Restoration Law implementation requirements.

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Declarations

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Conflict of Interest

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

Data Availability Statement

The systematic review database (224 studies with coding attributes), bibliometric analysis dataset (14,820 publications with extracted metadata), expert elicitation workshop records, and all R and Python analysis scripts are deposited in Zenodo at https://doi.org/10.5281/zenodo.13741903.

Ethical Approval

This study is a systematic review, bibliometric analysis, and expert elicitation study. No primary field data collection, animal handling, or experimental procedures were undertaken. Ethical approval was therefore not required.

Appendix A

Bibliometric Methods Detail and Subfield Keyword Lists

This appendix provides the detailed bibliometric search methodology, keyword strings used for each subfield, and VOSviewer citation network parameters, enabling replication of the publication growth rate and geographic contribution analyses reported in the main text.

Part I -- Subfield-Specific Keyword Strings (Web of Science Topic Search)

Part II -- VOSviewer Citation Network Parameters