frontiers | Frontiers in Ecology and Evolution

TYPE Editorial
PUBLISHED 07 August 2025
DOI 10.3389/fevo.2025.1655346

OPEN ACCESS

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RECEIVED 27 June 2025
ACCEPTED 27 July 2025
PUBLISHED 07 August 2025

CITATION
Ahmed DA (2025) Editorial: Advances in modelling and analysis of animal movement. *Front. Ecol. Evol.* 13:1655346.
doi: 10.3389/fevo.2025.1655346

Editorial: Advances in modelling and analysis of animal movement

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KEYWORDS

encounter dynamics, hierarchical movement frameworks, anthropogenic impacts on wildlife, biologging and tracking data, multi-scale behavioural ecology, movement-informed conservation, movement ecology

Editorial on the Research Topic
Advances in modelling and analysis of animal movement

Introduction

Understanding why, how, where, and when animals move is fundamental to ecology and evolution (Nathan et al., 2008). Animal movement occurs across a range of spatial and temporal scales, from local foraging and home-range use to seasonal migrations spanning continents. Analyses of movement patterns provide insights at all these scales, with direct applications in conservation, invasive species control, and ecological monitoring. In recent years, technological advances such as high-resolution GPS tracking and biologging have produced an explosion of movement data, allowing more refined recordings of animal movement paths (Williams et al., 2020). However, making sense of this deluge remains challenging, as many movement mechanisms and their ecological consequences such as navigation, foraging strategies, dispersal, and space use are still not fully understood. Integrating rich empirical observations with robust theoretical frameworks is therefore essential to advance movement ecology.

This Research Topic offers fresh insights and methodological developments that enhance our understanding of animal movement across spatio-temporal scales and taxa. The contributions span theoretical and empirical methods, individual and population-level analyses, and terrestrial, aquatic, and aerial systems. Here, we synthesise these studies' findings, highlight emerging themes and discuss knowledge gaps and future directions for the field.

Novel frameworks and methodological advances

Quantifying encounters through reaction–diffusion theory

Das et al. revisit a core question: how should we quantify encounters between moving animals? They highlight that different modelling assumptions can lead to vastly different encounter-rate predictions. Using reaction-diffusion theory from statistical physics, they derive analytical expressions for first-encounter probabilities between animals moving within home ranges. They show that treating encounters as first-passage events yields well-behaved (normalised) probabilities, whereas an approach based on joint occupancy (distance-threshold overlaps) produces non-normalised measures. By mathematically linking these approaches, the researchers explain why the classic “ideal gas” model of encounters (which assumes straight-line random motion and a simple law-of-mass-action) often fails for more realistic diffusive movement. This work provides a rigorous approach for quantifying encounter and interaction rates, relevant to processes like predation, infectious disease transmission, and social contacts among animals.

A hierarchical framework for forecasting movement under global change

At a broader scale, Getz offers a hierarchical perspective on movement patterns over an animal’s lifetime. In this *perspective* piece, Getz proposes a movement track segmentation framework that partitions an individual’s trajectory into a nested hierarchy of behavioural modes and phases. Anchored by repeatable diel activity routines (e.g. day–night cycles), the framework defines fundamental movement elements and canonical activity modes (such as localised foraging bouts, commuting trips, and resting periods) that can be identified from tracking data. By linking these fine-scale segments to larger-scale phases (e.g. seasonal migrations or lifetime dispersal events), the approach aims to improve forecasts of how animals will adapt their space use under environmental change. A key challenge in global change biology is predicting how shifts in climate or landscape will alter animal ranges and movement patterns (Gomez et al., 2025). This hierarchical approach suggests that understanding scaling-up rules, i.e. how changes in short-term movement behaviour aggregate into longer-term range shifts, could enable more mechanistic predictions of species’ responses to changing environments. This framework underscores the importance of multi-scale analysis, connecting individual behavioural decisions to population-level outcomes.

Movement and ecological interactions

Temporal niche partitioning and coexistence

In a different ecological context, He et al. investigate how a diminutive ungulate coexists alongside much larger herbivores. Williamson’s mouse deer (*Tragulus williamsoni*), one of the world’s smallest deer (≈2 kg), shares habitat with far larger ungulates (muntjac, wild boar, serow, sambar, all 20–200 kg) in Southeast Asian forests. Using camera-trap surveys and spatio-temporal occupancy models, they tested whether the tiny mouse deer avoids its bigger neighbours in space or time. Strikingly, they found no evidence of spatial avoidance, that is, the mouse deer’s occupancy was not negatively associated with the presence of larger ungulates at shared sites. Instead, the mouse deer showed clear temporal avoidance: it had distinct daily activity patterns that minimised overlap with each larger species. In essence, this small deer shifts its foraging to times when the big ungulates are less active, reducing direct encounters and potential competition. This finding supports the idea that extreme body-size differences can facilitate niche partitioning in time rather than space. Temporal niche separation allows the smallest ungulate to exploit the same habitat while avoiding interference or aggression from larger ones. More broadly, the study highlights how integrating movement and activity data with community ecology can reveal behavioural mechanisms of coexistence. As human disturbances (like hunting or livestock presence) alter wildlife activity patterns, understanding these temporal dynamics becomes important for managing multi-species communities.

Collective behaviour under predation

In the context of predator–prey interactions and collective behaviour, Papadopoulou et al. investigate how bird flocks respond to predation threats through co-ordinated turning. Using GPS-tracked pigeons under simulated attacks by a robotic predator, they analyse how individuals within a flock rearrange their relative positions during collective escape manoeuvres. The researchers combine empirical data with agent-based modelling to assess the *diffusion* of individuals within the flock, i.e. how quickly birds change neighbours during turns. They find that this diffusion is shaped by behavioural rules such as alignment and cohesion, and that pigeons exhibit lower diffusion than starlings, suggesting species-specific strategies for predator evasion. Their results show that the degree of internal reorganisation during a collective turn depends on both flock structure and turning style (e.g. equal-radius arcs versus parallel paths). This study offers a novel metric for quantifying coordinated movement under threat, and more broadly, a framework for linking individual decision-making to group-level outcomes in collective animal behaviour.

Movement in changing environments and conservation applications

Energetics and wind-driven migration in globe-skimmer dragonflies

Ranjan et al. combine movement modelling with climate data to unravel a long-distance insect migration. *Pantala flavescens*, the globe-skimmer dragonfly, undertakes a multi-generational, transoceanic migration circuit across the Indian Ocean – one of the longest insect migrations known. Its exact routes and mechanisms, however, have been hard to pin down. The study addresses this with an energetics-informed network model for pathfinding. They modified Dijkstra’s algorithm to include the dragonfly’s flight-time energy constraints and incorporated seasonal wind patterns (with behaviour to compensate for wind drift). Running this model on reanalysis wind data from 2002–2007 yielded a plausible migration network linking India and East Africa.

The prevailing monsoon winds (notably the Somali Jet stream) likely carry dragonflies from Africa toward India in one season, while the return leg requires stopover 'stepping stones' at island chains such as the Maldives and Seychelles for refuelling. The predicted routes and timing aligned with field observations, supporting a branched migration circuit hypothesis. This study shows how combining movement ecology with atmospheric science can reveal the drivers of insect migrations. It also raises conservation concerns: if these dragonflies rely on ephemeral habitats (like seasonal ponds or transient islands) as stopovers, then climate change or habitat loss could disrupt their migration network. Understanding and protecting such migratory connectivity is key to preserving the ecological phenomenon that transports nutrients, propagules, and genetic exchange across oceanic distances.

Mapping cumulative threats to migratory marine megafauna

On the marine front, Ferreira et al. present a comprehensive synthesis of satellite tracking data to assess how migratory marine megafauna overlap spatially with anthropogenic threats. They compiled satellite-telemetry tracks from 484 individuals across six marine megafauna species (including sea turtles, humpback and blue whales, whale sharks, and tiger sharks) in the waters of north-western Australia. By overlaying these animal movement data with maps of anthropogenic threats (such as coastal development, shipping traffic, fishing effort, oil and gas infrastructure, underwater noise, and light pollution), they quantified the cumulative exposure of each species to human impacts. The analysis revealed distinct hotspots where critical habitats overlap with multiple threats: for example, near the Ningaloo and Pilbara regions, important turtle nesting and whale migration areas coincide with intensive industrial and maritime activity. Notably, while high-risk zones made up < 14% of the animals' total tracked area, no species was found entirely outside the influence of human stressors, even nominally protected areas saw some level of exposure. This multi-species assessment demonstrates the utility of integrating biologging data with threat mapping for conservation planning. By identifying where and when animals face the greatest overlap with human pressures, it provides science-based guidance for mitigation (e.g. adjusting shipping lanes or expanding protected areas) to better safeguard these migratory species. More generally, the study exemplifies 'biologging meets threat mapping': combining animal movement data with human footprint data to inform proactive conservation and policy decisions.

Synthesis and future directions

Recent advances in movement ecology reflect a growing integration of empirical data with theoretical models, enabling more comprehensive and predictive understandings of animal movement. Methodological innovation, increasingly informed by other disciplines, is expanding the range and resolution at which researchers can analyse movement patterns. This has opened new avenues for addressing questions about navigation, space use, social interactions, and responses to environmental change. Technological developments such as high-resolution biologging, drone-based observation, and remote sensing have enriched datasets across taxa and ecosystems. These tools allow for the continuous tracking of individuals in natural settings, generating detailed data on movement trajectories, behaviours, and environmental conditions. Such advances have made it possible to examine not only where animals move, but also why and how, in relation to their internal states, ecological roles, and external pressures. The growing synergy between data and theory signals a shift in the field, from documenting patterns to explaining mechanisms and forecasting outcomes.

Key challenges now include scaling up from individual-level analyses to community and ecosystem-level processes. Understanding how interactions among individuals and species shape movement decisions is crucial for uncovering broader dynamics in food webs and species assemblages. This may involve tracking multiple species simultaneously, detecting feedback loops between movement and resource availability, or modelling how behavioural adaptations influence broader ecological patterns. Equally pressing is the need to link animal movement to demographic parameters, such as survival, reproduction, and dispersal success, to predict population-level consequences under environmental change.

Another frontier is integrating movement ecology more explicitly with ecosystem function. Animal movements drive essential processes such as pollination, seed dispersal, nutrient redistribution, and disease transmission. Quantifying these links requires connecting movement data with biogeochemical flows, interaction networks, and habitat connectivity. Doing so can help clarify the role of mobile species as ecosystem engineers or as vectors of change across fragmented landscapes.

Continued progress will rely on further refinement of tracking technologies — including smaller, longer-lasting, and more versatile tags — as well as on improved remote sensing of habitat conditions and climate variables. Advances in machine learning and data assimilation will be increasingly important for analysing large-scale, high-dimensional movement datasets. Combining these tools with mechanistic models can improve our ability to anticipate how animals will respond to shifting environments, from changing migration routes to altered species interactions.

As global change accelerates, with expanding human infrastructure, climate shifts, and habitat loss, understanding and managing wildlife movement and connectivity is more critical than ever. Cross-scale, interdisciplinary approaches will be essential not only for building predictive models but also for applying them in conservation planning, ecological forecasting, and the design of resilient landscapes. A key direction of movement ecology now lies in bridging behaviour, population dynamics, and ecosystem function, offering deeper insights into how life on the move sustains biodiversity and ecosystem health.

Author contributions

DA: Conceptualization, Writing – original draft, Writing – review & editing.

Conflict of interest

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