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Migration AI: A Predictive Framework for Modeling Seasonal Wildlife Movement and Migration Behavior

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Key Words

Seasonal migration, Movement ecology, Wildlife migration, Behavioral ecology, Phenology, Conservation management, Migration prediction.

Abstract

Migration during different seasons is one of the most noticeable and significant behaviors exhibited by animal species in terms of their ability to survive, reproduce, and affect the structure of the ecosystem. Prediction of the timing, destination, and cause of migration among animals between their seasonal ranges has become one of the main goals for the field of wildlife biology and conservation. In this paper, a framework called Migration AI is introduced that relies on the concepts of behavioral and physiological ecology and incorporates information about movements based on telemetry, phenological data, and individual condition into one comprehensive model of decision-making related to seasonal migration behavior. Instead of considering migration as an innate and constant characteristic of the particular species, this framework views migration as a variable behavior influenced by both physiological state and environmental conditions. The theoretical model incorporates well-known concepts in movement ecology such as the full annual cycle approach and the use of state-dependent behavioral models to explore connections between resource availability, heat resistance, and body condition in relation to migratory tendencies. Biological constraints, such as individual differences and phenotypic flexibility, which limit the predictability of the model are considered, along with applications in population management, conservation corridors, and adaptive wildlife management. Migration AI is conceived as a biologically informed model for arranging animal science knowledge into a forward-looking narrative of migration.

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Introduction

Migration, broadly defined as the seasonal, typically round-trip movement of animals between geographically separate regions, for either breeding, foraging, or hibernation, is one of the key components in the life cycle of myriad vertebrate and invertebrate species (Flockhart et al., 2015). Mammals migrate to follow the emergence of forage according to both latitude and altitude, birds migrate to alternate between breeding and non-breeding regions to take advantage of the temporally available food, and fish as well as marine mammals migrate seasonally to mate and feed. This activity is not coincidental but essential to survival and breeding success and the interruption of migration paths has been known to lead to a reduction in numbers (Flockhart et al., 2015).

Migration prediction has thus become a key consideration for wildlife management, especially considering the ways in which anthropogenic activities have affected migration cues and the continuity of habitats in favor of which the migratory decision is made. There has been increasing amount of research done in the field of animal science, from focusing on migratory routes to understanding the factors behind the timing, probability and reasons for the migration of individuals as well as the proportion of the population involved in migration (Hostetler et al., 2015; Buchan et al., 2020). This review presents a synthesis of this evidence as part of an organizing structure, known as Migration AI.

Key Contributions

- Suggests a predictive model for studying seasonal animal movements and migration.
- Uses physiological state, environmental triggers, and annual cycle ecology to forecast migration patterns.
- Contributes towards wildlife management, conservation of corridors, and migration monitoring.

The remaining structure of this paper is as follows. In Section 2 the physiological and behavioral foundation for seasonal migration is presented. Section 3 is about environmental and ecological factors influencing seasonal movements, Section 4 provides information on the Migration AI theoretical framework, Section 5 focuses on the applications of wildlife management and conservation, Section 6 highlights the limitations of this research, and Section 7 concludes the paper.

Physiological and Behavioral Basis of Seasonal Migration

Ultimately, migratory behavior is reflected in the physiological state and behavioral state of the individual animal. Physiological state, body condition, fat levels, and hormones affect the decision to migrate by having animals in poor condition delay migration, reduce their migratory range, or choose not to migrate at all, remaining resident (Buchan et al., 2020). This creates partial migration, in which two different types of migration exist within one population and may vary in their proportions over time in response to the environment (Payo-Payo et al., 2022; Buchan et al., 2020). Since both types of migratory behavior can continue to evolve in the long run if both give equally viable results, the proportion between them becomes a sensitive signal of environmental changes that take place in the population (Buchan et al., 2020).

Other factors influencing behavior include age, gender, and previous migratory experience. For example, younger animals or those with less migratory experience may exhibit later or more varied departure times, whereas the reproductive state may limit when and how movement occurs especially when young have to follow their parents during migration. This makes it clear that migratory behavior is not a monolithic trait for any species, but rather something that needs to be modeled in terms of individual behaviors that are contingent upon physiological state.

Environmental and Ecological Drivers of Seasonal Movement

Migration is highly associated with phenology factors such as seasonal greening of vegetation, snow pack depth and melting time, photoperiod, and temperature limits that signal the arrival of good or bad conditions within the certain range (Flockhart et al., 2015; Morrison et al., 2024). A lot of herbivores practice "green wave surfing" by following the movement of good-quality grazing on the landscape during the growing period, and animals from the temperate and boreal zone are guided by the presence or absence of snow cover (Morrison et al., 2024).

Increased climate variability adds another layer of complication. Warmer fall temperatures and shorter winters with milder temperatures have been correlated with decreased migratory tendency in some ungulate species, since animals find it more energetically profitable to stay in the areas where they would typically leave before winter arrives (Morrison et al., 2024). These alterations may cause disconnection between migratory triggers and actual conditions of suitable habitats, leading to mismatch between time of departure and conditions at the destination area (Buchan et al., 2020). Factors such as predation pressure, competition, and habitat connectivity also influence route choice and stopover sites used; thus, to develop a predictive theory of animal migration, one needs to consider the habitat structure on a landscape level as well as individual and climatic factors (Somveille & Ellis-Soto, 2022).

The Migration AI Conceptual Framework

Migration AI is based on the interaction of three components taken directly from known concepts in the field of movement ecology; namely, the internal state component, the external cue component, and the full annual cycle linkage component.

The internal state component is related to how ready an individual is physiologically to migrate and is based on body condition index, reproductive status, and age class because it has been proven that the tendency to migrate is state-dependent and not trait-based (Buchan et al., 2020). The external cue component uses the information about phenology and climate, such as forage phenology, snow conditions, and temperature accumulations, and impacts the departure date and probability of migrating (Flockhart et al., 2015; Morrison et al., 2024). The full annual cycle linkage component is founded on the idea that the events in one season affect future survival and reproduction in following seasons (Hostetler et al., 2015; Payo-Payo et al., 2022).

The integration of the three components results in population-level expectations regarding the proportion of individuals that migrate in a year, the timing window during which they will migrate, and the vital rate costs associated with being either a migratory or resident individual in the given environment (Payo-Payo et al., 2022; Buchan et al., 2020). The framework structure follows the methods used to build models for partially migratory metapopulation, where migration probability and its survival costs are considered vital rates, which could be traced and forecast throughout the whole year (Payo-Payo et al., 2022). Being based on biological state variables, but not following any set rules, the framework aims to capture the variability among real migratory populations and is not meant to predict one particular migratory path for a species.

Applications for Wildlife Management and Conservation

Such a model is directly applicable for the purpose of wildlife management. The prediction of seasonal migration helps in planning protective actions during the period of peak vulnerability within the route of migration (Gomez et al., 2025). Knowledge about the factors that cause an individual to change its behavior from migration to resident status may act as an indicator for any degradation of the environment or stress from climatic conditions on a particular population, long before it can be determined by any direct census techniques (Morrison et al., 2024; Buchan et al., 2020).

At the landscape level, appreciating the role that forage phenology and habitat connectivity play in influencing migration paths is helpful to justify corridor protection and determine potential bottleneck locations where migrants may be susceptible to disturbances (Somveille & Ellis-Soto, 2022). For managers who deal with partially migrating populations, measuring the fitness differences between migrants and residents can provide biological justification for predicting changes in the demography of the population and designing monitoring efforts for the entire spectrum of behaviors exhibited by a particular population (Payo-Payo et al., 2022; Buchan et al., 2020).

Limitations and Future Directions

There are several biological facts that limit the predictability of migratory behaviors within the framework. Migrations are influenced by phenotypic plasticity, implying that the same environmental factors will result in a diverse response depending on an animal’s previous experience, physiological status, and social setting (Buchan et al., 2020). Predictions become even more difficult in light of non-linear and threshold responses to climatic factors due to small changes close to a threshold resulting in large changes in the timing or likelihood of migrations (Morrison et al., 2024). Moreover, there is an abundance of data concerning migratory patterns for only a few taxonomic groups including ungulates and migratory birds (Flockhart et al., 2015; Hostetler et al., 2015).

In the future, more accurate results would be provided by long-term data sets of migratory tactics for several populations as well as a more thorough consideration of reproductive and survival consequences throughout the entire year cycle (Hostetler et al., 2015; Payo-Payo et al., 2022).

Conclusion

Wildlife seasonal migrations are contingent upon physiology and environment and not innate behavioral characteristics within species; hence any frameworks that predict them have to capture their complexities in order to be effective. The framework known as Migration AI integrates information about individual physiology, phenology, climate, and full-annual-cycle carry-over effects into a format that can help predict when migration happens and also when there is an equal mix of migrating and resident strategies among species populations. Given that migratory birds have continued to be threatened by habitat fragmentation and changing climates, such biologically informed prediction methods become very important for effective wildlife management.

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