Movement Ecology

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Contents

1. Enquadramento

A unidade curricular "Movement Ecology"/"Ecologia do Movimento" é proposta para os cursos de Mestrado em Biologia Marinha (https://www.ualg.pt/curso/1433/plano), Aquacultura e Pescas (https://www.ualg.pt/curso/1430/plano), Sistemas Marinhos e Costeiros (https://www.ualg.pt/curso/1740/plano), e para o Mundus International Master of Science in Marine Biological Resources (IMBRSea; https://www.ualg.pt/curso/1836/plano), da Universidade do Algarve. Esta unidade curricular complementa a oferta formativa existente, particularmente numa área de importância crescente, relevante e interligada com várias outras áreas de investigação. Pode ser considerada como unidade curricular obrigatória ou opcional. Este curso proporcionará aos estudantes conhecimentos e experiência estreitamente ligados a outras unidades curriculares oferecidas nos mestrados da Universidade do Algarve, como Gestão e Conservação, Biologia de Populações Marinhas, Biogeografia e Evolução Marinha e Áreas Marinhas Protegidas.

Trata-se de uma unidade curricular de 6 ECTS, correspondente a um total de 156 horas, das quais 51 horas de contacto e 104 horas de trabalho autónomo por parte dos estudantes (Tabela 1. Regulamento n.º 131/2021 da Universidade do Algarve). Propõe-se que esta unidade curricular seja lecionada no 2.º semestre, uma vez que se beneficia de algumas competências e conhecimentos adquiridos ao longo do primeiro semestre. Durante o 1.º semestre, os estudantes frequentam a unidade curricular de Estatística Básica em R, que oferece formação em manipulação de dados, gestão de pacotes e análises estatísticas básicas em ambiente R. Esta preparação prévia garante que os estudantes estão mais aptos para as componentes práticas de análise de dados da UC proposta, que serão realizadas utilizando o R. Além disso, outras unidades curriculares oferecidas no 2.º semestre — como Gestão e Conservação e Áreas Marinhas Protegidas — estão relacionadas com os conteúdos abordados no curso de Ecologia do Movimento. A oferta desta unidade em simultâneo com essas disciplinas reforça a coerência temática, promove a integração interdisciplinar e permite aos estudantes aplicar os conceitos de ecologia do movimento num contexto mais amplo de conservação e gestão.

Tabela 1. Distribuição das horas de contacto e de trabalho autónomo por tipo de aula na unidade curricular de Ecologia do Movimento.

Tipo de aula	Horas de contacto	Trabalho autónomo	Total
Teórica (T)	10 x 2h = 20 h	30 h	50 h
Trabalho de campo (TC)	8 x 2h = 16 h	10 h	26 h
Teórico-prática (TP)	3 x 3h = 9 h	40 h	49 h
Seminários (S)	3 x 2h = 6 h	4 h	10 h
Exame	1 x 1h = 1 h	20 h	21 h
Total	52 h	104 h	156 h (6 ECTS)

Apesar de ser uma área de investigação relativamente recente, já existem diversos cursos de licenciatura e mestrado que incluem unidades curriculares sobre esta temática. Estes incluem, por exemplo, o Mestrado em Biologia de Organismos e Ecologia da Université Catholique de Louvain, o Mestrado em Ecologia e Evolução da Goethe Universität, e programas oferecidos pela University of Glasgow e pela University of Windsor. Adicionalmente, várias outras universidades e institutos oferecem cursos avançados ou workshops em ecologia do movimento, como a Hebrew University of Jerusalem, o Max Planck Institute of Animal Behaviour e a Universidade do Porto (BIOPOLIS – CIBIO).

A ecologia do movimento é uma área em rápido crescimento, situada na interseção entre a investigação ecológica, a conservação e a inovação tecnológica. Este curso irá oferecer aos estudantes uma base sólida dos princípios e aplicações da ecologia do movimento, fornecendo-lhes os conhecimentos necessários para compreender como os animais se movem, por que se movem, quais as ferramentas utilizadas para estudar o movimento de animais aquáticos e de que forma a ecologia do movimento pode ser aplicada na gestão e conservação.

Para além do seu valor académico, este curso prepara os estudantes para carreiras na investigação, conservação e gestão ambiental, ao desenvolver competências altamente valorizadas no mercado de trabalho. Os estudantes terão contacto com tecnologias de monitorização de última geração, métodos de análise de dados e casos de estudo reais. A expansão de iniciativas colaborativas como a Ocean Tracking Network (OTN - https://oceantrackingnetwork.org/), a European Tracking Network (ETN - https://europeantrackingnetwork.org/en), a Megamove (https://megamove.org/), entre outras, evidencia a importância da ecologia do movimento a uma escala global. Estas redes demonstram a crescente procura por especialistas em biotelemetria, integração de dados e interpretação ecológica do movimento animal. Ao envolverem-se com os conceitos e ferramentas abordados neste curso, os estudantes estarão bem preparados para contribuir para este campo em plena expansão.

O restante documento é apresentado em inglês, dado que esta unidade curricular será lecionada nessa língua.

2. Introduction

Movement ecology is a rapidly emerging new research field that explores the underlying mechanisms of organism movement, from animals to plant and microorganisms, across a range of environmental contexts and spatiotemporal scales, from individual behaviour to population-level processes. Research in this area combines a diverse range of disciplines including animal behaviour, ecology, physiology, statistics, and utilizes a wide range of techniques and technologies, including biotelemetry, remote sensing, modelling, and bioacoustics (Nathan et al. 2008; Holyoak et al. 2008). Animal movement is determined by a combination of individual characteristics and environmental factors, such as food availability, predation risk, and habitat quality. Movements can range from small-scale foraging excursions within a home-range to seasonal migrations over thousands of kilometres, with characteristic patterns at different spatial scales (Shaw 2020). Animal movement may affect reproductive success, genetic diversity, and disease transmission within populations, and can play a role in wider ecosystem functioning via nutrient cycling or dispersal of propagules. The rapid growth of movement ecology since the early 2000s has been driven by the increased functionality, availability, and reliability of modern biologging technology that allows detailed data to be collected from a wide range of species (Hussey et al. 2015). In turn, this has required the development of new mathematical, statistical, and computational methods for modelling and analysing the very large data sets that are obtained (Nathan et al. 2022). In its broadest sense, movement ecology encompasses a wide-ranging set of concepts, theories, and practical approaches that relate to animal movement.

Movement affects individual fitness, regulates population dynamics, and shapes ecosystem structure, playing a vital role in how species respond to both natural and anthropogenic changes. In conservation and management, understanding movement patterns informs habitat protection, fisheries regulation, and biodiversity conservation (Abecasis et al. 2014; Barton et al. 2015). Studying species movement ecology is therefore essential to uncover how animals interact with their environment and adapt to changing conditions - ultimately supporting more effective species management and conservation efforts (Cooke et al. 2004; Alós et al. 2022).

3. Course objectives

This course aims to provide students with a solid theoretical and practical background in the field of movement ecology, with a particular emphasis on aquatic organisms. By the end of the course, students will be able to:

- Understand the core concepts and principles of movement ecology
- Explain the ecological and evolutionary drivers underlying animal movement.
- Critically assess the main methods to study animal movement, including biotelemetry technologies and data analyses approaches.
- Apply appropriate analytical approaches to interpret movement data.
- Recognize the relevance and applicability of movement ecology for the management and conservation of species and ecosystems.

4. Competences to be developed

Upon completion of the course, students will have developed the following competences:

- Scientific knowledge in the domain of animal movement ecology, including the ability to formulate relevant ecological questions and hypotheses.
- Technical proficiency in the use of tracking technologies (particularly acoustic telemetry) and in managing and analysing movement data using R.
- Critical thinking to evaluate research designs, select suitable analytical methods, and interpret spatial ecological data in a conservation context.
- Communication skills, both oral and written, through the preparation of reports and participation in seminars, enabling effective dissemination of scientific findings.
- Collaboration and teamwork, enhanced through group-based fieldwork and data analysis projects.
- Problem-solving skills related to real-world conservation and management scenarios, particularly those involving aquatic species and dynamic environments.

5. Course structure

The course will consist of lectures, fieldwork, practical classes, seminars and distributed along the semester (Table 2). During the lectures students will be introduced to theoretical concepts of movement ecology, its drivers and consequences, the different methods to track aquatic animal movement, a brief introduction to data analyses, and the relevance of movement ecology data for management and conservation. During the fieldwork students will have the opportunity to set up an experimental acoustic telemetry array and create a simulated dataset that will then be explored during the practical lab classes. The practical lab classes will consist of the analyses of the data collected during the fieldwork and will include acoustic receiver detection range, and residency and space use metrics. The seminars, lectured by invited scientists, will provide the students specific case studies and contact with ongoing research.

Table 2. Chronogram with the weekly distribution of the classes over the semester.

Week	Lecture (T)	Fieldwork (TC)	Practical (TP)	Seminars (S)	Evaluation	Total number of hours
1	L1 (2h)					2
2	L2 (2h)					2
3	L3 (2h)					2
4	L4 (2h)			S1(2h)		4
5		TC 1 (8h)				8
6		TC 2 (8h)				8
7				S2 (2h)		2
8			TP 1 (3h)			3
9			TP 2 (3h)			3
10			TP 3 (3h)			3
11	L5 (2)					2
12				S3 (2h)		2
13					E1 (1h)	1

5.1. Theoretical classes

The theoretical component will be composed of 6 main modules distributed between 10 classes of 2 hours each. These modules will be focused on the following themes:

1. Foundations of Movement Ecology (2 hours)
2. Ecological and evolutionary drivers of movement (2 hours)
3. Spatiotemporal scales (1 hour)
4. Methods to study animal movement (2 hours)
5. Analysis and interpretation of movement data (1 hour)
6. Applications of Movement Ecology for Conservation and Management (2 hours)

For each module literature will be provided for students to follow the contents and expand their knowledge on specific areas introduced during the classes.

5.1.1 Foundations of Movement Ecology

Lecture 1: Foundations of Movement Ecology (2 hours class)

Movement ecology has emerged as a critical and interdisciplinary field dedicated to understanding species movement within ecological and evolutionary contexts (Nathan 2008). It provides a unifying paradigm that seeks to elucidate the causes, mechanisms, patterns, and consequences of all forms of movement. Recognizing that movement is fundamental to the survival and reproduction of all organisms, from the smallest microbes to the largest animals, movement ecology moves beyond simply describing movement paths to explore the intrinsic and extrinsic factors that drive these behaviours (Nathan 2008; Cooke et al. 2022). This holistic approach is essential for addressing a wide range of ecological and evolutionary questions, including those related to conservation, invasive species, disease spread, and responses to environmental change (Holyoak et al. 2008).

At the heart of movement ecology lies the movement ecology paradigm, which posits that four fundamental and interacting components underpin organismal movement (Nathan et al. 2008). These components are:

- Internal State: This encompasses the organism's intrinsic motivation and physiological condition that predisposes it to move. Factors such as hunger, thirst, reproductive status, energetic reserves, hormonal levels, personality traits, and life-history stage all contribute to an individual's propensity and readiness to move ("why" move?). For instance, a migratory fish (e.g. salmon) preparing for a long journey for reproduction will experience physiological changes, such as increased fat stores and hormonal shifts, that motivate and enable migration.
- Motion Capacity: This refers to the suite of biomechanical and morphological traits that enable an organism to execute or facilitate movement ("how" to move?). This includes physical attributes like limb structure, muscle strength, swimming ability, flight capabilities, and even the physical properties of propagules like seed terminal velocity in plants (Damschen et al. 2008). An organism's motion capacity determines its potential speed, agility, dispersal, and the types of environments it can navigate (Nathan et al. 2008).
- Navigation Capacity: This involves the sensory and cognitive abilities that allow an organism to orient itself, determine its location, and choose a direction or destination ("where" and "when" to move?). This can include the use of visual cues, olfaction, magnetic senses, acoustic signals, cognitive maps, and social information to guide movement in space and time. For example, salmon utilize geomagnetic imprinting for natal homing over long distances (Lohmann et al. 2008).
- External Factors: This broad category includes the array of abiotic and biotic environmental influences that affect an organism's movement. Abiotic factors can include temperature, wind and water currents, habitat structure, resource distribution, and physical barriers (e.g., Garel et al. 2024; Papadopoulo et al. 2023). Biotic factors involve interactions with other organisms, such as predation risk, competition for resources, the presence of conspecifics and its density (e.g., Simpson et al. 2021; Papadopoulo et al. 2023). These external factors can trigger, modify, or constrain movement decisions and pathways.

It is crucial to recognize that these four components are not independent but rather interact in complex and dynamic ways to shape movement paths and strategies. An organism's internal state might influence its responsiveness to external cues, while its motion and navigation capacities will determine how it can act upon its motivations within the constraints of the environment (Nathan et al. 2008). Furthermore, feedback loops exist where the resulting movement path can, in turn, influence the organism's internal state (e.g., energy expenditure affecting motivation) and its interaction with external factors (e.g., encountering a predator due to a particular movement choice). Density-dependent effects, where the number of conspecifics influences movement behaviour and resource availability, are also important feedback mechanisms (Abesamis and Russ 2005).

Movement itself can be viewed as a propagation process resulting from the interaction of an organism's internal state, capacities, and the external environment. The realized movement is a consequence of the motion process (how motion capacity is exerted given current conditions) and can be optionally affected by the navigation process (directed movement based on navigation capacity) (Nathan et al. 2008). Understanding movement as a dynamic process highlights the importance of considering the temporal aspects of movement, from instantaneous movements to lifetime tracks.

The study of organismal movement has a rich historical development, evolving from early descriptive natural history observations to the more recent quantitative and mechanistic approaches. Early work focused on phenomena like migration and dispersal, often within specific taxonomic groups (e.g. birds, diadromous fish). The emergence of movement ecology as a distinct field represents a paradigm shift towards a more unified and integrative framework. Key milestones include the development of theoretical frameworks, such as random walk models and optimal foraging theory, as well as advancements in tracking technologies, like biotelemetry. This historical trajectory underscores a growing recognition of the need to consider the underlying mechanisms and ecological significance of movement across all taxa and scales. By embracing this comprehensive framework, movement ecology aims to achieve a deeper understanding of the ecological and evolutionary roles of movement and to provide a robust scientific basis for addressing pressing environmental challenges (Nathan et al. 2008).

5.1.2. Ecological and Evolutionary Drivers of Movement

Lecture 2: Ecological and Evolutionary Drivers of Movement (2 hours class)

This module focuses on the ecological and evolutionary forces that fundamentally shape the movement strategies of organisms. Understanding these drivers is crucial for comprehending the diversity of movement patterns observed in nature and their implications for ecological and evolutionary processes.

Ecological Forces Shaping Movement:

- Foraging Ecology: Movement is intrinsically linked to resource acquisition. Optimal foraging theory posits that animals will move in ways that maximize energy intake while minimizing the costs associated with searching and handling resources (MacArthur and Pianka 1966). This can involve various search strategies and decisions about when and where to forage. For example, Atlantic bluefin tuna undertake long-distance migrations to exploit predictable, high-density prey patches in the North Atlantic, likely optimizing energy gain to support growth and reproduction (Golet et al. 2015; Aarestrup et al. 2022). Environmental factors like resource distribution and predictability strongly influence foraging movements.
- Habitat Selection and Distribution: Organisms move to locate and remain in suitable habitats that meet their physiological requirements and offer resources for survival and reproduction (Nathan et al. 2008). The ideal free distribution theory suggests that individuals will distribute themselves among habitats in proportion to resource availability (DiNuzzo and Griffen 2020). Habitat connectivity plays a critical role in allowing movement between suitable patches, influencing space use and population dynamics. Moreover, because aquatic environments are dynamic and change across space and time, animals must adapt their movement behaviour in response to shifting environmental conditions and resource distribution (Humphries et al. 2010).
- Predator-Prey Interactions: The risk of predation is a significant driver of movement behaviour. Animals may move to avoid predators in space or time, altering their foraging patterns, habitat use, and activity levels. Conversely, predators move to locate and capture prey. Group behaviours like schooling in fish can be an anti-predator defence that influences movement (Tien et al. 2004).

- Social Interactions: Inter and intraspecific interactions profoundly affect movement. This includes competition for resources like space, food, and mates (Brena et al. 2018). Social dominance hierarchies can influence the movement scope of individuals (Rodriguez-Santiago et al. 2020). Coordinated group movements can arise from social cues and serve functions like enhanced foraging and/or mating success (Tien et al. 2004; Bshary et al. 2006; Afonso et al. 2008a; Afonso et al. 2008b).
- Environmental Factors: Abiotic factors such as temperature, salinity, oxygen availability, water currents, light intensity, and habitat structure directly influence physiological processes and thus drive movement decisions (e.g., Garel et al. 2024; Vedor et al. 2021; Rankin et al. 2013). Aquatic systems are characterized by high spatial and temporal variability, requiring animals to move in response to dynamic environmental layers.

Evolutionary Perspectives on Movement:

- Movement and Fitness: Ultimately, movement strategies are shaped by their impact on an individual's fitness, defined by its survival, growth, and reproductive success (Nathan et al. 2008). Movement patterns that enhance access to resources, reduce predation risk, and facilitate reproduction are favoured by natural selection. The movement ecology paradigm links lifetime movement to fitness, considering it part of a species' life history (Nathan et al. 2008).
- Dispersal: the movement of individuals from their natal site or breeding site, has significant ecological and evolutionary consequences. It can influence gene flow, colonization of new habitats, avoidance of inbreeding, and population persistence in fragmented landscapes (e.g., Abecasis et al. 2024). Natal dispersal, though difficult to study, is an important lifetime trait. The movement ecology framework can be applied to understand dispersal even in passively transported organisms like propagules (e.g., Abecasis et al. 2023; Assis et al. 2021).
- Migration: often defined as recurrent movements between distinct areas, is often an evolutionary adaptation to seasonal resource fluctuations and breeding opportunities. It involves energetic costs but allows access to spatially and temporally variable resources or suitable spawning grounds. Examples include seasonal movements to overwintering or spawning grounds (e.g., Kraft et al. 2023b; Gandra et al. 2024). The

timing and success of migration can even be predicted by internal states like cortisol levels (Birnie-Gauvin et al. 2019).

- Adaptation to Change: Movement is a key mechanism by which species can respond and potentially adapt to environmental change over ecological and evolutionary timescales. Shifts in distribution and movement patterns can be among the first adaptive responses to ecosystem changes (Matich et al. 2024). Understanding how movement strategies mediate responses to changing conditions is crucial for management and conservation in the face of climate change.
- Life History and Movement Strategies: Movement patterns are often linked to an organism's life history stage. For example, ontogenetic habitat shifts, where individuals move to different habitats as they grow and mature, are common in fish (e.g., Abecasis et al. 2009; Macpherson 1998; Giacalone et al. 2022). Different life stages may have different movement capacities and motivations. Adult movement strategies exist on a continuum from site-attached to highly migratory, each with its own set of advantages and trade-offs.

By considering these diverse ecological and evolutionary drivers within the movement ecology framework, we can gain a deeper understanding of why organisms move and the drivers shaping their movement strategies. This knowledge is essential for addressing various ecological and conservation challenges.

5.1.3. Spatiotemporal Scales

Lecture 3a: Spatiotemporal Scales (1st hour of a 2-hour class)

This module explores the critical role of temporal and spatial scale in understanding animal movement and dives into the diverse array of movement behaviours.

Movement patterns are organized across a wide spectrum of spatial and temporal scales (Figure 1). Studies on aquatic species have examined movement ranging from fine-scale steps to long-distance migrations spanning entire oceans, and from short-term foraging trips to multi-year tracks. The resolution of movement data (temporal frequency and spatial accuracy) is paramount, as conclusions drawn from lower-resolution data can significantly differ from those obtained with higher-resolution data. Higher resolution can reveal crucial details about foraging strategies, social interactions, and avoidance behaviours that might be missed at coarser resolutions. However, studies focusing on larger spatiotemporal scales may inherently be confined to lower resolution tracking due to technological limitations.

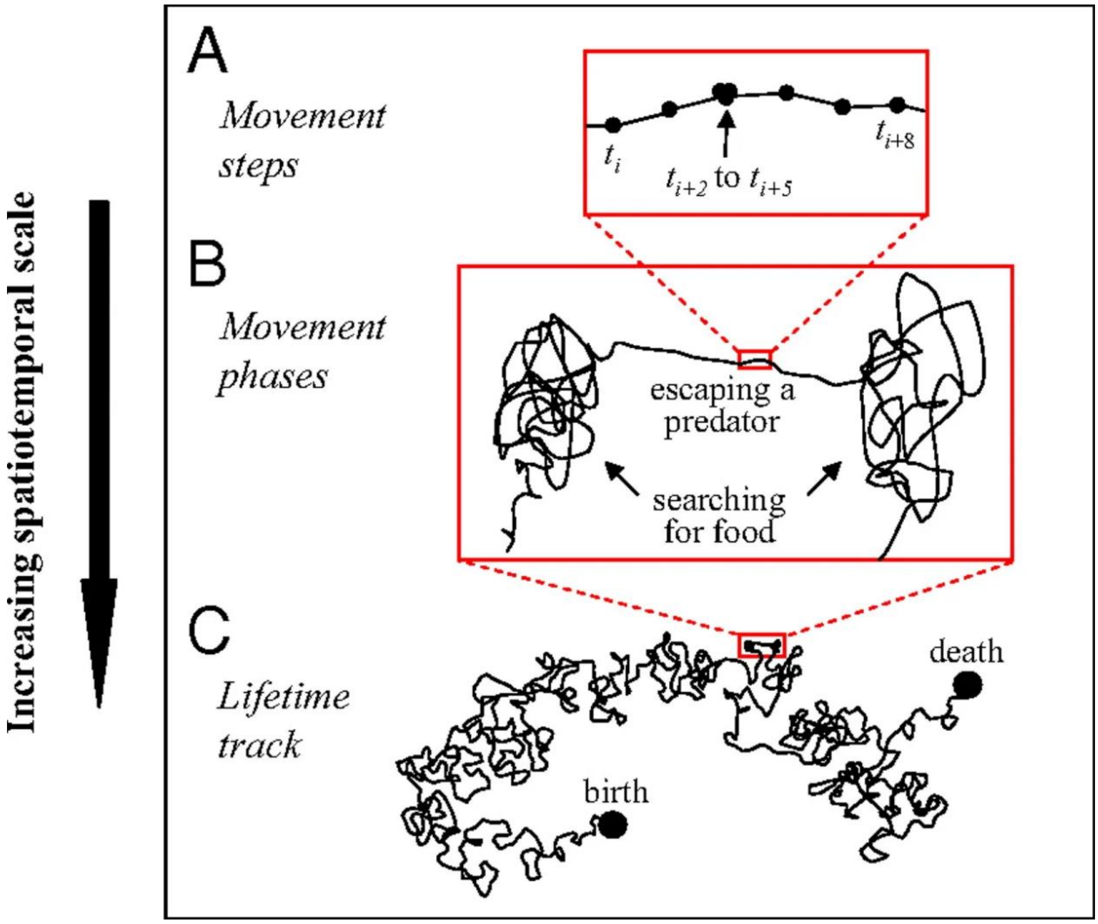

Figure 1. Spatiotemporal scales of individual movement. A short movement path composed of five steps and one stop (A), a longer path comprising three distinct movement phases (B), and a complete lifetime track of an individual (C). (adapted from Nathan et al. 2008).

Movement ecology aims to classify and understand the diverse movement events, which serve different ecological functions. These include:

- Foraging: This involves movement related to resource acquisition, often characterized by search strategies and area-restricted search behaviour where animals concentrate their movements in areas of high resource availability (Humphries et al. 2010). High-resolution data can reveal distinct foraging phases that might be obscured at lower resolutions.

- Dispersal: This refers to the movement of individuals away from their natal area or nursery site, playing a crucial role in gene flow, colonization of new habitats, and avoidance of inbreeding (e.g., Abecasis et al. 2009). Natal dispersal, while ecologically significant, can be challenging to study with electronic tracking due to the small size of the individuals.
- Migration: This involves recurrent movements between distinct areas, often in response to seasonal changes in resource availability or for reproduction. Examples include seasonal movements to overwintering or spawning grounds (e.g., Kraft et al. 2023b; Aarestrup et al. 2022).

The scale of analysis directly influences the interpretation of movement patterns. What appears as random movement at a fine scale might reveal directed movement or specific behavioural states at a coarser scale, and vice versa. Therefore, the appropriate spatial and temporal scales relevant to their ecological questions need to be carefully considered.

Finally, movement ecology recognizes individual variation in movement behaviour. For example, some individuals might consistently be more exploratory than others. Understanding this intra-specific variability is important because it can affect catchability, disease transmission potential, and a population's resilience to disturbance, and is of particular relevance to conservation (Villegas-Ríos et al. 2021). Averaging movement patterns across populations can sometimes mask important individual-level differences in movement patterns and habitat use (de Benito-Abelló et al. 2022; Shaw 2020).

In summary, this module emphasizes that understanding organismal movement requires a consideration of the nature of movement across spatiotemporal scales and the diverse movement patterns that arise from ecological and evolutionary pressures. The resolution of data and the scale of analysis are critical methodological considerations, and recognizing individual variation provides a more comprehensive understanding of movement ecology.

5.1.4. Methods to study animal movement

Lecture 3b: Methods to study animal movement (2^{nd} hour of the 2 hours class - lectures 3a and 3b)

Lecture 4a: Acoustic telemetry (1^{st} hour of a 2-hour class)

This module will be complemented with Fieldwork 1: Implementation of an acoustic telemetry array (8h fieldwork) and Fieldwork 2: Simulation of animal movements in the field (8h fieldwork).

This module provides a comprehensive insight of the diverse methods employed to study animal movement in aquatic environments. Understanding the strengths and limitations of each method is crucial for designing effective studies and interpreting movement data accurately.

This module will explore the wide range of methodologies used to collect aquatic animal movement data, including tagging and non-tagging approaches. A stronger emphasis will be placed in biotelemetry tools, but alternative methods will also be introduced.

Biotelemetry methods:

- Radio Telemetry: A method mostly used in freshwater due to the poor propagation of radio signals in marine environments.
- Satellite Telemetry: A method that enables tracking of animals at a global scale. There are two main types of tags: position transmitters (SPOT tags), and pop-up archival transmitters (PSATs) which also log data on different environmental (e.g., light, temperature) and movement (depth, acceleration) variables.
- Acoustic Telemetry: The most widely used method in marine environments. This method involves tagging animals with acoustic transmitters and deploying networks of receivers to detect their presence (although active tracking is also possible). New platforms like drifting buoys and autonomous marine vehicles (UAVs and ASVs) are extending the reach of acoustic telemetry. While range-limited compared to satellite telemetry, acoustic telemetry can provide more precise locations within receiver arrays.

Alternative methods including non-tagging options:

- Archival loggers: store environmental information such as depth, temperature and light that can then be used to reconstruct trajectories (e.g., Gandra et al. 2024; Winkler et al. 2023). Some loggers can also record animal variables such as acceleration. These loggers need to be recovered to have access to the data.
- Biogeochemical tracers: Analysing elements and isotopes in tissues (otoliths, muscle, vertebrae) can provide a record of past environments and inferred movement, especially useful when electronic tracking is not feasible as for example in larval stages (e.g., Besnard et al. 2023; Durbec et al. 2010).
- Parasites. The use of parasites as biological tags has advanced fish movement ecology by providing insights into fish movement patterns and stock structure (Morales-Serna et al. 2024).

Given the importance of movement ecology in aquatic systems and the increasing use of acoustic telemetry, a more detailed understanding of this highly used technology will be provided (Hussey et al. 2015; Matley et al. 2022). This will focus specifically on:

- Principles of operation and the different types of transmitters and receivers available.
- Key considerations for study design, including strategic receiver deployment according to study questions (Heupel et al. 2006), and effective tagging protocols that minimize harm to the animals (Baras and Jeandrain 1998; Bégout Anras et al. 2003; Cooke et al. 2011).
- Factors that can affect detection probability and range, such as environmental noise, water depth, and receiver sensitivity (Heupel et al. 2008; Payne et al. 2010).
- Understanding the sources of error and limitations inherent in acoustic telemetry data, including false detections and challenges in converting detection data to precise movement paths (Simpfendorfer et al. 2002).

Challenges and considerations in movement data collection will be addressed including potential biases associated with different tracking methods, the limitations of each technology in terms of spatial and temporal resolution, cost, and applicability to different species and environments. Ethical considerations regarding animal welfare and the potential for tag effects on behaviour and survival will be discussed. The importance of tagging validation studies to assess these effects will be emphasized.

Finally, we will cover the essential steps involved in preparing movement data for analysis, including cleaning (e.g., removing duplicate or erroneous detections), filtering (e.g., removing unrealistic movements), and effectively managing the often large and complex datasets generated by modern tracking technologies. The need for improved equipment compatibility, and better data archiving including access and sharing for collaborative research will be highlighted.

By the end of this module, students will have a strong understanding of the methodological landscape of movement ecology, enabling them to critically evaluate different approaches and select the most appropriate tools for addressing specific research questions.

5.1.5. Analysis and interpretation of movement data

Lecture 4b: Analysis and interpretation of movement data (2nd hour of the 2-hour class)

This module will be complemented with the theoretical-practical classes. TP 1: Acoustic telemetry data management (3 hours), TP 2: Acoustic telemetry data exploration (3 hours), and TP 3: Advanced acoustic telemetry data analysis (3 hours).

This module will introduce some of the data analyses methods used to extract meaningful ecological insights from the raw data collected using the biotelemetry transmitters presented in the previous module. Creating informative and impactful data visualizations is a key aspect of interpreting movement patterns and communicating findings. This can involve mapping individual tracks, displaying space use with kernel density estimates, and visualizing network connections. Exploratory data analysis often involves initial assessments of space use and residency (Kraft et al. 2023a).

Emerging high-throughput tracking technologies generate massive datasets, necessitating efficient model fitting tools and robust data pre-processing techniques including cleaning, filtering unrealistic movements, and potentially using smoothing methods or fitting movement models to approximate animal paths (Nathan et al. 2022). The development of transparent and well-documented raw-data processing pipelines, such as R packages, and the adoption of computational science best practices are becoming increasingly important. For example, machine learning algorithms are being used to classify behaviours from high-resolution tracking data (Aspillaga et al. 2021).

During this lecture students will be introduced to the most common analytical approaches. These include:

- Descriptive analyses: This involves calculating fundamental movement metrics such as residency, speed, distance travelled, and tortuosity to characterize basic movement patterns.
- Space use estimation: Techniques like home range analysis using methods such as kernel density estimation and minimum convex polygons are crucial for understanding how animals utilize their environment (Kraft et al. 2023a).
- Path analysis: This involves analysing the movement paths themselves using techniques like step selection functions to understand habitat selection and movement decisions.
- Identifying movement states: the use of Hidden Markov Models (HMMs) to infer underlying behavioural states (e.g., foraging, resting, traveling).
- Network analysis: This approach is used to examine connectivity and movement corridors within a population or across species, often based on detection data from telemetry networks. It can also be used to infer on inter and/or intraspecific social networks.

Finally, the students will be introduced to some of the challenges inherent to movement data, namely:

- Autocorrelation: data points are often not independent, and accounting for spatial and temporal autocorrelation is critical in analysis.
- Varying sampling rates: data can be collected at different temporal frequencies, which can affect the interpretation of movement patterns.
- Observation error: Location data is never perfectly accurate, and understanding and accounting for positioning error is crucial. Effective error calibration and modelling data error structure can improve positioning estimates.

- The diverse challenges of opportunistic acoustic telemetry data obtained from compatible networks.

5.1.6. Applications of movement ecology for conservation and management

Lecture 5: Applications of movement ecology for conservation and management (2h class).

This lecture will explore how the principles and findings of movement ecology can be used to address real-world conservation challenges and inform management decisions. It aims to bridge the gap between research and practical application. This module highlights the crucial role of movement ecology in addressing pressing environmental issues and emphasizes the need for integrating movement data into conservation planning and management practices. Understanding movement is fundamental to effective management and conservation actions. Three main topics will be addressed:

Movement ecology in conservation biology:

- Identification of critical habitats and movement corridors for conservation planning (e.g., Kraft et al. 2023b). Understanding that where animals move is crucial for effective spatial conservation strategies.
- Designing and evaluating the effectiveness of Marine Protected Areas (MPAs). Movement data can help determine the optimal size, location, and connectivity of MPAs (e.g., Abecasis et al. 2014; Abecasis et al. 2015; Assis et al. 2021).
- Understanding connectivity in fragmented seascapes. Assessing how movement is affected by habitat fragmentation is vital for maintaining population viability (Abecasis et al. 2024).
- Management of endangered and threatened species, including migratory species (e.g., smalltooth sawfish - Carlson et al. 2014). Tailoring conservation efforts to the specific movement patterns of vulnerable species.

Movement ecology in fisheries management:

- Understanding stock structure and connectivity for effective fisheries management. Movement data can inform the definition of management units and the assessment of population connectivity (e.g., Abecasis et al. 2024; Hussey et al. 2017).
- Developing spatially explicit management strategies. Incorporating movement information into the design of fishing regulations and spatial closures (e.g., McDonnell et al. 2024).
- Mitigating bycatch and understanding the impacts of fishing effort. Using movement data to predict and reduce bycatch of non-target species (e.g., Smith et al. 2021).

Movement ecology and climate change:

- Assessing the impacts of climate change on species distributions and movement patterns. Understanding how changing environmental conditions are altering animal movement (e.g., Matich et al. 2024; Shaw 2016; Ramos Martins et al. 2021).
- Understanding how animals respond to changing environmental conditions. Examining behavioural plasticity and shifts in movement strategies as species cope with environmental change (e.g., Vedor et al. 2021; Shaw 2016).
- Informing conservation strategies in the face of climate change. Developing adaptative management strategies based on predicted movement responses to climate change will be critical (e.g., Lawler 2009).

5.2. Fieldwork classes

This course will have a strong practical component on acoustic telemetry anchored in two field classes of 8 hours each. The practical classes will provide the students with hands-on experience on 1) the initial setting of an acoustic telemetry array including range testing, and 2) collecting acoustic telemetry data.

Fieldwork will be carried out in one of Ria Formosa's channels close to Clube Naútico da Praia de Faro. These lessons will preferably take place onboard the University's boat, but other alternatives can be used. A similar setup has been used recently to test the compatibility of different equipment manufacturers (Aspillaga et al. 2024).

On the first fieldwork class three to four acoustic receivers will be deployed at the bottom of Ria Formosa at predefined locations. Existing infrastructures (pontoons, mooring buoys) and purpose-built moorings (already available) will be used. Following receiver deployment students will proceed with range tests to later determine the detection range of each of the receivers. This will be done by placing acoustic transmitters at known distance from the receivers for a determined period of period (approximately 30 minutes). Tag transmissions will also be logged by a portable receiver allowing live tracking of signal transmissions. This will then allow the students to determine how many of the transmitted signals were logged by each receiver.

The second day of fieldwork will be used to create an acoustic telemetry dataset. Students will be split into groups (three to five depending on the number of students) and each group will have an acoustic transmitter and instructions on specific movements they should perform (random, within a small area, within a wider area) to emulate different species. Each group will use a canoe, a kayak or paddle board (from Clube Náutico de Faro) on which an acoustic transmitter will be trailed according to the instructions provided. This will generate a series of acoustic detections at the previously deployed acoustic receivers. At the end of the simulation all acoustic receivers will be retrieved and the data downloaded. The analysis of the detection range and the simulation data will be carried out during the theoretical-practical classes.

5.3. Theoretical-Practical classes

During these classes (three classes of 3 hours each) students will get familiarized with acoustic telemetry datasets and how to run data analyses. All the analyses will be performed in R, using dedicated R packages (e.g., moby, adehabitatHR) and following code provided to students (Annexe II). Students will be required to use their own computers during classes, as this facilitates a more efficient learning environment by ensuring they are familiar with their computer's settings and configurations.

The first class will start with downloading data from the fieldwork classes and getting familiarized with the acoustic receiver manufacturer proprietary database (Fathom, Innovasea). Students will also be introduced to the functioning of the European Tracking Network database, including data upload via the web platform, and query and download through the ETN R package. Students will then use the data collected during the first day of fieldwork to determine the detection range of the acoustic receivers. Students will estimate the distance at which the detection rate equals 50% following the R code provided (Annexe I). The second part of the class will consist of the initial exploration of the dataset. For this, students will start by creating abacus plots to visualize detections, through time, at each of the receiver stations. Each group will start by creating an abacus plot of all the detections and then subset so that they can have a visualization of the detections by "individual fish" and receivers.

In the second class, students will estimate several spatial ecology metrics based on the data generated during the second day of fieldwork. Each group will then proceed with calculating basic metrics such as the total number of detections, the number of stations visited, and the number of detections per station. Once the basic metrics are estimated students will calculate the centres of activity (COAs - Simpfendorfer et al. 2002) for the whole dataset. These COAs will then be used to estimate home ranges through different methods (e.g., kernel utilization distributions, dynamic Brownian bridge movement models), and several movement metrics (total distance travelled, rate of movement, etc) for each of the simulated species. All the analyses will be carried out in R, using the R packages moby[1] and adehabitatHR (Calenge 2006).

The third and final class will be used to explore more complex data analysis based on an existing long-term dataset of several species. Students will start by running the analyses carried out in the previous class with the new dataset to have a better understanding of the dataset. Then, they will investigate habitat selection, as well as diel, seasonal and sex differences in habitat use metrics (e.g., home range, residency). For this, students will have to assign classifications to each of the detections (diel phase, season, sex) and estimate the metrics (home range areas, residency). Differences between the distinct groups (seasons, diel phase, sex) will be tested using the t-test or the non-parametric equivalent Mann-Whitney U test.

[1] Developed by Miguel Gandra, one of my PhD students, this work is currently being prepared for publication

5.4. Seminars

The seminars will focus on case studies on a variety of taxa (birds, marine mammals, fish), novel technologies, and/or data analyses, contributing to one or more of the course modules. There will be three seminars with a duration of 2 hours each. During these seminars, invited speakers will present specific case studies related to their own research followed by questions and debate. These seminars will provide students with direct contact with a group of scientists whose research focuses on different aspects of movement ecology. Potential guest speakers include Pedro Afonso (Okeanos, IMAR), José Alves (U. Aveiro), Jorge Assis (CCMAR), Rui Coelho (IPMA), Jorge Fontes (Okeanos, IMAR), Eliza Fragkopolou (CCMAR), Miguel Gandra (CCMAR), Sebastian Kraft (CCMAR), Sara Magalhães (MarIlimitado), Nuno Queiroz (CIBIO, U. Porto), Vitor Paiva (U. Coimbra), Rui Prieto (Okeanos, IMAR), among others.

6. Evaluation

Students will be evaluated based on a group report and one final exam ("Avaliação por frequência" - Regulamento n.º 516/2021 – Regulamento de Avaliação da Universidade do Algarve). The report, developed in groups of up to three students, will account for 35% of the final grade and should focus on one of the following topics:

- Range tests – based on data collected during fieldwork
- Seasonal changes in residency and habitat use – based on an existing dataset
- Habitat selection – based on an existing dataset
- Diel patterns – based on an existing dataset

The final exam will represent 65% of the final grade. It will be conducted on a computer room and will include questions covering both the theoretical and practical components of the course. The exam will include true or false questions, multiple-choice questions, and matching questions. These formats allow for an objective assessment of the knowledge acquired by students throughout the course unit.

To be approved, students must achieve a minimum final grade of 10, with a minimum of 8 points in both the group report and the final exam.

7. Literature

The following list contains the key literature for this course.

Cooke SJ, Hinch SG, Wikelski M, Andrews RD, Kuchel LJ, Wolcott TG, Butler PJ (2004) Biotelemetry: a mechanistic approach to ecology. Trends Ecol Evol 19 (6):334-343. doi:https://doi.org/10.1016/j.tree.2004.04.003

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Nathan R, Getz WM, Revilla E, Holyoak M, Kadmon R, Saltz D, Smouse PE (2008) A movement ecology paradigm for unifying organismal movement research. Proc Natl Acad Sci USA 105 (49):19052

This list will be complemented with supplementary readings that will be provided throughout the course. Supplementary readings will include relevant book chapters, scientific journal articles, and online resources. These will cover a diversity of taxa and movement ecology sub-fields and be frequently updated reflecting the most up to date research and knowledge.

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Annex I - FUC

English version at the end of this document

Ano letivo	2025-2026
Unidade Curricular	Ecologia do Movimento
Cursos	BIOLOGIA MARINHA (2º CICLO) AQUACULTURA E PESCAS (2º CICLO) SISTEMAS MARINHOS E COSTEIROS (2º CICLO) RECURSOS BIOLÓGICOS MARINHOS – ERASMUS MUNDUS (2º CICLO)
Unidade Orgânica	FACULDADE DE CIÊNCIAS E TECNOLOGIA
Código da Unidade Curricular	A DETERMINAR
Área científica	Ciências do Ambiente
Sigla da Área Científica	
Código CNAEF	422
Língua(s) de Aprendizagem	Inglês
Modalidade de ensino	Presencial

Caracterização da Unidade Curricular

Ano	Período	Horas de Contacto	Horas de trabalho	ECTS
1º	S2	51	105	6

* A-Anual;S-Semestral; Q-Quadrimestral; T-Trimestral

Horas de contacto

(T) Teóricas	20 horas	(TP) Teórico-Práticas	0
(PL) Práticas Laboratoriais	9 horas	(TC) Trabalho de campo	16 horas
(OT) Orientação Tutorial	0	(S) Seminário	6 horas
(E) Estágio	0	(O) Outras	0

Docente Responsável David Maria Aguiar Abecasis

Avaliação final com exame? Sim

Precedências – sem precedências

Conhecimentos prévios recomendados – Conhecimentos básicos de ecologia

Objetivos de aprendizagem (conhecimentos, aptidões e competências a desenvolver pelos estudantes)

Este curso tem como objetivo proporcionar aos estudantes uma base teórica e prática sólida na área da ecologia do movimento, com particular ênfase em organismos aquáticos. No final, os estudantes deverão ser capazes de compreender os conceitos e princípios fundamentais da ecologia do movimento; explicar os fatores ecológicos que determinam o movimento dos animais; avaliar criticamente os principais métodos utilizados no estudo do movimento animal, incluindo as tecnologias de biotelemetria e as abordagens de análise de dados; aplicar métodos analíticos adequados para interpretar dados de movimento; e reconhecer a relevância e aplicabilidade da ecologia do movimento para a gestão e conservação de espécies e ecossistemas.
Os estudantes desenvolverão ainda as seguintes competências:

- Conhecimento científico no domínio da ecologia do movimento animal, incluindo a capacidade de formular questões e hipóteses relevantes.
- Proficiência na utilização de tecnologias de monitorização (particularmente a telemetria acústica) e na gestão e análise de dados de biotelemetria em R.
- Pensamento crítico para avaliar desenhos experimentais, selecionar métodos analíticos adequados e interpretar dados ecológicos espaciais num contexto de conservação.
- Competências de comunicação, oral e escrita, através da elaboração de relatórios e da participação em seminários, promovendo a disseminação eficaz de resultados científicos.
- Capacidade de colaboração e trabalho em equipa, desenvolvida através de atividades práticas de campo e projetos de análise de dados em grupo.

Conteúdos programáticos

1. Fundamentos de ecologia do movimento.

- Evolução histórica e o paradigma da ecologia do movimento
- Componentes do movimento: estado interno, capacidade de locomoção, capacidade de navegação, fatores externos

2. **Determinantes ecológicos e evolutivos do movimento**

- Teoria do forrageamento e seleção de habitat
- Risco de predação, comportamento social e influências ambientais
- Dispersão, migração e mudanças ontogenéticas

3. **Escalas espaço-temporais do movimento**

- As diferentes escalas do movimento
- Variabilidade individual no movimento

4. **Métodos para o estudo do movimento animal**

- Visão geral das tecnologias de monitorização dos movimentos (marcação-recaptura, telemetria acústica, satélites, marcas de arquivo etc.)
- Telemetria acústica: instalação, testes de alcance e recolha de dados
- Considerações éticas e desenho experimental

5. **Análise e interpretação de dados de movimento**

- Gestão de dados, visualização e métricas básicas
- Estimativa de áreas de utilização e trajetórias de movimento

6. **Aplicações na conservação e gestão**

- Desenho de Áreas Marinhas Protegidas e identificação de habitats críticos
- Gestão de espécies migratórias e estrutura de unidades populacionais

Demonstração da coerência dos conteúdos programáticos com os objetivos de aprendizagem da unidade curricular

O conteúdo programático está estruturado de forma a desenvolver conhecimentos e competências em linha com os resultados de aprendizagem da unidade curricular. Os módulos teóricos abordam os conceitos fundamentais e os fatores que influenciam o movimento, enquanto os componentes práticos e de trabalho de campo promovem o desenvolvimento de competências analíticas e técnicas. Os módulos finais garantem a aplicação dos conhecimentos a contextos reais de conservação e gestão.

Metodologias de ensino

Esta unidade curricular combina aulas teóricas, trabalho de campo, sessões práticas e seminários, promovendo uma compreensão integrada da ecologia do movimento. As aulas teóricas introduzem os conceitos e metodologias fundamentais; o trabalho de campo proporciona experiência prática com telemetria acústica; as aulas práticas centram-se na análise de dados utilizando o software R; e os seminários expõem os estudantes a casos de estudo reais.

Avaliação

A avaliação dos estudantes será baseada num relatório de grupo e num exame final. O relatório, desenvolvido em grupos de até três estudantes, contará 35% da nota final. O exame final representará 65% da nota final. Para obter aprovação, os estudantes deverão alcançar uma nota final mínima de 10 valores, com um mínimo de 8 valores tanto no relatório de grupo como no exame final.

Demonstração da coerência das metodologias de ensino e avaliação com os objetivos de aprendizagem da unidade curricular

A combinação de aulas teóricas, trabalho de campo, sessões práticas e seminários garante que os estudantes adquiram tanto conhecimentos teóricos como competências aplicadas, em concordância com os resultados de aprendizagem da unidade curricular. Os métodos de avaliação — compostos por um relatório de grupo e um exame final — permitem avaliar a compreensão dos conceitos-chave, a capacidade de analisar dados de movimento e a aptidão para aplicar os princípios da ecologia do movimento em cenários de conservação e gestão.

Contributo para os Objetivos de Desenvolvimento Sustentável - ODS

ODS 4 – Educação de Qualidade: através da promoção de uma educação de elevada qualidade, baseada na investigação, que prepara os estudantes para carreiras em gestão ambiental, conservação e ciências marinhas.

ODS 13 – Ação Climática: ao explorar como as espécies respondem às alterações ambientais e ao dotar os estudantes de ferramentas para prever e mitigar os impactos das alterações climáticas na biodiversidade.

ODS 14 – Proteger a Vida Marinha: através da promoção de conhecimento e ferramentas para a conservação e utilização sustentável dos ecossistemas marinhos e costeiros, bem como para a proteção de espécies aquáticas e habitats vulneráveis.

Demonstração da articulação entre os Objetivos de Desenvolvimento Sustentável (ODS) indicados e os conteúdos programáticos

O programa desta unidade curricular contribui para o ODS 4 (Educação de Qualidade) ao oferecer uma formação de elevado nível orientada para a sustentabilidade, baseada em investigação, que combina conhecimentos teóricos com trabalho de campo, análise de dados e pensamento crítico. Contribui para o ODS 13 (Ação Climática) ao abordar as respostas dos organismos às alterações ambientais e dotar os estudantes de ferramentas para analisar e prever alterações nos padrões de movimento face às mudanças climáticas. Através das aulas sobre uso do habitat, áreas marinhas protegidas e planeamento da conservação, esta UC apoia diretamente o ODS 14 (Proteger a Vida Marinha) ao desenvolver competências essenciais para a gestão sustentável e conservação da biodiversidade marinha.

Bibliografia principal

Cooke SJ, Hinch SG, Wikelski M, Andrews RD, Kuchel LJ, Wolcott TG, Butler PJ (2004) Biotelemetry: a mechanistic approach to ecology. Trends Ecol Evol 19 (6):334-343. doi:https://doi.org/10.1016/j.tree.2004.04.003

Holyoak M, Casagrandi R, Nathan R, Revilla E, Spiegel O (2008) Trends and missing parts in the study of movement ecology. Proc Natl Acad Sci USA 105 (49):19060-19065

Hussey NE, Kessel ST, Aarestrup K, Cooke SJ, Cowley PD, Fisk AT, Harcourt RG, Holland KN, Iverson SJ, Kocik JF, Mills Flemming JE, Whoriskey FG (2015) Aquatic animal telemetry: A panoramic window into the underwater world. Science 348 (6240). doi:10.1126/science.1255642

Kraft S, Gandra M, Lennox RJ, Mourier J, Winkler AC, Abecasis D (2023a) Residency and space use estimation methods based on passive acoustic telemetry data. Movement Ecology 11 (1):12. doi:10.1186/s40462-022-00364-z

Nathan R, Getz WM, Revilla E, Holyoak M, Kadmon R, Saltz D, Smouse PE (2008) A movement ecology paradigm for unifying organismal movement research. Proc Natl Acad Sci USA 105 (49):19052

Esta lista será complementada com literatura adicional que será fornecida ao longo do curso. A literatura adicional pode incluir capítulos de livros relevantes, artigos de revistas científicas e recursos online. Estes abrangerão uma diversidade de taxa e subcampos da ecologia do movimento e serão atualizadas frequentemente, refletindo a investigação e os conhecimentos mais recentes.

UNIVERSIDADE DO ALGARVE

Academic Year	2025-2026
Course Unit	MOVEMENT ECOLOGY
Programme(s)	MARINE BIOLOGY (2nd cycle) AQUACULTURE AND FISHERIES (2nd cycle) MARINE AND COASTAL SYSTEMS (2nd cycle) MUNDUS INTERNATIONAL MASTER OF SCIENCE IN MARINE BIOLOGICAL RESOURCES (2nd cycle)
Faculty / School	FACULTY OF SCIENCES AND TECHNOLOGY
Course Unit Code	TO BE DETERMINED
Scientific Area	ENVIRONMENTAL SCIENCES
Scientific Area Acronym	
CNAEF Code	422
Language(s) of Instruction	ENGLISH
Teaching/Learning Modality	In-class

Course Unit Characterization

Year	Term*	Contact Hours	Working Hours	ECTS
1º	S2	51	105	6

* A-Annual;S-Semester; Q-Quadrimester; T-Trimester

Contact hours

(T) Theoretical	20 hours	(TP) Theoretical-Practical	0
(PL) Pratical Labs	9 hours	(TC) Fieldwork	16 hours
(OT) Tutorial Orientation	0	(S) Seminar	6 hours
(E) Internship	0	(O) Others	0

Coordinating teacher David Maria Aguiar Abecasis

Final Examination with Exam? Yes

Pre-requisites – No pre-requisites

Prior knowledge and skills - Basic knowledge of ecology

Learning outcomes (knowledge, skills and competences to be developed by students)

This course aims to provide students with a solid theoretical and practical foundation in the field of movement ecology, with a particular emphasis on aquatic organisms. By the end of the course, students will be able to understand the core concepts and principles of movement ecology; explain the ecological drivers underlying animal movement; critically assess the main methods to study animal movement, including biotelemetry technologies and data analyses approaches; apply appropriate analytical approaches to interpret movement data, and recognize the relevance and applicability of movement ecology for the management and conservation of species and ecosystems.
Students will also develop the following competences:

- Scientific knowledge in the domain of animal movement ecology, including the ability to formulate relevant ecological questions and hypotheses.
- Technical proficiency in the use of tracking technologies (particularly acoustic telemetry) and in managing and analysing movement data using R.
- Critical thinking to evaluate research designs, select suitable analytical methods, and interpret spatial ecological data in a conservation context.
- Communication skills, both oral and written, through the preparation of reports and participation in seminars, enabling effective dissemination of scientific findings.
- Collaboration and teamwork, enhanced through group-based fieldwork and data analysis projects.

Syllabus

1. Foundations of movement ecology
    - Historical development and the movement ecology paradigm
    - Components of movement: internal state, motion capacity, navigation capacity, external factors
2. Ecological and evolutionary drivers of movement
    - Foraging theory and habitat selection
    - Predation risk, social behaviour, and environmental influences
    - Dispersal, migration, and ontogenetic shifts
3. Spatio-temporal scales of movement
    - Movement patterns across scales
    - Individual variability in movement behaviour
4. Methods for studying animal movement
    - Overview of tracking technologies (mark-recapture, acoustic telemetry, satellite tags, archival loggers, etc.)

- Acoustic telemetry: deployment, range testing, and data collection
- Ethical considerations and study design

5. Analysis and interpretation of movement data
    - Data management, visualization, and basic metrics
    - Estimating home ranges and movement paths
6. Applications in conservation and management
    - Designing Marine Protected Areas and identifying critical habitats
    - Managing migratory species and stock structure

Demonstration of the coherence between syllabus and the course unit's learning outcomes

The syllabus is structured to build knowledge and skills that match the course's learning outcomes. Theoretical modules cover core concepts and drivers of movement, while practical and fieldwork components develop analytical and technical competences. The final modules ensure application of knowledge to real-world conservation and management contexts.

Teaching/Learning Methodologies

The course combines lectures, fieldwork, practical sessions, and seminars to promote an integrated understanding of movement ecology. Lectures introduce core concepts and methodologies; fieldwork provides hands-on experience with acoustic telemetry; practical classes focus on data analysis using R; and seminars expose students to real-world case studies.

Evaluation

Students will be evaluated based on a group report and one final exam. The report, developed in groups of up to three students, will account for 35% of the final grade. The final exam will represent 65% of the final grade. To be approved, students must achieve a minimum final grade of 10, with a minimum of 8 points in both the group report and the final exam.

Demonstration of the coherence between teaching/learning methodologies and evaluation and the course unit's learning outcomes

The combination of lectures, fieldwork, practical sessions, and seminars ensures that students acquire both theoretical knowledge and applied skills aligned with the course outcomes. The evaluation methods—comprising a group report and a final exam—assess students' understanding of key concepts, ability to analyse movement data, and capacity to apply movement ecology to conservation and management scenarios

Contribution to Sustainable Development Goals - SGD

SDG 4 – Quality Education: by fostering high-quality, research-based education that prepares students for careers in environmental management, conservation, and marine sciences.

SDG 13 – Climate Action: by exploring how species respond to environmental change and by equipping students with tools to predict and mitigate climate-related impacts on biodiversity.

SDG 14 – Life Below Water: by promoting knowledge and tools for the conservation and sustainable use of marine and coastal ecosystems, and for the protection of vulnerable aquatic species and habitats.

Demonstration of the articulation between Sustainable Development Goals (SDG) indicated and syllabus

The course syllabus supports SDG 4 (Quality Education) by providing students with high-level, research-informed training in movement ecology, integrating theoretical knowledge with hands-on fieldwork, data analysis, and critical thinking. It contributes to SDG 13 (Climate Action) by examining how species respond to environmental change and equipping students with tools to analyse and predict movement shifts under climate scenarios. Through modules on habitat use, marine protected areas, and conservation planning, the course directly supports SDG 14 (Life Below Water) by fostering skills essential for the sustainable management and conservation of marine biodiversity.

Main Bibliography

Cooke SJ, Hinch SG, Wikelski M, Andrews RD, Kuchel LJ, Wolcott TG, Butler PJ (2004) Biotelemetry: a mechanistic approach to ecology. Trends Ecol Evol 19 (6):334-343. doi:https://doi.org/10.1016/j.tree.2004.04.003

Holyoak M, Casagrandi R, Nathan R, Revilla E, Spiegel O (2008) Trends and missing parts in the study of movement ecology. Proc Natl Acad Sci USA 105 (49):19060-19065

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Nathan R, Getz WM, Revilla E, Holyoak M, Kadmon R, Saltz D, Smouse PE (2008) A movement ecology paradigm for unifying organismal movement research. Proc Natl Acad Sci USA 105 (49):19052

This list will be complemented with supplementary readings that will be provided throughout the course. Supplementary readings will include relevant book chapters, scientific journal articles, and online resources. These will cover a diversity of taxa and movement ecology sub-fields and be frequently updated reflecting the most up to date research and knowledge.

Annex II – R code for data analysis (practical classes)

```
#set working directory

setwd("C:/....")


#install moby package

devtools::install_github("miguelgandra/moby")


# Load libraries

library(dplyr)

library(lubridate)

library(geosphere)

library(ggplot2)

library(readr)

library(moby)


############################
### Detection range analysis ###
############################


# Load the detection data

rangedata <- read_csv("VUE_Export.csv")


# Define parameters

transmitter_id <- "A69-1602-9100"

expected_transmissions <- 360  # e.g. one ping every 10s for 1 hour

start_time <- ymd_hms("2019-04-03 06:30:00") # set according to fieldwork

end_time <- ymd_hms("2019-04-03 07:30:00") # set according to fieldwork
```

```
# Define transmitter location (according to fieldwork)
tx_lat <- 38.43300
tx_lon <- -9.06000

# Combine date and time into datetime
rangedata <- rangedata %>%
  mutate(datetime = ymd_hms(paste(`Date(UTC)`, `Time(UTC)`))) %>%
  filter(Transmitter == transmitter_id,
         datetime >= start_time,
         datetime <= end_time)

# Calculate detection efficiency per receiver
efficiency_ rangedata <- rangedata %>%
  group_by(Receiver, StationName, Latitude, Longitude) %>%
  summarise(detections = n(), .groups = "drop") %>%
  mutate(expected = expected_transmissions,
         efficiency_pct = round((detections / expected) * 100, 1),
         distance_m = distHaversine(cbind(Longitude, Latitude), c(tx_lon, tx_lat)))

# Plot detection efficiency vs distance
ggplot(efficiency_ rangedata, aes(x = distance_m, y = efficiency_pct)) +
  geom_point(size = 3, color = "steelblue") +
  geom_smooth(method = "loess", se = FALSE, color = "darkred") +
  labs(title = "Receiver Detection Efficiency vs Distance to Transmitter",
       x = "Distance to Transmitter (m)",
       y = "Detection Efficiency (%)") +
  theme_minimal()
```

```
# Save the results

write_csv(efficiency_ rangedata, "detection_efficiency_by_distance.csv")



##########################################
### Creating abacus plots and summary table ####
##########################################


#import data

testdata <- read.csv("C:/.....csv")


#combine date and time columns and set as POSIXct

testdata$Datetime <- as.POSIXct(paste(testdata$Date.UTC., testdata$Time.UTC.),
format = "%Y-%m-%d %H:%M:%S", tz = "UTC")


#set tagging date (dd/mm/YYYY – fieldwork date)

tagging_date <- as.POSIXct("dd/mm/YYYY", format = "%d/%m/%Y", tz = "UTC")


#plot abacus

plotAbacus(

        testdata,

        id.col="TransmitterName",

        datetime.col = "Datetime",

        tagging.dates = tagging_date,

        top.mural = FALSE)
```

```
# create table with summary information

table <-summaryTable(

testdata,id.col="TransmitterName",

        datetime.col = "Datetime",

        tagging.dates = tagging_date,

        station.col="StationName",

        tag.durations=1292) #this number needs to be set accordingly


####################
### Estimating COAs ####
####################

# create time bins for COAs

testdata$timebin <- getTimeBins(datetimes=testdata$Datetime, interval = "30 mins",
rounding.method = "floor")


# summary table

summary_df <- testdata %>%

     group_by(timebin, StationName, TransmitterName, Latitude, Longitude) %>%

     summarise(detections = n(), .groups = "drop")


### Calculate COAs

calculateCOAs(

     summary_df,

     id.col = "TransmitterName",

     timebin.col = "timebin",

     lon.col = "Longitude",

     lat.col = "Latitude",

     station.col = "StationName"

)
```

```
### Calculate KUDs
calculateKUDs(
	data,
	bandwidth,
	spatial.grid = NULL,
	subset = NULL,
	id.groups = NULL,
	land.shape = NULL,
	id.col = “TransmitterName”,
	lon.col = "Longitude",
	lat.col = "Latitude",
	epsg.code = "32629", # this code is for Portugal projected coordinates
	contour.percent = c(50, 95),
	verbose = FALSE
	)

#### Create movement stats table
movementTable(
	testdata,
	kud.results,
	land.shape,
	epsg.code = "4326"),
	id.groups = NULL,
	id.col = "TransmitterName",
	timebin.col = "timebin",
	lon.col = "Longitude",
	lat.col = "Latitude",
```

```
	dist.col = "dist_m",
	discard.missing = TRUE,
	)



########################
#### Advanced analysis #####
########################

###Estimate diel phase


getDielPhase(
	datetimes,
	coordinates, #one single location is enough for Arrabida
	phases = 2,  # day/night, if 3 day/night/crepuscule, 4 dawn, day, dusk, night
	solar.depth = 18 # based on astronomical twilight
	)



### Estimate season
getSeason(
	datetimes,
	hemisphere = "Northern"
	)

## Estimate the KUDs and summary table for each diel phase and season
```

```
###########################
##### Habitat selection ratios ###
############################

### Example with Uganda dataset

# Habitat availability and relocations:: All Fish

habitat_data <- data.frame(

Habitat = c("Forest edge", "water lillies", "Miscand","hippo grass", "type 5","type 34"),

        Available_Proportion = c(0.137157, 0.027431, 0.199501, 0.17207, 0.461347, 0.002494),  # % of total area

        Used_Proportion = c(0.16443, 0, 0.392617, 0.442953, 0, 0),      # % of relocations

        Used_Count = c(49, 0, 117, 132, 0, 0)          # Number of relocations

)


# Compute Manly's Selection Ratio (Wi)

habitat_data <- habitat_data %>%

  mutate(Wi = Used_Proportion / Available_Proportion)


# Compute Standard Error (SE) of Wi

habitat_data <- habitat_data %>%

  mutate(SE_Wi = Wi * sqrt((1 - Used_Proportion) / sum(Used_Count)))


# Compute 95% Confidence Interval

Z_alpha <- 1.96  # Z-score for 95% CI

habitat_data <- habitat_data %>%

  mutate(

    Lower_CI = Wi - Z_alpha * SE_Wi,

    Upper_CI = Wi + Z_alpha * SE_Wi

  )
```

```
# Print results

print(habitat_data)


# Habitat availability and relocations:: individual Fish

habitat_data <- data.frame(

Habitat = c("Forest edge", "water lillies", "Miscand","hippo grass", "type 5","type 34"),

        Available_Proportion = c(0.137157, 0.027431, 0.199501, 0.17207, 0.461347,
0.002494),  # % of total area

        Used_Proportion = c(1, 0, 0, 0, 0, 0),      # % of relocations

        Used_Count = c(8, 0, 0, 0, 0, 0)            # Number of relocations

)


# Compute Manly's Selection Ratio (Wi)

habitat_data <- habitat_data %>%

  mutate(Wi = Used_Proportion / Available_Proportion)


# Compute Standard Error (SE) of Wi

habitat_data <- habitat_data %>%

  mutate(SE_Wi = Wi * sqrt((1 - Used_Proportion) / sum(Used_Count)))


# Compute 95% Confidence Interval

Z_alpha <- 1.96  # Z-score for 95% CI

habitat_data <- habitat_data %>%

  mutate(

    Lower_CI = Wi - Z_alpha * SE_Wi,

    Upper_CI = Wi + Z_alpha * SE_Wi

  )
```

```
# Print results

print(habitat_data)



####################################
#### Visualization of Manly's index ########
####################################

# Load necessary libraries

library(FactoMineR)  # For PCA/MCA

library(factoextra)  # For visualization


# import data

wi_matrix <- read.csv("C:/....wi_matrix.csv", header=TRUE)


# Set the first column (Fish IDs) as row names

rownames(wi_matrix) <- wi_matrix[,1]  # Assign Fish IDs as row names


# Remove the first column (Fish IDs) since it's now stored as row names

wi_matrix_clean <- wi_matrix[,-1]


# Convert to numeric matrix

wi_matrix_clean <- as.matrix(wi_matrix_clean)

wi_matrix_clean <- apply(wi_matrix_clean, 2, as.numeric)


# Check structure

str(wi_matrix_clean)
```

```
# Perform PCA
pca_result <- PCA(wi_matrix_clean, scale.unit = TRUE, graph = FALSE)

# Plot habitat loadings (equivalent to Fig. 4a)
fviz_pca_var(pca_result, col.var = "blue", repel = TRUE,
        ) ###Habitat Type Loadings on PCA Axes

# Plot individual fish scores (equivalent to Fig. 4b)
fviz_pca_ind(pca_result,
          col.ind = "red",
          repel = TRUE,
          ) ###"Fish Scores on First Factorial Plane"

fviz_pca_biplot(pca_result,
           label = "all",     # Show both individuals & habitat labels
           col.ind = "red",    # Color individuals (fish)
           col.var = "blue",   # Color habitat types
           repel = TRUE   # Avoid overlapping labels
          )
```