aeet
ASOCIACIÓN ESPAÑOLA DE ECOLOGÍA TERRESTRE

Ecosistemas 32 (2): 2427 [Mayo-Agosto 2023]
https://doi.org/10.7818/ECOS.2427

MONOGRÁFICO: Ecología del Movimiento: del análisis individual a la provisión de servicios ecosistémicos

Editores: Eneko Arrondo, Zaida Ortega y Juan Manuel Pérez-García

ARTÍCULO DE REVISIÓN

ecosistemas
REVISTA CIENTÍFICA DE ECOLOGÍA Y MEDIO AMBIENTE

ISSN 1697-2473
Open access / CC BY-NC 4.0
disponible en www.revistaecosistemas.net

Challenges and perspectives of movement ecology research in Brazil

Milene Amâncio Alves-Eigenheer[1,2,*], Bernardo Brandão Niebuhr[1,3], Julia Emi de Faria Oshima[4,1], Claudia Zukeran Kanda[1,5], Danielle Christine Tenório Leal Ramos[1], Natália Stefanini Da Silveira[1], Laura Kyoko Honda[1], Patrícia Kerches-Rogeri[1], Lígia Pereira de Souza Salzano[1], André Luiz Bitencourt Moraes[6], Karl Stephan Mokross[7], Milton Cezar Ribeiro[1,7,8]

(1) Laboratório de Ecologia Espacial e Conservação (LEEC), Departamento de Biodiversidade, Instituto de Biociências, Universidade Estadual Paulista (UNESP), Avenida 24 1515 13506-900, Rio Claro, Brazil.
(2) Laboratório de Ciências Ambientais, Universidade Estadual Norte Fluminense Darcy Ribeiro, Avenida Alberto Lamego, 2000, Parque Califórnia, Campos dos Goytacazes, Brazil.
(3) Norwegian Institute for Nature Research, Department of Terrestrial Biodiversity, 5685, Trondheim, Norway.
(4) Laboratório de Ecologia de Movimento, Instituto de Biociências, Departamento de Ecologia, Universidade de São Paulo, 05508-090, São Paulo, Brazil.
(5) Laboratório de Genética & Biodiversidade, Universidade Federal de Goiás (UFG), Av. Esperança, s/n 74001-970, Goiânia, Brazil.
(6) Laboratório de ecologia de aves (LECAVE), Departamento de Biodiversidade, Instituto de Biociências, Universidade Estadual Paulista (UNESP), Avenida 24 1515 13506-900, Rio Claro, Brazil.
(7) Departamento de Biodiversidade, Instituto de Biociências, Universidade Estadual Paulista (UNESP), Avenida 24 1515 13506-900, Rio Claro, Brazil
(8) Centro de Estudos Ambientais (CEA) Universidade Estadual Paulista (UNESP), Avenida 24 1515 13506-900, Rio Claro, Brazil.

* Corresponding author: M. Alves-Eigenheer [mileneaae@gmail.com]

> Recibido el 16 de julio de 2022 - Aceptado el 02 de mayo de 2023

Como citar: Alves-Eigenheer, M., Niebuhr, B.B., de Faria Oshima, J.E., Zukeran Kanda, C., Leal Ramos, D.C.T., Stefanini Da Silveira, N., Honda, L.K., Kerches-Rogeri, P., Pereira de Souza Salzano, L., Bitencourt Moraes, A.L., Mokross, K.S., Ribeiro, M.C. 2023. Challenges and perspectives of movement ecology research in Brazil. *Ecosistemas* 32(2): 2427. https://doi.org/10.7818/ECOS.2427

Challenges and perspectives of movement ecology research in Brazil

Abstract: Challenges and perspectives of movement ecology research in Brazil. The recent progress in movement ecology research was driven by technological advances that facilitated the quantification and analysis of fine scale movement. Here we review and comprehensively describe scientific research on movement ecology in Brazil, its main topics, challenges and perspectives. To assess it, we performed a literature survey of movement ecology in Brazil and analyzed responses of a questionnaire completed by attendees that took place at the I Movement Ecology Brazil Workshop, in 2015. We describe the most studied taxa, topics of research and technologies, the most studied biomes, and the greatest challenges faced by Brazilian scientists. We propose collaborations among different lines of study and interdisciplinary research centers, besides recommending more education beyond the technical aspects of this research field, towards the development of competent and well-rounded scientists. Access to technology without bureaucracy, the growth of Brazilian tracking equipment companies, enhancement of national and international research networks and partnerships among biological and statistical sciences are some factors that will shape the autonomy of Brazilian researchers working in movement ecology. Our main suggestion for future directions is to integrate biomechanical, cognitive and optimality paradigms with movement-related ecological processes such as predation and seed dispersal, and the unique biodiversity and fieldwork context found in Brazil..

Keywords: animal movement; GPS collar; movement analysis; radiotelemetry

Desafíos y perspectivas de la investigación en ecología del movimiento en Brasil

Resumen: Desafíos y perspectivas de la investigación en ecología del movimiento en Brasil. El progreso reciente en la investigación de la ecología del movimiento fue impulsado por avances tecnológicos que facilitaron la cuantificación y el análisis del movimiento a pequeña escala. Este trabajo describe la investigación científica sobre la ecología del movimiento en Brasil, sus principales temas, desafíos y perspectivas. Para evaluarlo, realizamos una revisión bibliográfica sobre la ecología del movimiento en Brasil y analizamos las respuestas de un cuestionario completado por los asistentes de un taller que tuvo lugar en el I Workshop de Ecología del Movimiento Brasil, en 2015. Encontramos un rápido aumento en la investigación de la ecología del movimiento en Brasil, con un total de 310 estudios, de los cuales el 51% han sido publicados a partir del 2010. Describimos los taxones más estudiados, temas de investigación y tecnologías, biomas más estudiados y desafíos que enfrentan los científicos y científicas de Brasil. Proponemos colaboraciones entre diferentes líneas de estudio y centros de investigación interdisciplinarios, y recomendamos aumentar la educación, más allá de los aspectos técnicos de esta línea de investigación, para fomentar el desarrollo de científicos competentes y completos. Algunos de los factores clave para dotar de autonomía a los investigadores e investigadoras brasileñas trabajando en ecología del movimiento serían: mejorar el acceso a las tecnologías, reducir la burocracia, el crecimiento de las empresas brasileñas de equipos de seguimiento de fauna, la mejora de las redes de investigación nacionales e internacionales y la colaboración entre profesionales de ciencias biológicas y de estadísticas. Nuestra principal sugerencia para el futuro es integrar los paradigmas biomecánicos, cognitivos y de optimización con los procesos ecológicos relacionados con el movimiento, como la depredación y la dispersión de semillas.

Palabras clave: análisis de movimiento; collar GPS; movimiento de animales; radiotelemetría

Introduction

Movement is a key process to understand and link the ecology of organisms, populations, communities, and ecosystems (Jeltsch et al. 2013). Understanding the movement of organisms is also important for conservation and has many applications such as for disease mitigation (Fèvre et al. 2006; Fuller et al. 2012), assessment of ecosystem services as pollination and seed dispersal (Kremen et al. 2007; Mitchell et al. 2015), ecophysiology (Williams et al. 2014; Altimiras and Anderson 2016), and dispersal of alien and native species in contexts of climate change and global native habitat loss (Trakhtenbrot et al. 2005).

Research on movement ecology has progressed in recent decades, driven mostly by advances in analytical techniques and technologies that allow movement to be quantified (Holyoak et al. 2008; Nathan et al. 2008; Kays et al. 2015; Nathan et al. 2022). Nathan et al. (2008) proposed a framework to classify the basic components describing the movement of organisms into the following conceptual categories: navigation capacity, internal state, motion capacity, movement path and external factors. This framework enabled a novel understanding of ecological and social dynamics, and it inspired innovative research perspectives within movement ecology (Nathan et al. 2008; Jeltsch et al. 2013; Baguette et al. 2014; Nathan et al. 2022) by assessing why, when, how, and where the movement of organisms occurs and the environmental variables that influence it.

Despite these recent developments, the advances in movement ecology are unevenly distributed globally, and different challenges arise mainly in tropical and developing countries. Our aim is to evaluate the recent scientific research in movement ecology in Brazil, as well as its main topics, obstacles, and perspectives. Also, we wish to identify and describe what questions were asked by researchers, in which study systems (biome, organism) and using which technology. The analysis was performed with a data survey based on a 30-year literature review, questionnaires filled by the participants of the I Movement Ecology Brazil (I MEB) Workshop in 2015, and discussions that occurred during the meeting.

Materials and Methods

Movement Ecology Brazil Workshop

The I Movement Ecology Brazil Workshop (I MEB) was hosted by the São Paulo State University (UNESP) in Rio Claro (SP) in September 2015 and aimed at sharing experiences on the state of the art and new perspectives in this field of ecological science. The I MEB meeting gathered 99 researchers from 32 Brazilian and 2 Argentinean institutions from the academic, government and environmental consultancy sectors. Twenty-one studies were presented as posters, and the content included a wide spectrum of topics such as the use of various ecological modeling techniques, testing of new technologies, and applications of movement ecology data.

All attendees (n = 99) answered an online questionnaire survey about their research group, the main challenges in their studies and other information reflecting important aspects of movement ecology research in Brazil (Supplementary Material; **Table SM1**). Here, we have synthesized this information and the discussions promoted at I MEB. We emphasize that the following is just a sample of this scientific field in Brazil, but we believe that these results and conclusions can be used as a proxy for the movement ecology research that is being done in the country. A second Movement Ecology Brazil Workshop (II MEB) was held in 2019 (see below), but the detailed analysis of the themes and key points are beyond our aims.

Literature survey

Movement ecology in Brazil was first studied by Cunningham and Reid (1932), who described movement by birds on a naturally heterogeneous landscape at the estuary of the Amazon River. Research on this topic was rarely conducted in Brazil in the following decades (Davis 1945; Best et al. 1981), but around 1990s the interest in movement ecology started to increase (**Fig. 1**).

To understand this rising interest, we conducted a search of movement ecology studies in Brazil over 30 years (1986-2015) through the scientific citation index "Web of Science"® (WoS), using the keywords "movement* ecolog* Brazil"; "animal* movement* Brazil"; "animal* track* Brazil"; "telemetry Brazil"; and "model* movement* Brazil". To include the literature related to simulation (i.e., mathematical or computational modeling used in spatially explicit models based on the literature or pre-existing data bank information) and modeling produced in the national institutions, we also included the keywords "movement* ecology*"; "simulation* OR model*; and "random search*" OR "Lévy", with "Brazil" in the address field. The studies found were filtered and only those with a focus on movement (according to Holyoak et al. 2008) were kept (Supplementary Material; **Table SM2**).

Data compilation

To situate the scientific production on movement ecology in Brazil, we recorded the location of the institution of the first author for each study found in the literature (either the state if inside Brazil, or the country if abroad) and the MEB participants. In case the first author was from a foreign institution, we checked whether there was collaboration with Brazilian institutions. To complete that information, we also recorded the biome where the studies were carried (since many studies are made in an ecosystem far from the authors' institutions), for both MEB participants and the literature review. Biomes were classified in the following categories: Amazon, Atlantic Forest, Caatinga, Cerrado, Pantanal, Pampas, Marine (organisms living in the Ocean or in estuary ecosystems), Multiple (in case of studies developed in more than one biome or studying animal migration beyond the borders of Brazil), and NA (simulation studies without a focus biome). Studies with freshwater organisms were classified according to the biome where they were located.

To understand which kind of ecological question has been asked, we used data on the classification that MEB attendees made on their research, regarding which components of the movement ecology framework proposed by Nathan et al. (2008) were related to their studies. Following the same method, we also classified the studies found between 1986-2015 (year of the first workshop in Brazil) in the literature review in one or more of these components. The classification followed the same terminology used by Holyoak et al. (2008), with the difference that we classified whether the components were present in the study approach, instead of the links between components.

We also identified, from both MEB participants' research and in the literature survey, the taxonomic group studied, and the technologies used in the studies. We intended to identify the most studied organisms and which technologies and tools have been used to answer movement ecology questions. We calculated the percentages of answers and classification in relation to the total of studies for both MEB questionnaire and the literature survey. Finally, we investigated the challenges and perspectives in movement ecology based on the discussions that occurred at the I MEB, the answers of the participants to these topics in the questionnaires and the patterns found in the studies from the literature survey.

Results

Movement ecology in Brazil: 30 years of growing research

The results of the literature survey showed that this topic of research has been steadily increasing in Brazil since 1999 – an average rate of 15.8% per year, which is twice as quickly than what was observed globally for movement ecology (7.2%; Holyoak et al. 2008; **Fig. 1**). A total of 310 studies were gathered, 51% of which were published since 2010. In the I MEB, although the focus of the participants' studies ranged from topics related directly to movement, as space use, foraging, and migration, to broader topics such as population dynamics, animal behavior and seed dispersal, 56.5% (56 people) of the participants declared they had explicit questions about movement ecology as main aims of their studies.

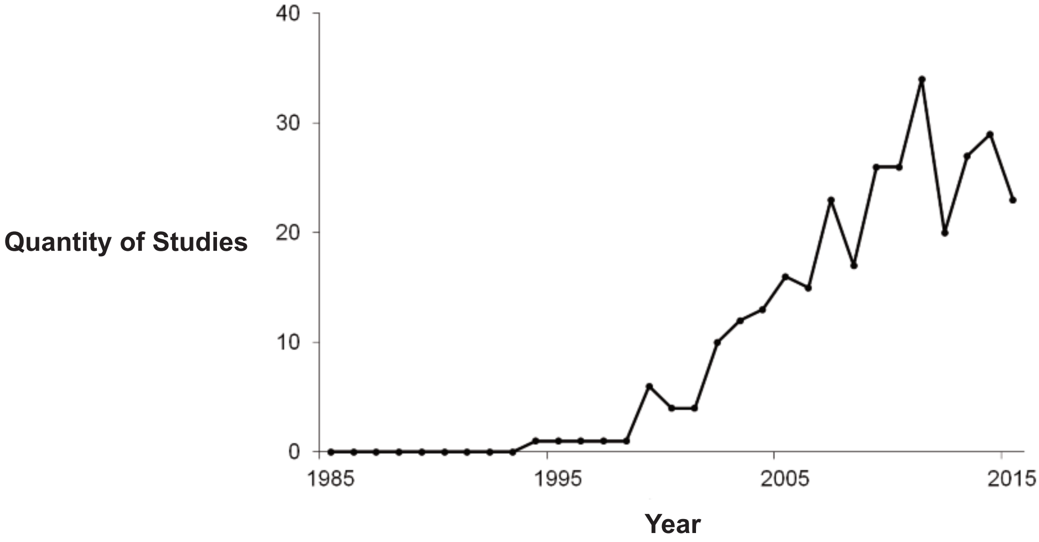

Figure 1. *Number of indexed studies related to animal movement research done in Brazil over 1986-2015 (Source: Web of Science). The number of studies started to increase in 1999. We searched the topics "movement* ecolog* Brazil"; "animal* movement* Brazil"; "animal* track* Brazil", "telemetry Brazil"; and "model* movement* Brazil". Also, the keywords "movement* ecolog*", "simulat* OR model*", and "random search* AND Lévy", were searched for with "Brazil" in the address field.*

Figura 1*. Número de estudios indexados relacionados con la investigación del movimiento animal realizados en Brasil durante 1986-2015 (Fuente: Web of Science). El número de estudios comenzó a aumentar en 1999. Buscamos los temas "movement* ecolog* Brasil"; "animal* movement* Brasil"; "animal* track* Brasil", "telemetry Brasil"; y "model* movement* Brasil". También se buscaron las palabras clave "movement* ecolog*", "simulat* OR model*", y "random search* AND Lévy", con "Brasil" en el campo de dirección.*

The increasing interest in the theme arose from the possibilities of ecological questions that might be answered with a growing amount of movement data, possible due to the recent technological tracking advances and their popularization (Kays et al. 2015), such as GPS devices, the most commonly used tracking device by the workshop participants. Most studies using this technology focused on conservation, use of space, home range metrics and animal behavior. These studies were conducted in large part by non-governmental organizations and public institutions.

Where is movement ecology being produced?

Despite the recent increase in movement ecology research in Brazil, this area is still incipient, with few specific working groups claiming to discuss and deal directly with movement ecology. The 6 institutions with proper movement ecology research groups present at I MEB were UNESP Rio Claro, UFRJ, UFMS-Campo Grande, USP-São Carlos and UFPR (**Fig. 2**).

Most participants of the I MEB were from institutions located in Southern and Southeastern Brazil (87 participants, 88%). The articles published in the period 1986–2015, which we gathered from the literature review, showed similar results – from the 229 studies whose first authors were from Brazilian institutions (~74% of all studies), 149 (65%) were led by researchers linked to institutions located only in five states in Southern and Southeastern Brazil (São Paulo, Rio de Janeiro, Minas Gerais, Paraná and Rio Grande do Sul, in a rank order of production). These results show that the country's scientific production on movement ecology is biased in favor of the richest and most populous regions of Brazil (IBGE 2017), as other authors have already pointed out regarding scientific production in all research areas in Brazil (Albuquerque et al. 2002; Silva and Simões 2004).

Another important consideration is that 26% (81 studies) of all studies from the literature review had foreigners as first authors (58% or 47 of them from USA and UK), and only 54% (44 studies) of these studies involved collaboration with Brazilian institutions. This means that 37 of these studies, or 12% of all studies, were authored by foreigners without collaboration with Brazilians. However, 38 of the 50 most cited articles have Brazilians as first authors or coauthors, which means that around 76% of the high impact scientific production in movement ecology in Brazil is made within the country.

Topic of research in Movement Ecology Framework

The 56 participants of the I MEB Workshop that had their studies focused on movement were asked to classify their own research based on the components of the Movement Ecology Framework from Nathan et al. 2008 — internal state, motion capacity, navigation capacity, movement path and external factors. We included the additional aspect "consequences of movement", which relates to ecological processes that result from movement, such as pollination, seed dispersal, predation–prey interaction and population dynamics (see the modifications to the framework, suggested by Jeltsch et al. 2013).

The most studied components reported by attendees were movement paths (n = 30, 53.5%) and external factors (n = 27, 48.2%). On the other hand, few studies involved motion capacity of organisms (n = 8, 14.2%), internal states (n = 10, 17.8%) and navigation capacity (n = 14, 25%). Around 26.7% (n = 15) of the studies were linked with the "consequences of movement" component (**Fig. 3**). We made the same classification to studies of the literature survey. The main components studied were motion capacity (n = 273, 88%), external factors (n = 230, 74%) and movement path (n = 202, 65%). The components less studied were internal state (n = 122, 39%), navigation capacity (n = 74, 24%), and consequences of movement (n = 68, 22%). We found significant differences when comparing the literature surveys and the questionnaire's answers (χ^2=29.2, df = 5, $p < 0.001$). This difference can be related to a lack of interpretation of the components' meaning proposed by Holyoak (2008) by MEB participants, especially the motion capacity.

The MEB participants' responses showed more studies related to internal state, less studies with external factors, and a small increase in studies on the consequences of movement. These results corroborate the revision presented by Holyoak et al. (2008), who showed that most of the studies have been trying to describe movement patterns, their correlations with environmental variables, and to correlate it with conservation issues. Studies of motion capacity, internal state motivation and navigation capacity require scientific techniques or scales that need integration with other areas of knowledge such as physics, neurosciences and physiology, and crossing these disciplinary boundaries is still a challenge (Holyoak et al. 2008). The disproportionality in the research investment among those different areas that compose the movement ecology paradigm

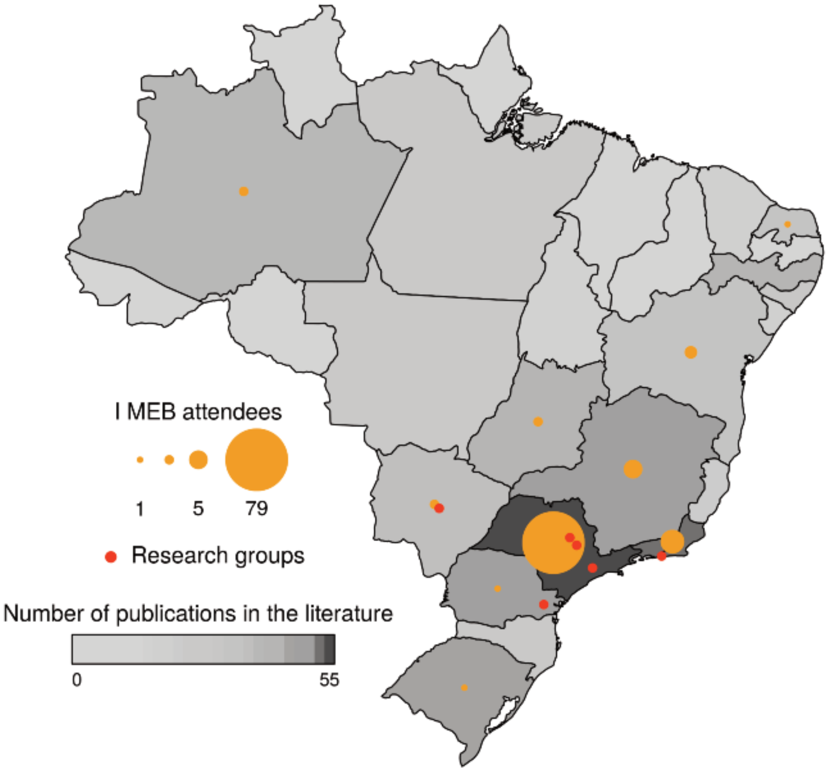

Figure 2. *Map representing movement ecology research in Brazil. The grey tons indicate the quantity of publications in Web of Science (WoS) per state; the red dots indicate the location of the research groups present at I MEB (UNESP Rio Claro, UFRJ, UFMS-Campo Grande, USP-São Carlos, UFPR and UFOP), and the orange circles indicate the location of the I MEB attendees.*

Figura 2. *Mapa representativo de la investigación en ecología del movimiento en Brasil. Los puntos grises indican la cantidad de publicaciones en Web of Science (WoS) por estado; los puntos rojos indican la localización de los grupos de investigación presentes en el I MEB (UNESP Rio Claro, UFRJ, UFMS-Campo Grande, USP-São Carlos, UFPR y UFOP), y los círculos naranjas indican la localización de los asistentes al I MEB.*

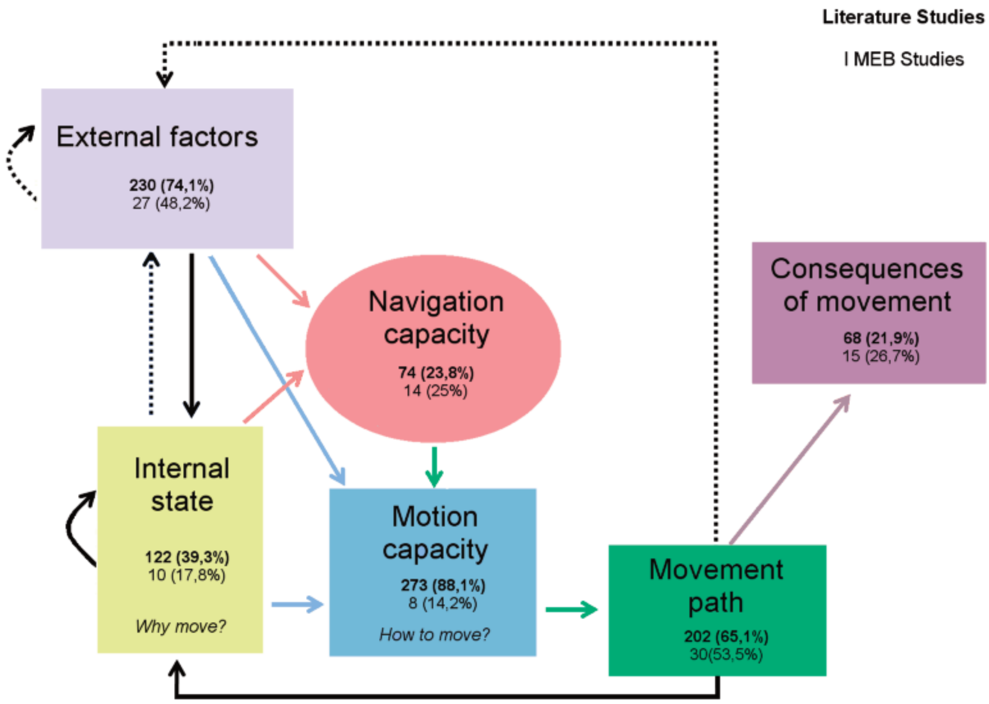

Figure 3. *Classification of research conducted by the I MEB attendees based on the "movement ecology framework" (Nathan et al. 2008) and on the additional component "consequences of movement" (related to ecological processes such as pollination, seed dispersal and predation). Most studies included movement path, external factors and consequences of movement components. Results from the literature survey are highlighted in bold.*

Figura 3. *Clasificación de las investigaciones realizadas por el I MEB basada en el "marco de la ecología del movimiento" (Nathan et al. 2008) y en el componente adicional "consecuencias del movimiento" (relacionado con procesos ecológicos como la polinización, la dispersión de semillas y la depredación). La mayoría de los estudios incluían los componentes de ruta de movimiento, factores externos y consecuencias del movimiento. Los resultados del estudio bibliográfico se destacan en negrita.*

could delay the real understanding that movement effects play in important questions where the context is composed by ecological, behavioral and evolutionary components.

Biomes

Another topic we explored in the survey was in which biomes the participants were developing their research. Because most participants were from institutions located in southeastern Brazil, and Atlantic Forest and Cerrado biomes are predominant in this region, those biomes were also the most studied according to the answers of the questionnaires (n = 22, 39.3%; and n = 16, 28.6%; respectively). Other important biomes such as Marine environments, (n = 6, 10.7%), the Amazon (the largest rainforest on Earth, n = 4, 7.1%), the Caatinga (the largest tropical semiarid area in the world, with strong seasonality, n = 1, 1.8%), and the Pantanal (one of the most important wetlands and freshwater systems in the world, n = 1, 1.8%) were hardly among the studies conducted by the participants of the I MEB (Alho et al. 1988; Moro et al. 2016). Four studies (7.1%) were conducted in multiple biomes and two (3,6%) were not related with any biome. There was no mention of studies focused on the Pampas, even though it is a threatened ecosystem (**Fig. 4**).

In the literature survey, we found that 107 (34.5%) studies were conducted in areas of Atlantic Forest, 57 (18.4%) in Marine environments, 34 (11%) in the Amazon, 33 (10.6%) in Cerrado, and 33 (10.6%) were simulations. The biomes less studied were Pampas (n=3, 1%), Caatinga (n=7, 2.3%) and Pantanal (n=12, 3.9%). Twenty-four studies (7.7%) were conducted in two or more biomes.

We also found differences when comparing the literature survey and the questionnaire answers (χ^2=17.6, df = 8, p = 0.02). In the literature we found more studies in the Cerrado, compared to the questionnaire answers. The biomes mostly studied reflect the regions where participants of the I MEB live and study. Beyond being just a geographic bias, these results are also related to other two important facts. First, some biomes are harder to reach since logistics and costs to travel to and explore remote areas are more expensive, consequently leading these areas to be less studied. Second, financial sources to research projects in Brazil are not uniformly distributed throughout the whole territory, with bigger investments in the southeastern region and most of the centers where movement research is being developed are placed in this region (Sidone et al. 2016; Chiarini et al. 2014).

Study taxa

The literature survey showed most studies focused on mammals (n = 128 studies, 41.3%) and birds (n = 50, 16.1%), followed by fishes (n = 41, 13.2%), reptiles (n = 30, 9.7%), simulated species (n = 28, 9%), invertebrates (n = 21, 6.8%), plants (n = 7, 2.3%) and amphibians (n = 3, 1%). One study (0.3%) compared movement patterns across a range of different taxa, as well as any taxa (n = 1, 0.3%). We observed similar results among the MEB workshop attendees whose study focus was movement and mammals (n = 32, 57.1%) or birds (n = 16, 28.6%). Overall patterns, however, differed between the literature and the I MEB (χ^2=53.4, df = 9, p < 0.001). The questionnaires revealed an increased interest in amphibians, compared to the literature results (n=6, 10.7%), what can be related to the recent development of small telemetry devices (Pittman et al. 2014; Kays et al. 2015), besides a better integration between ecology and physiology researchers. Both fishes and invertebrates constituted, each one, 7.1% (n=4) of study subjects. Plants (n=3, 5.4%), simulated species (n=3, 5.4%), and reptiles (n=2, 3.6%) received the least interest from I MEB workshop attendees. Nine participants (16.1%) are working in multiple taxa (**Fig. 5**).

The studied taxa scenario is in accordance with the revision made by Holyoak et al. (2008) for the movement ecology literature worldwide, where they report that mammals, birds, and fish were the study taxa for which the percentage of studies focusing specifically on movement was higher (55-59% of the articles). Furthermore, the patterns that influence the most studied taxonomic groups are also dependent on the places where research groups are working in movement ecology. In this specific case, available technology restricted most of the studies to larger vertebrates. Track equipment is generally expensive and as more technology is demanded to build smaller devices, the prices of equipment to monitor and transmit movement information for small organisms tend to be higher (Bridge et al. 2014; Kays et al. 2015).

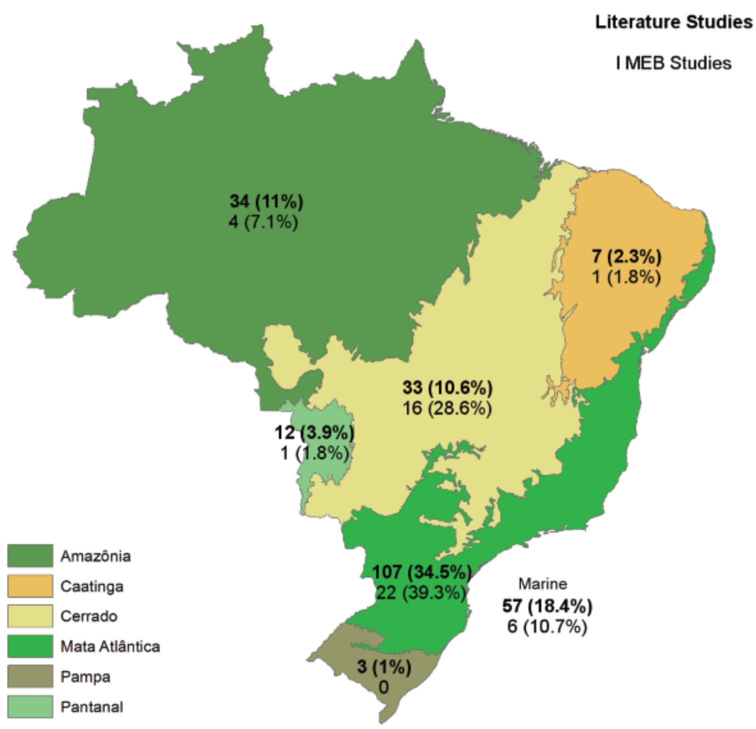

Figure 4. *Number (and percentage) of studies that were developed per biome by the I MEB attendees. Results from the literature survey are highlighted in bold.*

Figura 4. *Número (y porcentaje) de estudios desarrollados por bioma por los asistentes al I MEB. Los resultados del estudio bibliográfico se destacan en negrita.*

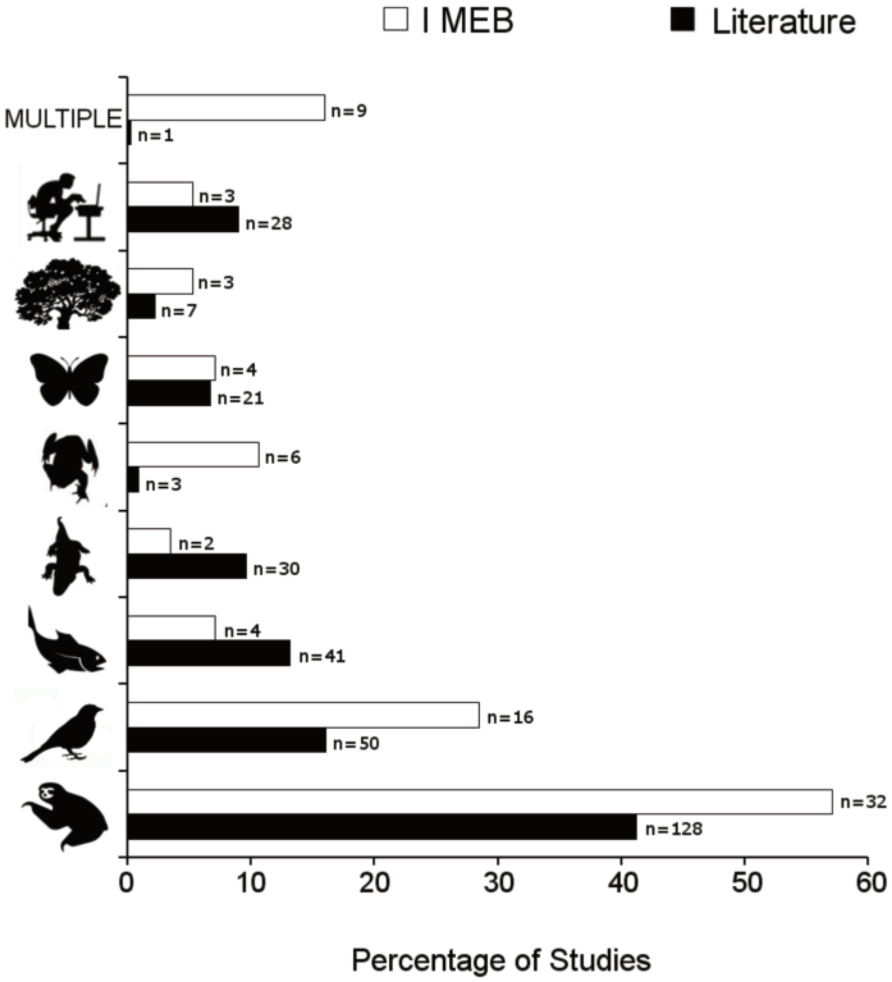

Figure 5. *Number (and percentage) of studies per taxon, according to the I MEB attendees (white) and the literature survey (black). The groups, from bottom to top, are mammals, birds, fishes, reptiles, invertebrates, amphibians, plants, and simulated species.*

Figura 5. *Número (y porcentaje) de estudios por taxón, según los asistentes al I MEB (blanco) y el estudio bibliográfico (negro). Los grupos, de abajo a arriba, son mamíferos, aves, peces, reptiles, invertebrados, anfibios, plantas y especies simuladas.*

Technologies

The literature survey revealed that the main technologies associated with movement ecology studies were VHF telemetry (n = 71 studies, 22.9%), capture-mark-recapture (n = 67, 21.6%) and simulation (n = 48, 15.5%). GPS was featured in less than 9% (n = 26) of studies, while 12.6% of the reviewed studies used other techniques (spool-and-line, geolocators, acoustic-based telemetry, accelerometers, isotopes, and genetic tools) and 16.5% used no technologies (direct observation accounted for 29 studies, or 9.4%, and the other ones did not measure movement directly). In contrast, the main technologies used by I MEB Workshop attendees were GPS telemetry (n = 26, 46.4% of participants whose research focus was movement ecology), followed by VHF telemetry (n = 20, 35.7%) and simulation (n = 8, 14.3%). Other techniques were used in approximately 28.6% of the participants, while about 14.3% of them reported not to use technologies. No participants used isotopes to track the movement of organisms (**Fig. 6**).

We observed differences between the results for the literature survey and the I MEB Workshop (χ^2 = 65.3, df = 12, p < 0.001), mainly because of the percentage of studies using mark-recapture was much greater in the literature, and because of the elevated frequency of studies with GPS tracking in the I MEB, compared to the literature. These differences were expected, given that the literature survey comprised 30 years of movement ecology research in Brazil and the I MEB gathered researchers that were developing their studies around 2015 - and the technology that researchers use tends to change as equipment and techniques develop. An interesting trend of our results (I MEB Workshop of 2015) compared to the literature review of the last 30 years is the gradual increase in the use of GPS tracking equipment and decrease of VHF. Although the battery duration of VHF devices is usually larger and the prices are lower, the use of GPS tracking equipment is getting more attractive to researchers since more options are available in the market and technology is being improved to lighter devices.

We also found differences comparing the studies using genetic tools (greater in literature), which might be related with a low integration between researchers working on movement ecology and genetics in Brazil. Another big difference was on studies on simulations. Probably this difference reflects the fact that most of the participants on I MEB were researchers and students of areas related to Ecology, and not directly involved with Math and Physics.

Big data, big challenges

New technologies also entail a new challenge: the large amount of data provided by high temporal resolution of movement trajectories (Kays et al. 2015; Nathan et al. 2022). Dealing with this kind of information requires specific knowledge to organize, process and analyze large quantities of data as well as to incorporate and relate all the available environmental spatial information, which is also becoming more developed and dynamic. This may explain why data analysis was the main challenge reported by the research participants in our survey (**Fig. 7**). This is an expected result, since most movement ecologists are specialists in environmental sciences, while the analysis in this kind of studies requires broader knowledge of math, statistics and physics (Nathan et al. 2022).

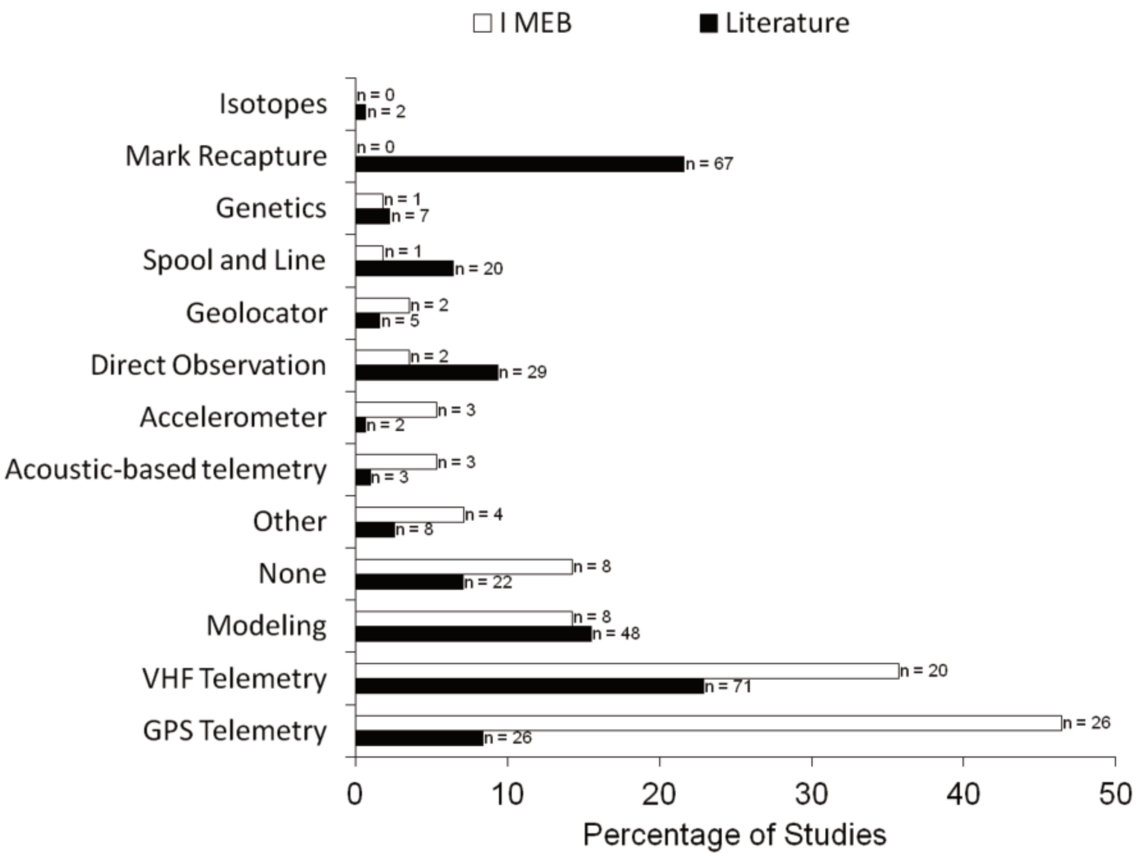

Figure 6. *Frequency distribution of types of technology used to measure/acquire movement data, according to the I MEB (black) and the literature survey (black).*

Figura 6. *Distribución de frecuencias de los tipos de tecnología utilizados para medir/adquirir datos de movimiento, según el I MEB (negro) y el estudio bibliográfico (negro).*

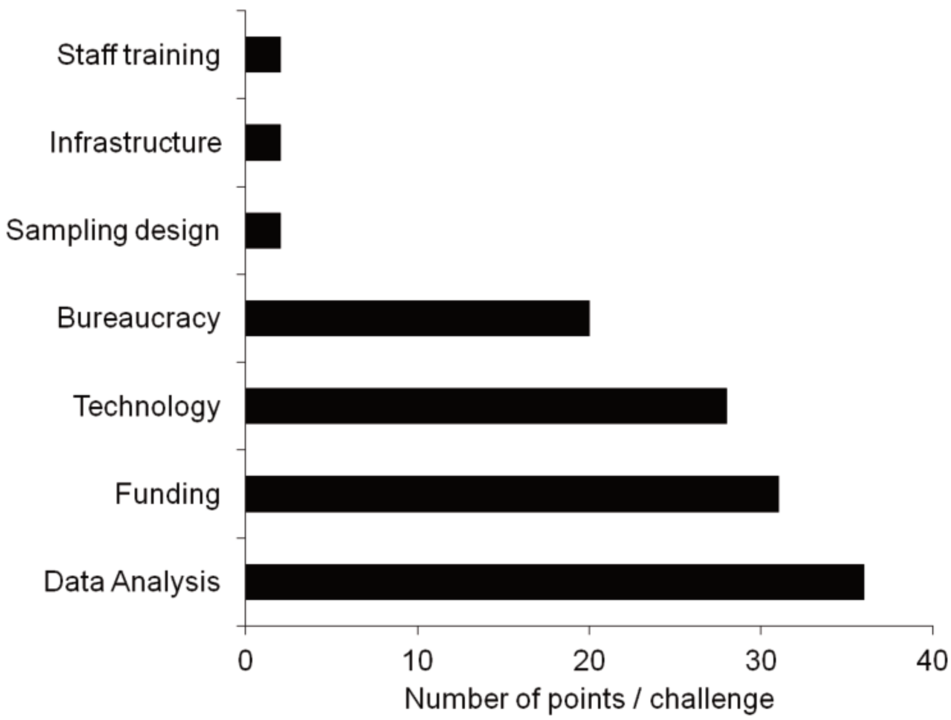

Figure 7. *Challenges of working in movement ecology according to the I MEB attendees.*

Figura 7. *Los desafíos de trabajar en ecología del movimiento según los asistentes al I MEB.*

The literature review and the MEB questionnaires presented nearly 15% of studies being developed using simulations, and many others also used complex statistical techniques to analyze data, as it is common in movement ecology (Kays et al. 2015). However, a great part of these studies (25 out of 48 studies, 52%) are developed exclusively inside Physics and Mathematics departments (without authors from biology or ecology departments), which indicates a difficulty in developing studies that integrate knowledge and tools from ecology and mathematics.

Over the last years, some institutions in Brazil are providing interdisciplinary trainings, like the Southern-Summer School on Mathematical Biology (IFT, Universidade Estadual Paulista) and the Hierarchical Modeling Workshop (Gonçalo Ferraz´s Lab, Universidade Federal do Rio Grande do Sul). These initiatives provide not just a deeper knowledge in methods and analyses, but also a better integration between researchers and students of different fields of science.

New technologies: little money and excessive bureaucracy

The I MEB survey showed that new technologies such as accelerometers and acoustic telemetry are starting to be used; however, we found no mention of innovative methods such as animal-mounted cameras or implanted electronics that obtain information about physiological parameters. This reflects the challenges described by the interviewed Brazilian researchers - scientific funding and bureaucracy involved in importing equipment were cited as the second and fourth greatest challenges, respectively (**Fig. 7**). The newest technologies that acquire real-time data or information on animal physiology and behavior are expensive, and funding for science in Brazil is proportionally low - around 50% less than top research countries like USA and Germany (data from 2013; World Bank Group 2016) – and is being reduced since 2013 by the Brazilian Federal Government (Angelo 2017).

These technological and bureaucratic challenges may also partly explain the bias towards studying larger animals such as mammals and birds, which can be tracked more easily than other organisms using GPS devices or other common technologies such as radio-telemetry and camera traps. The development of smaller devices is one priority in the field of movement ecology - allowing an increase of studies with small species respecting their weight limit (usually 5%), facilitating the fixation of the equipment and avoiding adverse effects on animal behavior (O'Mara et al. 2014; Kays et al. 2015; Marvin et al. 2016; Lameris and Kleyheeg 2017).

A need for national technology development

Few Brazilian companies currently manufacture tracking equipment (e.g. Trapa®, Nortronic® and Tigrinus®). Most researchers interested in using such equipment must import them and usually pay in US dollars, the value of which is five times higher on average than the Brazilian Real. In addition, such devices must be adapted to different climatic environments and often present problems related to batteries, durability and resistance. Researchers opting for such wildlife tracking technologies face a common situation: the inevitable bureaucracy and high taxation when ordering devices or sending them for maintenance or repairs.

For these reasons, some researchers have been developing alternative low-cost methods to study animal movement, such as the adapted GPS harness system from Zucco and Mourão (2009) or using methods that are less accurate but more affordable like direct observation (Paulo and Lopes 2014; Garrone Neto and Uieda 2012) and mark recapture (Barreto-Lima et al. 2013). We identified a great need for cheaper and national technology development to stimulate and assist the movement ecology of the Brazilian rich biodiversity.

Ethical issues on animal tracking

Another issue widely discussed during the event is the ethical aspects of marking animals with tracking equipment. The main questions concerned the right of biologists to anesthetize or euthanize animals during field work and the necessity of a veterinarian, the payment of whom would increase field work costs. On the other hand, the presence of a veterinary specialist in wildlife can be essential for monitoring the vital parameters of animals or acting in cases of a veterinary emergency.

In Brazil, this discussion started when the Biology Federal Council created the resolution 301/2012 that discussed the rights of biologist in capturing, containment, marking, release and collection of the animal specimen or to obtain samples of biological material from native wild animals, besides the rights of biologists to use anesthesia when necessary. In 2013, the Veterinary Federal Council started a lawsuit against the 301/2012 resolution claiming that biologists did not have the necessary training to execute anesthetic procedures in wild animals. Although the 301/2012 resolution is still valid, veterinarians and most biologists working in movement monitoring that gave their opinion during the I MEB think that the presence of a veterinarian during capturing and anesthesia procedures.

A recent Brazilian Resolution of the National Council for the Control of Animal Experimentation (No. 49, of May 7, 2021) provides for the mandatory training of personnel involved in teaching and scientific research activities that use animals. This training involves ethical, practical, and specific learning activities focused on the techniques and procedures that will be used in the research. This requirement may be one of the alternatives to address these ethical concerns.

It was also discussed that the specific training to capture, anesthetize and monitor wild animals is necessary for both biologists and veterinarians and with the increase of the accessibility to buy GPS tracking devices and more use of anesthetics it is important to promote the integration of common research interests between both professionals. This could be a promising and necessary alternative to reduce costs and risks for the health of animals during capture and handling procedures.

Data: to share or not to share?

Another issue raised in the discussions was a resistance to integrating and sharing data among researchers in the country. Data sharing through movement ecology databases, such as MoveBank® (Wikelski and Kays 2016) and ZoaTrack® (Dwyer et al. 2015), would save unnecessary investments and risks of injury inherent in capture procedures and fitting animals with tracking devices. Data integration and accessibility could also favor large-scale research and ecological investigation of interspecific relations. Lastly, the information provided by movement parameters may have applications that improve our understanding of the consequences of movement – individual-based models. This kind of model is a key tool in ecological forecasts, such as species invasion (Wilson et al. 2009), the spread of diseases (Fèvre et al. 2006) or seed dispersal (Morales et al. 2013), with potential implications for conservation.

Hot topics in I MEB

During the I MEB, 21 studies were presented, and the content included a wide spectrum of topics such as the use of various ecological modeling techniques, the testing of new technologies, and the practical applications of movement ecology data (the abstracts are available on-line –https://leec.eco.br/i-movement-ecology-brazil-workshop-i-meb/). All the studied species were vertebrates, four studies (19%) applied the knowledge obtained through animal movement monitoring to better comprehend seed dispersal and only one study (5%) focused on migration. Seventy-six percent of the studies (n = 14) were in areas suffering some anthropic impact such as forest fragmentation or river barriers, reflecting the current scenario of native habitat loss in most natural areas (Haddad et al. 2015). These studies are just a sample of all the movement ecology research being produced in Brazil, but they can be considered as representative of this field of study at the national level.

Current research – 2016-2022

After the first workshop in Brazil in 2015, the interest in this scientific topic, as well as the national and international collaborations significantly increased. As for quick research about publication between 2016 and 2022 (Supplementary Material; **Table SM3**), at least fifty-five new articles were published, with an average of 7.8 publications/year and oscillations in the number of publications over the years. Of these publications, only 9% of all studies with Brazilian researchers (5 studies – 3 from USA, 1 from Paraguay and 1 from Germany) had foreigners as first authors, with an evident growth of publications by Brazilian as first authors (50 studies). It was also evident the greater growth of collaborations between institutions located in different Brazilian states in the most recent publications, with emphasis on institutions from Mato Grosso do Sul and São Paulo with other states.

Between 2016-2022, most studies were focused on Cerrado, Pantanal and in the Atlantic Forest (respectively 29, 25, 22% of the studies that we found), studies on multiple biomes represented 11%, studies in the Amazon and simulations represented 5% each, finally marine studies represented 2% of our search. Also, the growth in interest in movement ecology brought the possibility of holding a second event in 2019 (https://ecomovbrasil.wixsite.com/home), with several presentations involving statistical movement modeling in applied contexts and the wider participation of international audience and key-note speakers Even though the event had a shorter duration (1 day), it was followed by a 4-day hands-on workshop focusing on improving students and participants abilities to analyze data and fomenting collaboration among them.

Conclusion

We know where we are; but where are we going?

The information gathered here on the scientific production within movement ecology in Brazil over these 30 years and on the results and discussions of the I MEB and the II MEB Workshops inspires some questions about the role of Brazil in understanding its ecosystems from the movement ecology perspective. The technological challenges and the lack of nationally manufactured technology, as well as the difficulties in analyzing complex and often large sets of movement data, are in part a reflection of the disciplinary character of Brazilian research institutions. Access to technology without bureaucracy, the growth of Brazilian companies that develop tracking equipment, enhanced national and international research networks and partnerships among biological and statistical sciences are some necessary factors that will shape the autonomy of Brazilian researchers working in the field of movement ecology.

These challenges can be overcome through collaborations among science fields and interdisciplinary research centers and institutes related to movement ecology. Furthermore, a comprehensive and multidisciplinary foundation at undergraduate and graduate research education institutions in Brazil (which are the main scientific producers in the country) would contribute to the formation of competent and well-rounded researchers able to develop new ideas and ecological questions, planning and conducting the collection and analysis of data, and writing projects and science skillfully.

There is still a need to link the mechanisms, processes and causes that influence movement in nature, to shape better ecological questions and to understand the consequences of movement for conservation. Specific capacitating training for wildlife veterinarians and biologists interested in handling wild animals would be an important development in Brazil. This kind of training is currently uncommon in the country despite the importance of dealing with animals in ways that guarantee safety for both the monitored species and the researcher during capture and monitoring procedures.

The main suggestion for the future directions in movement ecology research in Brazil is to explore organism movement data without forgetting the guiding principles, i.e. the underlying ecological questions. When this scientific field emerged, studies were often describing movement patterns, or they sought to understand very specific questions pertinent to related fields of knowledge such as the biomechanical, cognitive and optimality paradigms (Nathan et al. 2008). However, it is now time to move beyond researching animal movement for its own sake and integrate patterns and specific questions with ecological processes involved in movement itself, such as predation, pollination and seed dispersal. Further exploration on how movement facilitates natural forest restoration, ecosystem services and other phenomena could advance conservation policy planning and implementation.

Author´s contribution

Milene Amâncio Alves-Eigenheer: Formal analysis, Conceptualization, Data collection, Investigation, Methodology, Writing, Software, Validation. Bernardo Brandão Niebuhr: Formal analysis, Conceptualization, Data collection, Investigation, Methodology, Writing, Software, Validation. Julia Emi de Faria Oshima: Conceptualization, Data collection, Investigation, Methodology, Writing, Validation. Claudia Zukeran Kanda: Conceptualization, Data collection, Investigation, Methodology, Writing, Validation. Danielle Christine Tenório Leal Ramos: Conceptualization, Data collection, Investigation, Methodology, Writing, Validation. Natália Stefanini Da Silveira: Conceptualization, Data collection, Investigation, Methodology, Writing, Validation, Visualization. Laura Kyoko Honda: Data collection, Methodology, Writing, Validation. Patrícia Kerches-Rogeri: Conceptualization, Data collection, Investigation, Methodology, Writing, Validation. Lígia Pereira de Souza Salzano: Data collection, Methodology, Writing. André Luiz Bitencourt Moraes: Data collection, Methodology, Writing. Karl Stephan Mokross: Conceptualization, Investigation, Methodology, Writing, Validation. Milton Cezar Ribeiro: Project administration, Conceptualization, Writing, Validation.

Acknowledgments

Authors would like to acknowledge to Trapa Câmera, Programas de Pós-Graduação em Biodiversidade at UNESP Rio Claro. We also thank M. King, a native English speaker from Canada, for proofreading the manuscript. This work was supported by Fundação de Amparo à Pesquisa do Estado de São Paulo (grant numbers 2013/50421-2; 2014/23132-2; 2014/24291-4; 2016/09957–4; 2016/115953; 2020/01779-5; 2021/08534-0; 2021/10195-0; 2021/02132-8), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES), Fundação de Amparo à Pesquisa do Estado de Goiás (FAPEG) (CZK - fellowship number 202210267000834) and CNPQ (grant numbers 161089/2014-3; 442147/2020-1; 402765/2021-4; 313016/2021-6).

References

Albuquerque, E.M., Simões R., Baessa A., Campolina B., Silva L. 2002. A Distribuição espacial da produção científica e tecnológica brasileira: uma descrição de estatísticas de produção local de patentes e artigos científicos. *Revista Brasileira de Inovação* 1:225-251.

Alho, C.J.R., Lacher, JR E.T., Gonçalves, H. 1988. Environmental Degradation in the Pantanal Ecosystem. *BioScience* 38:164-171.

Altimiras, J., Anderson, W.G., 2016. Ecophysiology methods: Refining the old, validating the new and developing for the future. *Comparative Biochemistry and Physiology Part A: Molecular and Integrative Physiology* 202:1-2.

Angelo, C. 2017. Scientists plead with Brazilian government to restore funding. Nature 550, 166–167.

Baguette, M., Stevens, V.M., Clobert, J. 2014. The pros and cons of applying the movement ecology paradigm for studying animal dispersal. *Movement Ecology* 2:13.

Barreto-Lima, A.F., Pires, E.O., Souza, B.M. 2013. Activity, foraging mode and microhabitat use of *Enyalius perditus* (Squamata) in a disturbed Atlantic rainforest in southeastern Brazil. *Salamandra* 49: 177-185.

Best, R.C., Montgomery, G.G., Yamakoshi, M. 1981. Avaliação de técnicas de rádiorastreamento e marcação do peixe-boi da Amazônia, *Trichechus inunguis* (Mammalia: Sirenia). *Acta Amazônica* 2: 247-254.

Bridge, E.S, Thorup, K., Bowlin, M.S., Chilson, P.B., Diehl, R.H., Fléron, R.W., Hartl, P., et al. 2011. Technology on the Move: Recent and Forthcoming Innovations for Tracking Migratory Birds. *BioScience* 61: 689-698.

Chiarini, T., Oliveira, V.P., Silva Neto, F.C.C. 2014. Spatial distribution of scientific activities: An exploratory analysis of Brazil, 2000–10. *Science and Public Policy* 41: 625–640.

Cunningham, J.T., Reid, D.M. 1932. Notes on the relationship of some common birds of NE Marajo (N. Brazil) to their environment. Journal of Animal *Ecology* 1:65-68.

Davis, D.E. 1945. The Home Range of Some Brazilian Mammals. *Journal of Mammalogy* 26:119-127.

Dwyer, R.G., Brooking, C., Brimblecombe, W., Campbell, H.A., Hunter, J., Watts, M., Franklin, C.E. 2015. An open Web-based system for the analysis and sharing of animal tracking data. *Animal Biotelemetry* 3(1).

Fèvre, E.M., Bronsvoort, B.M.C., Hamilton, K.A., Cleaveland, S. 2006. Animal movements and the spread of infectious diseases. *Trends in Microbiology* 14:125–31.

Fuller, T., Bensch, S., Müller I., Novembre, J., Pérez-Tris, J., Ricklefs, R.E., Smith, T.B., Waldenström, J., 2012. The ecology of emerging infectious diseases in migratory birds: an assessment of the role of climate change and priorities for future research. *EcoHealth* 9:80-88.

Garrone Neto D., Uieda, V.S. 2012. Activity and habitat use of two species of stingrays (Myliobatiformes: Potamotrygonidae) in the upper Paraná River basin, Southeastern Brazil. *Neotropical Ichthyology* 10: 81-88.

Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., Lovejoy, T.E. 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances* 1:e1500052.

Holyoak M., Casagrandi R., Nathan R., Revilla E., Spiegel O. 2008. Trends and missing parts in the study of movement ecology. *Proceedings of the National Academy of Sciences* 105: 19060–19065.

IBGE 2017. *Censo Agropecuário, Florestal e Aquícola 2017*. Instituto Brasileiro de Geografia e Estatística, Governo Federal do Brasil. Ministério da Economia, Rio de Janeiro, Brazil. Available at https://censoagro2017.ibge.gov.br/sobre-censo-agro-2017.html

Jeltsch, F., Bonte, D., Pe'er, G., Reineking, B., Leimgruber, P., Balkenhol, N., Schröder, B., et al. 2013. Integrating movement ecology with biodiversity research - exploring new avenues to address spatiotemporal biodiversity dynamics. *Movement Ecology* 1: 1-6.

Kays, R., Crofoot, M., Jetz, W., Wikelski, M., 2015. Terrestrial animal tracking as an eye on life and planet. *Science* 348:aaa2748.

Kremen, C., Williams, N.M., Aizen, M.A., Gemmill-Herren, B., LeBuhn, G., Minckley, R., Packer, L., et al. 2007. Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land use change. *Ecology Letters* 10: 219–314.

Lameris, T.K.; Kleyheeg, E. 2017. Reduction in adverse effects of tracking devices on waterfowl requires better measuring and reporting. *Animal Biotelemetry* 5(24).

Marvin, D.C., Koh, L.P., Lynam, A. J., Wich, S., Davies, A.B., Krishnamurthy, R., Stokes, E., et al. 2016. Integrating technologies for scalable ecology and conservation. *Global Ecology and Conservation* 7: 262–275.

Mitchell, M.G.E., Suarez-Castro, A.F., Martinez-Harms, M., Maron, M., McAlpine C., Gaston K.J., Johansen, K., Rhodes, J.R. 2015. Reframing landscape fragmentation's effects on ecosystem services. *Trends in Ecology and Evolution* 30: 190–198.

Morales, J.M., García, D., Martínez, D., Rodriguez-Perez, J., Herrera, J.M. 2013. Frugivore Behavioural Details Matter for Seed Dispersal: A Multi-Species Model for Cantabrian Thrushes and Trees. *Plos One* 8: e65216.

Moro, M.F., Lughadha, E.N., Araújo, F.S., Martins, F.R. 2016. A Phytogeographical Metaanalysis of the Semiarid Caatinga Domain in Brazil. *The botanical Review* 82:91–148.

Nathan, R., Getz, W.M., Revilla, E., Holyoak, M., Kadmon, R., Saltz, D., Smouse, P.E. 2008. A movement ecology paradigm for unifying organismal movement research. *Proceedings of the National Academy of Sciences of the United States of America* 105:19052–19059.

Nathan, R., Monk, C.T., Arlinghaus, R., Adam, T., Alós, J., Assaf, M., Baktoft, H, et al. 2022. Big-data approaches lead to an increased understanding of the ecology of animal movement. *Science* 375(6582), eabg1780.

O'Mara, M.T., Wikelski, M., Dechmann, D.K.N. 2014. 50 years of bat tracking: device attachment and future directions. *Methods in Ecology and Evolution* 5: 311-319.

Paulo, J.L.A., Lopes, F.A. 2014. Daily activity patterns of Saanen goats in the semi-arid northeast of Brazil. *Revista Brasileira de Zootecnia* 43: 464-470.

Pittman S.E., Osbourn M.S., Semlitsch, R.D. 2014. Movement ecology of amphibians: A missing component for understanding population declines. *Biological Conservation* 169:44–53.

Sidone, O.J.G., Haddad, E.A., Mena-Chalco, J.P. 2016. Science in Brazilian Regions: Development of scholarly production and research collaboration networks. *TransInformação* 28:15-31.

Silva, L., Simões, R. 2004. Oportunidades tecnológicas e produção científica: uma análise microregional para o Brasil. *EURE* 30:85-102.

Trakhtenbrot, A., Nathan, R., Perry, G., Richardson, D.M. 2005. The importance of long-distance dispersal in biodiversity conservation. *Diversity and Distributions* 11: 173–181.

Williams, T.M., Wolfe, L., Davis, T., Kendall, T., Richter, B., Wang, Y., Bryce, C., et al. 2014. Instantaneous energetics of puma kills reveal advantage of felid sneak attacks. *Science* 346: 81–85.

Wikelski, M., Kays, R. 2016. *Movebank*: archive, analysis and sharing of animal movement data. Hosted by the Max Planck Institute for Ornithology. Available at: https://www.movebank.org/cms/movebank-main

Wilson, J.R.U., Dormontt, E.E., Prentis, P.J., Lowe, A.J., Richardson, D.M. 2009. Something in the way you move: dispersal pathways affect invasion success. *Trends in Ecology and Evolution* 24: 136–144.

World Bank Group 2016. *World Development indicators*. Available at: http://databank.worldbank.org/data/reports.aspx?source=2andseries=GB.XPD.RSDV.GD.ZSandcountry=

Zucco, C.A., Mourão, G. 2009. Low Cost Global Positioning System Harness for Pampas Deer. *The Journal of Wildlife Management* 73: 452-457.