Editorial: Biologging Special Feature

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Introduction

Imagine yourself, as an ecologist during field work, deep in the woods. *Eerily silent was the forest, when loudly from the tree above a wren started to sing. A quick, skilful use of the binoculars showed it was the male ringed last week, but swiftly the bird disappeared again among the leaves*. Similar difficulties in reliably observing the behaviour of the study species will be familiar to many ecologists and can strongly affect the choice of the study species; for example the ethologist and zoologist Nikolaas Tinbergen mentioned ease of observation as a motivation to study seabirds instead of forest birds (Tinbergen, 1939). Whilst certainly smart choices of the study species are key to successful research, typified by the Krogh principle: "for a large number of problems there will be some animal of choice, or a few such animals, on which it can be most conveniently studied" (Krogh, 1929), most terrestrial, aquatic, and aerial species cannot be well observed in the field. Technological solutions to record the movements, behaviour and physiology of animals, and associated methodological advancements for analysing the data collected, have revolutionised research in animal ecology and beyond (Kenward, 2001; Ropert-Coudert & Wilson, 2005; Ropert-Coudert, Beaulieu, Hanuise & Kato, 2009; Weimerskirch, 2009; Brisson-Curadeau, Patterson, Whelan, Lazarus & Elliott, 2017). The general term for this technological approach to study animals is called Biologging – 'the use of miniaturized animal-attached tags for logging and/or relaying data about an animal's movements, behaviour, physiology, and/or environment' (Rutz & Hays, 2009). It is closely related to and comprises the field of Biotelemetry – the remote measurement of the physiological conditions and activity/behavioural state of animals (Cooke et al., 2004), including biomedical applications in humans. The use of electronic loggers and transmitters offers unprecedented opportunities for uncovering the 'hidden lives' of animals and achieve a more mechanistic understanding of their ecology, and indeed the first ‘Virtual Issue’ (an online collection of papers published on a specific topic) published by the Journal of Animal Ecology was on ‘Biotelemetry and Biologging’ (Hays, 2008). Progress in this broad field has been exceptional in the last decade (Baratchi, Meratnia, Havinga, Skidmore & Toxopeus, 2013; Hussey et al., 2015; Kays, Crofoot, Jetz & Wikelski, 2015; Wilmers et al., 2015; Brisson-Curadeau et al., 2017; Tibbetts, 2017; Harcourt et al., 2019; Lowerre-Barbieri, Kays, Thorson & Wikelski, 2019), with exciting ongoing developments often occurring outside the field of animal ecology, including in different disciplines such as engineering, physics, or computer science. As such, the Journal of Animal Ecology issued an Open Call in 2018 for a *Special Feature* on ‘Biologging’, with the aim to showcase the novel developments in the field and the range of ecological questions which can now be addressed. The call resulted in the largest number of submitted manuscripts to any *Special Feature* in the Journal so far, which is a further indication of the interest in the topic. In this Editorial for the *Special Feature* we discuss the papers and topics covered and conclude with a brief outlook on ongoing and future developments.

Questions and topics covered by papers in the *Special Feature*

This *Special Feature* comprises 18 contributions, of which 13 present novel analyses and approaches, 3 are reviews, 1 is a meta-analysis, and 1 is a ‘How-To’ paper. Overall the papers cover a broad range of biologging technologies used to address a variety of fundamental questions in animal ecology, in aquatic, terrestrial and aerial species.

Three papers use light-level geolocator tags – miniature light-weight tags which measure ambient light levels to determine sunrise and sunset times, and hence estimate the approximate location of the animal (Wilson, Ducamp, Rees, Culik & Niekamp, 1992; Bridge et al., 2011) – to investigate the ontogeny of migratory behaviour in a long-lived seabird species (Campioni, Dias, Granadeiro & Catry, 2020), quantify effects of biologgers on the survival of tagged birds (Brlík et al., 2020), and provide a practical guide for the effective application of geolocator tags to track animals (Lisovski et al., 2020).

Seven papers use GPS loggers (for a review of GPS technology, see Tomkiewicz, Fuller, Kie & Bates, 2010), often combined with other sensor technologies such as accelerometers (see Shepard et al., 2008 for a review of the technology) and/or complementary methods including stable isotopes (see Hobson & Wassenaar, 2008 for information about the method) and behavioural observations (see Altmann, 1974 about observational methods to study animal behaviour). These GPS-based papers investigate predator-prey spatiotemporal interactions among elk *Cervus canadensis* and wolf *Canis lupus* (Cusack et al., 2020), quantify foraging niche overlap between sympatric seabird species (Dehnhard et al., 2020), or assess effects of personality on the consistency and repeatability of foraging trips in black-legged kittiwakes *Rissa tridactyla* (Harris et al., 2020). Other contributions present novel statistical methods to estimate individual variation in habitat selection (Muff, Signer & Fieberg, 2020) or to identify different movement modes in movement tracks (Patin, Etienne, Lebarbier, Chamaillé-Jammes & Benhamou, 2020), whereas other studies use fine-scale movement data to quantify the impact of wind turbines on functional habitat loss of a soaring terrestrial bird, the black kite *Milvus migrans* (Marques et al., 2020), or identify mating tactics of male African elephants *Loxodonta africana* (Taylor et al., 2020),

Seven papers primarily use other biologging sensors, alone or in combination with GPS tags, including inertial measurement unit sensors (see Baratchi et al., 2013 for information on the technology) such as accelerometers (Shepard et al., 2008) and magnetometers (see Williams et al., 2017 for information on magnetometers), or wet-dry and pressure and depth sensors (for a review see Ropert-Coudert et al., 2009), to markedly enhance the quantity of information on animal behaviour, individual state, and performance that can be obtained from the tagged animals. In particular, Wilson et al. (2020) critically assesses the use of metrics derived from accelerometers as a proxy for movement-related metabolic energy expenditure, with Benoit et al. (2020) using such metrics to quantify the cost of dispersal in roe deer *Capreolus capreolus*, and Corbeau et al. (2020) to quantify and compare average energy expenditure during different flight phases (soaring and flapping flight) in juvenile and adult great frigatebirds *Fregata minor* during their foraging trips, to study the ontogeny of flight and foraging behaviour. Bonnot et al. (accepted) use activity sensors in roe deer to disentangle the contrasting effects of predator density and human disturbance on diel activity patterns, whereas Nuiten et al. (accepted) present a new data compression approach for accelerometer data to overcome limitations in storage and energy capacity of loggers and aid data transmission whilst preserving the behavioural signal in the data. Barkley et al. (accepted) develop a novel multi-sensor biologging package, combined with a new statistical modelling approach, to detect and record sub-surface interactions among aquatic animals and ensuing movement-related behavioural responses, and apply it to Greenland sharks *Somniosus microcephalus*. More generally, Williams et al. (2020) review a large set of biologging sensors and address the question of how to select the most appropriate type or combination of devices for different biological questions. Finally, Joo et al. (2020) review an astonishing number of 58 different R packages which have become available in the last few years for analysing movement and biologging data, to act as a road map for ecologists and software developers.

We now describe in more detail the questions and topics addressed by the papers of this *Special Feature*. We structure this section around the diverse research questions and themes addressed by these article – ranging from topics in Behavioural Ecology, Community Ecology, Statistical Ecology and Functional Ecology, to methodological approaches, with some papers linking multiple research fields.

BEHAVIOURAL ECOLOGY

Ontogeny of behaviour in long-lived species

Understanding how behaviour arises is a key question in behavioural ecology. An adaptive behaviour can be informed by genetically controlled (innate) or learned components, but while some seem to be mostly programmed from birth, such as pecking in young domestic chicks (Dawkins, 1968), others, like the chaffinch song, have an innate basis but require the animal to practise and even learn from others (Thorpe, 1958). The scope for learnt behaviours may be particularly important in long-lived species, whose long lifespan increases the opportunity to practise and learn. In fact, the breeding deferral observed in many long-lived species is thought to be driven by high costs of early breeding (Lack, 1968), which could be caused by an incomplete set of skills (Daunt, Afanasyev, Adam, Croxall & Wanless, 2007). Thanks to ever smaller loggers which can record an animal's behaviour for ever longer periods of time, biologging is now allowing researchers to study with unprecedented detail how behaviours develop in slow-maturing animals. In this *Special Feature*, two papers push the boundaries of this emerging field and highlight the potential of biologging to advance our understanding of the ontogeny of animal behaviour.

Corbeau et al. (2020) demonstrate how juvenile great frigatebirds progressively improve their flight skills in the first few months following their first flight. Combining

GPS and accelerometers to distinguish between different flight behaviours (e.g. flapping, gliding, soaring), they show that juveniles' flight skills, initially inferior, improve gradually until becoming comparable to adults'. Interestingly, juveniles outperformed adults in some aspects, likely due to their morphology, and this may explain their remarkable months-long dispersive flights (Weimerskirch, Bishop, Jeanniard-du-Dot, Prudor & Sachs, 2016). These findings provide one of the first insights into the development of flight in long-lived birds (Yoda, Kohno & Yasuhiko, 2004; Rotics et al., 2016), and highlight the importance of early-life learning for the acquisition of physical skills.

Campioni et al. (2020) focus on another behaviour whose ontogeny is poorly understood: migration. Some animals learn their migration routes by following older conspecifics (Mueller, O'Hara, Converse, Urbanek & Fagan, 2013), while others follow an innate migratory distance and direction (Liedvogel, Åkesson & Bensch, 2011). Campioni et al. (2020) provide the first robust evidence for a third mechanism by which long-lived animals may acquire a migratory strategy. In an impressive long-term study tracking the migration of Cory's shearwaters *Calonectris borealis* across ages, from immatures to established breeders, they show that young birds follow more exploratory routes, and as they aged they gradually advance their migration timings and shorten their migration route. These findings show that learning, memory and experience can play a key role in the development of migration behaviour in long-lived species, and provide support for the exploration-refinement hypothesis (Guilford et al., 2011) as another mechanism for the development of migration behaviour in long-lived animals (Fayet, accepted).

Individual differences in behaviour and animal movements

Animal movements are fundamentally characterized by facultative switches between distinct movement modes (Fryxell et al., 2008) and many methods have been developed to identify and segment movement paths into different behavioural sections (Barraquand & Benhamou, 2008; Beyer, Morales, Murray & Fortin, 2013; Gurarie et al., 2015; Edelhoff, Signer & Balkenhol, 2016; Leos-Barajas et al., 2017; Michelot & Blackwell, 2019; Wang, 2019), where issues of scale and the difference between stationary and non-stationary movements are of particular importance (Benhamou, 2014). Here Patin et al. (2020) contribute to this growing literature by extending the *K*-segmentation approach of Lavielle (2005) to identify breakpoints in time-series of biologging data (or more generally any multivariate time-series) and potentially categorize resulting segments into common groups based on similarities in data characteristics. This provides a viable alternative to established but often statistically complicated methods (e.g. Hidden Markov models) for identifying "behavioural states" across time-series data. Indeed, the authors content that in some circumstances such segmentation can actually outperform these increasingly popular yet more complicated methods, and through application to both fine- and broad-scale biologging data (and through simulation) they demonstrate that their approach is scale-insensitive and may be applied to many ecologically relevant questions.

An alternative to using statistical segmentation methods to identify different movement modes is to observe the behaviour and state of tagged individuals, annotate the movement paths with the observed behaviour or state time series, derive from the annotated time series a set of criteria to distinguish different individual states or behaviour modes from the characteristics of the movement path alone, and use these rules to identify changes in state or movement mode from tagged animals which had not been also visually monitored. To do so, Taylor et al. (2020) employ a novel use of

Hidden Markov models, to identify different types of sexual behaviour in male African savanna elephants *Loxodonta africana*, as a function of their movement. The study shows that the activity and home range of elephants vary with male reproductive status and age and as such offer an exceptional opportunity to reliably estimate fitness metrics from movement itself. The authors further discuss the implications for the conservation and management of elephants, as well as the opportunities of long-term biologging of individuals for linking movement to life-history trade-offs.

Whilst an increasing body of research has shown the impact of consistent individual differences in behavioural phenotypes, called animal personalities or behavioural syndromes (Sih, Bell, Johnson & Ziemba, 2004; Réale et al., 2010), on foraging behaviour, exploratory movements and other spatial behaviours (Wilson & McLaughlin, 2007; Boon, Réale & Boutin, 2008; Minderman et al., 2010; van Overveld & Matthysen, 2010; Bijleveld et al., 2014; Villegas-Ríos, Réale, Freitas, Moland & Olsen, 2018), the important relationship between animal personality and foraging site fidelity has not been studied yet. Here, Harris et al. (2020) GPS-tagged over 100 breeding kittiwakes *Rissa tridactyla* across four colonies in Svalbard and used a robust type of novel object tests to measure the personality (especially, boldness) of the tagged individuals, Hidden-Markov models to identify the foraging sites at sea, and also quantified the repeatability of foraging trips. Their results show that individual differences in site fidelity can be driven by differences in individual personality, with bolder birds showing more repeatable foraging trips and a higher degree of site fidelity during the chick incubation stage. This has important implications for studies on individual differences in foraging behaviour and movements, indicating that in addition to age and sex or environmental drivers, also personality differences such as boldness will need to be considered.

Habitat selection

A key aim of movement ecology research is to quantify and predict habitat/resource selection by animals (Johnson, 1980; Arthur, Manly, McDonald & Garner, 1996; Rhodes, McAlpine, Lunney & Possingham, 2005; Christ, Hoef & Zimmerman, 2008; Moorcroft & Barnett, 2008; Matthiopoulos et al., 2015). Importantly, individual movements lead to the emergence of habitat selection and space use patterns at larger scales (Johnson, 1980; Moorcroft & Lewis, 2006; Börger, Dalziel & Fryxell, 2008) and differences in habitat use between individuals may be caused by differences in the individual state (Bijleveld et al., 2016) or the external environment (sensu Nathan et al., 2008). Quantifying individual differences in behaviour is a key focus of ecological research (Lomnicki, 1988; Bolnick et al., 2003) and implicit examples for resource selection functions (RSFs) have emerged as early as Gillies et al. (2006) and Hebblewhite and Merrill (2008). However, explicit examples were only occurring more recently, e.g., Dzailak et al (2011) and Leclerc et al. (2016). Though solutions existed for RSFs, these same solutions were less clear for step selection analysis (SSF, Fortin et al., 2005) or integrated step selection analyses (iSSF, Avgar, Potts, Lewis & Boyce, 2016).

Here Muff et al. (2020) resolve this challenge and present new statistical methods to estimate individual variation in habitat selection. The approach stems from the classical distinction between RSFs and SSFs, whereby SSF have been typically analysed as a conditional logistic regression, which compares used relocations in space to a paired set of available locations, and the more recent understanding that selection and avoidance are a Poisson point process (Hooten, Johnson, McClintock & Morales, 2017). The authors capitalize on this relationship between conditional logistic models and Poisson models and develop an approach based on stratum-specific fixed intercepts to estimate individual-specific slopes for resource selection, and consequently habitat selection parameters, for individuals and populations, using both frequentist and Bayesian approaches, and exemplify the approach using simulations and empirical datasets. This methodological advance represents a new benchmark for resource and habitat selection studies and allows researchers to confidently estimate individual variation, enabling an unprecedented opportunity to tackle questions of consistent-individual differences in the spatial ecology of habitat selection.

Quantifying and mapping the habitat used by animals is also critically important for applied questions. For instance, the growing need for renewable energy and the accompanying demand on land-use will cause increased human-wildlife conflict over habitat (Perrow, 2017). By combining state-of-the-art tracking devices, movement analyses, and environmental modelling, Marques et al. (2020) showed that soaring black kites avoided turbines during southward migration. With a marked loss of up to 14% of habitat for these birds, the authors highlight that the effect of wind turbines are greater than previously recognized and urge authorities to establish regulations that protect soaring habitat.

COMMUNITY ECOLOGY

Foraging behaviour and community ecology

A fundamental concept of the Movement Ecology framework is that the interactions between individual conditions and the characteristics and dynamics of the external environment generate the structure and geometry of movement paths (Nathan et al., 2008). Thanks to the rapid progress in biologging technology, there has been a consequent increase in detailed datasets recording the movements and behaviour or survival of multiple individuals from co-occurring species. Here, Dehnhard et al. (2020) use a large tracking dataset, combining GPS and wet-dry sensors, to investigate inter- and intraspecific niche overlap in three sympatrically breeding and closely related species of fulmarine petrels. They combine stable isotope analysis to investigate diet, GPS locations, immersion data, and expectation-maximisation binary clustering to identify foraging activities in the tracking data. Results reveal a high degree of inter- and intraspecific overlap in foraging distributions in both incubation and chick-rearing stages, with partial niche overlap, and low individual specialisation of foraging location or habitat. The study provides novel evidence that generalist foraging strategies may be advantageous in certain environments, even under competition from con- and hetero-specifics, a contrasting strategy to niche partitioning by allochrony exhibited by other Southern Ocean seabirds (Clewlow et al., 2019; Granroth-Wilding & Phillips, 2019).

Similarly, Cusack et al. (2020) combined movement and predation data from a predator-prey system – elk and moose living in the Yellowstone National Park - to investigate the controversial question regarding how much prey space use can minimise predation risk. Using a comprehensive set of empirical data, combined with a strong theoretical framework, addressing the three common challenges in the field – inconsistent measures of predation risk, lack of robust null expectations, and response measures obtained at biased spatiotemporal scales – the authors show an absence of strong spatio-temporal prey avoidance of predation risk, contrary to expectations.

Bonnot et al. (accepted) also tackle notions of predator influences on prey activity. Notably, the authors use activity sensor and accelerometer data from GPS collars that date back to 2003 from the EURODEER project, deployed on replicate populations of roe deer, to look at changes in diurnal activity rates in response to disturbance and predator risk, both by human hunters and lynx *Lynx lynx*. Roe deer seek refuge in time by shifting their activities toward nocturnality in response to human disturbance, captured here with the human footprint index (HFI); and this shift is exacerbated when HFI interacts with human hunters. However, the shift in roe deer activity faces a trade-off when juxtaposed to the presence of lynx, a nocturnal predator, highlighting how human activities may interfere with predator-prey interactions. More generally, the paper is also an example of how technological advances in biologging may also stimulate researchers to revisit large existing data sets through a contemporary biologging lens.

Finally, biologging provides new opportunities to examine intra-specific interactions for rare and hard-to-detect species. Barkley et al. (accepted) demonstrate this possibility by developing and testing a novel multi-sensor biologging package - composed of a combined acoustic telemetry transmitter and a mobile hydrophone, together with a tri-axial accelerometer and a temperature-pressure sensor, inside a floatation device to recover the tag at sea after deployment (including VHF and ARGOS transmitters) - deployed on a rare marine predator, the Greenland shark. This is paired to an analytical framework utilizing both simulation and statistical methods to estimate the likelihood of animal interactions based on device characteristics and duration of contact events between tagged individuals. The authors use these sensors to assess behavioural changes in swim speed and depth during and following contact events, and they discuss how this framework may be adapted and applied to many elusive marine species, with an exciting potential for future studies.

FUNCTIONAL ECOLOGY

Movement costs and energy expenditure

Daily energy needs of animals are mostly achieved by the metabolization of macromolecules (protein, lipid and carbohydrates) obtained from foods (Nagy, Girard & Brown, 1999). Environmental fluctuations influence the nutritional composition and energy contents of foods shaping the foraging behaviour and habitat use of wild animals (Machovsky-Capuska et al., 2018). Under these circumstances, field-based research has the challenge to overcome complex logistical constraints to collect reliable data on nutritional and energy requirements in free-ranging animals (Machovsky-Capuska et al., 2016). One of the main challenges in the wild is undertaking the prolonged observations necessary to estimate energy budgets. Here, Wilson et al. (2020) fill this knowledge gap by critically assessing the use of metrics derived from accelerometers as a proxy for movement-related metabolic energy expenditure.

Similarly, biologging enables Benoit et al. (2020) to quantify energy expenditure, coupling dynamic body acceleration and distance travelled as a proxy for energy, applied to the costs of dispersal. To stay, i.e., exhibit philopatry, or to go, i.e., disperse, is a fundamental question in how we understand animal movement with implications for gene flow and mating systems (Clobert, Le Galliard, Cote, Meylan & Massot, 2009). For roe deer Benoit et al. (2020) find that indeed, the transient phase of dispersal is markedly more costly; that these energy costs become more expensive in landscapes fragmented by roads; and that these costs are primarily spent at dawn. Where so many behavioural decisions are trade-offs between energy gained and energy spent, biologging helps us quantify then test these precise notions.

Conversely, Corbeau et al. (2020) combine GPS with measures of altitude and tri-axial acceleration to identify different flight behaviours (e.g. soaring, flapping) in great frigatebirds and quantify energy expenditure during those phases. This allows them to compare the ascent rate, gliding efficiency, flapping rate and proportion of time spent soaring or gliding between age classes and to test the hypothesis that juvenile birds have inferior flight skills than adults, but that they learn how to improve their skills over time (see also above in the Behavioural Ecology section).

METHODS – STATISTICAL ECOLOGY

Tagging effects and animal ethics

There is a general consensus that biologging has improved our understanding of charismatic and cryptic species (Ropert-Coudert & Wilson, 2005; Wilmers et al., 2015). It is also widely known that that the deployment of biologgers presents considerable welfare concerns to those animals carrying them (Culik & Wilson, 1991; Wilson & McMahon, 2006). Hawkins (2004) identified major areas for refinement including the attachment procedures, optimal location of the devices on the body and their dimensions (e.g. mass, shape and size). Although few studies assessed the behavioural reactions to deployments (e.g. Vandenabeele et al., 2014; Pearson et al., 2017; Pearson, Jones, Brandon, Stockin & Machovsky-Capuska, 2019), here Williams et al. (2020) discuss how many of these concerns have not been fully addressed yet. In particular, the authors highlight the need for more comprehensive information on physical principles (e.g. fluid dynamics) to understand the real short- and long-term effects for animals. Among those potential consequences, this issue presents a contribution from Brlik et al. (2020) that uses meta-analysis to quantitatively review the existent literature to examine effects of geolocator tagging on small bird species. Their findings suggest that the devices' load may lead to a potential effect on the survival of tagged birds. Overall, both articles are consistent with their recommendations on the consideration of ethical aspects and scientific benefits prior to biologger deployments.

Handling and analysing biologging data

Critical to the application of biologging technologies to ecological research is the proper management of the devices themselves and preparation of the tremendous amounts of data they produce. It is not uncommon for a single high-resolution device to collect millions if not billions of observations on a given deployment (Kays et al., 2015), which complicates storage both on-board the device during data collection and subsequently in data drives. These are themselves limited by battery capacities relative to animal size such that deployments do not adversely affect the animal nor the quality of resulting data. Rarely are such issues covered in great detail in the ecological literature, and a significant contribution of this *Special Feature* is in providing guidelines and best practices for would-be users. Here, Lisovski et al. (2020) provide a practical "How-To" paper on the effective use of light-based geolocators, and how resulting data should be handled and manipulated for subsequent analyses. This includes multiple online resources laying out in an approachable fashion the deceptively complex matter of linking daylight hours to decimal-degree global positioning systems. Critically, the authors also provide data standards and archiving guidelines to facilitate reproducibility of geolocator studies and encourage common data reporting structures to simplify data sharing and comparison between studies, which may move this body of scientific data toward strongly needed common data standards for all such studies.

Promising approaches to solve the data storage and transmission problem of modern biologgers, comprise methods to compress, subset, and analyse on-board the data before storing and transmitting the data (Cox et al., 2018; Heerah, Cox, Blevin, Guinet & Charrassin, 2019), or the use of AI on board to trigger the sensors to record data only when the animals display the behaviour of interest (Korpela et al., 2019). Here, Nuiten et al. (2020) present a new data compression approach for summarising accelerometer data on board to increase on-board storage capacity and reduce power requirements for transmitting the data, whilst retaining the original data's information. Using data from tagged Bewick's swans *Cygnus columbianus bewickii* the authors compare the information from short bouts of raw accelerometer data and from summary statistics, collected in parallel, demonstrating a six-fold reduction in data size and energy use whilst maintaining the same accuracy in behaviour identification and time budgets. The gains in power use and storage size can hence be used to decrease tag size, or to increase the monitoring effort and obtain a more detailed quantification of the time budget of tagged individuals.

Optimising the use of biologging sensors, however, requires a good technical knowledge of the characteristics of the many different sensors available. Interestingly, in the Preface to the influential 'Handbook on Biotelemetry and Radio Tracking' (Amlaner & Macdonald, 1980) the Editors motivated the need to bring together researchers from contrasting fields: "The development of ever more obscure jargon is divisive among scientists, inhibiting communication between people who might otherwise solve at least some of each other's problems. Nowhere is this unnatural rift more obvious than between biologists and engineers and yet with a little patience it can be bridged." Forty years later, the importance of establishing multidisciplinary collaborations is as important as ever to take full advantage of the opportunities offered by the biologging revolution, as Williams et al. (2020) highlight in a wide-ranging review of the field in this *Special Feature*. Importantly, the authors identify four critical areas – questions, sensors, data, analyses – for multidisciplinary collaborations and synthesize it into an Integrated Biologging Framework (IBF), to aid decision making for ecologists to optimise the use of biologging technologies for answering ecological questions. Based on the IBF the authors also address in detail the crucial, yet seldom asked, question of how best to match biological questions with the most appropriate type and combination of biologging sensors, as well as how to optimise the experimental/field design and how best to visualise and analyse big, complex biologging data, and conclude with an outlook of the most promising future developments for optimising the use of biologgers.

Finally, as the amount and complexity of movement and environmental data has increased exponentially, so has the number of statistical and mathematical methods to analyse movement data, as well as the number of dedicated software packages for movement analyses. Most researchers are not aware anymore of the number and diversity of software packages available for movement analysis, often hampering the ability to select the most appropriate method and software tool for the question addressed. Here, Joo et al. (2020) provide the first critical analysis of the field and review a staggering 58 different packages available for analysing movement and biologging data in the R Software Environment (R Development Core Team, 2019). Importantly, the authors first set up a workflow model for the analysis of tracking data, identifying three key analysis stages which they use to group the software packages by the function(s) performed, before reviewing each package, including assessing the quality of the available supporting documentation. Furthermore, the authors use network analysis to assess the linkages between packages, highlighting the fragmented and isolated development of the field, and provide a comprehensive road map for ecologists and software developers to choose the most appropriate tool for a given research question and improve the quality of software packages.

Future Outlook

Notwithstanding the current ‘biologging revolution’, the movements and behaviour of most animal species still cannot be studied using biologgers, or not over sufficiently long-time scales. Continued technological development – including smaller sensors, smaller batteries, novel attachment and recovery methods and their ability to transmit their recorded data – will be crucial to advance research in animal ecology and will only be achieved through enhanced multidisciplinary collaborations. These cross disciplinary teams could lead to fresh insights into a wide range of research fields enabling for example (a) assessments of anthropogenic pollution impacts in wildlife (e.g. oil spills, Montevecchi et al., 2011; Montevecchi et al., 2012; marine debris ingestion, Fukuoka et al., 2016); (b) predictions of the distribution and expansion of invasive species (Lennox, Blouin-Demers, Rous & Cooke, 2016); (c) a better understanding of the terrestrial and aquatic species involved in human-wildlife conflicts and their possible geographic areas (Cooke et al., 2017); and (d) unravelling the effects of climate change and environmental fluctuations in habitat use, foraging behaviour and nutrient acquisition in individuals and their communities (Machovsky-Capuska et al., 2018). Exciting ongoing technical developments include the miniaturization of GPS-technology, but also the development of alternative technology that uses smaller tracking-devices (MacCurdy et al., 2009; Toledo, Kishon, Orchan, Shohat & Nathan, 2016; MacCurdy, Bijleveld, Gabrielson & Cortopassi, 2019), and biologgers with improved sensors to measure speed, reduce the impact of devices on tagged animals, enable lifetime tracking, and novel approaches for real-time processing and remote transmission of data (Williams et al., 2020). Similarly, a strong advancement of the theoretical and mathematical foundations of movement ecology, combined with improved computational methods, will be required to take full advantage of the unprecedentedly rich and complex types and amounts of data now collected by modern biologging tags.

Not only will multidisciplinary collaborations be key to achieve strong future progress, ecologists will also need to considerably invest to obtain the necessary training and expertise to properly deploy and recover the loggers, and specialised training in data management, storage, manipulation, and visualization; programming, workflow development, and metadata standards; and quantitative and statistical analysis. The papers included in this *Special Feature* demonstrate an exciting set of the leading-edge scientific and methodological advancement which can be achieved and give an idea of how much more may yet be possible with modern biologging technologies. We hence submit that biologging, if fully adopted by the ecological, conservation, and management communities, has the capacity to transform modern ecology as much as VHF, ARGOS, and GPS did 30-50 years ago. It is our hope that this *Special Feature* highlights the many fascinating insights enabled by the creative application of biologging to animal ecology and encourages the upcoming generation of scientists to consider adopting them for their own research.

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