frontiers in Marine Science

PERSPECTIVE
published: 16 March 2017
doi: 10.3389/fmars.2017.00070

Addressing Challenges in the Application of Animal Movement Ecology to Aquatic Conservation and Management

Matthew B. Ogburn[1]*, Autumn-Lynn Harrison[2], Frederick G. Whoriskey[3], Steven J. Cooke[3,4], Joanna E. Mills Flemming[3,5] and Leigh G. Torres[6]

[1] Smithsonian Environmental Research Center, Edgewater, MD, USA, [2] Migratory Bird Center, Smithsonian Conservation Biology Institute, National Zoological Park, Washington, DC, USA, [3] Ocean Tracking Network, Dalhousie University, Halifax, NS, Canada, [4] Department of Biology, Carleton University, Ottawa, ON, Canada, [5] Department of Mathematics and Statistics, Dalhousie University, Halifax, NS, Canada, [6] Department of Fisheries and Wildlife, Marine Mammal Institute, Oregon State University, Hatfield, OR, USA

OPEN ACCESS

Edited by:
Samantha Oester,
George Mason University, USA

Reviewed by:
Leslie Cornick,
Alaska Pacific University, USA
Joshua Adam Drew,
Columbia University, USA

***Correspondence:**
Matthew B. Ogburn
ogburnm@si.edu

Specialty section:
This article was submitted to Marine Conservation and Sustainability, a section of the journal Frontiers in Marine Science

Received: 02 December 2016
Accepted: 28 February 2017
Published: 16 March 2017

Citation:
Ogburn MB, Harrison A-L, Whoriskey FG, Cooke SJ, Mills Flemming JE and Torres LG (2017) Addressing Challenges in the Application of Animal Movement Ecology to Aquatic Conservation and Management. Front. Mar. Sci. 4:70. doi: 10.3389/fmars.2017.00070

The dynamic nature of most environments forces many animals to move to meet their fundamental needs. This is especially true in aquatic environments where shifts in spatial ecology (which are a result of movements) are among the first adaptive responses of animals to changes in ecosystems. Changes in the movement and distribution of individuals will in turn alter population dynamics and ecosystem structure. Thus, understanding the drivers and impacts of variation in animal movements over time is critical to conservation and spatial planning. Here, we identify key challenges that impede aquatic animal movement science from informing management and conservation, and propose strategies for overcoming them. Challenges include: (1) Insufficient communication between terrestrial and aquatic movement scientists that could be increased through cross-pollination of analytical tools and development of new tools and outputs; (2) Incomplete coverage in many studies of animal space use (e.g., entire life span not considered); (3) Insufficient data archiving and availability; (4) Barriers to incorporating movement data into decision-making processes; and (5) Limited understanding of the value of movement data for management and conservation. We argue that the field of movement ecology is at present an under-tapped resource for aquatic decision-makers, but is poised to play a critical role in future management approaches and policy development.

Keywords: conservation, movement ecology, telemetry, tagging, decision-making, life history

INTRODUCTION

Animal movement studies are conducted for many reasons including basic scientific discovery, as tools for education and outreach, to address management and conservation questions, as part of environmental assessments, to determine the success or failure of management or conservation interventions, and for long-term monitoring of environmental change. Theoretical, methodological and technological advances have provided insights into aquatic animal behavior amid constantly-changing environmental conditions that could not be obtained using traditional conceptual frameworks and methods (Nathan et al., 2008; Costa et al., 2012; Hussey et al., 2015). This paper complements recent reviews discussing key achievements (Hussey et al., 2015) and key questions (Costa et al., 2012) in the study of aquatic movement ecology, and comprehensive reviews of how movement data have been used successfully in conservation decision-making and practice (for fish, see Cooke et al., 2016 and Crossin et al., accepted; for seabirds see Burger and Shaffer, 2008 and Lascelles et al., 2016), or how their use could be improved (McGowan and Possingham, 2016; McGowan et al., 2016).

A framework for linking movement ecology with wildlife management and conservation was recently introduced by Allen and Singh (2016) and adapted by McGowan and Possingham (2016) to illustrate how information about movement attributes of species can enhance conservation planning. We submit that many conservation issues can benefit from a more pro-active and strategic approach to integrating movement ecology with conservation efforts given the dynamic nature of aquatic ecosystems in space and time. We also discuss recent criticisms of the ability of movement data to aid conservation efforts. We review five key challenges to maximizing the conservation impact of movement ecology information in aquatic conservation, and we propose strategies for overcoming them. Two challenges focus on the conduct of movement science, one on building a culture of data openness, and two on practical applications of movement information. The challenges, while similar to other fields of study, are nonetheless critical to aquatic conservation, and management:

(1) Disciplinary divides: Inadequate integration of terrestrial and aquatic movement science limits scientific advances and practical applications.
(2) Limited coverage: Many studies are limited in their coverage of the space animals use throughout their lifetimes.
(3) Insufficient data access and sharing: Improving data archiving, access and use in collaborative research projects is needed to enhance the study of animal movement.
(4) Incorporating movement data into decision-making: There are often real or perceived barriers to incorporating movement data into decision-making processes.
(5) Assessing the utility and impact of movement information: The full value of movement data for management and conservation is poorly documented.

BRIDGING THE TERRESTRIAL/AQUATIC DIVIDE

The goal of movement ecologists in all ecosystems is similar: gain a better understanding of animal distribution and resource use by collecting individual-level location data. Despite inherent differences, more integration between movement ecology studies in aquatic and terrestrial ecosystems will enhance methods, ecological knowledge, effort efficiency, and conservation or management.

Strengths in Our Differences

A major difference between terrestrial and aquatic movement data lies with the inherent ability to observe these ecosystems. While it is often possible to observe tagged individuals for behavior validation in terrestrial systems, this type of validation is rare in aquatic systems. Aquatic observing systems often generate temporally irregular data that include substantial measurement error (due typically to the limits of satellite communication and receiver coverage). These features generally make it harder to infer "true" behavioral states of tagged aquatic animals. Behavior ambiguity often affects the analytical focus (i.e., in aquatic systems analyses typically focus on behavior segmentation and habitat use, compared to terrestrial work that addresses mechanistic drivers or resource use), and accuracy limitations can cause substantial difficulties with aligning environmental data for associated habitat modeling.

Both terrestrial and aquatic ecologists strive to link movement patterns with environmental covariates, which tend to be better mapped (more coverage, more diversity of data layers, and higher spatial resolution) in terrestrial systems. Aquatic systems are typically highly spatially and temporally variable (Carr et al., 2003), emphasizing the need for dynamic environmental layers acquired from satellites or *in situ* sensors.

Terrestrial movement data are typically two-dimensional, reflecting the traditional view of terrestrial ecosystems (Carr et al., 2003), although this is changing (e.g., deployment of altimeters or accelerometers on birds) with growing attention to the dynamics of air (Shepard et al., 2016) and the developing field of aeroecology (Kunz et al., 2008). Aquatic movement data are regularly interpreted in three spatial dimensions, for example, vertical diving behavior of marine mammals coupled with horizontal space-use. Additionally, terrestrial technologies allow tracking of tiny animals (spiders: Persons and Uetz, 1997, fruit flies: Berman et al., 2014), but aquatic efforts are often more size-limited by the sizes of water-proof housings, captivity challenges, capture/re-capture ability, and battery power demands.

Both marine and terrestrial systems are being impacted by climate change and shared model frameworks will allow ecologists to comparatively evaluate responses to environmental change. Moreover, those managing and designing aquatic protected areas can learn from successes and critiques of the longer established and better studied terrestrial protected area networks (Brockington et al., 2008; Watson et al., 2014). Conversely, terrestrial managers can learn from aquatic efforts at applying protected area approaches to dynamic features in marine environments (Hyrenbach et al., 2000; Lewison et al., 2015), and to river catchments and hydrologic regimes for conservation of freshwater species and habitats (Saunders et al., 2002). Anthropogenic impacts in the systems may be different, but the goals of reduced impact and sustainable extraction align.

Pathways to Better Integration

- Align our analysis platforms and use standard terminology. A unified analytical framework [through free software like R (R Development Core Team, 2015) to ensure broad participation and dissemination] and terminology system (see Holyoak et al., 2008) will enhance cross-pollination of methods and findings.

- Analytical methods should be applicable to both ecosystems. Opportunities to explore ecological systems more thoroughly occur when methods that are applied predominantly in one discipline are transferred to the other. For example, Byrne and Chamberlain (2012) successfully applied first passage time (Fauchald and Tveraa, 2003)—a traditionally marine analysis method–on a terrestrial animal. Additionally, state-space models are widely applied in aquatic systems to account for location error (Auger-Méthé et al., 2016), which can benefit terrestrial studies. Many aquatic movement studies are "discovery science" because species' distributions are still being documented, whereas terrestrial studies are more likely to involve advanced hypothesis testing and conservation applications (Carr et al., 2003), such as understanding of animal movement in human-altered landscapes (Anadón et al., 2012), or theoretical studies on predator-prey dynamics (Vanak et al., 2013; Courbin et al., 2014).
- Use ecosystem differences to enhance our collective ecological understanding of animal movement patterns. For instance, examine behavioral differences and similarities in animals that cross ecosystem boundaries like semi-terrestrial crabs (Hübner et al., 2015), alligators (Nifong et al., 2015) and gulls that forage in both ecosystems (Christel et al., 2012). Furthermore, studies that assess the mechanistic drivers of movement, such as internal and external factors (Nathan et al., 2008), regardless of ecosystem can inform conservation efforts.
- Encourage participation of terrestrial movement ecologists at biologging conferences (Rutz and Hays, 2009, http://www.bio-logging.net) where they are typically underrepresented.
- Cross-validate methods and ecological concepts through comparative ecosystem meta-analyses. These efforts can address pressing questions such as how movement patterns scale with body size in different ecosystems. The recently developed method, Residence in Space and Time (RST; Torres et al., 2017), shows promise for such meta-analyses.

EXPANDING MOVEMENT STUDIES TO COMPLETE LIFE HISTORIES AND FULL LIFETIMES

Effective conservation and management of terrestrial and aquatic species requires a full understanding of changes in habitat use and movement patterns as organisms age/grow. However, the ability to study movement throughout the complete life history of species and full lifetime of individuals remains a great challenge, hampered in many cases by small body sizes, long lifetimes, and challenging habitats for tracking of individuals. In aquatic systems, technologies have expanded from inexpensive traditional mark-recapture tagging approaches (Kohler and Turner, 2008) to coordinated electronic telemetry efforts costing millions of dollars and scaled to cover ocean basins (Block et al., 2011; Cooke et al., 2011; Hussey et al., 2015). Innovative tags have enabled movement studies throughout a greater range of life stages and for longer durations (Hazen et al., 2012; Pinnix et al., 2013; Mansfield et al., 2014; Lu et al., 2016). New platforms (moored buoys, autonomous marine vehicles) are extending the reach of acoustic telemetry studies, with the potential for global networks of oceanographic, and other infrastructure (Hayes et al., 2013). In addition, existing data highlight the need to recognize differences in movement patterns among individuals, life stages, and segments of populations (Secor, 1999).

When tracking is not technologically feasible or is cost-prohibitive, other solutions are needed to understand the consequences of movement for conservation. For example, biogeochemical tracers in hard body parts can provide records of environmental conditions throughout part or all of an individual's lifetime (including larval stages of fish, mollusks, and other taxa) from which habitats used and trophic level can be inferred (Rubenstein and Hobson, 2004; Thorrold et al., 2007; McMahon et al., 2013). Model simulations can provide insights into movement patterns when behavioral responses to environmental conditions are known (e.g., Criales et al., 2015). As we move to an ecosystem based management framework, the costs of acquiring movement data may be reduced by focusing studies on flagship species (Douglas and Verissimo, 2013), but this approach deserves careful evaluation using multi-species tracking datasets (Harrison, 2012).

Opportunities to Expand Movement Studies

- Work with tag manufacturers to design and test new technologies, recognizing that collaborations between manufacturers and scientists can be risky for both sides due to potential loss of investment, anticipated data, and time. Allow for publication of such trials (even when negative) to provide transparency and understanding of the process (Scarpignato et al., 2016).
- Integrate conventional tagging, telemetry, biogeochemical markers, and other emerging techniques to provide full life-time data.
- Increase the geographic coverage and funding stability of telemetry networks, including extending networks into the open ocean by taking advantage of existing oceanographic and industrial infrastructure.
- Initiate and prioritize funding for long-term studies of movement of individuals and populations to evaluate responses to global change.

STRENGTHEN OUR CULTURE OF COLLABORATION

Animal movement studies are most often conducted by individuals or small research teams doing time-limited work on a single species within a restricted geographic range. While this has been valuable, it fails to unlock the full potential of the data (Nguyen et al., 2017). Archiving ecological data provides a historic record against which future studies can be compared, makes the information available for cross-species comparisons, allows secondary analysis of data that may differ from the vision of the original investigators, and provides other benefits to science and society (Whitlock, 2011). Although synthesizing and archiving data is challenging (Thomas, 2009; Tenopir et al., 2011), collaborations (Block et al., 2011), and data repositories (e.g., http://www.Movebank.org, http://www.seabirdtracking.org/, http://motus.org/, https://animaltracking.aodn.org.au/, http://oceantrackingnetwork.org/, https://ioos.noaa.gov/project/atn/) have fostered immense knowledge growth. Limitations still exist including the lack of common metadata and data standards; the need for secure data storage systems with long-term funding for development, staffing, and regional network building; and common frameworks for quality control and sufficient annotation of archived data. A remaining challenge is to develop a culture of data sharing (Vision, 2010; Whitlock, 2011; Vines et al., 2013) that reverses the traditional scientific view that data are not public but rather belong to the investigator who conducted the study (Nguyen et al., 2017). However, collaborating scientists are more prolific publishers, and the scale and scope of their collaborative work makes it more impactful (e.g., Piwowar et al., 2007; Young et al., 2013).

Pathways to Strengthen Our Science Culture

- Share and promote research (with colleagues and students) highlighting the personal, institutional, and societal benefits of collaboration and data sharing, including greater individual scientific productivity and better science being done on larger geographic scales.
- Incorporate existing tracking scientists, and new users (especially students), into large research teams to unlock the present and future potential of tracking technology.
- Movement data networks must adopt common data and metadata standards across networks or develop open source code to merge data when common formats are not practical. Open source software and architecture will help keep data systems affordable and accessible to all countries.
- Researchers and movement data networks should systematically archive and make freely available published and historical data for use in novel analytical activity and to document animal adaptation to changing environmental conditions, while addressing potential challenges of free access to ongoing long-term studies (Mills et al., 2015).
- Researchers should contribute data to shared data repositories that ensure that the originators of the data are given full credit for their work, that undertake quality control during the submission process to minimize data recording error, and that require sufficient annotation to fully inform future researchers of the characteristics and potential limitations of the work and to help avoid analytical errors and incorrect interpretations (e.g., https://www.dataone.org/best-practices, Whitlock, 2011; White et al., 2013; Goodman et al., 2014; Roche et al., 2015).

INCORPORATING MOVEMENT DATA INTO DECISION-MAKING PROCESSES

There is growing recognition that environmental managers do not make full use of all available scientific evidence when making decisions (Pullin et al., 2004), tending instead to rely on their experiences or those of their colleagues (Pullin et al., 2004; Young et al., 2016). The reasons for this apparent science-action divide are many (see Cook et al., 2013) and best considered in the context of knowledge mobilization, rooted in principles such as reliability, trust, access, institutional/cultural norms, values, and properties of one's network (Young et al., 2016). Knowing the factors that impede knowledge mobilization can be useful for identifying strategies to effectively employ movement data in decision-making. These factors include the perception of disruptive technology (Young et al., 2016), concerns about data reliability due to low detection efficiency, error in location estimates, or the effect of the tracking device on the animal's behavior, and that the data generated simply fail to provide the information that managers need (Young et al., 2013) even when studies are conducted at the request of managers and engage managers in the research process (e.g., reviewed in Cooke et al., 2016; Crossin et al., accepted).

Movement data generated using biologging tools (Rutz and Hays, 2009) are one of multiple types of scientific evidence. Given the novelty of these tools to managers, it is necessary to understand how the use of information generated by new technologies compares to the use of information provided by more conventional tools or dogma/experience. It is also important to communicate the types of new knowledge that can be generated by electronic tagging that have here-to-fore been unattainable [e.g., determining fate of individual animals (Yergey et al., 2012); identifying behavioral changes using animal movement data (Gurarie et al., 2009); evaluating consistency of behaviors and thus behavioral syndromes in wild animals (Harrison et al., 2015)]. Preparing managers for the capabilities of the technology so that they are ready to receive new, potentially transformative, information may be a useful strategy for helping to ensure that data from electronic tagging studies are more likely to be used by managers. There is a growing suite of "success stories" in application of electronic tagging and tracking techniques to management (e.g., Deguchi et al., 2014, 2016; Crossin et al., accepted) which is promising, but there is also need for additional social science research to better understand (from the perspective of the manager) the relevance of these techniques to contemporary management challenges.

How to Strengthen the Impact of Telemetry Information

- Engage early and often with practitioners and stakeholders to co-create the research agenda and ensure that tracking studies are relevant to end-users. At this stage it is important to not over-sell the technology and recognize that tracking may not be the only or best tool to address a given management question.
- Recognize that tracking studies generate data that contain inherent uncertainties (e.g., Does the tagged animal behave the same way as an untagged animal? How do we know if we are tracking the animal we tagged or something that ate it? How big a sample size is needed to reliably address a given question?). Address issues about limitations and uncertainty directly where possible through parallel methodological studies (e.g., tagging validation studies).

- Work closely with data scientists to create data visualization products that are both informative and impactful.

UNDERSTANDING THE IMPLICATIONS OF ANIMAL MOVEMENT RESEARCH

Conservation dollars are limited and are allocated toward a diversity of species, habitats, countries, and activities (McCarthy et al., 2012). Many studies demonstrate that conservation resources are often not optimally allocated (Wu and Boggess, 1999; Wilson et al., 2006). For example, charismatic species (and scientific activities) receive disproportionately more funding than less-charismatic species (Bennett et al., 2015). Animal tracking has arisen as one such charismatic activity that has produced a number of scientific and conservation achievements (Burger and Shaffer, 2008; Block et al., 2011; Lascelles et al., 2016; Crossin et al., accepted).

Since studies of animal movement can be expensive (McGowan et al., 2016), managers with conservation dollars to spend should carefully weigh whether the data obtained through studies of animal movement are worth the cost given actual conservation needs and anticipated return on investment (McGowan and Possingham, 2016). We agree it is important to strategically assess the cost-benefit function of expensive tracking studies. However, funding for both animal movement studies and conservation practice comes from a wide variety of sources for a wide variety of reasons (Evans et al., 2012; Lennox, 2012). Some studies are born of the passion of private individuals, companies, or foundations for species, oceans, or animal migration and others are driven by organizational missions grounded in basic science or education and outreach. We posit that dollars coming from the above sources are often not in play in conservation prioritization discussions and their effect on conservation practice is added value.

It can be difficult to measure the downstream conservation impacts of movement studies that were conducted primarily for other reasons (basic science and discovery, education, etc.). These endeavors have drawn criticism regarding return on investment of expensive satellite tracking studies in the context of specific conservation planning scenarios (see McGowan et al., 2016). However, studies of animal movement include a wide-variety of approaches that provide critical pieces of biological information enabling us to determine species abundance trajectories, ecology of critical life history stages, and acceptable harvest or bycatch rates.

Suggestions to Improve the Conservation Relevance and Return on Investment of Animal Movement Data Include

- The field of conservation biology in general has difficulty translating research into action (Robinson, 2006). To achieve greater conservation impact, review and employ recommendations from the extensive literature on bridging the "knowing-doing" gap in fields as diverse as business management and healthcare (Pfeffer and Sutton, 2000), and targeted conservation recommendations (Habel et al., 2013; Hulme, 2014; Thornhill, 2014).
- When an animal movement study is determined to be the most strategic approach to achieve a conservation objective, estimate the optimal investment needed (McGowan and Possingham, 2016) and the value of additional scientific information to reducing uncertainty in the decision, including the the potential costs of NOT knowing the answer (Morgan et al., 1992) when tracking technology could provide it.
- Be a good steward of data and data products to maximize their value. Contribute data to shared repositories to ensure data are available for use in conservation and management and be available to managers and educators to help them understand the species and data.
- When data have been meaningful to a conservation process, consider contributing examples to synthetic initiatives like http://www.conservationevidence.com.

SYNTHESIS

Movement ecology can provide unique insights for addressing difficult conservation and management problems. Technological advances are likely to increase the number and type of species and the range of body sizes followed, and habitats examined in movement studies. Improved data archiving, accessibility, sharing, and collaborative analysis/meta-analysis will increase the use of movement data. However, effective visualization, interpretation and communication of the results of movement studies will be critical to applying movement data in decision-making processes and realizing their full potential for conservation and management.

AUTHOR CONTRIBUTIONS

MO and A-LH were co-leads of manuscript preparation. Each author contributed a draft section of the manuscript and all six authors participated in revision.

ACKNOWLEDGMENTS

This manuscript synthesizes and extends the presentations and discussions of the International Marine Conservation Congress Symposium "Perpetual Motion: The Future of Animal Movement Ecology in Marine Conservation" held on 31 July 2016 in St. John's, Newfoundland, Canada. We thank two reviewers for comments that substantially improved the manuscript. Funding support for the symposium was provided by VEMCO, OregonRFID, Ocean Tracking Network (via NSERC and CFI), ConocoPhillips Global Signature Programs for the Migratory Connectivity Project, and the Smithsonian Institution Office of the Under Secretary for Science.

REFERENCES

Allen, A. M., and Singh, H. J. (2016). Linking movement ecology with wildlife management and conservation. *Front. Ecol. Evol.* 3:155. doi: 10.3389/fevo.2015.00155

Anadón, J., Wiegand, T., and Giménez, A. (2012). Individual-based movement models reveals sex-biased effects of landscape fragmentation on animal movement. *Ecosphere* 3, 1–32. doi: 10.1890/ES11-00237.1

Auger-Méthé, M., Field, C., Albertsen, C. M., Derocher, A.E., Lewis, M. A., Jonsen, I. D., et al. (2016). State-space models' dirty little secrets: even simple linear Gaussian models can have estimation problems. *Sci. Rep.* 6:26677. doi: 10.1038/srep26677

Bennett, J. R., Maloney, R., and Possingham, H. P. (2015). Biodiversity gains from efficient use of private sponsorship for flagship species conservation. *P. R. Soc. B* 282:20142693. doi: 10.1098/rspb.2014.2693

Berman, G. J., Choi, D. M., Bialek, W., and Shaevitz, J. W. (2014). Mapping the stereotyped behaviour of freely moving fruit flies. *J. R. Soc. Interface* 11:20140672. doi: 10.1098/rsif.2014.0672

Block, B. A., Jonsen, I. D., Jorgensen, S. J., Winship, A. J, Shaffer, S. A., Bograd, S. J., et al. (2011). Tracking apex marine predator movements in a dynamic ocean. *Nature* 475, 86–90. doi: 10.1038/nature10082

Brockington, D., Duffy, R., and Igoe, J. (2008). *Nature Unbound: Conservation, Capitalism, and the Future of Protected Areas*. London: Routledge.

Burger, A. E., and Shaffer, S. A. (2008). Perspectives in ornithology: application of tracking and data-logging technology in research and conservation of seabirds. *Auk* 125, 253–264.

Byrne, M. E., and Chamberlain, M. J. (2012). Using first-passage time to link behaviour and habitat in foraging paths of a terrestrial predator, the racoon. *Anim. Behav.* 84, 593–601. doi: 10.1016/j.anbehav.2012.06.012

Carr, M. H., Neigel, J. E., Estes, J. A., Andelman, S., Warner, R. R., and Largier, J. L. (2003). Comparing marine and terrestrial ecosystems: implications for the design of coastal marine reserves. *Ecol. Appl.* 13, S90–S107. doi: 10.1890/1051-0761(2003)013[0090:cmatei]2.0.co;2

Christel, I., Navarro, J., Del Castillo, M., Cama, A., and Ferrer, X. (2012). Foraging movements of Audouin's gull (*Larus audouinii*) in the Ebro Delta, NW Mediterranean: a preliminary satellite-tracking study. *Estuar. Coast. Shelf Sci.* 96, 257–261. doi: 10.1016/j.ecss.2011.11.019

Cook, C. N., Mascia, M. B., Schwartz, M. W., Possingham, H. P., and Fuller, R. A. (2013). Achieving conservation science that bridges the knowledge–action boundary. *Conserv. Biol.* 27, 669–678. doi: 10.1111/cobi.12050

Cooke, S. J., Iverson, S. J., Stokesbury, M. W., Hinch, S. G., Fisk, A. T., VanderZwaag, D. L., et al. (2011). Ocean Tracking Network Canada: a network approach to addressing critical issues in fisheries and resource management with implications for ocean governance. *Fisheries* 36, 583–592. doi: 10.1080/03632415.2011.633464

Cooke, S. J., Martins, E. G. Struthers, D. P., Gutowsky, L. F. G., Power, M., Doka, S. E., et al., (2016). A moving target – incorporating knowledge of the spatial ecology of fish into the assessment and management of freshwater fish populations. *Environ. Monit. Assess.* 188:239. doi: 10.1007/s10661-016-5228-0

Costa, D. P., Breed, G. A., and Robinson, P. W. (2012). New insights into pelagic migrations: implications for ecology and conservation. *Annu. Rev. Ecol. Evol. Syst.* 43, 73–96. doi: 10.1146/annurev-ecolsys-102710-145045

Courbin, N., Fortin, D., Dussault, C., and Courtois, R. (2014). Logging-induced changes in habitat network connectivity shape behavioral interactions in the wolf–caribou–moose system. *Ecol. Monogr.* 84, 265–285. doi: 10.1890/12-2118.1

Criales, M. M., Cherubim, L. M., and Browder, J. A. (2015). Modeling larval transport of pink shrimp in south Florida: dynamics of behavior and tides. *Mar. Coast. Fish.* 7, 148–176. doi: 10.1080/19425120.2014.1001541

Crossin, G.T., Heupel, M., Holbrook, C.M., Hussey, N., Lowerre-Barbieri, S., Nguyen, V.M., et al. (accepted). Acoustic telemetry and fisheries management. *Ecol. Appl.*

Deguchi, T., Sato, F., Eda, M., Izumi, H., Suzuki, H., Suryan, R. M., et al. (2016). Translocation and hand-rearing result in short-tailed albatrosses returning to breed in the Ogasawara Islands 80 years after extirpation. *Animal Conserv.* doi: 10.1111/acv.12322. [Epub ahead of print].

Deguchi, T., Suryan, R. M., Ozaki, K., Jacobs, J. F., Sato, F., Nakamura, N., et al. (2014). Translocation and hand-rearing of the short-tailed albatross *Phoebastria albatrus*: early indicators of success for species conservation and island restoration. *Oryx* 48, 195–203. doi: 10.1017/S0030605313000094

Douglas, L. R., and Verissimo, D. (2013). Flagships or battleships: deconstructing the relationship between social conflict and conservation flagship species. *Environ. Soc. Adv. Res.* 4, 98–116. doi: 10.3167/ares.2013.040107

Evans, D. M., Barnard, P., Koh, L. P., Chapman, C. A., Altwegg, R., Garner, T. W. J., et al. (2012). Funding nature conservation: who pays? *Anim. Conserv.* 15, 215–216. doi: 10.1111/j.1469-1795.2012.00550

Fauchald, P., and Tveraa, T. (2003). Using first-passage time in the analysis of area-restricted search and habitat selection. *Ecology* 84, 282–288. doi: 10.1890/0012-9658(2003)084[0282:UFPTIT]2.0.CO;2

Goodman, A., Pepe, A., Blocker, A. W., Borgman, C. L., Cranmer, K., Crosas, M., et al. (2014). Ten simple rules for the care and feeding of scientific data. *PLoS Comput. Biol.* 10:e10035432. doi: 10.1371/journal.pcbi.1003542

Gurarie, E., Andrews, R. D., and Laidre, K. L. (2009). A novel method for identifying behavioural changes in animal movement data. *Ecol. Lett.* 12, 395–408. doi: 10.1111/j.1461-0248.2009.01293.x

Habel, J. C., Gossner, M. M., Meyer, S. T., Eggermont, H., Lens, L., Dengler, J., et al. (2013). Mind the gaps when using science to address conservation concerns. *Biodivers. Conserv.* 22:2413. doi: 10.1007/s10531-013-0536-y

Harrison, A.-L. (2012). *A Synthesis of Marine Predator Migrations, Distribution, Species Overlap, and Use of Pacific Ocean Exclusive Economic Zones*. Doctoral dissertation. University of California, Santa Cruz, Santa Cruz, CA.

Harrison, P. M., Gutowsky, L. F. G., Martins, E. G., Patterson, D. A., Cooke, S. J., and Power, M. (2015). Personality-dependent spatial ecology occurs independently from dispersal in wild burbot (*Lota lota*). *Behav. Ecol.* 26, 483–492. doi: 10.1093/beheco/aru216

Hayes, S. A., Teutschel, N. M., Michel, C. J., Champagne, C., Robinson, P. W., Fowler, M., et al. (2013). Mobile receivers: releasing the mooring to 'see' where fish go. *Environ. Biol. Fish.* 96, 189–201. doi: 10.1007/s10641-011-9940-x

Hazen, E. L., Maxwell, S. M., Bailey, H., Bograd, S. J., Hamann, M., and Gaspar, P. (2012). Ontogeny in marine tagging and tracking science: technologies and data gaps. *Mar. Ecol. Prog. Ser.* 457, 221–240. doi: 10.3354/meps09857

Holyoak, M., Casagrandi, R., Nathan, R., Revilla, E., and Spiegel, O. (2008). Trends and missing parts in the study of movement ecology. *Proc. Nat. Acad. Sci. U.S.A.* 105, 19060–19065. doi: 10.1073/pnas.0800483105

Hübner, L., Pennings, S. C., and Zimmer, M. (2015). Sex- and habitat-specific movement of an omnivorous semi-terrestrial crab controls habitat connectivity and subsidies: a multi-parameter approach. *Oecologia* 178, 999–1015. doi: 10.1007/s00442-015-3271-0

Hulme, P. E. (2014). EDITORIAL: Bridging the knowing-doing gap: know-who, know-what, know-why, know-how and know-when. *J. Appl. Ecol.* 51, 1131–1136. doi: 10.1111/1365-2664.12321

Hussey, N. E., Kessel, S. T., Aarestrup, K., Cooke, S. J., Cowley, P. D., Fisk, A. J., et al. (2015). Aquatic animal telemetry: a panoramic window into the underwater world. *Science* 348:1255642. doi: 10.1126/science.1255642

Hyrenbach, K. D., Forney, K. A., and Dayton, P. K. (2000). Marine protected areas and ocean basin management. *Aquat. Conserv.* 10, 437–458. doi: 10.1002/1099-0755(200011/12)10:6<437::AID-AQC425>3.0.CO;2-Q

Kohler, N. E., and Turner, P. A. (2008). "Stock structure of the blue shark (*Prionace glauca*) in the North Atlantic Ocean based on tagging data," in *Sharks of the Open Ocean: Biology, Fisheries and Conservation*, eds M. D. Camhi, E. K. Pikitch, and E. A. Babcock (Oxford, UK: Blackwell Science), 339–350.

Kunz, T. H., Gauthreaux, S. A. Jr., Hristov, N. I., Horn, J. W., Jones, G., Kalko, E. K., et al. (2008). Aeroecology: probing and modeling the aerosphere. *Integr. Comp. Biol.* 48, 1–11. doi: 10.1093/icb/icn037

Lascelles, B. G., Taylor, P. R., Miller M. G. R., Dias, M. P., Oppel, S., Torres, L., et al. (2016). Applying global criteria to tracking data to define important areas for marine conservation. *Divers. Distrib.* 22, 422–431. doi: 10.1111/ddi.12411

Lennox, M. (2012). *Monies for Marine Conservation: A White Paper Examining New Funding Sources for Oceans and Coasts.* The Nature Conservancy.

Lewison, R., Hobday, A. J., Maxwell, S., Hazen, E., Hartog, J. R., Dunn, D. C., et al. (2015). Dynamic ocean management: Identifying the critical ingredients of dynamic approaches to ocean resource management. *Bioscience* 65, 486–498. doi: 10.1093/biosci/biv018

Lu, J., Deng, Z. D., Li, H., Myjak, M. J, Martinez, J. J., Xiao, J., et al. (2016). A small long-life acoustic transmitter for studying the behavior of aquatic animals. *Rev. Sci. Instr.* 87:114902. doi: 10.1063/1.4967941

Mansfield, K. L., Wyneken, J., Porter, W. P., and Luo, J. (2014). First satellite tracks of neonate sea turtles redefine the 'lost years' oceanic niche. *Proc. R. Soc. B.* 281:20133039. doi: 10.1098/rspb.2013.3039

McCarthy, D. P., Donald, P. F., Scharlemann, J. P. W., Buchanan, G. M., Balmford, A., Green, J. M. H., et al. (2012). Financial costs of meeting global biodiversity conservation targets: current spending and unmet needs. *Science* 338, 946–949. doi: 10.1126/science.1229803

McGowan, J., Beger, M., Lewison, R. L., Harcourt, R., Campbell, H., Priest, M., et al. (2016). Integrating research using animal-borne telemetry with the needs of conservation management. *J. Appl. Ecol.* doi: 10.1111/1365-2664.12755. [Epub ahead of print].

McGowan, J., and Possingham, H. P. (2016). Commentary: Linking movement ecology with wildlife management and conservation. *Front. Ecol. Evol.* 4:30. doi: 10.3389/fevo.2016.00030

McMahon, K. W., Hamady, L. L., and Thorrold, S. R. (2013). A review of ecogeochemistry approaches to estimating movements of marine animals. *Limnol. Oceanogr.* 58, 697–714. doi: 10.4319/lo.2013.58.2.0697

Mills, J. A., Teplitsky, C., Arroyo, B., Charmantier, A., Becker, P. H., Birkhead, T. R., et al. (2015). Archiving primary data: solutions for long-term studies. *Trends Ecol. Evol.* 30, 581–589. doi: 10.1016/j.tree.2015.07.006

Morgan, M. G., Henrion, M., and Small, M. (1992). *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*, *Revised Edn*. Cambridge: Cambridge University Press.

Nathan, R., Getz, W. M., Revilla, E., Holyoak, M., Kadmon, R., Saltz, D., et al. (2008). A movement ecology paradigm for unifying organismal movement research. *Proc. Nat. Acad. Sci. U.S.A.* 105, 19052–19059. doi: 10.1073/pnas.0800375105

Nguyen, V. M, Brooks, J., Young, N., Lennox, R., Haddaway, N., and Whoriskey, F. G. (2017). To share or not to share in the emerging era of big data: perspectives from fish telemetry researchers on data sharing. *Can. J. Fish. Aquat. Sci.* doi: 10.1139/cjfas-2016-0261

Nifong, J. C., Layman, C. A., and Silliman, B. R. (2015). Size, sex and individual-level behavior drive intrapopulation variation in cross-ecosystem foraging of a top predator. *J. Anim. Ecol.* 84, 35–48. doi: 10.1111/1365-2656.12306

Persons, M. H., and Uetz, G. W. (1997). The effect of prey movement on attack behavior and patch residence decision rules of wolf spiders (Araneae: Lycosidae). *J. Insect Behav.* 10, 737–752.

Pfeffer, J., and Sutton, R. I. (2000). *The Knowing-Doing Gap: How Smart Companies Turn Knowledge into Action*. Cambridge: The Harvard Business School Press.

Pinnix, W. D., Nelson, P. A., Stutzer, G., and Wright, K. A. (2013). Residence time and habitat use of coho salmon in Humboldt Bay, California: an acoustic telemetry study. *Environ. Biol. Fish.* 96, 315–323. doi: 10.1007/s10641-012-0038-x

Piwowar, H. A., Day, R. S., and Fridsma, D. B. (2007). Sharing detailed research data is associated with increased citation rate. *PLoS ONE* 2:e308. doi: 10.1371/journal.pone.0000308

Pullin, A. S., Knight, T. M., Stone, D. A., and Charman, K. (2004). Do conservation managers use scientific evidence to support their decision-making? *Biol. Cons.* 119, 245–252. doi: 10.1016/j.biocon.2003.11.007

R Development Core Team (2015). *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Robinson, J. G. (2006). Conservation biology and real-world conservation. *Conserv. Biol.* 20, 658–669. doi: 10.1111/j.1523-1739.2006.00469.x

Roche, D. G., Kruuk, L. E. B., Lanfear, R., and Binning, S. A. (2015). Public data archiving in ecology and evolution: how well are we doing? *PLoS Biol.* 13:e1002295. doi: 10.1371/journal.pbio.1002295

Rubenstein, D. R., and Hobson, K. A. (2004). From birds to butterflies: animal movement patterns and stable isotopes. *Trends Ecol. Evol.* 19, 256–263. doi: 10.1016/j.tree.2004.03.017

Rutz, C., and Hays, G. C. (2009). New frontiers in biologging science. *Biol. Lett.* 5, 289–292. doi: 10.1098/rsbl.2009.0089

Saunders, D. L., Meeuwig, J. J., and Vincent, A. C. J. (2002). Freshwater protected areas: strategies for conservation. *Conserv. Biol.* 16, 30–41. doi: 10.1046/j.1523-1739.2002.99562.x

Scarpignato, A. L., Harrison, A.-L., Newstead, D. J., Niles, L. J., Porter, R. R., van den Tillaart, M., et al. (2016). Field-testing a new miniaturized GPS-Argos satellite transmitter (3.4g) on migratory shorebirds. *Wader Study* 123, 240–246.

Secor, D. H. (1999). Specifying divergent migrations in the concept of stock: the contingent hypothesis. *Fish. Res.* 43, 13–34.

Shepard, E. L., Ross, A. N., and Portugal, S. J. (2016). Moving in a moving medium: new perspectives on flight. *Philos. Trans. R. Soc. B* 371:20150382. doi: 10.1098/rstb.2015.0382

Tenopir, C., Allard, S., Douglass, K., Aydinoglu, A. U., Wu, L., Read, E., et al. (2011). Data sharing by scientists: practices and perceptions. *PLoS ONE* 6:e21101. doi: 10.1371/journal.pone.0021101

Thomas, C. (2009). Biodiversity databases spread, prompting unification call. *Science* 324, 1632–1633. doi: 10.1126/science.324_1632

Thornhill, J. L. (2014). *Bridging the Gap between Research and Decision-Making: Empirical Evidence from a Case Study of Gray Wolf (Canis lupus) Management in the U.S.* Doctoral dissertation. George Mason University, Fairfax, VA.

Thorrold, S. R., Zacherl, D. C., and Levin, L. A. (2007). Population connectivity and larval dispersal: using geochemical signatures in calcified structures. *Oceanography* 20, 80–89. doi: 10.5670/oceanog.2007.31

Torres, L. G., Orben, R. A., Irina, T., and Thompson, D. R. (2017). Classification of animal movement behavior through residence in space and time. *PLoS ONE* 12:e0168513. doi: 10.1371/journal.pone.0168513

Vanak, A. T., Fortin, D., Thaker, M., Ogden, M., Owen, C., Greatwood, S., et al. (2013). Moving to stay in place: behavioral mechanisms for coexistence of African large carnivores. *Ecology* 94, 2619–2631. doi: 10.1890/13-0217.1

Vines, T. H., Andrew, R. L., Bock, D. G., Franklin, M. T., Gilbert, K. J., Kane, N. C., et al. (2013). Mandated data archiving greatly improves access to research data. *FASEB J.* 27, 1304–1308. doi: 10.1096/fj.12-218164

Vision, T. J. (2010). The social contract of scientific data. *Bioscience* 60, 330–331. doi: 10.1525/bio.2010.60.5.2

Watson, J. E., Dudley, N., Segan, D. B., and Hockings, M. (2014). The performance and potential of protected areas. *Nature* 515, 67–73. doi: 10.1038/nature13947

White, E. P., Baldridge, E., Brym, Z. T., Locey, K. J., McGlinn, D. J., and Supp, S. R. (2013). Nine simple ways to make it easier to (re)use your data. *Ideas Ecol. Evol.* 6, 1–10. doi: 10.4033/iee.2013.6b.6.f

Whitlock, M. C. (2011). Data archiving in ecology and evolution: best practices. *Trends Ecol. Evol.* 26, 61–65. doi: 10.1016/j.tree.2010.11.006

Wilson, K. A., McBride, M. F., Bode, M., and Possingham, H. P. (2006). Prioritizing global conservation efforts. *Nature* 440, 337–340. doi: 10.1038/nature04366

Wu, J., and Boggess, W. G. (1999). The optimal allocation of conservation funds. *J. Environ. Econ. Manag.* 38, 302–321. doi: 10.1006/jeem.1999.1091

Yergey, M. E., Grothues, T. M., Able, K. W., Crawford, C., and DeCristofer, K. (2012). Evaluating discard mortality of summer flounder (*Paralichthys dentatus*) in the commercial trawl fishery: developing acoustic telemetry techniques. *Fish. Res.* 115, 72–81. doi: 10.1016/j.fishres.2011.11.009

Young, N., Corriveau, M., Nguyen, V. M., Cooke, S. J., and Hinch, S. G. (2016). How do potential knowledge users evaluate new claims about a contested resource? Problems of power and politics in knowledge exchange and mobilization. *J. Environ. Manage.* 184, 380–388. doi: 10.1016/j.jenvman.2016.10.006

Young, N., Gingras, I., Nguyen, V. M., Cooke, S. J., and Hinch, S. G. (2013). Mobilizing new science into management practice: the challenge of biotelemetry for fisheries management, a case study of Canada's Fraser River. *J. Int. Wildlife Law Pol.* 16, 331–351. doi: 10.1080/13880292.2013.805074

Conflict of Interest Statement: Travel funds for IMCC symposium participants were provided by VEMCO and OregonRFID, two manufacturers of telemetry equipment. The manufacturers were in no way involved in writing or reviewing the research or manuscript.

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.