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EDITORIAL

The Ocean Tracking Network: Advancing frontiers in aquatic science and management[1]

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Abstract: Aquatic animals are integral to ocean and freshwater ecosystems and their resilience, are depended upon globally for food sustainability, and support coastal communities and Indigenous peoples. However, global aquatic environments are changing profoundly due to anthropogenic actions and environmental change. These changes are altering distributions, movements, and survival of aquatic animals in ways that are not well understood. The Ocean Tracking Network (OTN) is a global partnership that is filling this knowledge gap. OTN Canada, a pan-Canadian (and beyond) research network, was launched in 2010 with visionary funding by the Canadian government. In our introduction to this special issue, we briefly overview how this interdisciplinary network has used state-of-the-art technologies, infrastructure, electronic tags and sensors, and associated cutting-edge research and training programs to better understand changing marine and freshwater dynamics and their impact on ecosystems, resources, and animal ecology. These studies have provided unprecedented insights into animal ecology and resource management at a range of spatial and temporal scales and by interfacing animal movements with novel measures of environment, physiology, disease, genetics–genomics, and anthropogenic stressors.

Résumé : Les animaux aquatiques sont des éléments essentiels des écosystèmes océaniques et d'eau douce et de la résilience de ces systèmes, ils assurent la pérennité de la disponibilité de nourriture à l'échelle planétaire et supportent des collectivités côtières et des peuples autochtones. Les milieux aquatiques planétaires font toutefois l'objet de modifications profondes causées par l'activité humaine et des changements environnementaux. L'incidence de ces modifications sur la répartition, les déplacements et la survie des animaux aquatiques n'est pas bien comprise. L'Ocean Tracking Network (OTN) est un partenariat international qui vise à combler ces lacunes dans les connaissances. OTN Canada, un réseau de recherche pancanadien (et au-delà) a été lancé en 2010 grâce au financement visionnaire du gouvernement du Canada. Dans notre introduction au présent numéro spécial virtuel, nous présentons un bref survol de l'emploi fait par ce réseau interdisciplinaire des plus récentes technologies, infrastructures, des étiquettes et capteurs électroniques et de la recherche et des programmes de formation de pointe associés pour mieux comprendre la dynamique changeante des milieux marins et d'eau douce et son incidence sur les écosystèmes, les ressources et l'écologie animale. Ces études jettent un éclairage sans précédent sur l'écologie animale et la gestion des ressources à différentes échelles spatiales et temporelles, en reliant les déplacements d'animaux à de nouvelles mesures du milieu, de la physiologie, des maladies, de la génétique–génomique et de facteurs de stress d'origine humaine. [Traduit par la Rédaction]

Introduction

Aquatic animals help meet global food needs, annually contribute billions of dollars in socioeconomic benefits and ecosystem services to society, support coastal communities, and are culturally important, particularly for Indigenous peoples (e.g., McCauley et al. 2015; Chuenpagdee et al. 2016). In the face of ever-increasing human demands and activities, major depletions in the abundance of aquatic animals ranging from fishes to baleen whales have occurred, with many species driven to commercial or ecological extinction (e.g., McCauley et al. 2015; Jones et al. 2018). Concomitantly, global aquatic environments are changing profoundly due to anthropogenic actions and environmental change (e.g., Bernal et al. 2016; World Economic Forum 2017) and are altering the distributions, movements, and survival of aquatic animals (e.g., Pinsky et al. 2013; McCauley et al. 2015). Technological advances have now made every part of the world's ocean and inland waters accessible for human use, allowing fisheries in previously inaccessible areas and enabling developments of deep-water oil and gas wells, installation of offshore renewables (wind, tidal, currents), seabed mining, and prospecting for marine pharmaceuticals. This "blue growth" (Eikeset et al. 2018) and associated per-

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turbations will potentially put additional strains on the ocean's ability to furnish the goods, services, and associated socioeconomic well-being that aquatic ecosystems provide to communities and nations around the world (e.g., fisheries and food sustainability, ecosystem resilience, coastal living, tourism).

Finding solutions to the pressures facing aquatic animals requires an understanding of what drives natural complexity. This information is essential to help guide development of a sustainable balance between exploitation and conservation in the face of other anthropogenic pressures (e.g., climate change, pollution, habitat destruction). Aquatic ecosystems are hugely varied, ranging from polar to tropical, abyssal to pelagic, and freshwater to saltwater. Within all these systems, many species must move to meet their basic needs (e.g., for food, shelter, mating sites). These movements may be short-term and local or of long duration and cover great distances (Hussey et al. 2015) — and the drivers and patterns are often poorly understood and (or) currently changing. It has never been more important to adopt multi-, trans-, and interdisciplinary research approaches to provide the critical knowledge required to understand, manage, restore, and sustain our interconnected ocean and inland waters and their biological resources (e.g., Cooke 2008; Miloslavich et al. 2018; Fraser et al. 2018). This is the premise that has guided the work of the Ocean Tracking Network (OTN; oceantrackingnetwork.org) since its inception: to create a global partnership that documents the movement and survival of aquatic animals and to understand how these populations are being influenced by changing environmental conditions and anthropogenic pressures, with the aim to support their sustainable management and stewardship around the world.

Cutting-edge science enabled by the Canadian government

In 2007, the Canadian government launched OTN, headquartered it at Dalhousie University, and tasked it with the challenge of uniting world aquatic telemetry through a visionary and explicitly coordinated funding structure: \$35 million from the Canada Foundation for Innovation's (CFI) International Joint Venture Fund (IJVF) to support global monitoring infrastructure, governance and operations; \$10 million in network science funding from the Natural Sciences and Engineering Research Council of Canada (NSERC) to support research and training across Canada using the OTN infrastructure; and \$327 000 from the Social Sciences and Humanities Research Council (SSHRC) to help support social science activities and knowledge mobilization. This coordinated funding model also leveraged extensive external funding (~\$130 million) from international partnerships. (All funds are in Canadian dollars.)

The NSERC funding was uniquely and explicitly coupled to the CFI investment in infrastructure, which combined created a Canadian national research network. This one-time funding model (pairing research funding with infrastructure funding) also allowed this pan-Canadian network program (henceforth referred to as OTN Canada) to become a training hub for OTN worldwide. Research plans were developed in 2008–2009 (Iverson et al. 2009) and launched in January 2010 after successful peer-review. The integrative network aimed to use state-of-the-art technologies and infrastructure and associated cutting-edge research and training programs to better understand changing marine and freshwater dynamics across Canada and their impact on ecosystems, resources, and animal ecology. Critical issues in resource management and their implications for ocean governance were at the forefront. By fitting animals with a broad array of electronic tags and sensors (e.g., acoustic, radio, passive integrated transponder (PIT), data loggers, satellite tags), these studies provided unique opportunities to investigate animal ecology at a range of spatial and temporal scales as well as to interface animal movements with novel measures of environmental conditions, physiology, disease, genetics–genomics, and anthropogenic stressors (both established or potential).

Research network design

Phase I of OTN Canada (2010–2013) addressed one key, multifaceted question across Canada's three ocean "Arenas" (the Atlantic, Arctic, and Pacific): What are the movements of continental shelf marine animals, how do these movements affect species interactions, and what are the consequences of environmental variability, change, and human activities on these species' distributions and abundance? Addressing this comprehensive question provided a unifying direction and fostered communication among regions and investigators while simultaneously providing maximum flexibility to the science teams to conduct research and ask other questions in what was, in many aspects, an exploratory discovery-based venture. Research programs were organized within the three ocean Arenas, but to stimulate comparative work across these Arenas, research programs were designed to integrate their studies into and across five key research themes that are interdisciplinary, interdependent, and complementary: (1) ocean physics and modeling; (2) migratory living marine resources; (3) trophic interactions; (4) impact of climate variability; and (5) ocean governance (Iverson et al. 2009; Cooke et al. 2011).

Phase II (2014–2017) of OTN Canada built off the initial successes of Phase I, increasing integration, expanding activities, and refocusing research efforts to address new scientific questions that strategically aligned OTN researchers in Canada and internationally. While the five key research themes remained relevant, new research projects were broadly structured around three major integrated "framework questions" (FQs), within which projects and themes were organized and coordinated:

- FQ 1: How do oceanographic and environmental features (both physical and biological) affect animal habitat use, movement, and migrations?
- FQ 2: How do aquatic species interactions and areas of ecological importance relate to habitat use, movement patterns, and biotic–abiotic features?
- FQ 3: How do anthropogenic activities and development influence aquatic animal behaviour and ecology?

Additional scientific activities addressed four major "cross-cutting activities" (CCAs), which intersected across all FQs and (or) across specific projects and subprojects and included methodologies and approaches that informed the three FQs:

- CCA 1: Assimilating animal tracking data with coastal and offshore oceanographic models;
- CCA 2: Visualization and modeling of complex aquatic and marine observations;
- CCA 3: Advancing animal tracking technology and tagging techniques; and
- CCA 4: Policy, stake holders, and mechanisms for feeding results into outreach and management (cooperation of natural and social scientists).

This overall organization ensured network members had a conceptual understanding of how all OTN projects were interrelated (both within Canada and internationally), illustrated how these could be most effectively integrated across OTN Canada's program to accomplish its mission, and allowed rapid dissemination to interested parties of information about and results from all individual research projects and programs. This approach also fostered a breadth of training opportunities and exposure for trainees, or highly qualified personnel (HQP), and helped advance the development and use of new technology. During Phase II, OTN

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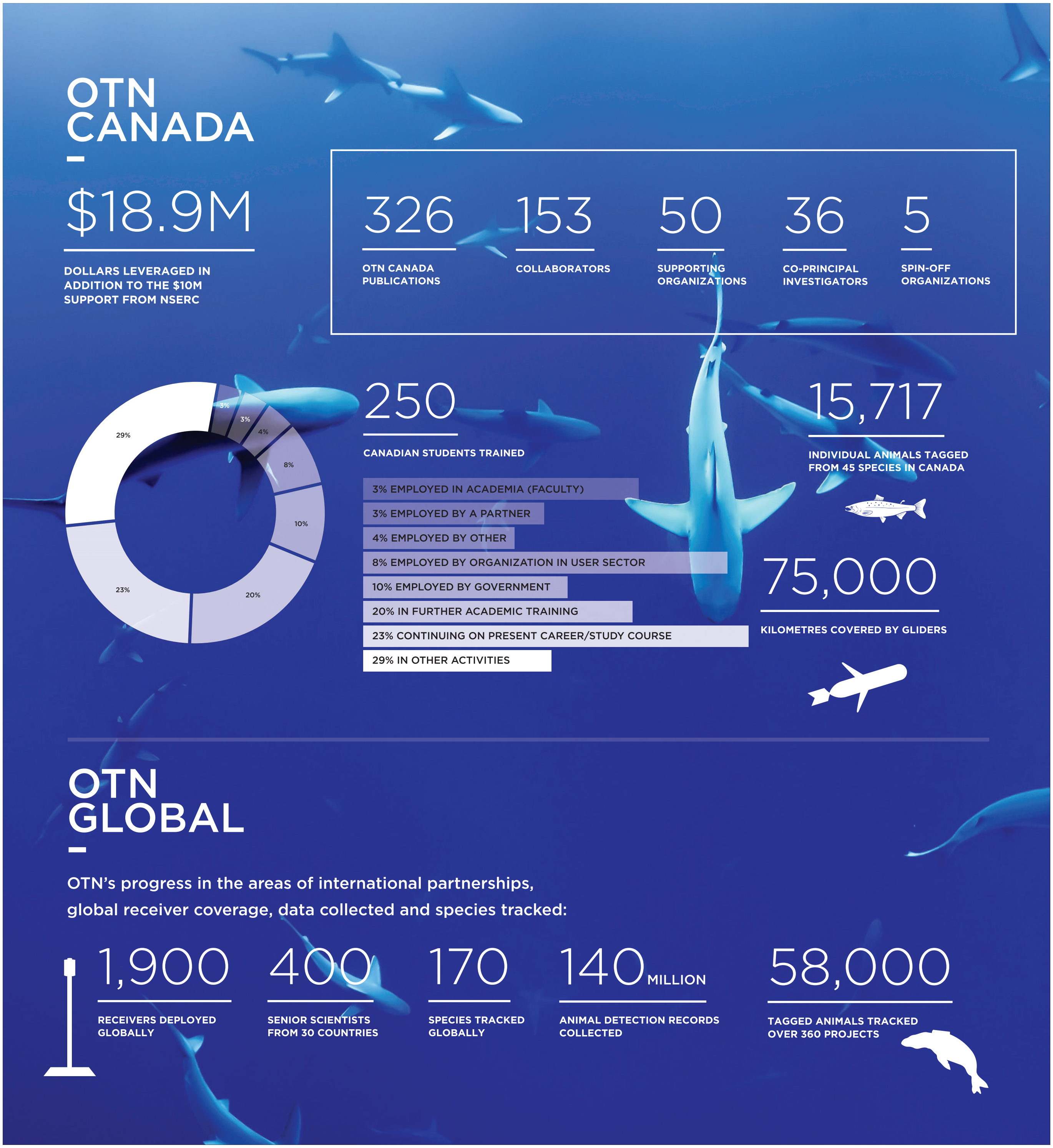
Fig. 1. Infographic summarizing the key achievements of OTN Canada by the numbers in the context of OTN global activities as of December 2018. Data for OTN Canada tracking, training, partnerships, and collaborations are taken from Iverson et al. (2017). Data for OTN's global receiver coverage and tracking are derived from OTN's data warehouse. [Colour online.]



Canada grew to involve 36 co-principal investigators (co-PIs), who represented 13 academic institutions across Canada, plus the network's key research partner — Fisheries and Oceans Canada (DFO) and an additional 153 primary collaborators (Iverson et al. 2017). Altogether, 50 academic, government, and private agencies across Canada participated in the network and its support (Fig. 1).

Research network achievements

Partnerships and world-class research

As OTN Canada wraps up its NSERC network funding, the aim of this special issue is to highlight recent examples of the work accomplished by our science teams to date. The NSERC network approach described above, which funded large-scale, multidisci-

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plinary research projects in targeted research areas, enabled the achievements of the network to be far greater than the sum of its individual parts. This was made possible through the creation within these targeted projects of new collaborations, the sharing of diverse expertise, the advancement of technology, the development of new analytical tools, and the establishment of interdisciplinary research and training programs (Iverson et al. 2017). Through its extensive networking, OTN Canada has addressed previously intractable and complex questions about aquatic life and responses to changing environments. By uniting world-class marine scientists to establish a program of data sharing and collaborative research, OTN became a model for partnership building that was emulated by other organizations (e.g., Motus Wildlife Tracking System, Integrated Tracking of Aquatic Animals in the Gulf of Mexico (iTAG), OTN Brazil, European Aquatic Animal Telemetry Network (EAATN)). OTN Canada collaborations have drawn on the multifaceted expertise that exists in its partners within Canadian universities, DFO, industry, nongovernmental organizations (NGOs), aboriginal groups, and in some cases the public. Participating individuals have come from a range of disciplinary backgrounds, fostering knowledge transfer across disciplines, regions, and sectors — crucial to ensure that the results of the work benefits Canada and Canadians scientifically, economically, and societally. Finally, through this partnership model, OTN Canada was able to leverage matching research support from partners totaling almost twice the amount of the NSERC award and also resulted in the formation of five small spin-off companies (Fig. 1). Although the OTN NSERC network funding is sunsetting, research teams continue to apply for and secure funding programs to conduct research that fits within the remit of the continuing OTN themes, focus, and collaborations.

Technology

The network has expanded electronic telemetry capabilities and made considerable advancements in the development of technologies and their use in innovative and novel ways, including

- the use of robotic tracking platforms (marine autonomous vehicles, or "roboprobes") to both actively (i.e., using electronically tagged animals) and passively (i.e., use of hydrophones that listen for animal sounds) track animals and monitor ocean conditions (Davis et al. 2018);
- the development of new tags and tracking techniques that advanced the concept of using large aquatic animals (i.e., "bioprobes") to carry combined tags and receivers that synchronously collect oceanographic data while tracking the movements of the tagged predators and documenting interactions between the predator and other tagged species (Lidgard et al. 2012, 2014*a*, 2014*b*);
- incorporating live animal biopsy with telemetry tracking to reveal physiological mechanisms underlying migration behaviour and mortality (Jeffries et al. 2014);
- developing unique accelerometer tags that relate fish acceleration to changing body size, providing the potential to estimate fish growth rates in the wild, as well as to validate at-sea time budgets and habitat use in a variety of fish and marine mammal species (Broell and Taggart 2015; Broell et al. 2013, 2016);
- the first ever large spatial-scale acoustic tracking of wild salmon smolts and first deployment of miniaturized acoustic transmitters (4 mm length), together allowing thousands of salmon smolts to be tracked for >1000 km during riverine and coastal migrations (Clark et al. 2016; Stevenson et al. 2019);
- the development of state-space and hidden Markov frameworks for rapidly modelling complex spatiotemporal animal tracking data (Albertsen et al 2015) and inferring behavioural states (Whoriskey et al. 2017, Lawler et al. 2019) while also making recommendations for the selection of appropriate statistical techniques (Whoriskey et al. 2019) and assuring best practice (Baker et al. 2015; Auger-Methe et al. 2016);
- expansion of the use of acoustic telemetry and satellite technology to the deep sea (>1200 m) and to extreme environments (under ice in the Arctic; Hussey et al. 2017) and to high current environments (i.e., Bay of Fundy; McLean et al. 2014), providing new data and demonstrating opportunities for these vulnerable but poorly studied ecosystems;
- the development of an internationally certified acoustic telemetry database that houses data from global freshwater and marine systems; recognized as an Associate Data Unit of the International Oceanographic Commission's International Oceanographic Data and Information Exchange; named as an Ocean Biogeographic Information System Tier 3 node (Canada).

Use of scientific knowledge

The scientific knowledge generated to date by OTN has been utilized to address socioeconomic and resource management issues in Canada's ocean Arenas and inland waters. Members of the network have examined the adequacy of existing laws, harvest regulations, user group conflicts, management policies and regimes, and barriers to the uptake of scientific information by government, stakeholders, user groups, and First Nations. They have suggested ways to provide better stewardship of Canada's aquatic resources and to better understand the sociology of knowledge and animal tagging–welfare issues (e.g., Young et al. 2016; Nguyen et al. 2019). Consultations with members of communities, where the research had direct implications, have helped to inform tracking study design and were an important part of planning, implementation, and relationship building. OTN Canada has been on the forefront of integrated management and consultation with stakeholder groups. For instance, in the Arctic, working with government, academia, and Inuit, co-PIs and HQP documented habitat use and migration patterns of species in emerging fisheries, which informed the development of a fishery management regime built on conservation of these species and fair allocations to Indigenous people and commercial fishermen (Hussey et al. 2017; Barkley et al. 2018). Results from the network's research are also informing policy and management decisions relating to DFO's framework acts and strategic objectives. This included assessing the adequacy of Marine Protected Areas; helping to inform effective management of transboundary fisheries; and assisting industry to meet regulatory requirements, sustainable development goals, and management of ecological risk as it accelerates ocean development (e.g., oil and gas exploration and production, shipping, aquaculture, tidal energy). In the Pacific, large annual workshops, which brought together government, First Nations, consultants, environmental NGOs, industry, and other fisheries stakeholders to inform and receive feedback on OTN research results and directions, led to changes in salmon harvest policy, particularly around the issue of bycatch mortality. OTN Canada researchers led the development of a Canadian Science Advisory Secretariat process that incorporated important aspects of Pacific Arena research and expertise to generate a framework and guidelines for DFO to manage bycatch and release mortality in Pacific salmon fisheries (DFO 2016; Patterson et al. 2017*a*, 2017*b*). In an era where rapidly expanding technologies can overwhelm agencies and stakeholders that could otherwise benefit from using cutting-edge approaches, OTN investigators studied how "disruptive sciences" like biotelemetry could be embraced by decision makers and the public in helping to take important management actions (Young et al. 2013, 2018). The success of integrating telemetry approaches into management has been examined broadly across taxa and regions (Brooks et al. 2019).

Training

From its inception, a paramount objective of OTN Canada has been the training of HQP (primarily students and postdoctoral fellows, but also technical training for research assistants and staff) in the fields of interdisciplinary aquatic sciences, physical

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and biological oceanography, climatic and oceanographic modeling, animal movement, animal physiology, quantitative ecology, mathematics and statistics, engineering and technology, and marine policy and conservation. The network approach has greatly enriched the training of HQP by facilitating interaction with industry and regulators as well as peers and academics from across Canada and internationally. Senior HQP formed **ideasOTN** to bring students and faculty together to share ideas and approaches to data analyses, which stimulated a variety of collaborative projects resulting in a number of journal publications (e.g., Hussey et al. 2015; Cooke et al. 2017; Lennox et al. 2017). Over the 8-year NSERC Network, OTN Canada trained 250 HQP. These trainees are now moving into academia, government, and industry and are assuming the duties of the next generation of top specialists in these strategic priority areas of ocean science (Fig. 1).

Special issue overview of contributions

This OTN special issue focuses primarily on aquatic animal movements and their implications for the management and conservation research carried out by OTN Canada. Although animal movements have been the core of the OTN research program, from the beginning collaborative multi- and interdisciplinary research has also focused on oceanography, climate, and ocean governance. This has resulted in many publications (Fig. 1), including a special two-part issue in the Journal of International Wildlife Law and Policy (VanderZwaag et al. 2013). The approach improved the scope of OTN research and is reflected in many of the studies described in this special issue, for example using oceanographic data to understand shorthorn sculpin (*Myoxocephalus scorpius*) movements in the Arctic (Landry et al. 2019) and temperature to study migrating Pacific salmon (Middleton et al. 2018).

The papers for this special issue present results from some of the most recent activities of the network and have been organized into five groups that reflect the geographical structure of OTN, which are also briefly summarized. The first three cover the Atlantic, Arctic, and Pacific Ocean Arenas of Canada that were the focus at the heart of the NSERC Network. The fourth group reflects the success of OTN and the Canadian Network in supporting international researchers by providing expertise and data management and importantly by expanding existing acoustic receiver platforms or providing new infrastructure to enable new collaborative telemetry studies. The final group presents recent cross-regional and method development papers that have used the data system and expertise from the three OTN Canada Arenas.

Atlantic OTN

OTN's Atlantic Arena focused on target migratory organisms that represent model or keystone species for their ecosystems, with the goals of clarifying their movements and population structure in relation to variability in oceanographic features. Additionally, Atlantic research led efforts in developing new tag technology and data modeling and visualization tools for all OTN research groups.

A strong Atlantic OTN emphasis included coupling ocean observations with mathematical models to examine the effects of physical and biogeochemical ocean changes on key Atlantic study species, many of which are endangered or threatened, such as American eel (*Anguilla rostrata*), Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*), Atlantic salmon (*Salmo salar*), and the northern right whale (*Eubalaena glacialis*). The observation component used physical data from bottom moorings and initiated the first sustained glider-based oceanographic observation program in Canada. Dalhousie University is now operating Canada's largest academic operational fleet of autonomous marine gliders that have travelled a total of over 75 000 km (Fig. 1) while collecting a wide array of physical, biological, chemical, and acoustic observations (e.g., Davis et al. 2018). Numerical ocean models have contributed to understanding aquatic animal habitat use and loss, as well as to the underlying mechanisms of tracked animal movement patterns (e.g., Beguer-Pon et al. 2016; Ohashi and Sheng 2016). Studies of the overwinter biology, migration, and survival of declining Atlantic salmon populations in the Bras d'Or Lakes revealed links between body condition and outmigration to the Atlantic Ocean, as well as consequences for survival (Strople et al. 2018). A particular showcase project for the Atlantic Arena has been the "Bioprobe" project, a group of studies using grey seals (*Halichoerus grypus*) as the model species and novel acoustic technology developed for OTN (see previous section on Technology). This long-term program used seals as oceanographic samplers and documented how seasonal oceanographic features (temperature, depth, phytoplankton biomass) influence seal movement, links between environmental change and impact on top marine predators, interactions of tagged individuals with each other and with potential prey (e.g., Atlantic cod, salmon, eel, snow crab (*Chionectes opilio*)), as well as with competing predators (e.g., tuna, sharks) co-occurring in ocean "hotspots", areas of high ocean productivity (Lidgard et al. 2012, 2014*a*, 2014*b*; Nowak 2019). In conjunction with these studies, another series of projects developed statistical procedures for visualization and modeling many types of complex marine observations and used across the NSERC Network (e.g., Albertsen et al. 2015; Baker et al. 2015; Auger-Methe et al. 2016).

For this OTN special issue, several recent Atlantic Arena projects are featured. Atlantic sturgeon have suffered drastic population declines due to anthropogenic actions (e.g., overfishing, dam installations). Although the IUCN Red List currently classifies these fish as "near threatened", they are not yet considered to be endangered or threatened in Canada. From a longer-term series of OTN studies on Atlantic sturgeon (e.g., Stokesbury et al. 2016), two projects examined the species seasonal distribution and movements (Whitmore and Litvak 2018*a*) and fine-scale movements during aggregations (Whitmore and Litvak 2018*b*), which provided important information to assist in designing management measures that will mitigate growing anthropogenic pressures. Another recent Atlantic study focused on snow crab; Canada is the world's largest producer of snow crab, accounting for about two-thirds of the global supply. These crab are mainly fished on the east coast, yet their movement ecology is not well understood. By integrating fine-scale positioning telemetry with larger-scale position estimates from autonomous mobile surveys and harvester returns, Côté et al. (2019) demonstrated little evidence of site fidelity and no strong environmental influences on movements in this species, suggesting behavioural plasticity of snow crab and relative stability of offshore environments.

For diadromous fish, which travel between fresh and salt water and often over extensive distances, it is difficult to discern where the greatest pressures on their populations lie. A series of studies in the Atlantic Arena focused on elucidating the migratory patterns of the endangered American eel and documented the first-ever adults entering their putative spawning grounds in the Sargasso Sea, after epic oceanic migrations of more than 2700 km and against ocean currents (Béguer-Pon et al. 2014, 2015). The most recent study (Béguer-Pon et al. 2018) describes the results of acoustically tagging 380 migrating female silver American eels between 2011 and 2014 to assess migration and escapement at the exit of the Gulf of St. Lawrence. Estimated escapement rates were low but variable (9.8% to 20%) and were attributed to a combination of predation or inefficiencies in the acoustic receiver lines that were operating at great depths and might have missed animals migrating high in the water column. A final Atlantic OTN paper examined behavioral thermoregulation of adult Atlantic salmon, which return to natal rivers several months before spawning and in fresh water during summer could be subjected to temperatures that exceed their upper temperature tolerance limits. Using a novel combination of thermal infrared remote sensing, river temperature monitoring, and acoustic telemetry, Frechette et al. (2018) showed that during summer in-river residence in a Quebec

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river, adults engaged in behavioural thermoregulation at cooler ambient temperatures than previously recorded for this species and maintained body temperature within a narrow range via use of cool, large, stable, stratified pools as refuges. Thus, identifying and maintaining connectivity to thermal refuges may be critical for persistence of Atlantic salmon populations as climate changes and rivers warm.

Arctic OTN

The warming of the climate and reduction of sea ice in the Arctic has rapidly increased the exploitation of fisheries and other natural resources in this vulnerable ecosystem, in addition to introducing other stressors (Bennett et al. 2015). Concerns about the negative impacts on these marine ecosystems are particularly worrying because this ecosystem is understudied, especially with regard to marine and anadromous animal movements. OTN's Arctic efforts addressed basic animal movement ecology and the influence of the changing environment upon them, often combining data and research objectives with projects from the other regions to give broad comparative geographic and climate scopes. As the key forage fish, much of Arctic OTN's focus was on the Arctic cod (*Boreogadus saida*), which generated new knowledge about the feeding ecology (Matley et al. 2013), predators (Matley et al. 2015), long-range movements (Kessel et al. 2017), and behavior (Kessel et al. 2016) of this important species. Arctic OTN assessed the impact of fish movement on the boundaries for fishery management zones and quotas related to commercial and Indigenous fisheries of important commercial fish species and bycatch. Projects were the first to use satellite and acoustic telemetry at great depths (>1000 m) and under sea ice, providing new information on movement and behavior of Greenland halibut (*Reinhardtius hippoglossoides*), Arctic skate (*Amblyraja hyperborea*), and Greenland shark (*Somniosus microcephalus*) (Peklova et al. 2012, 2014; Hussey et al. 2017; Barkley et al. 2018). Other projects examined the relationship between migration and genomics in the Arctic char (*Salvelinus alpinus*) (Moore et al. 2016, 2017), a valuable commercial and cultural ionic species in the Arctic. OTN Arctic also studied the movement and behavior of ringed seals (*Pusa hispida*), generating new insights on the influence of sea ice on this abundant and important marine mammal (Yurkowski et al. 2016).

For this special issue, two of the OTN Arctic papers focus on shorthorn sculpin, a common nearshore benthic fish found throughout the Arctic and thought to play a key role in integrating benthic and pelagic food webs (McMeans et al. 2015), but whose movement ecology has been largely unknown. Working in the High Arctic and using acoustic telemetry and the Vemco positioning system (which provided high-resolution location and movement data), Landry et al. (2019) demonstrated that these Arctic fish displayed three unique movement types that had analogues in temperate benthic fish. These movement types (foraging, feeding, and large transit movements) were influenced by the presence of other fish, temperature, and sea ice, suggesting that changes in climate will have considerable implications for Arctic fishes. Ivanova et al. (2018) further demonstrated that ship traffic and noise in this environment resulted in a change in the movement behaviour and the location and size of home ranges of shorthorn sculpin. Given increasing ship and vessel traffic in polar regions, this paper lays the foundation for additional studies on this growing anthropogenic stressor. A third Arctic OTN paper presents results from a study of thermal habitat use of Arctic char in fresh water during the ice-covered period, which is poorly understood (Mulder et al. 2018). The authors found that the char occupied a narrow range of temperatures (0.5–2 °C) in the middle and upper water column, likely to lower metabolic costs and minimize energy expenditure during this food-poor period.

Pacific OTN

The Pacific Arena research focused on Pacific salmon (several species) and white sturgeon (*Acipenser transmontanus*) because of their ecological, cultural, and socioeconomic importance to the region. A strong research program examined out-migrating salmon smolts (e.g., Rechisky et al. 2019; Healy et al. 2018) and coastal and upriver migrating adult salmon (e.g., Drenner et al. 2015; Middleton et al. 2018; Bass et al. 2018) in a range of migratory environments including glacial and nonglacial rivers, estuaries, coastal oceans, and rivers with regulated flows. A major technological contribution and innovation coming from research in the Pacific was the integration of individual animal tracking data with physiological data. Physiological assessments were performed on migrating fish, using blood or tissue biopsy subsequently analyzed using bioassays and high throughput genomic biomarker approaches, to rapidly assess numerous transcriptome (gene expression) and pathogen metrics. This innovative approach led to numerous discoveries: pathogens could play a large role in the outmigration success of juvenile salmon smolts (Jeffries et al. 2014); predators were keying in on pathogen laden smolts (Furey 2016); adult salmon migrants that were physiologically stressed and immune-compromised rapidly migrated out of marine areas into fresh water (Drenner et al. 2018); and adult salmon riverine migration survival to natal areas was strongly affected by river temperature interacting with particular pathogen loads and disease processes (Teffer et al. 2017, 2018). Another innovation was the linking of accelerometer tag swimming speed data with "excess oxygen consumption" data generated from swim tunnel respirometry, enabling the first ever field assessment of cardiometabolic collapse during adult salmon migrations — a likely cause of enroute mortality for some migrants after they ascended a fishway (Burnett et al. 2014).

Foraging behaviour and predator–prey interactions were also a focus of study in the Pacific region and led to the discovery that predatory bull trout (*Salvelinus confluentus*) could consume up to 20 times their theoretical maximum daily ration composed largely of out-migrating salmon smolts (Furey et al. 2016*a*). On the other hand, survival of smolts increases when they numerically "swamp" predators on some days (Furey et al. 2016*b*).

Many coastal fisheries occur along the homeward migration routes of Pacific salmon, and for conservation reasons, current management regulations require that harvesters and anglers release alive any protected salmon species that they may unintentionally capture. It was not known whether these released fish survived or perished from capture stress. The effects of this stress on survival and behaviour of adult Pacific salmon and the recreationally angled sturgeon were studied, incorporating assessments of stress physiology and disease using physiological biopsy (Bass et al. 2018; Teffer et al. 2018). Laboratory work on adult salmon and adult sturgeon in captivity (Teffer et al. 2017, 2018) complemented the fieldwork and helped to identify physiological mechanisms of stress and mortality, including tagging burden. Some of the Pacific research involved working directly alongside First Nations, recreational, and commercial fishers, tagging and tracking bycaught and released animals, and evaluating other fishing practices (Raby et al. 2015*a*; Cook et al. 2018*a*, 2018*b*). The research provided estimates of survival probabilities and investigated potential mitigation measures to improve survival. These mitigations included testing various approaches and apparatus for reviving fish (Robinson et al. 2015; Raby et al. 2015*b*, 2015*c*) and examining approaches to minimize handling and stress to fish (Cook et al. 2019). Through surveys and interviews with fishers (Nguyen et al. 2016, 2019; Watson et al. 2018), researchers developed a better understanding of how management agencies could work with fishers to implement solutions and assist in resolving some of the ongoing conflicts that can impede conservation efforts.

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Global OTN

An important goal of OTN was to provide equipment and data support to acoustic telemetry initiatives around the globe, which ranged from shark movement projects in Australia and South Africa to implications of fish movements in the Laurentian Great Lakes. We also connected OTN researchers, and especially HQP, with international researchers to build future research connections and to exchange methods and perspectives. Most recently, Braccini et al. (2018) tagged dusky sharks (*Carcharhinus obscurus*) in Western Australia to better understand the influences of large-scale migrations of marine predators on population dynamics. Large (>200 cm fork length) dusky sharks migrated between open and closed areas for commercial fishing, while smaller sharks did not, with large males and females making major migrations of more than 2000 km round trip. This study provided new information for assessing the vulnerability of dusky sharks to commercial fishing.

Site fidelity and connectivity among habitats are important issues in nearshore marine environments, particularly for juvenile fishes. Murray et al. (2018) used acoustic telemetry to show very high habitat connectivity between marine and estuary environments for juvenile leerfish (*Lichia amia*) in South Africa. Movements were significantly influenced by environmental factors (e.g., water temperatures), tides, diel patterns, and season and demonstrated the importance of tracking animals across habitats. A recent study of Pacific cod (*Gadus macrocephalus*) in Alaska demonstrated low connectivity between Prince William Sound and the Gulf of Alaska and that cod spent a high majority of their life in small fjords, although a small percentage (<11%) of larger fish migrated away from the fjord during the summer (Lewandoski et al. 2018). These two projects provided comparative information that demonstrated the difference between species and ecosystems and the value of acoustic telemetry networks.

A project supported by OTN in Australia demonstrated the utility of using acoustic telemetry to study the benefits of fishing closures on aggregate-spawning species (Crisafulli et al. 2019). This study found that the closure areas might not be effective in protecting snapper (*Chrysophrys auratus*) because individuals entered and left the closure area, which varied by season, leaving the fish open to exploitation despite the closure. Potts et al. (2018) undertook an assessment of acoustic telemetry and more traditional methods for understanding two coastal fisheries in southern Africa. Telemetry demonstrated movement patterns of one of the coastal fishery species that were not identified by traditional methods and also found that telemetry receiver placement was critical for the project.

The brown trout (*Salmo trutta*) is an anadromous salmonid that exhibits a complex continuum of migration tactics, from freshwater residency to short- to long-distance coastal migrations, but little has been known about the factors driving differences in individual marine habitat use. Thirty-two brown trout veteran migrants (having previously undertaken annual return migrations between fresh water and the sea) within their native range in Europe were acoustically tagged prior to their seaward migration and sampled for indices of their nutritional state (Bordeleau et al. 2018). Results showed that body condition factor differed among fish adopting different migratory tactics, supporting the idea of condition-dependent migration in veteran migrants, with individual variation in nutritional state influencing the spatio-temporal aspects of marine habitat use.

The final two global OTN papers focused on research in the Laurentian Great Lakes. The Great Lakes Acoustic Telemetry Observation System (GLATOS) was established in 2012 and has changed our understanding of fish dynamics and behavior in this large freshwater system. Krueger et al. (2018) provide a summary of the organization, as well as successes and challenges faced by this network. Faust et al. (2019) provides an excellent example of the success and impact of GLATOS and the power of telemetry by showing the feasibility of using telemetry to estimate the contribution of spawning population to a mixed-stock walleye (*Sander vitreus*) in Lake Erie. This is one of the largest and most valuable freshwater fisheries in the world, and acoustic telemetry has provided novel data for refining management.

Crossing-cutting OTN papers

From the beginning, OTN fostered collaborations across regions and disciplines (e.g., Fig. 1) that not only improved the scope of more focused projects, but also resulted in broad assessments and reviews. This special issue highlights three such papers. Demonstrating the potential for telemetry to improve management of aquatic resources was an important goal of OTN, but the integration of this knowledge was not well known. Using a sociological knowledge–action framework, Nguyen et al. (2019) identified four primary challenges to using telemetry findings in management, and that the collaboration, trust, and relationship building that are at the core of this research will be important for overcoming barriers. Equally important to integration of telemetry into management is knowledge mobilization, which is rarely published in peer-reviewed literature. Brooks et al. (2019) used three geographically disparate case studies to demonstrate that early and active communication outside of traditional science communications, along with visual evidence of animal movements, were key to engaging all parties and needed for real change in conservation and management. Finally, marine spatial planning (MSP) is a key component of current conservation and management efforts, particularly to avoid conflicts between anthropogenic activities and marine life. Lennox et al. (2019) reviewed the application of animal tracking to address MSP objectives using case studies and explored ways in which this technology will benefit MSPs.

Concluding remarks

To date, OTN has generated a vast amount of new knowledge related to management of aquatic resources. In most cases, the science conducted as part of OTN yielded the first robust data on where animals were distributed in space and time and on the drivers of their distributions relative to environmental features, human activities and infrastructure, and other organisms. However, the tracking studies have also provided information on sources and levels of mortality. Because OTN science teams were not constrained by the need to "only do telemetry", there have been ample opportunities to layer on and integrate other methods such as stable isotopes, genomics, and bioenergetics. As documented above, sometimes this has meant obtaining nonlethal tissue samples from tagged animals and in other cases it has meant conducting parallel laboratory or field sampling. There has also been opportunity to employ various novel sensors on transmitters or biologgers. Collectively, these tools have enabled researchers to explore the mechanistic basis of animal movements and fate. The science generated by OTN has spanned the entirety of the fundamental–applied continuum, with many discovery studies uncovering basic phenomena about how aquatic ecosystems work, while other studies were directly conceived of and commissioned by resource management agencies to meet specific real-world challenges. The reality is that most of the work from OTN studies has enabled both fundamental and applied outcomes.

What is remarkable is that research teams involved in OTN have been able to tackle and answer questions that were previously considered "unanswerable". That is, detailed knowledge of the movements and survival of free-swimming animals was not possible without telemetry, or without being able to make the linkages among drivers that we could not previously make, or discovering threats we did not know about (e.g., Miller et al. 2014). Another important outcome of OTN has been the emphasis on synthesis — identifying opportunity for synthesizing ideas, knowledge, and perspectives to improve the science and practice of tracking re-

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search. Many of these syntheses have not been possible until the later phases of OTN and are included in this special issue. Teams of OTN PIs, trainees, and collaborators have worked together to identify, for example, ways in which tracking data can inform spatial planning (e.g., Lennox et al. 2019), how to properly range test acoustic telemetry systems (Kessel et al. 2015), and how to share one's data in ways that are unlikely to yield unintended consequences (e.g., Cooke et al. 2017). OTN has also been an important advocate of telemetry data sharing and partnerships in advancing scientific knowledge for effective management of global aquatic resources (Hussey et al. 2015), as well as very forward-looking in projecting what tracking science may look like in the future (Lennox et al. 2017).

Although the scientific legacy arising from OTN to date is admirable, the greatest lasting benefit is perhaps in the way that the next generation of environmental problem solvers have been trained. The students and postdoctoral fellows that spent weeks working on a remote sandbar in the middle of the North Atlantic in January each year to implement the grey seal bioprobe project, months living on ice floes in the Arctic, or conducting studies sampling moribund Pacific salmon during the heat of summer did much more than just "do science". They learned how to engage partners and co-create research projects; they learned how to work alongside Indigenous peoples and commercial fishers to collect data; they learned how to share their findings in manners that were likely to result in knowledge uptake and policy formation; they learned the value of working alongside people different from themselves — legal scholars, social scientists, oceanographers, technology developers, and more. These skills will serve these trainees well as they move into positions in academia, government, the NGO world, and industry and recognize and embrace the value of interdisciplinarity. An earlier special issue that brought together scholars working on law and policy (published in the Journal of International Wildlife Law & Policy; VanderZwaag et al. 2013) emphasized how different disciplines could converge to tackle complex problems.

OTN is now beginning its third phase, which presents both opportunities and challenges. The CFI renewed support of the OTN infrastructure, data system, and headquarters staff for a 5-year period (2017–2022) under its Major Science Initiatives (MSI) program. The MSI program has the advantage that there is no predetermined sunset date for a platform; as long as an MSI remains productive and useful to a broad base of researchers (and successfully passes through quinquennial peer review cycles), its funding can be renewed. A major challenge to the third phase of OTN is finding predictable and sustained funding that will enable scientists' research to benefit fully from the current OTN infrastructure. The OTN platform helps with this, as it provides research technical support and offers a unique opportunity to demonstrate to research funding agencies a high-quality leveraging opportunity. OTN science teams have recently built successful mid-scale research applications around these benefits internationally (e.g., EU Interreg V program) and here in Canada (e.g., NSERC Strategic Partnership Programs), and we hope other investigators will avail themselves of these kinds of opportunities. But the existence of the MSI platform provides a unique opportunity for the Canadian scientific and funding communities to design long-term research programs around MSI infrastructures, such as was the case for the paired CFI–NSERC–SSHRC funded IJVF, which proved to be a visionary funding structure to enable outstanding science and leveraging partnerships. Research-wise, there is no shortage of future challenges that could and should be productively addressed by OTN technologies as climate change and blue growth accelerate, and we increasingly depend on effective Marine Protected Areas to add resilience to our ocean systems. While the ocean is facing human-driven challenges, these research tools provide us with the opportunity to generate the knowledge needed to design a better future.

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