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PERSPECTIVE

The Lobster Node of the CFRN: co-constructed and collaborative research on productivity, stock structure, and connectivity in the American lobster (*Homarus americanus*)[1]

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Abstract: In 2010, more than 20 associations representing harvesters from five provinces bordering the range of American lobster (*Homarus americanus*) in Canada, from the Gulf of Maine to southern Labrador, joined government research scientists at Fisheries and Oceans Canada (and one provincial department) and researchers from Canadian universities (two English- and four French-speaking) to establish the Lobster Node. This partnership was formed to address knowledge gaps on lobster productivity, stock structure, and connectivity through collaborative research under the auspices of the Canadian Fisheries Research Network (CFRN), which was funded by the Natural Sciences and Engineering Research Council of Canada. In so doing, the research partners overcame barriers of geography, language, culture, education, and, in some cases, longstanding disputes around management and conservation measures. This paper reviews why and how the Lobster Node was formed, what it achieved scientifically, what benefits (and challenges) it provided to the partners, and why it succeeded. It concludes by advocating for the creation of a permanent collaborative platform to conduct research in support of lobster fisheries in Canada.

Résumé : En 2010, plus de 20 associations représentant des pêcheurs de cinq provinces bordant l'aire de distribution du homard Américain (*Homarus americanus*) au Canada, du Golfe du Maine au sud du Labrador, se sont joints à des chercheurs gouvernementaux au Ministère des Pêches et Océans Canada (et un ministère provincial) et des chercheurs d'universités canadiennes (deux anglophones et quatre francophones) pour établir le Groupe Homard. Ce partenariat fut formé afin de combler des lacunes de connaissances au niveau de la productivité, de la structure et de la connectivité des stocks de homard par l'entremise de recherche collaborative sous les auspices du Réseau canadien de recherche sur la pêche (RCRP), financé par le Conseil de recherches en sciences naturelles et en génie du Canada. Ce faisant, les partenaires ont dû surmonter des obstacles liés à la géographie, la langue, la culture, l'éducation et, dans certains cas, des différends historiques autour des mesures de gestion et de conservation. Cet article explique pourquoi et comment le Groupe Homard a été formé, ce qu'il a accompli scientifiquement, quels avantages (et défis) il a donnés aux partenaires, et pourquoi cette initiative fut couronnée de succès. Nous concluons en plaidant pour la création d'une plate-forme collaborative permanente pour mener des recherches en appui à la pêche au homard au Canada.

Introduction

It has been argued that Canada does not invest sufficient resources in research on the American lobster (*Homarus americanus*; hereinafter lobster), considering the species' socioeconomic importance to the country and the extreme dependency on lobster of many fishing communities in eastern Canada (Chadwick 2001). In 2010, an opportunity arose to create a 5-year tripartite collaboration among lobster harvesters, government research scientists, and academics to conduct research over the species' range in Canada on questions concerning the resource that were of importance to, and identified by, harvesters. This paper first explores empirically the relation between the economic importance of lobster fisheries to Canada and the amount of research published by government and university scientists on these fisheries. It then documents the creation of the Lobster Node (hereinafter LNode) collaboration, the research it accomplished, its benefits, the major challenges and limitations it experienced, and finally the factors that contributed to its success. It concludes by advocating for

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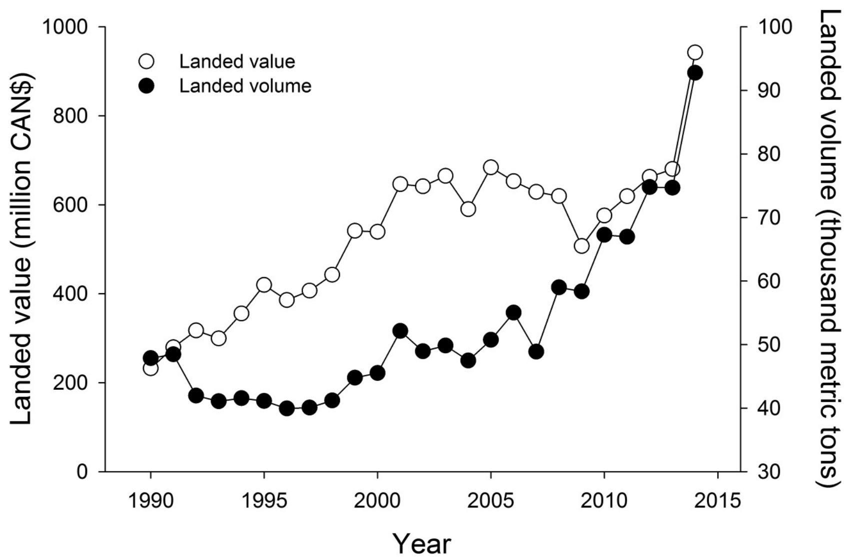
Fig. 1. Landed value (million Canadian dollars, CAN$) and volume (thousand metric tons) of American lobster (*Homarus americanus*) in Canada over the last 25 years.



the creation of a permanent collaborative platform to conduct research in support of lobster fisheries in Canada.

Socioeconomic importance of the lobster fishery in eastern Canada

The lobster supports the single most important marine fishery in Canada (statistics from http://www.dfo-mpo.gc.ca/stats/commercial/sea-maritimes-eng.htm; accessed 15 August 2016). It was the most valuable fishery in 22 of 25 years between 1990 and 2014. Lobster landings more than doubled between 2007 and 2014, reaching an historic high of 92.8 kt valued at CAN$942 million in 2014 (Fig. 1). The importance of lobster is particularly striking when considered in relative terms; from 1990 to 2014, it accounted for between 15% and 35% of the total landed value of all Canadian marine fisheries combined.

The lobster is found on the east coast of Canada (and the US), where it supports fisheries in all five Atlantic Canadian provinces (Fig. 2). Although the statistics concerning the importance of lobster to Canadian fisheries are staggering, they understate Atlantic Canada's acute dependency on lobster, which represents 83%, 64%, and 54% of the value of all fisheries in Prince Edward Island, New Brunswick, and Nova Scotia, respectively. Quebec's reliance on lobster (25% of all fisheries' landed value) is also considerable. Only Newfoundland and Labrador, where colder-water crustaceans (i.e., northern shrimp (*Pandalus borealis*) and snow crab (*Chionoecetes opilio*)) predominate, do not depend on lobster for overall fishery performance (3% of all fisheries). Currently, there are approximately 10 000 licensed lobster harvesters in Canada (http://www.dfo-mpo.gc.ca/fm-gp/sustainable-durable/fisheries-peches/lobster-homard-eng.htm; accessed 15 August 2016), and combined with processing, holding, and shipping employment, the lobster fishing industry sustains more communities in Atlantic Canada than any other species (Gardner Pinfold Consulting 2006).

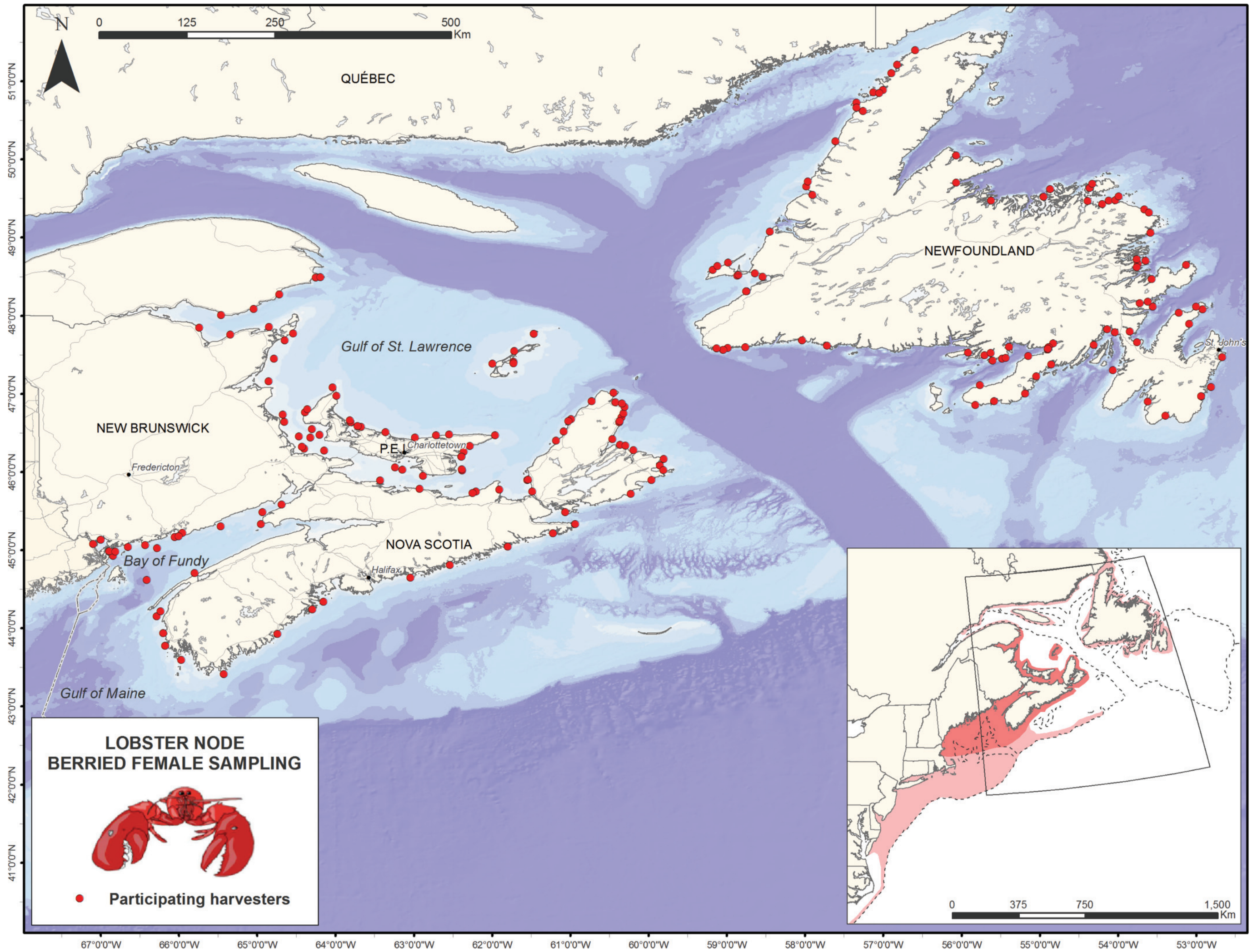
Research on lobster in Canada and the USA

Although the lobster occupies a preeminent position among Canadian fisheries, there has been a longstanding concern that this importance is not reflected in terms of research efforts or output (Chadwick 2001; FRCC 2007). Prior to the LNode collaboration, there has been only one other concerted and multidisciplinary effort to investigate lobster biology and ecology at the scale of eastern Canada, which came in the form of the strategic research project called "Canada Lobster Atlantic Wide Studies" (CLAWS). This 4-year project involved research on larval drift, juvenile biology and ecology, catchability, stock assessment parameters, and traditional ecological knowledge. It culminated in a symposium (Tremblay and Sainte-Marie 2001) that showcased some of the first pilot "experiments", conducted in the Bay of Fundy (Lawton et al. 2001) and Bonavista Bay, Newfoundland (Ennis and Rowe 2001), which demonstrated the feasibility and, more importantly, the necessity of collaboration between scientists and harvesters to advance the goals of scientific knowledge and management of the lobster resource.

To evaluate Canada's contribution to research on lobster, and the importance of this research relative to that of other major fisheries in Canada, we did a Web of Science (WOS) search (25 July 2016) of papers published by North Americans between 1975 and 2016 on the 10 taxa that supported the most important marine fisheries in eastern Canada in 2014 in terms of landed value (Table 1). Searches were conducted with three fields: (*i*) "Title", searching for the common or scientific names of each of the 10 focal taxa (e.g., "American lobster" OR "*Homarus americanus*"), (*ii*) "Year published", searching in periods of 10 years (e.g., "1975–1984"), and (*iii*) "Address", searching for publications with authors from Canada, the USA, Fisheries and Oceans Canada ("DFO" OR "Fisheries and Oceans" OR "Fisheries & Oceans" OR "MPO" OR "Pêches et Océans" OR "Pêches & Océans"), Canadian universities and colleges ("Canada" AND ["Univ* OR Coll*"]), and American universities and colleges ("USA" AND ["Univ* OR Coll*"]). One limitation of this search method is that publications where only the generic common name of the taxon was used in the title, instead of the specific common name and (or) scientific name (i.e., "lobster" instead of "American lobster" or "cod" instead of "Atlantic cod"), were not tabulated.

We found a total of 1109 publications from the US and Canada on lobster in the WOS search, which was the highest number of the 10 taxa surveyed, followed closely by the catch-all category clams–quahogs with 944 publications and by Atlantic cod (*Gadus morhua*) with 929 publications; fourth place went to scallops (*Placopecten magellanicus* and *Chlamys islandica*), far behind with 329 publications. In Canada alone, however, the number of publications on lobster (n = 405) was much greater than those on clams–quahogs (n = 166) but was far second to cod (n = 706). The skew in favour of cod existed in all but the 1975–1984 period, and it increased continuously from 1985–1994 to 2005–2016. This is

Fig. 2. Map of eastern Canada showing the five provinces (Quebec, Newfoundland and Labrador, New Brunswick, Prince Edward Island (PEI), Nova Scotia) where American lobsters (*Homarus americanus*) are fished, along with the centroid fishing location of the 283 lobster harvesters that sampled a total of 138 738 ovigerous females (to estimate egg and larval production) for the Lobster Node project between 2011 and 2014. The map was created by Brent Wilson, based on a bathymetry layer by Greenlaw and McCurdy (2014). The inset shows location of this sampling within the lobster's range on the east coast of North America, with light and dark red areas showing regions of low and high lobster abundance, respectively (adapted from Pezzack 1992). Digital lobster illustration by Vincent Rochette.



somewhat surprising if one considers the economic value of these two fisheries (e.g., between 2005 and 2014, the mean annual landed value of lobster in Canada was 23.5 times higher than that of cod, but the number of papers Canadians published on lobster (in 2005–2016) only represented slightly more than a third (37%) of the number they published on cod). Whereas much of this bias undoubtedly has to do with cod's iconic and vulnerable-species status, the latter arising as a consequence of the late 1980s to early 1990s stock collapses (Lambert and Dutil 1997; Olsen et al. 2004), it probably also reflects to some extent a bias in favour of research on commercially exploited fishes relative to invertebrates. For example, between 2005 and 2014 the landed value of the five invertebrate taxa included in the WOS survey was nine times higher (896%) than the landed value of the five fishes surveyed, but over roughly the same period (2005–2016), the papers published by Canadians (n = 336) on these five invertebrate taxa (actually 13 species) represented only 81.1% of the papers (n = 414) they published on the five fish species. The numbers are not as imbalanced if cod and lobster are excluded, but still the landed value of the remaining four taxa of invertebrates (12 species) is almost six times higher (589%) than that of the four species of fishes, while the number of publications on these invertebrates is only twice (196%) that on these fishes.

The rate of publication on lobster has been consistently higher in the USA than in Canada (Fig. 3). In Canada, publication rate per 10-year period fluctuated around 100 papers from 1975 to 2016, whereas in the USA it fluctuated around 170 papers from 1975 to 2004 and then increased to 231 papers in 2005–2016, due at least in part to the collapse of the Long Island Sound fishery (Pearce and Balcom 2005). Since 1975, USA researchers have published 84% more papers on lobster than Canadian researchers, despite higher landings, landed value, export volume, number of vessels, number of processing plants, and total number of related jobs in Canada than in the USA (Gardner Pinfold Consulting 2006). Also, academic researchers in the USA have a stronger tradition of lobster research compared with their Canadian counterparts. Between 1975 and 2016, for example, university and college researchers in the USA published almost three times more papers on lobster (n = 637) than their Canadian counterparts (n = 223), and approximately 86% of the lobster publications coming out of the USA were authored or co-authored by university or college researchers compared with only 55% in Canada.

Table 1. Common and scientific names of the ten taxa that supported the most important marine fisheries in eastern Canada in 2014, ranked by landed value and volume (DFO 2016) and that were used in the Web of Science (WOS) search.

Common name	Scientific name	Rank by value:volume
American lobster	*Homarus americanus*	1:4
Snow crab	*Chionoecetes opilio*	2:3
Northern shrimp	*Pandalus borealis*	3:1
Giant and Iceland scallops	*Placopecten magellanicus* and *Chlamys islandica*	4:5
Greenland halibut	*Reinhardtius hippoglossoides*	5:9
Clams and quahogs	Ten principal species[a]	6:7
Atlantic halibut	*Hippoglossus hippoglossus*	7:17
Atlantic herring	*Clupea harengus*	8:2
Haddock	*Melanogrammus aeglefinus*	9:8
Atlantic cod	*Gadus morhua*	10:10

[a]The following scientific names only were used for the WOS search on clams–quahogs: *Mercenaria mercenaria*, *Mya arenaria*, *Arctica islandica*, *Spisula solidissima*, *Ensis directus*, *Serripes groenlandicus*, *Mactromeris polynyma*, *Cyrtodaria siliqua*, *Clinocardium ciliatum*, *Siliqua costata*.

In Canada, a similar number of papers on lobsters have been authored or co-authored by DFO scientists (n = 219) and academics (n = 223) in peer-reviewed scientific journals between 1975 and 2016, but these numbers have shown different trends over time. The number of such publications by DFO scientists peaked at 89 in 1985–1994 and then declined to a low of 43 in 2005–2016 (and only 16 between 2010–2016), whereas the low number of papers from academics in 1975–1994 increased to a maximum of 85 in 2005–2016 (Fig. 3). It must be noted, though, that these numbers considerably undersell the total and relative (to academics) contribution of DFO scientists to lobster science and management, as they do not include the substantial research the latter publish in "grey literature" technical reports and research documents, as well as the scientific advice they provide to industry, managers, and policy makers.

Creation of the Lobster Node

Context

The opportunity for collaborative research on lobster arose from a special Government of Canada funding allocation to the Natural Sciences and Engineering Research Council of Canada (NSERC) for industry-led research collaborations on fisheries (the opportunity was also provided to the automotive, forestry, and manufacturing sectors), between harvesters and academics, to address issues of international competitiveness related to the economic crisis of 2008 (NSERC 2009). Although the NSERC funds were meant for industry–academic collaborations, harvester groups insisted that government lobster scientists be full partners in the initiative from the beginning, to ensure the new research would be relevant and complementary to existing research initiatives. Government researchers not only fulfilled this important role throughout the project, but they also served as essential "interpreters" by bridging gaps in understanding and communications between harvesters and academic researchers, who, for the most part, were new to fisheries issues and research. Government researchers also played a critical role in recruiting academic researchers as principal investigators to the LNode when the initial outreach to academics failed to generate lasting interest. The LNode comprised two of 13 projects in the eventual NSERC-funded Canadian Fisheries Research Network (CFRN), which operated from 2010 to 2015 with the goal of linking academic researchers with the fishing industry and with government scientists and managers on research of high priority to industry and of relevance to management.

This funding opportunity coincided with ill-understood large-scale and rapid increases in lobster landings (Fig. 1) and changes in the timing of important biological events (e.g., molting), which harvesters and government scientists had been observing for several years but that were not being addressed in a comprehensive way by existing research. This challenging context of dynamic change in lobster resource abundance, along with the unsettled legacies of CLAWS and the 1995 and 2007 Fisheries Research Conservation Council (FRCC) reports, were unifying factors across fleets and government scientists that provided an incentive, especially for harvester organizations — the initiators of the project — for a joint, large-scale research initiative that required collaboration. It is not clear if a more stable, geographically varying, or declining resource situation would have provided the same incentive for collaboration given the disparate nature of the harvester organizations and the many different barriers (e.g., geography, varying capacity, language) that existed to their collaboration.

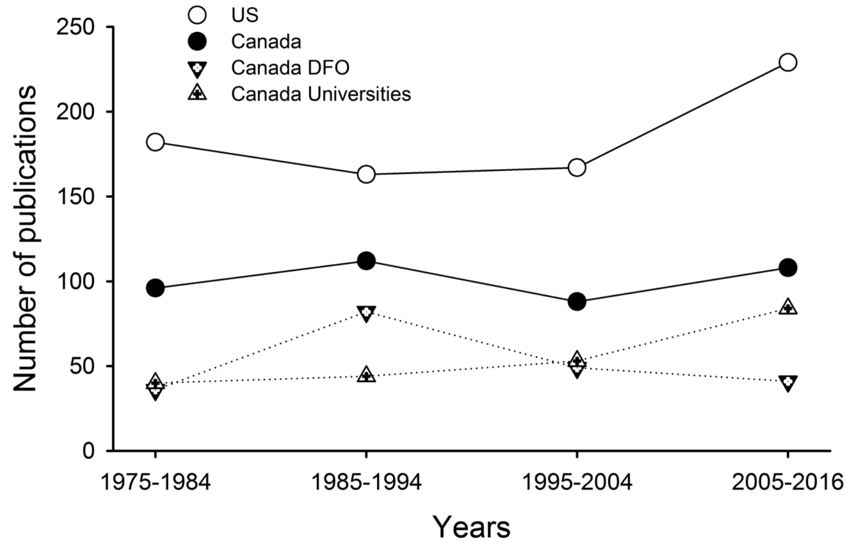
Process

The creation of the LNode followed a very thorough and carefully planned process. The partners benefited greatly from an externally facilitated (see below) participatory process to build consensus on research objectives well before research proposals were developed for the CFRN. Scoping workshops with broad geographic harvester and DFO representation were organized in 2008 and 2009, with the sole objective of identifying research objectives and methodologies that required partnership and collaboration. Academic researchers also attended these initial workshops, but as the identified research topics did not match their areas of interest or expertise, they did not stay involved and eventually new academic partners were recruited to the LNode as principal investigators.

The initial scoping workshop followed a very simple but important methodology. Harvester representatives were asked to initiate and lead the discussion by proposing lobster research questions, which they were mandated to identify when invited to the workshop, and scientists were simply asked to observe. Once the harvester representatives reached consensus on their priority research questions, the scientists were prodded to comment on whether the questions were of strategic importance to management and whether they had been addressed in previous research. For DFO scientists, this input was provided within the advisory context of the 1995 and 2007 FRCC reports and the CLAWS initiative, which all pointed to the need for research aimed at developing indicators of stock status and sustainability, understanding productivity and connectivity across management areas throughout the lobster range in Canada (identifying lobster biological–production units), developing predictive capability through monitoring of juvenile recruitment, and assessing the efficacy of various conservation measures.

This initial step accomplished three things: (*i*) it gave the harvester representatives ownership over the research questions; (*ii*) it validated these questions in terms of their scientific merit and usefulness to management; and (*iii*) it forged a consensus between harvesters and scientists around the importance of broad research objectives. Once this consensus was established, research scientists were asked to propose methods and protocols to address the research objectives with a particular emphasis on data collection requiring collaboration with harvesters. This exercise created complicity between harvesters and scientists in the practicalities of research design, making it a joint, problem-solving endeavor, which further cemented their relationship and extended ownership of the research to the scientists. The results were a series of very practical and innovative proposals for collaborative research to address major gaps in the understanding of lobster productivity, stock structure, and the connectivity between management areas, which formed the foundation of the research initiative.

Fig. 3. Total number of publications on American lobster (*Homarus americanus*) authored or co-authored by researchers in the USA and Canada over the past 40 years (publications co-authored by USA and Canadian researchers were counted towards each country's total), along with numbers authored or co-authored by Canadian researchers working for Fisheries and Oceans Canada or a university–college.



Importance of external facilitation

The workshops were the joint initiative of two national organizations: the Canadian Council of Professional Fish Harvesters (CCPFH), the national coordinating body for human resource development for the Canadian owner–operator fishery, and the Ocean Management Research Network (OMRN), a national oceans policy research coordinating body established in 2001 with funding from the DFO and NSERC's counterpart for the social sciences, the Social Sciences and Humanities Research Council of Canada. Although these organizations (CCPFH and OMRN) are both located in Ottawa — a mere four city blocks from each other — they had no knowledge of each other's existence prior to being introduced by the DFO Science Directorate in 2008, as part of its attempts to facilitate fishing industry take-up of the NSERC opportunity.

Given the varied nature of the fish harvesting and academic sectors, with virtually no history of research collaborations in the natural sciences, CCPFH and OMRN played a central role as planners and conveners of the first events and in attracting key participants from their respective sectors. The fact that neither organization had a vested interest in the outcome of the discussions, other than fostering collaboration, allowed them to play this facilitation role. This detached external facilitation was subsequently "institutionalized" in the LNode partnership through the services of the CFRN Facilitator, a position created by the CFRN to assist the research partners in building consensus around research objectives. The CFRN Facilitator worked with the LNode partners in developing agendas for planning meetings and annual or semiannual general assemblies (which gathered up to 35–55 participants representing the three partners from all regions), chaired the meetings and assemblies, and worked with the governance structure (see below) between meetings to enable the partners to plan, identify issues, solve problems, and make decisions.

The research of the Lobster Node

The scoping workshops resulted in two complementary research projects, one on metapopulation dynamics and management areas and the second on benthic recruitment of early life stages. These two projects were merged into the LNode, the overarching goal of which was to enhance our understanding of lobster productivity, stock structure, and connectivity in Canada. This goal was of considerable interest to harvesters because it involves better defining the true biological–production units (versus management areas) upon which they rely for their livelihoods and estimating the degree of interdependence between such units. It has immediate implications for harvesters' dependency on, and responsibility to, fishing neighbours, as well as for the benefits they should expect to accrue from conservation practices they adopt (e.g., increasing minimum legal size). The LNode collaboration tackled this goal via integrated research on (1) egg and larval production, (2) larval dispersal, (3) benthic recruitment, (4) benthic movements, and (5) genetic structure. It involved over 250 boat captains with their crew and association representatives, eight DFO and one provincial research scientists and biologists, five university professors, 14 graduate students (eight masters, six doctoral), over 20 undergraduate students (summer research assistants and honours), and a similar number of full-time and term technicians based within harvester organizations, DFO, and universities.

(1) Egg and larval production

The LNode developed simple and standardized protocols and tools (e.g., measuring gauge, egg-staging scheme, instruction videos and manuals; http://www.cfrn-rcrp.ca/Public-Products-EN) to quantify the abundance, size, and clutch condition of ovigerous female (i.e., bearing eggs on their abdomen) lobsters. With these tools, 138 738 ovigerous females were sampled during the summer fishing seasons of 2011, 2012, 2013, and 2014 from 283 fishing boats and 193 fishing ports across all five provinces of eastern Canada (Fig. 2). Statistical models were developed to account for "nuisance variables" that may have affected catches (e.g., fishing effort, trap size, water temperature) and were used to document relatively strong geographic patterns of larval production, which are expected to assist future studies of large-scale changes in zones of production (e.g., in relation to climate change). These models also enable estimates of geographic variation in egg production that can be used to parameterize biophysical models of larval dispersal.

During this sampling, harvesters raised concerns over the occurrence of females possessing "abnormal clutches", in which eggs covered less than 50% of the abdomen. This observation led to the co-construction of a new research project within the LNode, which aimed to assess the incidence, costs (in terms of egg loss), and causes of abnormal clutches in female lobsters in Canada. Analyses of the LNode database revealed the presence of ovigerous females with abnormal clutches at the vast majority of fishing ports sampled, and these estimates combined with lab work revealed that abnormal clutches represent major production costs at the level of the individual and non-negligible ones at the level of the population (Tang 2016). Additional sampling revealed that abnormal clutches are more prevalent among smaller females in the majority of Lobster Fishing Areas (LFAs), and a laboratory experiment suggested that sperm limitation (MacDiarmid and Sainte-Marie 2006), but not oocyte limitation, likely contributes to this phenomenon (Tang 2016).

The LNode collaboration also provided an opportunity for in-depth analyses of large data sets and time series existing within the DFO. For example, "grey literature" data from multiple sources within the DFO, along with new data collected by the LNode, were included in a meta-analysis of the literature that provided evidence of a reduction in female lobster size at sexual maturity in many regions in Canada over the past 50–90 years, a reduction that seems to be partly attributable to intense size-selective harvesting (Haarr et al. 2018).

(2) Larval dispersal

The LNode built on work done within DFO to develop a large-scale biophysical model of larval dispersal and to map predicted larval-mediated connectivity among lobster management areas in Canada and the USA (Quinn et al. 2017). The model predicts larvae dispersing up to hundreds of kilometres prior to settlement and connecting each of the 47 Canadian lobster management areas to at least one and up to ~10 different management areas. Although the patterns of settlement predicted by the model have yet to be thoroughly validated, the patterns of connectivity it predicts are correlated with the species' genetic population structure (see section on Genetic structure below).

Hatch time can markedly modify larval dispersal before settlement, as it will affect the currents and temperatures experienced by developing larvae (Incze and Naime 2000; Xue et al. 2008). The LNode did a field study in Cheticamp, southern Gulf of St. Lawrence, to validate a method to predict hatch time of lobster larvae in nature, based on measurements of embryo eye size (proxy for development; Perkins 1972) and water temperature. In this study, 96% of larvae were predicted to hatch within the observed hatch period, and the dates on which hatch was predicted to occur covered 100% of the observed hatch period (Miller et al. 2016). Applying this method to egg samples collected from 22 locations in Atlantic Canada revealed relatively long hatch periods in all locations (≈50–120 days), the timing of which tended to minimize the predicted period of larval drift (M. Haarr, B. Quinn, and R. Rochette, personal communication). It also revealed geographic differences in hatch time that affected the predictions made by the biophysical model of larval dispersal. These last analyses assume, however, geographically invariant development functions of lobster embryos, and work is under way to test this assumption in the lab and in the field. Similarly, rearing experiments were conducted in the lab that demonstrated evidence of geographic variation in the survival, development rate, and size of lobster larvae raised in a common environment, including one experiment that provided evidence of local adaptation in larval development rate, with larvae from cold-water origin seemingly developing faster at lower temperature than conspecifics of warm-water origin (Quinn et al. 2013).

(3) Benthic recruitment

The LNode's research provided rare evidence of a link between spatial variation in the supply of postlarval lobsters and their benthic recruitment to an area (Sigurdsson et al. 2014). It also showed patchiness in benthic recruitment of lobster at the spatial scale of 0.4–4 km^2 in the southwest Bay of Fundy (Sigurdsson et al. 2016), and preliminary analyses indicate that this patchiness is most strongly related to variation in the North Atlantic Oscillation Index and the abundance of juvenile lobsters.

The LNode conducted a number of lab experiments to enhance understanding of the processes affecting the recruitment of competent lobster postlarvae to the sea floor. These experiments confirmed that water temperature affects the behaviour of lobster postlarvae (e.g., time to reach the bottom, tendency to cross a thermocline; see also Boudreau et al. 1992; Annis 2005), but they also revealed that acclimation can reduce the effect of temperature on these settlement behaviours and decisions (Chiasson et al. 2015). Results of these experiments did not support the hypothesis of local thermal adaptation, since settlement behaviour did not differ among postlarvae of females from different thermal regimes (Barret et al. 2017). Experiments confirmed (Dinning 2014) that competent lobster postlarvae settle as soon as they encounter cobble substrate (see also Botero and Atema 1982; Cobb et al. 1983), but delay settlement if swimming over mud and sand (see also Botero and Atema 1982). They also showed for the first time that postlarvae swimming over sand (i.e., very poor substrate) may delay settlement to the point of incurring developmental costs that result in a smaller size at instar V (Dinning 2014). Finally, laboratory experiments demonstrated that the sand shrimp (*Crangon septemspinosa*), and to a lesser extent the green crab (*Carcinus maenas*), will readily attack and prey upon settling and newlysettled lobsters (Sigurdsson and Rochette 2013), and experiments are ongoing to determine if the presence of benthic predators impedes bottom exploration, which could impact settlement time and dispersal distances.

Although lobster postlarvae clearly prefer settling on complex cobble bottom rather than on more homogeneous mud or sand, evidence was provided that settlement does occur on mud bottom in nature (Dinning 2014); settlement on mud was low by unit area, but may still be demographically important given the prevalence of fine-sediment bottom over much of the species' range. Importantly, morphometric and molecular (protein, RNA–DNA) analyses indicated that growth and body condition of juvenile lobsters sampled from mud bottom were comparable, or perhaps even slightly better, than those of juveniles sampled from cobble bottom in the same bay (Tang et al. 2015).

(4) Benthic movements

The LNode used ultrasonic telemetry in upper Passamaquoddy Bay, southwest Bay of Fundy, to generate the first empirical data concerning activity levels and movements of juvenile lobsters (20–47 mm carapace length) in nature (Morse and Rochette 2016). These data confirm observations made in the lab (Lawton 1987) suggesting that juvenile lobsters behave as nocturnal "central place foragers", but reveal they are more active than expected, with some individuals spending on average as much as 33% of each day outside of shelter (Morse and Rochette 2016). The results also did not suggest an increase in activity with increasing size of the juvenile (Morse and Rochette 2016), as suggested by the literature (Wahle 1992; Lawton and Lavalli 1995), although the first juvenile phase (i.e., shelter-restricted) could not be tagged in this study due to its small size. These findings were mostly confirmed in a second ultrasonic telemetry study that was conducted in Anse Bleue, southern Gulf of St. Lawrence, which further showed a marked increase in activity (including seasonal migration) of adolescent and adult individuals compared with juveniles (Morse et al., in review).

The LNode has more recently used "pop-up" archival satellite tags to quantify the temperature experienced by ovigerous female during seasonal inshore–offshore migrations in the Bay of Fundy and developed an individual-based model to contrast observed thermal histories with those expected under different assumptions of movements (e.g., random walk, directed movement towards warmer water; P. Hanley, E.P. Bjorkstedt, B. Morse, and R. Rochette, personal communication). The data are being used to test the hypothesis that these seasonal movements accelerate embryo development (e.g., Campbell 1986; Cowan et al. 2007; Goldstein and Watson 2015) and to determine the extent to which the females' movements maximize the number of "growing degree days" (a measure of heat accumulation for development; e.g., Campbell 1986) their embryos experience. Finally, the LNode analyzed historical data from 33 tagging studies conducted in the southern Gulf of St. Lawrence between 1980 and 1996, and these suggest that movements of adult lobsters in this region lead to considerable genetic connectivity, and potentially to moderate demographic connectivity, between fishing ports and management areas when considering the movements of individuals (rather than a "group average") over multiple (rather than single) years (B. Morse, B. Quinn, M. Comeau, and R. Rochette, personal communication).

(5) Genetic structure

Prior to the LNode research, the best representation of the genetic stock structure of lobster was provided by Kenchington et al. (2009), based on 13 microsatellite markers and 27 sample locations in the US and Canada. This study revealed relatively weak population structure, consisting mainly of a "north–south" discontinuity between lobsters in the Gulf of St. Lawrence and those in the Gulf of Maine – Bay of Fundy. Using Next Generation Sequencing technologies, the LNode created an enhanced map of stock structure for lobster, based on 10 000+ single nucleotide polymorphisms applied to samples of ovigerous females from 17 locations throughout the species' range. This work confirmed the divide between "northern" and "southern" lobsters and further revealed significant (although small) genetic differentiation between lobsters from most locations within both of these broad geographic areas (Benestan et al. 2015). Data from this study revealed 11 genetically distinguishable populations (Benestan et al. 2015), which included cases of both agreement and disagreement with the LFAs currently used as management units. More recently, the LNode used population differentiation approaches combined with environmental association analyses to assess the relative importance of spatial distribution, ocean currents, and sea surface temperature to patterns of putatively neutral and adaptive genetic variation among ovigerous female lobster from 19 locations (Benestan et al. 2016). These three factors explained 32% of the neutral genetic variation among sample locations, with ocean currents driving the majority (66%) of this relationship. In contrast, minimum annual sea surface temperature was the factor most strongly related to putatively adaptive genetic variation, accounting for 28% of this variation. Benestan et al. (2016) also discovered variation within genes previously shown to play a role in thermal adaptation. These results have direct implications for the management of the lobster and provide a foundation on which to predict how this species will cope with climate change.

Looking forward

Despite the progress made, further research is needed under each of the LNode's five research themes. First, the quality of the settlement predictions made by the biophysical model of larval dispersal should be evaluated to assess the model's usefulness and guide research for its improvement. Whereas similar models have been used to study larval dispersal in numerous species of invertebrates (Arnold et al. 2005; White et al. 2010; Jolly et al. 2014; Jorde et al. 2015) and fishes (Koeck et al. 2015), the spatiotemporal settlement patterns they predict have been rigorously validated in only a few studies (Bolle et al. 2009; Kough et al. 2013; Koeck et al. 2015). Second, research should be done to assess the usefulness of further parameterizing the dispersal model on the basis of vertical and horizontal larval swimming behaviour (e.g., Stanley et al. 2016) and settlement decisions (e.g., substrate and thermal effects). Whereas larval dispersal models often do not include realistic functions of swimming or settlement behaviour, such considerations have been shown to increase the accuracy of benthic recruitment predictions for spiny lobsters (Kough et al. 2013) and plaice (Bolle et al. 2009). Third, work is needed to quantify settlement, growth, and movements of young lobsters on different substrates and to model the importance of these different substrates to benthic and fisheries recruitment. Although cobble bottom is the preferred habitat of settling larvae and young benthic stages (Wahle and Steneck 1991, 1992), it is scarce over much of the species' range, and patterns of benthic recruitment may vary greatly depending on the ability of these early life stages to use alternative bottom types. Fourth, more consideration should be given to the contribution of benthic movements by adolescents and adults to genetic and demographic connectivity, as has recently been argued more generally for marine fishes (Frisk et al. 2014). For example, there are regions where lobsters regularly undertake long-ranging (tens to hundreds of kilometres) movements (Campbell and Stasko 1985, 1986), and even in regions where lobsters display low mean displacements during a fishing season or over 1 year (Comeau and Savoie 2002), longer movements made by a small proportion of the population over multiple years could contribute meaningfully to genetic (in particular) and demographic (to a lesser extent) connectivity. Fifth, genetic work should be done at smaller spatial scales and with different life stages to enhance the spatial resolution of the lobster's map of genetic stock structure and determine how and why the latter might change during development and between genders. Finally, and most importantly, these different scientific advances, and in particular estimates of genetic versus demographic connectivity, should be integrated in a common understanding of lobster stock structure in support of sustainable fisheries. There is arguably a pressing need for this research, given that climate change will likely affect the development and dispersal of lobster larvae, seasonal migrations of adults, the timing of important biological processes (e.g., moulting, spawning, hatching), and even the species' distribution.

Benefits of the Lobster Node

The Lobster Node created a platform for research on Canadian lobster fisheries

The most tangible benefit of the LNode is that it brought together harvesters and scientists from government and academia to engage in concerted research on lobster fisheries over most of the species' range in Canada, as advocated by the FRCC (1995, 2007) and the CLAWS collaboration (Tremblay and Sainte-Marie 2001). The complementary expertise and resources of the three partners were essential to the success of the LNode's ambitious research agenda.

Another important benefit of the LNode is that it provided opportunities for DFO scientists from different regions to discuss large-scale issues concerning the fishery and its science. Whereas DFO scientists participating in the LNode had considerable research experience on lobster and lobster fisheries, opportunities for direct interactions among DFO colleagues at the Atlantic scale, let alone with industry and academia, were uncommon since the early 2000s. The DFO's extensive knowledge of lobster biology and fisheries carried all activities of the LNode.

Lobster harvesters similarly have deep traditional and first-hand knowledge of lobster and the ecosystem in which they live, as well as a long tradition of participatory research, but the LNode represented the largest concerted research initiative ever undertaken involving harvesters from different management areas. The extensive at-sea sampling realized during the LNode, which was mostly done by harvesters or in collaboration with them aboard their boats, represents a cornerstone of the LNode research initiative.

The LNode markedly enhanced, as already mentioned, the involvement of academics in lobster research in Canada. Scientists from different universities led much of the sample processing, data analyses, and preparation of papers, with input from partners at many steps along the way (e.g., annual CFRN and LNode assemblies, supervisory committee meetings, phone calls, and email exchanges). Academics were able to leverage additional funding (i.e., outside the CFRN envelope) for this collaboration, as granting agencies in Canada increasingly encouraged such partnerships between industry and scientists.

The LNode has published 11 peer-reviewed papers since 2013 and should publish at least 17 more before the end of 2018, for a mean of 4.7 papers per year, all relevant to lobster productivity, connectivity, and stock structure. This publication rate represents 62% (28/45) of that by all Canadian researchers on all topics related to lobster for the preceding 6-year period (2007–2012). But more important than the actual number of publications by the LNode is the nature of the work it accomplished, which in most instances would not have been possible without the knowledge and resources brought to the table by the different collaborators.

The Lobster Node created trust among partners and a desire to work together

Another major benefit of the LNode is the trust and relationships it fostered among the partners. Participants from all partner groups commented on having never experienced such dedication, positivity, and synergy among government, industry, and academia. The making of a "common cause" is a hallmark, although intangible, benefit of the LNode. In particular, this initiative enabled all participating harvester organizations to set aside their traditional and substantial differences to cooperate in collecting baseline information throughout eastern Canada on topics of common interest — productivity, stock structure, and connectivity of lobster among management areas. For some organizations this meant contributing their long-standing research and monitoring data series, which were the result of equally long-standing collaborations with federal and provincial scientists, to a broader research effort. For others it meant the validation of data collection that they had been doing on their own and in isolation. For others, the involvement in data collection was a foray into a new area of activity. The fact that they did this together, as harvester associations and with scientists from governments and universities as equals, is seen as a major accomplishment and benefit.

The importance of the trust and relationships established during the LNode is perhaps best illustrated by considering the new activities and initiatives that have emerged from this project, including (*i*) regular exchanges among the three partners, (*ii*) preparation of materials by graduate students for fishermen associations (e.g., a computer program to assist in extracting and summarizing sampling data and dispersal model outputs), (*iii*) participation of academics in lobster stock assessment meetings, including the contracting by the Newfoundland Fish Food and Allied Workers organization of an LNode student to analyze data and present results at a regional assessment meeting, (*iv*) new research involving the entire collaboration based on some of the LNode's major findings (via an NSERC Strategic Project Grant), (*v*) joint planning of research on contaminants by two provincial associations historically divided on conservation measures, and (*vi*) new research aiming to quantify the effects of salmon aquaculture on lobster. The networking also extended to the international arena, as several LNode collaborators participated in an international exchange through the CFRN (http://gap2.eu/the-gap2-exchange/the-gap2-exchange-blogs/cfrn-gap2/). These relationships may in the end represent the most beneficial achievement of the LNode, if they can be maintained beyond the life of this project.

Recognizing the knowledge of harvesters and their role in sustainability

Harvester representatives approached the initial opportunity to collaborate on the LNode with the desire to be recognized as research partners, rather than solely as a source of data. They wanted to be recognized as an important source of knowledge on lobster behaviour, ecosystem dynamics, and a host of other factors important to science. They feel that their unique knowledge and experience as "sea naturalists" was noticed, valued, and respected by their scientific partners. They also came to recognize that they were capable of collecting useful data and making a more valuable contribution to science than they themselves generally appreciate.

Harvester organizations also valued the LNode research initiative for providing them with the opportunity to view lobster sustainability beyond landings' information and to foster a nonconfrontational dialogue with (DFO) scientists on stock status indicators in a context of rapid changes. This was favoured by the innumerable learning opportunities for harvester representatives on research methods and approaches, as well as through new knowledge gained from the research results of the LNode. In particular, industry participants learned through, and helped shape, science presentations in a conference setting, especially student poster sessions, which soon became a highlight of the annual General Assemblies.

The Lobster Node provided a strong environment for student training

The LNode offered an exceptional environment for the training of students due to the quality and diversity of support it, and more broadly the CFRN, provided in terms of infrastructure and research equipment, intellectual capacity and support, and experiences and perspectives of different stakeholders. All students had a DFO scientist as co-supervisor or member of their supervisory committee and many also had an industry representative. All students also had the opportunity to tap into the expertise of lobster harvesters and DFO scientists on a regular basis throughout their degree, through formal and informal opportunities provided by the LNode and CFRN interactions. Many students remarked that the frequent occasions they had to discuss and present their work in a supportive environment greatly helped them improve their communication skills and in particular their ability to address audiences with different backgrounds. Through their work, students also gained an appreciation for the socioeconomic importance of the lobster fishery, which increased their dedication and excitement about their research. They felt that collaborators cared about their contribution to this project and that a genuine sense of camaraderie and "working together on a common goal" developed among all partners.

This unique training environment has likely well prepared LNode students for a competitive and varied workforce, including potentially as biologists or research scientists with governments or lobster harvester associations.

Limitations and regrets

There were no negative outcomes of the LNode collaboration, but there were two major resource limitations and challenges that are worth pointing out, for the benefit of future similar enterprises.

Insufficient funding for certain critical activities

The partners all agree that they seriously underestimated the costs of coordinating data collection over vast areas involving large numbers of volunteer harvesters who had to follow strict protocols while still going about the strenuous demands of fishing. The LNode partially subsidized some of the harvesters for field work, but most of these costs were assumed by the harvester organizations, largely by "piggybacking" on other research projects, and by the harvesters themselves. LNode harvesters contributed ~$1.25 million in kind to support the at-sea sampling done from 2011 from 2015. The LNode also had insufficient resources to support full participation of industry associations, and consequently harvesters from less organized areas (e.g., southwest Nova Scotia), or current marginal areas of the lobster range (e.g., north shore of the Gulf of St. Lawrence), were under- or not represented at meetings of the LNode and in most of its sampling activities.

Although DFO was generous with in-kind support, including salaries, facilities, and equipment, funding was insufficient for DFO scientists to fully engage in the project, which is in part a consequence of government budget constraints and the NSERC funds being earmarked for industry–academic collaborations. However, the partners note that caution must be exercised in diverting too many funds to industry–academic collaborations, as academics will often shy away from natural history research (i.e., low-profile, descriptive research of the type emphasized in Anderson et al. 2008) and cannot easily fulfill monitoring roles essential to sustainability because of funding cycles and uncertainty.

Insufficient resources for communication among partners

The partners also underestimated the time and costs necessary for adequate reporting of research results, given the amount of information generated by the project and the large number of collaborators involved. Although some academics devoted considerable time to these activities with their students, they were unable to meet the partners' expectations or their own for that matter.

The partners similarly regret that there were not more opportunities to inform the broad membership of harvesters' associations of the results of the LNode research through formal presentations by students and principal investigators at regular association meetings. Harvesters commented in this regard that they also would have been interested in hearing about research results from their fishing areas as they relate to other lobster management areas and geographic regions. The main impediment here appeared to be time and scheduling problems related to the availability of students during the periods of the year when associations hold their annual meetings, although better (earlier) planning might have mitigated these problems.

Why was the Lobster Node such a success?

The importance of good governance

The success of the LNode was in large part due to the mutual understanding, trust, and respect between partners that rapidly emerged through the co-construction of research objectives, subsequent regular meetings, and collaborative execution of projects, as well as the very active and synergic contribution of all students. However, another major reason for the LNode's success was the development of what the partners consider to be an exemplary governance process to oversee the collaboration. In considering the collaboration, an initial concern expressed by harvesters was the accountability of the academic researchers to them. Based on some previous experiences, harvester representatives feared being mined for data and ideas that would be appropriated for scientific publications in which they would have no input or for which they would receive no acknowledgement. This concern was dealt with in a very straightforward and innovative manner. Harvester representatives proposed that all parties to the initiative sign a memorandum of understanding (MOU) as a formal contract binding the parties prior to the initiation of the research and as a precondition for the release of any research monies to academics (this initiative was subsequently adopted by the CFRN as a whole). The MOU, which the harvester representatives drafted, identified the partners to the initiative, the project summaries and objectives per research laboratory, the means to achieve objectives (funding and students), and the project activities and deliverables.

Most importantly, the MOU detailed the LNode governance. It established the General Assembly to bring together the partners to build consensus on strategic directions, research priorities, methodologies, division of labour, and the all-important review of results. Between meetings of the General Assembly, decision-making was vested in a 10-person Steering Committee (six fleet representatives, two academic Principal Investigators, one DFO representative, and the CFRN Facilitator), and the authority for the regular operations was delegated to the Principal Investigators and the CFRN Facilitator. The MOU further committed the partners to consensus decision-making, the necessary agreement of all three partners in major undertakings, and a conflict resolution process should disagreements of either governance or scientific nature arise. It also addressed the challenges of dealing in two languages through parallel conference calls in French and English, with bilingual representatives providing the necessary overlap between language groups. Fortunately, both Principal Investigators, the CFRN Facilitator, several DFO scientists, and industry representatives were bilingual francophones, which greatly facilitated communications in both languages.

Lastly, the MOU committed the parties to the principles of transparency and accountability and discussed in detail the ownership rights to the data, the right to publish, and the acknowledgement of contributions. The MOU made explicit the expectations and responsibilities of the parties in an open and transparent way, and harvester participants consider it to have been respected to the letter despite never having been referred to once after its signing, so deep was the commitment of all the parties to its observance.

Fundamental nature of the research topics

An important outcome of the initial scoping workshops that should not be overlooked in explaining the LNode's success is that they brought industry participants to a different kind of forum for discussing fisheries issues. The more customary platform for discussing fisheries issues is the DFO science advisory process, which is conducted under the auspices of the Canadian Science Advisory Secretariat (http://www.dfo-mpo.gc.ca/csas-sccs/index-eng.htm; accessed 14 September 2016). Although the process is inclusive, the lobster fishing industry has always felt that it was not an integral part of it, especially in the planning phase prior to the scientific peer review of stock status. Furthermore, awareness of the social and economic consequences of management decisions looms over these processes and taints them for all participants, but especially so for industry representatives, who often have personal stakes in the outcomes related to their own livelihoods and investments.

In contrast, the forum provided by the LNode scoping workshops was intellectually liberating for industry participants, as the focus was on things they identified as important — knowledge gaps in the understanding of ecosystem dynamics, the productivity of lobster stocks, and the effectiveness of management measures — that did not have direct implications for harvest controls. In the collective experience of the industry participants, some of whom had been involved for decades in DFO science advisory processes for different species, there had been no science forum like it. In the workshop evaluation, several senior industry participants remarked that these workshops were the most interesting and productive fisheries meetings they had ever attended.

Conclusion

Canada's investment in lobster research has not been commensurate with the species' socioeconomic importance to the country and fishing communities in eastern Canada (Chadwick 2001; this paper). The DFO CLAWS project was a major and successful concerted and multidisciplinary research effort on lobster biology and ecology at the scale of eastern Canada, but it only lasted 4 years, was completed 16 years ago, and was almost exclusively a government undertaking. A follow-up was envisioned to help "rebuild an interest in lobster science that is more proportional to the value of lobster to the economy" (Chadwick 2001). CLAWS II would pursue the general objectives of CLAWS I, but with an increased industry involvement and would focus on four themes: visualizing stock status, evaluating conservation measures (including closed areas), tracking long-term recruitment trends, and identifying lobster production areas (Chadwick 2001). However, due in part to funding constraints, CLAWS II never materialized as an integrated program, although some components (e.g., monitoring of benthic recruitment) went ahead on a small scale in some DFO regions. In some ways, the LNode has been a worthy successor to CLAWS I, meeting or surpassing expectations in terms of geographic coverage, industry involvement, interregional collaboration and co-decision, and academic motivation to address lobster biology and ecology.

The LNode's resounding success has created a desire to establish a "permanent" research platform to support Canadian lobster fisheries. A de facto research group, with regular meetings and channels of communications, would increase the efficacy with which research (*i*) priorities are identified, (*ii*) methodologies are developed, (*iii*) activities are undertaken, and (hopefully) (*iv*) results are considered in management. The LNode has demonstrated the value of such a collaborative research platform, and its experiences (successes and challenges) should help make the second phase even better. An "LNode II" should adopt the principles that contributed to the success of the LNode, particularly co-construction of research objectives and methods, transparency, and strong governance. It should also address limitations identified by the LNode, particularly with respect to the need for resources to help harvesters engage in the research and to support adequate reporting and communication among partners, including more interaction with local harvesters associations. The new platform should also expand to include social scientists to conduct socioeconomic analyses of the fisheries in relation to the value of the resource and the timing of important biological processes (e.g., molting). It should also engage DFO managers to more effectively incorporate science-based information into management decisions.

The LNode collaboration is well positioned to build a permanent research platform in support of lobster fisheries science in Canada, and the time to do this is now, as there currently exists an unprecedented level of trust and good faith among lobster harvesters, government scientists, and academics, along with a shared enthusiasm for collaborative research in support of lobster fisheries. A novel and effective approach to carry out research on lobster fisheries has been developed, which should be maintained to help address changes to lobster populations and the fisheries they support for years to come. This represents a strategic and arguably necessary investment, given the importance of lobster to the economy and social fabric of eastern Canada and the rapid changes that are occurring to lobster and the ecosystem in which it lives.

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