Evaluating the knowledge base for expanding low-trophic-level fisheries in Atlantic Canada

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Abstract: Over the last two decades, low-trophic-level fisheries have rapidly expanded in Atlantic Canada, largely compensating for collapsed groundfisheries; however, concerns have been raised regarding the limited background knowledge for many newly targeted species and their overexploitation in other regions. Using government stock assessments, we evaluated the amount of information available to assess population, fisheries, and ecosystem status in emerging (new since 1988), developing (expanding since 1988), and established fisheries on the Scotian Shelf. Emerging fisheries had significantly lower levels of population knowledge than developing and established fisheries. Importantly, knowledge was often lacking in basic population parameters such as growth rates, current biomass, and geographic range. In contrast, ecosystem knowledge, such as habitat disruption and recovery, was higher in emerging than established fisheries. Overall, quantitative knowledge was positively related to fishery value and greatest for 30- to 100-year-old fisheries. Although the number of government and general scientific publications greatly increased since 1990 for developing and established fisheries, publications for emerging fisheries remained at low levels. Emerging fisheries represent important socio-economic value in Atlantic Canada but may be progressing too rapidly for adequate knowledge to be gained, presenting a risk for their sustainable development.

Résumé : Au cours des deux dernières décennies, les pêches de niveau trophique inférieur ont connu une expansion rapide dans l'Atlantique canadien, compensant l'effondrement des pêches de fond; des inquiétudes ont, cependant, été formulées concernant le peu de connaissances de base disponibles sur ces nouvelles espèces ciblées et leur surexploitation dans d'autres régions. À l'aide d'évaluations de stocks gouvernementales, nous déterminons la quantité de données disponibles pour estimer le statut des populations, des pêches et des écosystèmes dans les pêches commerciales en émergence (nouvelles depuis 1988), en croissance (en expansion depuis 1988) et les pêches établies sur la plate-forme néo-écossaise. Il existe significativement moins de connaissances démographiques sur les pêches en émergence que sur les pêches croissantes ou établies. En particulier, il manque souvent de données sur les variables démographiques de base, telles que les taux de croissance, la biomasse courante et la répartition géographique. En revanche, les connaissances de l'écosystème, telles que les perturbations des habitats et leur récupération, sont plus grandes dans le cas des pêches en émergence que dans celui des pêches établies. Globalement, il existe une relation positive entre les informations quantitatives disponibles et la valeur de la pêche commerciale; ces informations sont le plus abondantes dans le cas de pêches en existence depuis 30 à 100 ans. Bien que le nombre de publications scientifiques gouvernementales et générales sur les pêches en croissance et les pêches établies ait augmenté depuis 1990, il reste bas dans le cas des pêches émergentes. Les pêches commerciales en émergence représentent une valeur socio-économique considérable dans l'Atlantique canadien, mais il se peut qu'elles progressent trop rapidement pour permettre l'acquisition de connaissances adéquates, ce qui représente un risque pour leur développement durable.

[Traduit par la Rédaction]

Introduction

The collapse of the groundfishery on the Canadian Scotian Shelf resulted in major ecosystem changes and economic challenges (Roy 1996; Worm and Myers 2003; Frank et al. 2005). This collapse was compensated for by the expansion of fisheries to lower trophic-level marine invertebrate and plant species (Lotze and Milewski 2004; Frank et al. 2005), thereby following a global trend of declining average trophic level of fisheries (Pauly et al. 1998, 2001). In Atlantic Canada, the monetary value of shrimp and crab landings alone now exceeds that of the former groundfishery (Frank et al. 2005); however, lessons from other parts of the world indicate that the rapid expansion and profit from low-trophic-level fisheries can be short term. For example, sea urchin and sea cucumber fisheries around the globe show rapid boom-and-bust patterns (Conand 2004; Berkes et al. 2006). This is not an entirely new phenomenon as can be seen in historical oyster fisheries (Kirby 2004). Recently, the sea cucumber fishery on the Canadian west coast was

Received 6 October 2007. Accepted 7 August 2008. Published on the NRC Research Press Web site at cjfas.nrc.ca on 13 November 2008.
J20208

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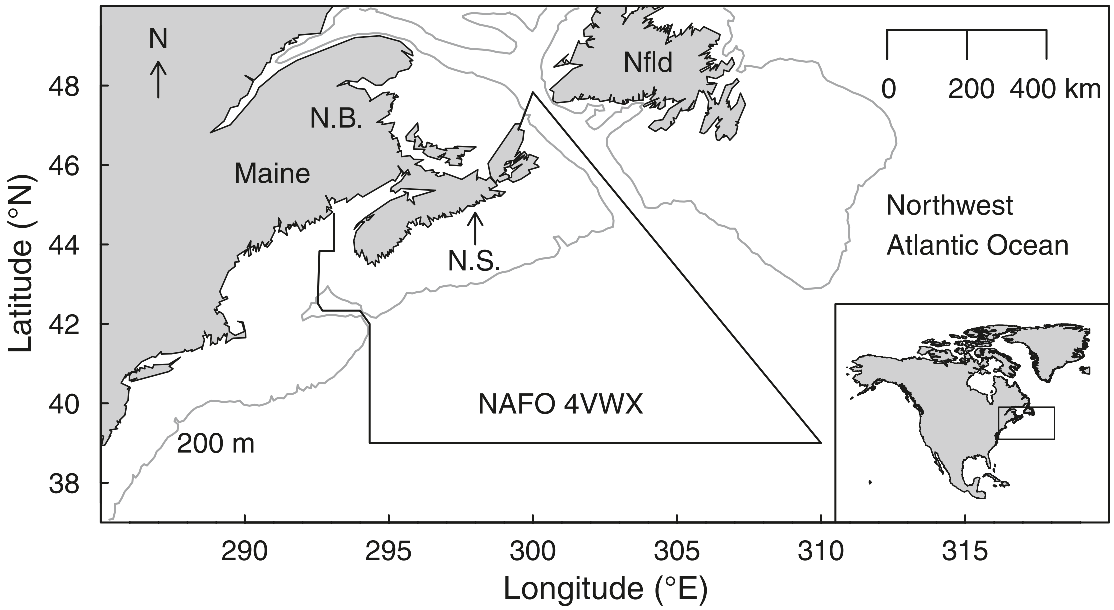
 doi:10.1139/F08-156

Fig. 1. Map of the study area showing NAFO (Northwest Atlantic Fisheries Organization) Divisions 4VWX and the Atlantic provinces of Canada (N.S. = Nova Scotia, N.B. = New Brunswick, Nfld = Newfoundland). The 200 m depth contour is shown.



on track to follow a similar pattern until stricter catch and license limitations and area closures were implemented (DFO 2002). It may be particularly important to ensure the long-term sustainable development of low-trophic-level fisheries in Atlantic Canada, since traditional groundfisheries are at low levels and so far not recovering (Frank et al. 2005).

In addition to their socio-economic importance, low-trophic-level species play important ecological roles in the marine ecosystem. Most low-trophic-level invertebrate and plant species act as prey to higher trophic levels, some provide vital three-dimensional habitat, and others provide filtering function and nutrient storage, regulating water quality on which other species depend (Rangeley 1994; DFO 1999; Dayton et al. 2002). Sea urchins in particular are known to be key engineers of the coastal algal community (Lawrence 1975). From an ecosystem perspective, a change in trophic balance or a change in the strength of species interactions increases the potential for instability (Frank et al. 2006, 2007). Soulé et al. (2005) have provided clear examples of altered ecosystems as a result of altering species interactions and argue that maintaining a trophic balance between strongly interacting species is necessary to ensure stability.

Despite their ecological and increasing economic importance, most efforts at collecting baseline fisheries data in Canada have been directed at higher trophic-level species (Rice and Rivard 2002). Concern has been raised about rapidly and simultaneously expanding low-trophic-level harvests while lacking sufficient baseline information to ensure sustainable fisheries development and marine ecosystem conservation (e.g., Rice and Rivard 2002; Lotze and Milewski 2004; Smith and Sainte-Marie 2004).

Perry et al. (1999) developed a framework for acquiring the necessary information to successfully manage a developing invertebrate fishery. Since these fisheries frequently occur for species with minimal existing knowledge, they propose three phases to acquiring population, fishery, and ecosystem knowledge: (Phase 0) existing information is compiled; (Phase 1) new information is obtained; and (Phase 2) management decisions are implemented, a commercial fishery begins, and monitoring to supplement knowledge continues. Further, the authors summarized a set of knowledge factors required to develop precautionary management strategies for emerging low-trophic-level fisheries (Perry et al. 1999).

In the present study, we used a modified version of the list provided by Perry et al. (1999) to evaluate the knowledge base for a set of emerging low-trophic-level fisheries on the Scotian Shelf. We tested whether the level of knowledge reported on population, fishery, and ecosystem parameters in government stock assessments and research documents varied between emerging and more established fisheries. We also analyzed factors that may explain differences in knowledge level and how knowledge changed over time. Based on our results, we discuss whether the fishing of emerging species is expanding more rapidly than knowledge can be gained and whether the available knowledge base is sufficient to enable sustainable management.

Methods

Selection of fisheries

We chose to investigate the knowledge base of established, developing, and emerging fisheries on the east coast of Canada (Fig. 1) because of the apparent shift from the historic predominance of groundfishing to rapidly expanding low-trophic-level harvesting after the groundfishery collapse. Our study focused on the Northwest Atlantic Fisheries Organization (NAFO) Divisions 4VWX on the Scotian Shelf and in the Bay of Fundy (Fig. 1).

To evaluate when a transition from groundfishing to lower trophic-level harvesting had occurred and to provide a cutoff for categorizing established, developing, and emerging fisheries, we calculated the mean fished trophic level $\overline{\mathrm{TL}}$ over each year k across all marine catch fisheries in NAFO Divisions 4VWX according to Pauly et al. (2001) as

$$(1) \qquad \overline{\mathrm{TL}}_k = \sum_{i=1}^{m}(\mathrm{TL}_i Y_{ik})/\sum_{i=1}^{m}(Y_{ik})$$

where Y_i is the landings of species group i, TL_i is the trophic level of that species group, and m is the total number of species groups. We extracted catch statistics for all fisheries from 1960 to 2004 from the NAFO database (NAFO, Dartmouth, Nova Scotia, Canada). Data on trophic levels were obtained from the Sea Around Us Project (seaaroundus.org) and FishBase (fishbase.org). Based on the initiation of a relatively linear decline after at least 27 years of a steady mean fished trophic level, we chose 1988 as our cutoff.

To select a set of robust fisheries for our analysis, we first removed all small-scale sporadic fisheries with less than five consecutive data points. Second, we removed those fisheries that had not been substantially fished since the groundfishery collapse, which were all fisheries in which the 3-year running mean of catch did not exceed 100 t·year^{-1} after 1988. Third, we refined the scope of our study to those finfish fisheries that were similar to lower trophic-level fisheries in terms of habitat and fishing practices by removing all highly migratory, large pelagic, and diadromous fish species.

We crosschecked our list of NAFO fisheries against DFO (Fisheries and Oceans Canada) Annual Fisheries Statistics (L. Sonsini, Statistical Services, Fisheries and Oceans, 200 Kent St., Ottawa, Ontario, Canada, personal communication, 2005), which includes all economically valuable fisheries. We added any fisheries with catch of over 500 t·year^{-1} in 2004 (sea cucumber and rockweed), the most recent year for which we had fishery value statistics for all species. Rockweed landings data from 1962 to 1985 were obtained from Canadian Atlantic Fisheries Scientific Advisory Committee (1991). Rockweed and sea cucumber landings from 1986 to 2004 were obtained from DFO Annual Fisheries Statistics (L. Sonsini, personal communication, 2005).

We aimed to divide the fisheries into those that were established prior to the groundfishery collapse (established), those that existed before but were expanded with the collapse (developing), and those that started as new fisheries after the collapse (emerging). We therefore used the following rules to select the three fisheries groups: (*i*) A fishery was considered emerging if the catch did not pass 500 t·year^{-1} or 10% of the long-term (1960–2004) maximum for more than 2 consecutive years prior to 1988, and the fishery had been fished for at least 5 consecutive years after 1988. If a fishery was not classified as emerging, it was considered (*ii*) developing if the mean catch after 1988 was 25% or greater than in the 1960–1988 period and (*iii*) established if the mean catch had declined or was less than 25% greater after 1988.

Given the length of the available documents on many established fisheries, we limited our knowledge analysis to a representative sample (n = 6) of two groundfish species (Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*)), one pelagic species (Atlantic herring (*Melanogrammus aeglefinus*)), two flatfish species (yellowtail flounder (*Limanda ferruginea*) and Atlantic halibut (*Hippoglossus hippoglossus*)), and one predominantly deepwater species (Atlantic redfishes (*Sebastes* spp.)) (Table 1). Among the developing and emerging species, several fisheries were difficult to evaluate. While the Canadian catches for spiny dogfish (*Squalus acanthias*) resembled our emerging fisheries, there was substantial catch in NAFO Divisions 2–6 by Russia and the United States since the early 1960s (DFO 2007*b*). We therefore categorized this species as developing. Catch statistics for sandgaper (*Mya arenaria*) and silver hake (*Merluccius bilinearis*) revealed substantial discrepancies between NAFO and DFO statistics and were therefore excluded. Finally, there were a number of emerging fisheries with no published DFO reports so far, including red hake (*Urophycis chuss*), roundnose grenadier (*Coryphaenoides rupestris*), Atlantic hagfish (*Myxine glutinosa*), northern quahog (*Mercenaria mercenaria*), and sculpins (family Cottidae). These fisheries may form an important part of the overall picture; however, we could not evaluate their knowledge level according to our method. In the end, our sample for the knowledge evaluation included seven developing and eight emerging fisheries (Table 1).

Knowledge analysis

Based on Perry et al. (1999), we developed a list of 21 population, 12 fisheries, and 7 ecosystem knowledge parameters that would aid in developing a precautionary management plan for emerging low-trophic-level fisheries (Appendix A, Table A1). The original table was designed to aid in developing management for an individual fishery (Perry et al. 1999). To provide an objective comparison for a set of fisheries, we refined the knowledge factors so that each factor could be designated as absent, present in a qualitative sense, or present in a quantitative sense. If a knowledge factor was deemed irrelevant to a certain fishery, such as size at maturity for rockweed (Appendix A, Table A1), it was removed from the evaluation of that fishery. Four of the factors could only be evaluated as qualitative knowledge and were excluded from the quantitative evaluation (Appendix A, Table A1).

To evaluate the knowledge level for each fishery, we searched for the most recent DFO Stock Status Reports (SSR), Canadian Stock Assessment Secretariat (CSAS) Science Advisory Reports (SAR, replaced SSR in 2005), DFO Habitat Status Reports (HSR), and CSAS Research Documents (Table 1). We restricted our evaluation of individual knowledge factors to these documents for three reasons: (*i*) we expected that individuals involved in the management of these fisheries would refer to these documents as their primary source of information; (*ii*) it allowed a consistent approach in the comparison of all fisheries studied; and (*iii*) these documents represented the most recent information considered in each fishery's assessment and management. Where available, we used the most recent of each type of document that evaluated the stock (SSR, SAR, HSR, and Research Documents). Where multiple fishing areas were evaluated in the same year (for example, Jonah crab), we included all fishing areas together. Therefore, if a knowledge factor was demonstrated in one of the documents, it was reported present for that species.

Table 1. Fisheries investigated, regulatory measures, and data sources for knowledge analysis.

Common name	Scientific name	Regulatory measure	Data source
Established fisheries			
Atlantic cod	*Gadus morhua*	Quota	Clark and Perley 2006; DFO 2006*a*
Haddock	*Melanogrammus aeglefinus*	Quota	Mohn and Simon 2004; DFO 2006*b*
Atlantic halibut	*Hippoglossus hippoglossus*	Quota	Zwanenburg et al. 2003; DFO 2006*c*
Atlantic redfishes	*Sebastes* spp.	Quota	McClintock 2006; DFO 2004*a*
Yellowtail flounder	*Limanda ferruginea*	Quota	Stone and Legault 2003*a*, 2003*b*; DFO 2003
Atlantic herring	*Clupea harengus*	Quota	Power et al. 2007*a*, 2007*b*; DFO 2007*a*
Developing fisheries			
Spiny dogfish	*Squalus acanthias*	Quota	DFO 2007*b*
American lobster	*Homarus americanus*	Effort	Robichaud and Pezzack 2007; DFO 2007*c*
Snow crab	*Chionoecetes opilio*	Quota	Choi and Zisserson 2007; DFO 2004*b*, 2007*d*, 2007*e*
Northern shrimp	*Pandalus borealis*	Quota	Covey and King 2006*a*, 2006*b*; DFO 2007*f*
Sea scallop	*Placopecten magellanicus*	Quota	Smith et al. 2007; DFO 2007*g*, 2007*h*, 2007*i*
Periwinkle	*Littorina littorea*	None	DFO 1998*a*
Rockweed	*Ascophyllum nodosum*	N.B. quota	DFO 1998*b*
		N.S. area-based	DFO 1999
Emerging fisheries			
Red crab	*Chaceon quinquedens*	Effort, quota	DFO 1997
Atlantic rock crab	*Cancer irroratus*	Effort	Robichaud et al. 2000*b*; Tremblay and Reeves 2000; DFO 2000*a*, 2000*b*
Jonah crab	*Cancer borealis*	Effort	Adams et al. 2000; Robichaud et al. 2000*a*, 2000*b*; DFO 2000*c*, 2000*d*, 2000*e*
Ocean quahog	*Arctica islandica*	Quota	Roddick et al. 2007*b*, 2007*c*; DFO 2007*j*
Arctic surfclam	*Mactromeris polynyma*	Quota	Roddick et al. 2007*a*; DFO 2007*j*
Atlantic surfclam	*Spisula solidissima*	Quota	DFO 1996*a*
Sea urchin	*Strongylocentrotus droebachiensis*	N.B. quota, N.S. ecosystem-based	Miller and Nolan 2000; DFO 2000*f*, 2000*g*
Sea cucumber	*Cucumaria frondosa*	—	DFO 1996*b*

For each fishery, we recorded whether qualitative or quantitative knowledge was reported for each knowledge factor. Qualitative knowledge was defined as any qualitative information provided for the knowledge factor in an appropriate context. Quantitative knowledge was defined as a numeric value, range of values, or, in the case of geographically based factors, a map. Except for those knowledge factors in the fishery category, quantitative knowledge factors had to be based on fisheries-independent research, surveys, or models because of the potential bias in data obtained from fisheries catch (for example, size–age structure based only on catch composition). We recorded these instances separately, but treated them as qualitative knowledge in our analyses. If quantitative knowledge was present, we assumed the same for qualitative knowledge. We maintained a separation of qualitative and quantitative knowledge to avoid making an assumption about the relative importance of each.

As a first step to compare the knowledge level across fisheries, we calculated the percentage of reported qualitative and quantitative factors within each knowledge group (population, fishery, and ecosystem) for each fishery. We then calculated the mean percentage and 95% confidence intervals (CI) of reported knowledge within each group of fisheries (established, developing, and emerging).

To assess the similarity among fisheries within and between the groups when the knowledge of each factor was taken into account, we performed Kruskal's nonmetric multidimensional scaling (MDS) (Kruskal and Wish 1978) using the isoMDS function in the MASS library (Venables and Ripley 2002) for the statistics package R (R Development Core Team 2008) on the qualitative and quantitative results using a binary calculated distance matrix.

We used an analysis of odds ratios to compare individual knowledge factors among established, developing, and emerging fisheries. Odds ratios provide a comparison statistic and a measure of confidence when comparing two groups with presence–absence data (Cooper and Hedges 1994). Further, they can be combined across studies or factors to provide a pooled comparison estimate. We used a Mantel–Haenszel common odds ratio to draw inference about whether the odds of finding each type of knowledge (population, fishery, ecosystem) were greater or lower in emerging fisheries compared with developing or established fisheries.

Odds ratios are calculated from binary presence–absence data. Given the following cell frequencies for a single knowledge factor:

	Present	Absent
Group_1	A	B
Group_2	C	D

the odds ratio o comparing Group_2 with Group_1 for a given factor i can be written as

$$(2) \qquad o_i = \frac{A/B}{C/D} = \frac{AD}{BC}$$

The standard error of the log odds ratio for each factor $\mathrm{SE}(\log(o_i))$ can be calculated

$$(3) \qquad \mathrm{SE}(\log(o_i)) = \sqrt{\frac{1}{A} + \frac{1}{B} + \frac{1}{C} + \frac{1}{D}}$$

and used to calculate the 95% CI for each factor

$$(4) \qquad 95\%\ \mathrm{CI}\ \log(o_i) = \log(o_i) \pm \mathrm{SE}(\log(o_i))$$

In many scenarios, including cases with small sample sizes but many factors, the Mantel–Haenszel technique provides a method of estimating a fixed-effect common odds ratio $\overline{o}_{\mathrm{MH}}$ across factors, given that homogeneity Q (calculation described in Cooper and Hedges (1994)) among the factors is not rejected (Cooper and Hedges 1994). The common odds ratio can be calculated as

$$(5) \qquad \overline{o}_{\mathrm{MH}} = \frac{\sum_{i=1}^{k} A_i D_i / T_i}{\sum_{i=1}^{k} B_i C_i / T_i}$$

where i represents each factor, k is the number of factors being compared, and T_i is the total number of observations for each factor across both groups ($T_i = A_i + B_i + C_i + D_i$). The calculation of a CI for $\overline{o}_{\mathrm{MH}}$ is described in Cooper and Hedges (1994).

Traditionally, when one of the cells (A, B, C, or D) is zero, 0.5 is added to each of the cells for that factor to prevent an odds ratio of zero or undefined (Cooper and Hedges 1994). The addition of 0.5 is done assuming that given a large enough sample size, we would not find complete presence or absence of knowledge for any factor across a fishery group (established, developing, and emerging); however, when combining odds ratios into a pooled estimate, this correction is unnecessary and may introduce bias in small sample sizes (Cooper and Hedges 1994; Bradburn et al. 2007). For ease of visual interpretation, we have shown the odds ratios for each factor with the 0.5 correction where appropriate, but shown and reported the Mantel–Haenszel common odds ratios using the original data. The results of the common odds ratio analysis should be interpreted with the knowledge that not all factors are independent (e.g., gear type and gear selectivity).

Temporal trends and possible drivers

For many of the emerging and some of the developing fisheries, there were only one or two CSAS documents available, so we could not evaluate a temporal increase in knowledge over time. Instead, we used an evaluation of the number of CSAS documents (SSR, SAR, HSR, or Research Documents) published each year for each species since 1977, when an online database of publications began (www.dfo-mpo.gc.ca/csas/csas/Publications/Pub_Index_e.htm). Similarly, to assess how general scientific knowledge of these species may have developed over time, we queried the Web of Science database (Thomson Scientific, isiknowledge.com) for each of our species. We limited our search to articles of any language in the "Science Citation Index Expanded" database. We searched for each species by scientific name in the topic or title and in which Canada was listed in the address field. Prior to 1970, no publications matched our queries. For both the CSAS documents and Web of Science publications, we calculated a mean number of publications per 5-year span for each fishery group. Standard error bars were calculated assuming a negative binomial distribution of the count data. To approximate the increase in indexed publications in the Web of Science over time, we obtained the total number of publications indexed with Canada in the address field for each year.

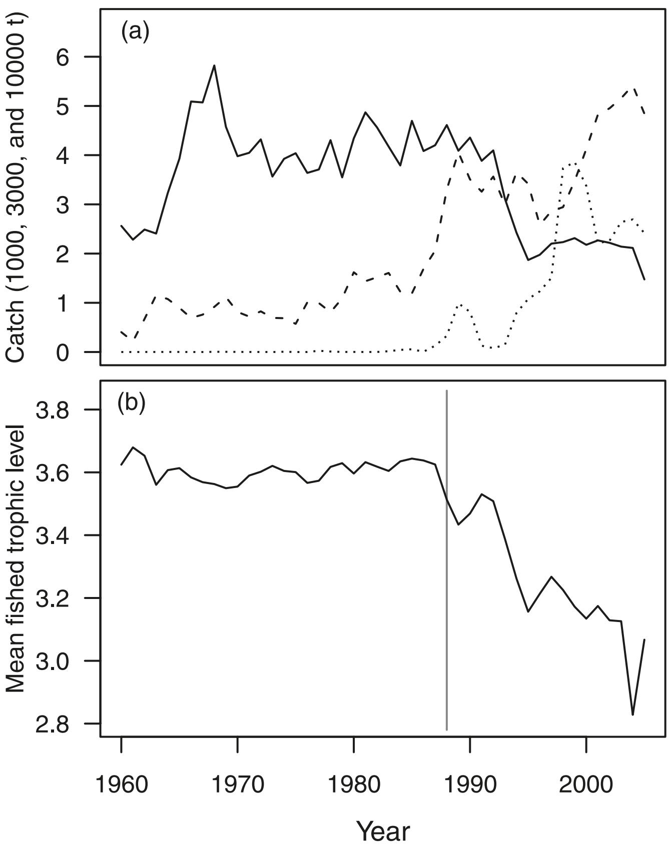
Lastly, we evaluated possible explanatory drivers for the difference in knowledge levels observed among fisheries. Therefore, we analyzed whether qualitative and quantitative knowledge level was a function of the longevity of a fishery or the value of the catch. We hypothesized that reported knowledge might be a function of the age of a fishery or that it might be correlated with the fisheries' value, as reported in the year that many of the emerging fishery reports were last written (2000). We tested these two hypotheses using least squares regression. We calculated the percentage of reported qualitative and quantitative knowledge for each fishery. Longevity data (the year that each fishery began as a directed fishery) were obtained from the CSAS reports used in the knowledge analysis (Table 1). Atlantic herring and haddock dates were obtained from Perley (1852), sea scallop from Lotze and Milewski (2004), yellowtail flounder from Stone et al. (2004), and Atlantic surfclam from the NAFO landings. Fisheries value data for 2000 were extracted from DFO Annual Fisheries Statistics (L. Sonsini, personal communication, 2005).

Results

On the Scotian Shelf, a strong shift in fishing occurred during 1980–2000 when established groundfisheries experienced strong declines while developing and emerging low-trophic-level fisheries rapidly increased (Figs. 2*a*, 3). This transition was marked by the decline of the mean fished trophic level that began around 1988 and continued throughout the 1990s and early 2000s (Fig. 2*b*). Overall, catches of developing species increased 5-fold over a 30-year period from the 1965–1975 average to 2000, while catches of emerging species increased 10-fold in just 10 years from 1988 to 1998 (Fig. 2*a*). Established fisheries declined 2-fold since 1988. Although this gap is shrinking, they still present a 1- to 2-fold higher catch than developing fisheries and a 5- to 10-fold higher catch than emerging fisheries (Fig. 2*a*). From 1988 to 2000, the value of the investigated emerging fisheries increased on average 13-fold and that of developing fisheries 2.5-fold, while the value of established fisheries halved (Table 2); however, many of the emerging and developing fisheries, except lobster, rockweed, and sea cucumbers, have experienced a decline in landings in recent years (Fig. 3).

The output of CSAS reports was most consistent for the established fisheries and some developing fisheries, includ-

Fig. 2. (*a*) Mean annual catch of the investigated fisheries divided into established (solid line, 10 000 t increments), developing (expanded since 1988, dashed line, 3000 t increments), and emerging (new since 1988, dotted line, 1000 t increments) categories. (*b*) Mean fished trophic level for NAFO Divisions 4VWX. The vertical line represents the chosen cutoff year (1988) for distinguishing fisheries groups.



ing lobster, snow crab, shrimp, and scallop (Fig. 3, circles). The output was less consistent for developing dogfish, periwinkle, and rockweed as well as all emerging fisheries. Five emerging fisheries had no CSAS document at all and were thus not included in our analysis (see Methods). Of the investigated eight emerging fisheries, three have only one published report, and all but two (red crab, rock crab, Jonah crab, Atlantic surfclam, sea urchins, and sea cucumbers) have not had a CSAS document published since 2000 (Fig. 3).

The level of reported knowledge among the three fisheries groups (established, developing, and emerging) depended on the knowledge factors considered. Quantitative population knowledge was more than two times lower in emerging fisheries compared with established or developing fisheries (Figs. 4*a*, 4*d*, 4*g*). Five of the eight emerging fisheries demonstrated less than 20% of the possible quantitative population knowledge factors, whereas all the developing and established fisheries had at least this much (Figs. 4*a*, 4*d*, 4*g*). Fishery knowledge was most consistently reported across the three groups, with the exception of quantitative fisheries knowledge in the Atlantic surfclam and sea cucumber fisheries (Figs. 4*b*, 4*e*, 4*h*). In contrast, ecosystem knowledge was higher for developing and emerging fisheries than for established fisheries (Figs. 4*c*, 4*f*, 4*i*). There was never more than one of the investigated ecosystem parameters discussed in the established fisheries documents, and quantitative ecosystem knowledge was never reported (Fig. 4*c*, Appendix A, Table A1). Besides the consistently low ecosystem knowledge of established fisheries, there was the least variability of reported fisheries knowledge in the developing fisheries (Fig. 4*e*).

Nonmetric MDS across all knowledge factors presented a better approximation of the similarity of the fisheries groups across quantitative knowledge factors (Fig. 5, stress = 13.3%) than qualitative factors (S.C. Anderson, unpublished data, stress = 19.1%). For both qualitative and quantitative knowledge, developing fisheries (with the exception of rockweed and periwinkle) were the most closely grouped, indicating similar patterns of knowledge across knowledge factors. Established fisheries were the next most closely grouped, showing considerable overlap with developing fisheries. In contrast, the emerging fisheries were the most scattered. The pattern of reported knowledge of sea cucumber and Atlantic surfclam was the most dissimilar to the other fisheries (Fig. 5).

The level of knowledge reported for individual knowledge parameters varied considerably across parameters and fisheries groups, as well as between qualitative and quantitative knowledge reported (Appendix A, Table A1). Importantly, emerging fisheries had limited knowledge on spatial structure (e.g., metapopulation, degree of aggregation, seasonal migration) and basic quantitative population parameters such as growth, recruitment, and natural mortality rates as well as current biomass levels and geographic range; however, knowledge on virgin biomass level was higher in emerging (reported in two fisheries) than in developing or established fisheries (Appendix A, Table A1).

In our odds ratio meta-analysis, homogeneity across the knowledge parameters was not rejected within each of the comparisons allowing for the evaluation of a common odds ratio (Table 3). The odds of finding population knowledge were significantly greater in the developing and established fisheries than the emerging fisheries. The odds were approximately six times greater for quantitative factors and seven times greater for qualitative factors that we would find population knowledge in developing fisheries over emerging fisheries (Fig. 6*a*, Table 3). In the established–emerging fisheries comparison, the odds were approximately four times greater for finding quantitative or qualitative population knowledge in the reports (Fig. 6*b*, Table 3). Within the population parameters, the odds of finding quantitative knowledge on growth rate, fecundity at size, and lifespan were significantly higher in the developing fisheries than in emerging fisheries (Fig. 6*a*). The odds of finding quantitative knowledge on geographic range and growth rate were significantly greater in established fisheries than in emerging fisheries (Fig. 6*b*). Although not significant at $P = 0.05$, our results suggest that the odds of finding knowledge of current biomass may be greater in developing and established fisheries compared with emerging fisheries (Fig. 6*a*, 6*b*).

The overall odds of finding fishery knowledge parameters reported in the emerging fisheries were not significantly different from the developing or established fisheries, although they were nearly so where comparing quantitative knowl-

Fig. 3. Individual catch trends for established (solid line), developing (dashed line), and emerging (dotted line) fisheries in NAFO Divisions 4VWX. The vertical line represents the cutoff year (1988), and the open circles identify years with Canadian Stock Assessment Secretariat (CSAS) documents published for the particular fisheries. Spiny dogfish (*Squalus acanthias*) landings represent Canadian catches only, but substantial USA and Russian landings have been recorded for the same population throughout NAFO Divisions 2–6 since the early 1960s.

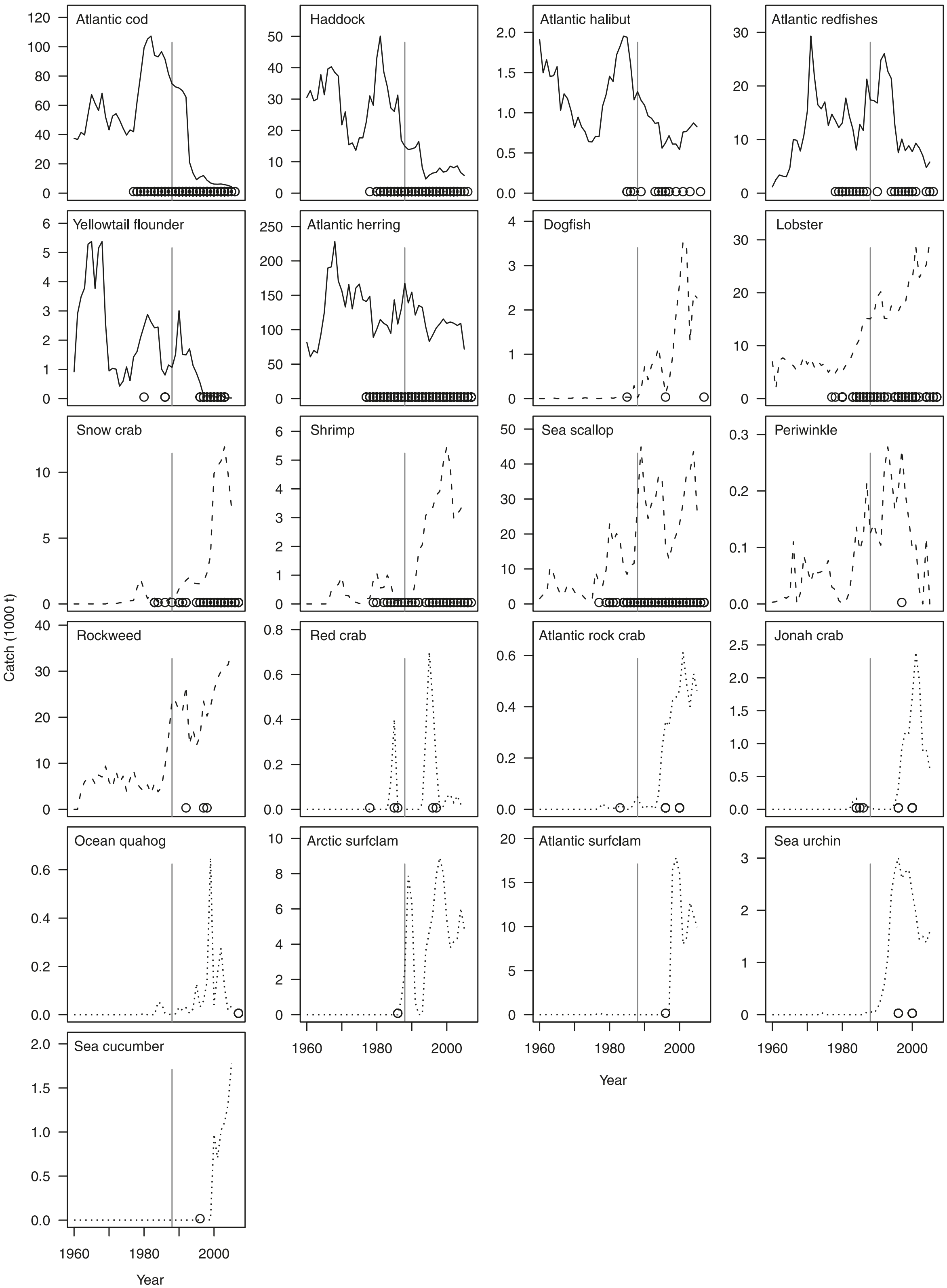


Table 2. Annual reported fishery catch value in 1988 and 2000 for established, developing, and emerging fisheries (data modified from L. Sonsini, personal communication, 2005).

	Value (CAN$)		
Fishery	1988	2000	% change
Established			
Atlantic cod	45 398 416	11 506 701	25.4
Haddock	17 071 125	13 912 413	81.5
Atlantic halibut	6 011 185	4 641 570	77.2
Atlantic redfishes	5 240 115	4 764 210	90.9
Yellowtail flounder	838 114	79 262	9.5
Atlantic herring	26 666 019	15 653 575	58.7
Mean	16 870 829	8 426 289	50.0
Developing			
Spiny dogfish	296	854 852	288 801.4
American lobster	122 791 881	291 481 992	237.4
Snow crab	1 609 349	52 453 976	3 259.3
Northern shrimp	146 091	11 913 709	8 155.0
American sea scallop	33 404 456	33 982 342	101.7
Periwinkle	122 241	172 322	141.0
Rockweed	945 445	1 023 510	108.3
Mean	22 717 108	55 983 243	246.4
Emerging			
Red crab	0	42 115	—
Atlantic rock crab	18 614	606 665	3 259.2
Jonah crab	3 196	2 932 321	91 749.7
Ocean quahog	2 912	138 498	4 756.1
Arctic surfclam	2 723 598	18 311 901	672.3
Atlantic surfclam	0	10 559	—
Sea urchin	35 811	5 954 098	16 626.5
Sea cucumber	0	181 749	
Mean	348 016	3 522 238	1 012.1

Note: There was a 33.7% change in the Canadian dollar between 1988 and 2000: CAN$1.00 in 1988 = CAN$1.34 in 2000 (Statistics Canada, Consumer Price Indexes for Canada, 1914–2006 (V41690973 series); www.bankofcanada.ca/en/rates/inflation_calc.html).

edge of emerging and developing fisheries (Figs. 6*c*, 6*d*, Table 3). Further, there may be greater odds of having maps of specific fishery locations (by catch or effort) in developing compared with emerging fisheries.

Ecosystem knowledge, especially quantitative knowledge, was the least known for all fisheries groups but higher for developing and emerging fisheries than for established fisheries (Fig. 4; Appendix A Table A1). The odds of finding ecosystem parameters reported in emerging fisheries were not significantly different from developing fisheries (Fig. 6*e*), but the odds of finding qualitative ecosystem parameters in the emerging fisheries were significantly greater than in the established fisheries (Fig. 6*f*).

Our analysis of the temporal trends in available knowledge revealed that there were large increases in the publication rate for developing and established fisheries in CSAS documents since the 1980s and in Web of Science documents since the 1970s (Fig. 7). In contrast, there was only a small increase in CSAS and Web of Science publications for emerging fisheries. In the period from 2000 to 2004, the average number of CSAS documents published per fishery was about five times greater for developing and seven times greater for established fisheries compared with emerging fisheries (Fig. 7*a*). These differences in publication rates among the three fisheries groups were similar in the Web of Science with an average of about four times more publications for developing fisheries and 10 times more publications for established fisheries compared with emerging fisheries (Fig. 7*b*). In comparison with the total number of Canadian publications in the Web of Science, which linearly increased over time, the publications on developing and established fisheries strongly increased in the 1990s (Fig. 7*b*).

Fisheries that began approximately 30–100 years ago and high-value fisheries generally had the most reported knowledge (Fig. 8). A quadratic regression relating overall quantitative knowledge to the log of fishery age (Fig. 8*a*) and a linear regression relating quantitative knowledge to the log of fishery value (Fig. 8*b*) were significant. Reported qualitative knowledge was weakly related to the log of fishery age (quadratic regression, $r = 0.39$, $P = 0.233$) and fishery value in 2000 (linear regression, $r = 0.43$, $P = 0.053$).

Discussion

We evaluated whether emerging low-trophic-level fisheries on the Scotian Shelf had similar levels of knowledge

Fig. 4. Percentage of reported qualitative (open circles) and quantitative (solid circles) knowledge levels for established (*a*, *b*, *c*), developing (*d*, *e*, *f*), and emerging (*g*, *h*, *i*) fisheries. Diamonds represent mean and 95% confidence intervals for percentage of qualitative (open) and quantitative (closed) knowledge reported for each fisheries group.

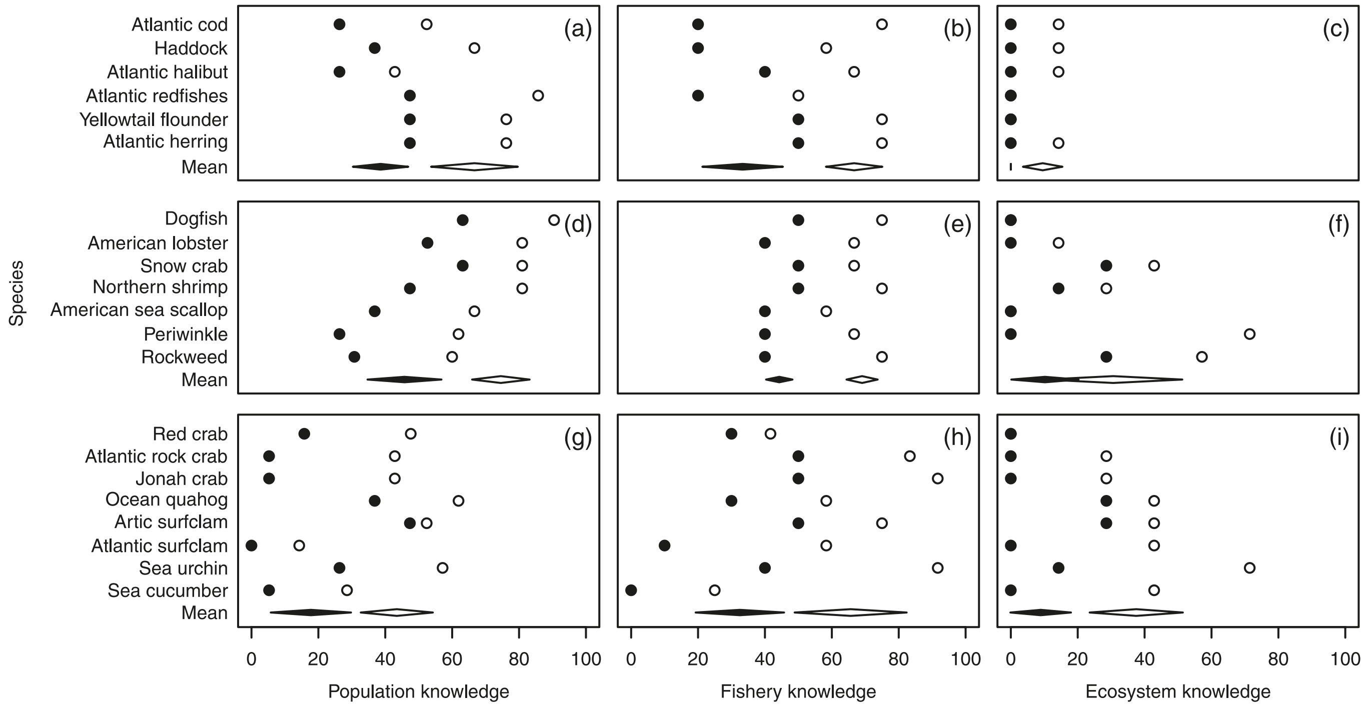
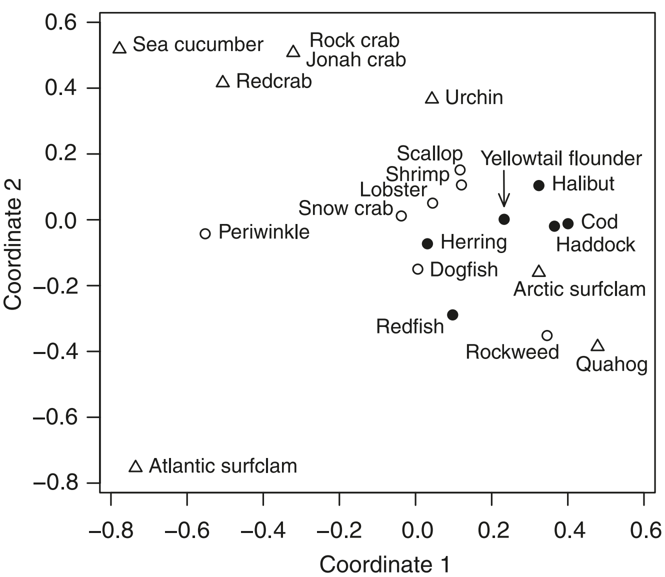


Fig. 5. Kruskal's nonmetric multidimensional scaling (MDS) for quantitative knowledge, based on all individual knowledge factors using a binary calculated distance matrix (stress = 11.3%). Solid circles represent established fisheries, open circles show developing fisheries, and open triangles indicate emerging fisheries.



reported for population, fishery, and ecosystem parameters compared with developing and established fisheries. Based on the most recently published government stock assessments and research documents for each species, we found that emerging fisheries had significantly lower levels of population knowledge reported than developing and established fisheries, but higher levels of ecosystem knowledge than established fisheries. The lack of important quantitative population parameters, such as biomass, growth rates, and geographic range, may hinder any thorough population assessment and impair a precautionary approach to management (Perry et al. 1999). The slightly higher ecosystem knowledge, on the other hand, may indicate that we have started to incorporate information on the ecological role of target species and the ecosystem effects of the fishery into management. Overall, however, emerging fisheries appear to have been developed more rapidly in terms of catches and value than knowledge has been acquired. Management based on the limited existing and only slowly increasing knowledge may be inadequate to ensure the long-term sustainability of emerging fisheries, which are of high ecological and increasing socio-economic importance in Atlantic Canada and elsewhere.

Status of emerging fisheries

Over the past two decades, a rapid expansion of low-trophic-level fisheries occurred in Atlantic Canada following the depletion and collapse of major groundfisheries (Lotze and Milewski 2004; Frank et al. 2005). On the Scotian Shelf, landings of several already existing invertebrate and plant fisheries, such as shrimp, lobster, and rockweed, increased greatly during the 1980s and 1990s. Simultaneously, a set of mainly invertebrate fisheries, such as rock crab, surfclams, sea urchins, and sea cucumbers, emerged that were previously not commercially targeted. In recent years, however, many emerging and developing fisheries experienced declining landings. The reasons for this may be manifold. Some catch trends may be declining because of lack of a market, some may be due to more restrictive quotas (e.g., DFO 2007*j*), while others may be due to de-

Table 3. Test for heterogeneity Q of the effect size and Mantel–Haenszel common odds ratio meta-analysis, comparing the qualitative and quantitative knowledge base of emerging with developing and established fisheries across three knowledge categories.

Comparison	df	Q*	P_Q	$\bar{o}_{MH}$†	Z‡	P_Z
(*i*) Emerging–developing, qualitative						
Population	20	13.01	0.877	7.50	5.95	<0.001
Fishery	11	9.20	0.604	1.22	0.55	0.580
Ecosystem	6	7.48	0.278	0.72	–0.77	0.444
(*ii*) Emerging–developing, quantitative						
Population	18	13.37	0.769	6.64	5.35	<0.001
Fishery	9	4.96	0.838	2.35	1.87	0.061
Ecosystem	6	3.14	0.791	1.16	0.22	0.823
(*iii*) Emerging–established, qualititative						
Population	20	24.07	0.239	3.46	4.28	<0.001
Fishery	11	13.89	0.239	1.06	0.16	0.872
Ecosystem	6	7.74	0.258	0.04	–2.78	0.006
(*iv*) Emerging–established, quantitative						
Population	18	21.82	0.240	3.64	3.86	<0.001
Fishery	9	6.20	0.720	1.06	0.13	0.895
Ecosystem§	6	—	—	—	—	—

*The assumption of homogeneity of the effect sizes was not violated in any of the comparisons (P_Q statistically nonsignificant).

†The Mantel–Haenszel common odds ratio $\bar{o}_{MH}$ tests how much more likely we are to find knowledge in the second group. A value of 1 indicates that the odds are equal.

‡The Z statistic tests whether $\bar{o}_{MH}$ is significantly different from 1.

§Established fishery quantitative knowledge was not reported, making a common odds ratio using our methodology undefined.

clines in catch per unit effort possibly indicating changes in abundance (e.g., DFO 2000*g*). The lack of recent stock assessments for many species makes such a distinction difficult. Such rapid increases and declines are not unusual for low-trophic-level fisheries, as can be seen, for example, in sea urchin and sea cucumber fisheries around the globe (Conand 2004; Berkes et al. 2006). The expansion of fisheries to lower trophic levels in the food chain was reflected by a strong decline in average trophic level of the catch since the groundfish depletion, suggesting the "fishing down the food web" phenomenon described by Pauly et al. (1998, 2001). This expansion may have several underlying drivers. (*i*) The collapse of the groundfishery created pressure to search for other socio-economic opportunities to earn an income and find employment (Roy 1996). (*ii*) Global markets for a number of invertebrate species were developed. For example, Berkes et al. (2006) have suggested the development of sea urchin fisheries worldwide may be driven by patterns of "roving banditry" in which the sequential decline of other sea urchin fisheries coupled with Asian demand and globalized trade may drive the development of new fisheries. (*iii*) Only those species that occur in sufficient abundance can be regarded as viable fisheries options. The depletion of higher trophic-level predators such as Atlantic cod has likely released many prey species from strong predation pressure (Worm and Myers 2003; Frank et al. 2005), indirectly enhancing their abundance. Increasing low-trophic-level landings in Atlantic Canada were accompanied by a strong increase in the value of developing and emerging species. Many of the emerging fisheries had exceeded \$1 000 000·year^{-1} by 2000. For example, the sea urchin fishery increased 166-fold in value from 1988 to 2000, exceeding \$5 000 000·year^{-1}, but experienced declining catches in recent years. Similarly, one of the newest emerging fisheries on the Scotian Shelf, sea cucumber, increased in value from zero in 1997 to nearly \$400 000·year^{-1} in 2005 (L. Sonsini, personal communication, 2005) a period in which catches increased from zero to 1800 t·year^{-1}. On the Canadian west coast, the sea cucumber fishery experienced a similarly rapid increase in landings and value over a span of 5–7 years before catch per unit effort declined substantially and restrictive management allowed the stock to recover (DFO 2002). Experience elsewhere with both sea urchin and sea cucumber fisheries suggests the potential for rapid boom-and-bust patterns in low-trophic-level fisheries (Andrew et al. 2002; Conand 2004; Berkes et al. 2006).

Knowledge base

There were clear differences in knowledge levels reported for emerging, developing, and established fisheries. Importantly, five emerging fisheries on the Scotian Shelf had no CSAS documents published at all as of 2008 and could thus not be evaluated in our analysis. Six of the remaining eight had not been evaluated since at least 2000. We included established fisheries as a reference of what a realistic target level of knowledge might be. Admittedly, catches for these fisheries have declined in recent decades, and several have closed because of overfishing, which suggests that having

Fig. 6. Meta-analysis of odds ratios for reported knowledge factors in emerging versus developing (*a*, *c*, *e*) and established (*b*, *d*, *f*) fisheries. Odds ratios and 95% confidence intervals are shown for qualitative (open circles, broken lines) and quantitative (solid circles, solid lines) knowledge of each knowledge factor. The fixed-effect Mantel–Haenszel overall odds ratios and 95% confidence intervals are shown for qualitative (open diamonds) and quantitative (solid diamonds) knowledge. All data are plotted on a log scale. Individual factors are shown with 0.5 added to all comparisons with a zero, but common odds were calculated with original values.

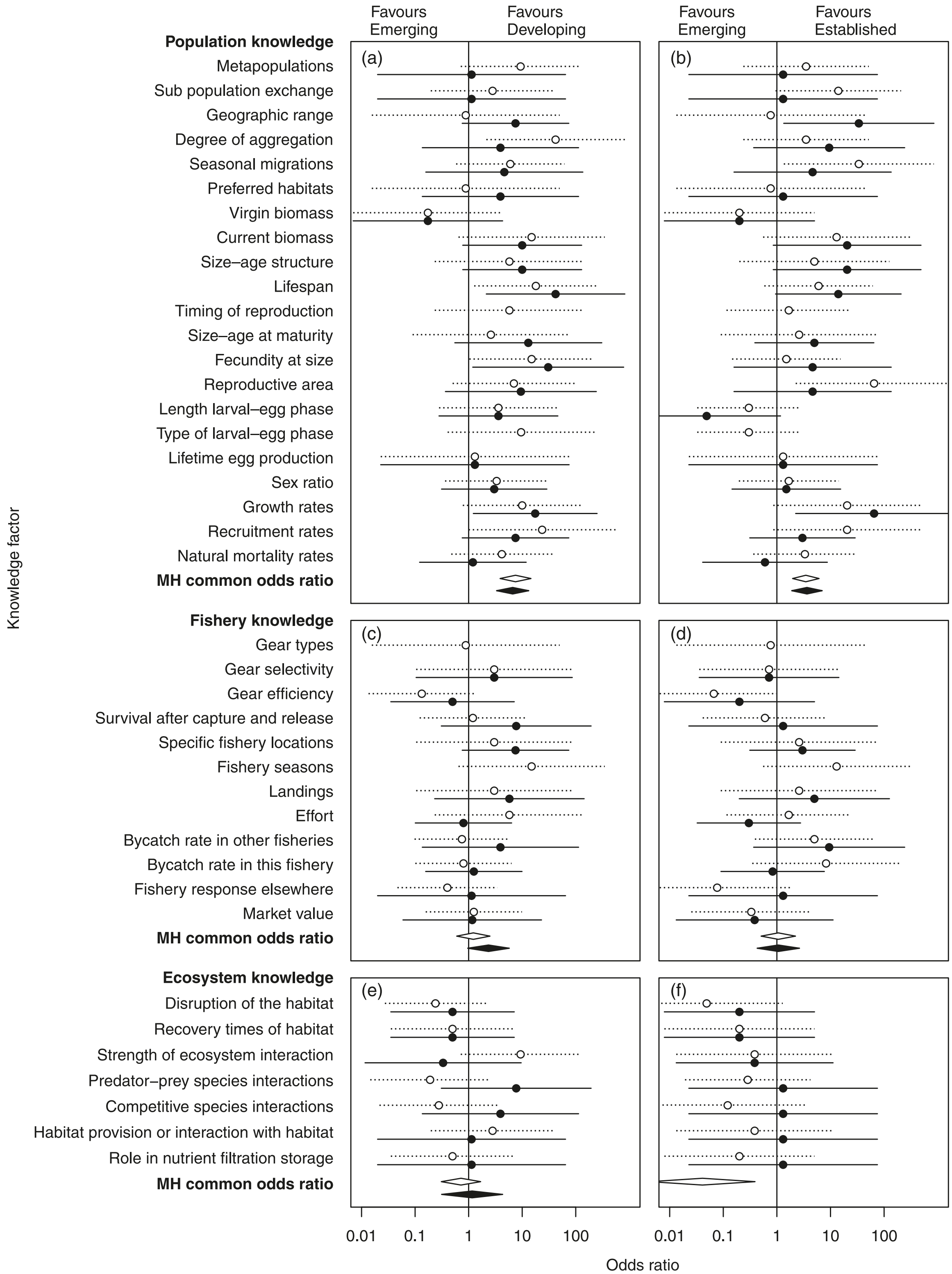
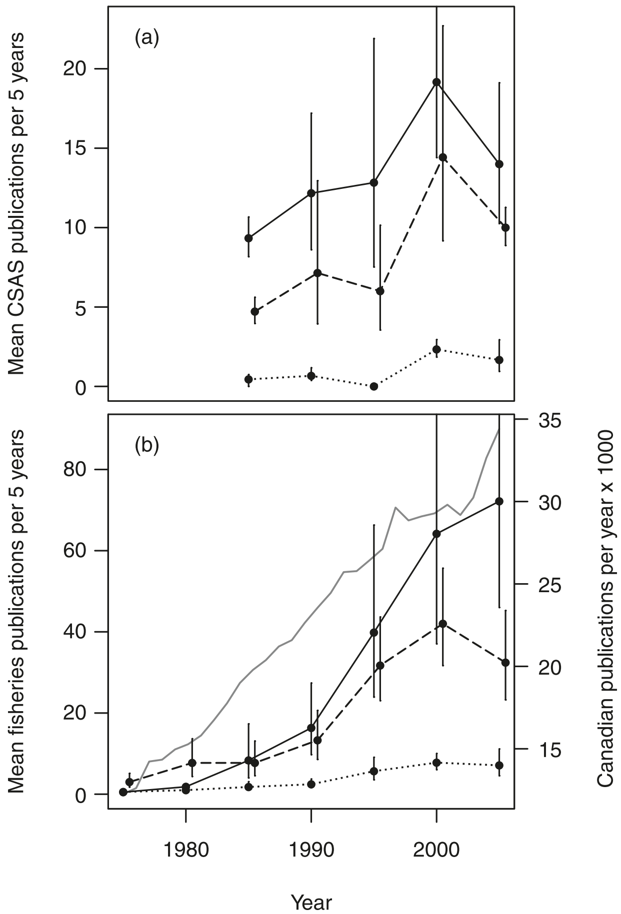


Fig. 7. Mean number of (*a*) all Canadian Science Advisory Secretariat (CSAS) Research Documents, Stock Status Reports, Science Advisory Reports, and Habitat Status Reports and (*b*) articles indexed in the Web of Science "Science Citation Database" per 5-year span for established (solid line), developing (dashed line), and emerging (dotted line) fisheries. Year values indicate first year of span (e.g., 2000–2004). Standard error bars are shown based on a negative binomial distribution of the count data. The grey line in (*b*) represents the total number of articles per year indexed by the Web of Science in which an author's address was in Canada.



knowledge does not necessarily ensure sustainability. Still, having knowledge is likely a prerequisite for developing a sustainable fishery.

The largest gap between emerging and more established fisheries was in population knowledge. In many emerging fisheries, some of the most basic quantitative population parameters such as growth rates, current biomass, and geographic range were lacking, which may impair proper population assessment. While obtaining fisheries-independent data on population parameters is cost- and labour-intensive, these data are vital to proper population assessment and fisheries management (Hilborn and Walters 1992; Chen et al. 2003). With a stronger population knowledge base comes lower uncertainty in stock assessment (Chen et al. 2003) and an increased likelihood that long-term ecologically and socially beneficial decisions can stand up against short-term political and financial pressures.

Three factors may have contributed to an underestimation of the population knowledge gap for some emerging and developing fisheries. (*i*) Five emerging fisheries could not be evaluated because a CSAS report had not yet been published. (*ii*) Many invertebrate species exhibit a greater diversity of life-history characteristics than finfish and may require a wider range of population parameters to be known for proper management (Caddy 2004). (*iii*) The amount of general scientific knowledge, especially for emerging but also for developing fisheries, is much reduced compared with established fisheries, and thus less general knowledge is available to be incorporated into government stock assessments.

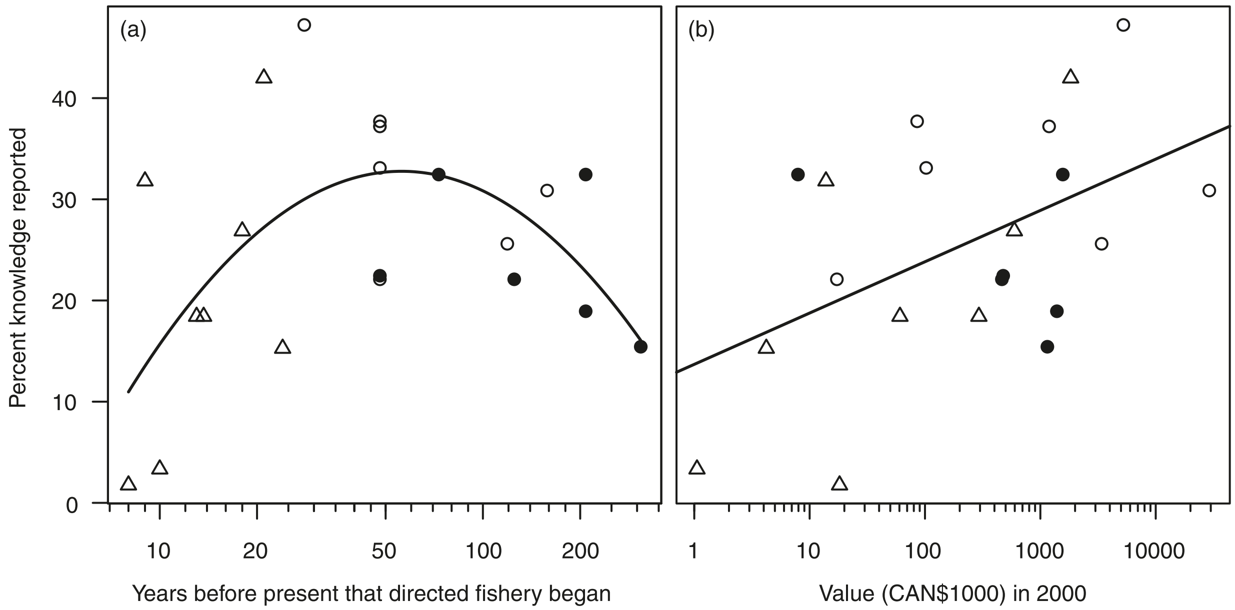
An essential reference point that was not reported for almost every species, virgin biomass, was known for some emerging fisheries. With these fisheries, we have the possibility of collecting data from the beginning of the fishery; however, these "virgin biomass" levels may not be natural but the result of predator or competitor release in severely altered ecosystems (Worm and Myers 2003; Frank et al. 2006; Myers et al. 2007). For more established fisheries, virgin biomass levels could be estimated using analyses of carrying capacity or historical data, but this has been attempted for only a few species (Myers et al. 2001; Lotze and Milewski 2004; Rosenberg et al. 2005).

Overall, fishery-related knowledge levels were similar across the types of fisheries. The availability of fisheries-dependent data is not surprising, since the fisheries directly acquire them and they are a focus of fisheries stock assessments; however, we were surprised to find that in some emerging fisheries, the most basic quantitative information on landings, effort, and fishing location were not known. Also, many of the assessment and research reports did not include knowledge from similar fisheries in other regions in the world, such as the population response to fishing. Such knowledge could be of particular use to emerging fisheries, such as the sea urchin and sea cucumber fisheries, for which valuable experience exists elsewhere. It was also our observation that landings and particularly effort data for individual fisheries and management areas are currently widely spread among DFO divisions, often split into short time series, and difficult to access and compile. As suggested earlier by Pauly et al. (2001), a consistent, long-term, and easily accessible series of Canadian landings and effort data would greatly aid in the analysis and management of fisheries resources.

Ecosystem knowledge was variable across fisheries but lowest in established fisheries. Management of some emerging and developing fisheries has made extensive use of ecosystem factors, while many other fisheries appear to be managed using a more traditional single-species model. For example, in the Nova Scotian sea urchin fishery, harvesters must demonstrate the maintenance or enhancement of habitat carrying capacity in exchange for exclusive access to fishing zones (DFO 2000*f*). The southwestern New Brunswick sea urchin fishery, in contrast, has used a more traditional total allowable catch (TAC) management strategy despite lacking sufficient fishing effort and population data (DFO 2000*g*).

Since 1996, under the Oceans Act (Department of Justice 1996), DFO has been given a mandate to gather information relating to the habitats and ecosystems that support all fisheries and base its management on this knowledge. The low

Fig. 8. Relationship between percentage of quantitative knowledge reported for established (solid circles), developing (open circles), and emerging (open triangles) fisheries with (*a*) the longevity of a fishery (i.e., the number of years a directed fishery has existed) (r = 0.60, P = 0.019) and (*b*) the value of a fishery (CAN$) in the year 2000 ($r$ = 0.50, P = 0.021). Lines indicate (*a*) quadratic (quadratic coefficient γ = –5.76, P = 0.008) and (*b*) linear regression fits.



levels of reported ecosystem knowledge may indicate that the Oceans Act has not been implemented in most fisheries. For example, the collapse and lack of recovery of Atlantic cod on the Scotian Shelf may be attributed to not only overfishing but also changes to the ecosystem structure as a consequence of high exploitation rates (Frank et al. 2006, 2007). In the case of lower trophic-level species, exploitation of forage fish, invertebrates, and plants affects the availability of prey, vital three-dimensional habitat, and water quality to the entire species community (Dayton et al. 2002; Lotze et al. 2006). Thus, ecosystem knowledge on these species is important for their fisheries and overall ecosystem management. To ensure ecosystem conservation while maintaining sustainable fisheries, ecosystem knowledge factors should be acquired and incorporated into an ecosystem-based management (EBM) approach (Pikitch et al. 2004).

Based on our results, we argue that a balanced knowledge base that includes basic population, fisheries, and ecosystem knowledge factors may be the best initial strategy to account for uncertainties as the fishery develops; however, not all knowledge factors may be equally important in developing sustainable management strategies. Perry et al. (1999) recommended an iterative process between knowledge requirements and proposed management approaches, such that not all types of knowledge would be required depending on the approaches selected. Also, a weighting scheme could be developed to account for the relative importance among individual knowledge factors. We did not incorporate these approaches into our analysis because both are likely to differ among the various species and management approaches, making it difficult to compare across fisheries.

Among the fisheries we evaluated, the increasing number of government and general scientific publications over the past two decades on developing and established fishery species may reflect an increase in knowledge over time. Publications on emerging fishery species, however, remained at low levels despite their rapid expansion. This led us to question whether fishing of emerging species may develop faster than knowledge is or can be acquired. For many established fisheries, resource inaccessibility, effort limitations (seasons, gear, vessels) and export restrictions slowed their development while scientific knowledge and management expertise developed over centuries (Lotze 2004). Technological progress and globalization has released emerging fisheries from these constraints, and market demand as well as globalized trade can spur rapid increases in exploitation (Berkes et al. 2006). Recent examples of rapidly increased and sequentially depleted emerging fisheries around the globe (Andrew et al. 2002; Uthicke and Conand 2005; Berkes et al. 2006) may indicate the great pressure on emerging fisheries and the lack of knowledge for proper management.

In our analyses, fisheries that began 30–100 years ago had a stronger knowledge base than more recent fisheries, which could be partly attributed to their greater value, but also to the timing of their development: before the collapse of the groundfisheries. Thus, there may have been a head start in gathering data before the pressure to enhance exploitation increased. In contrast, emerging fisheries were developed after the groundfishery collapse with strong pressure to expand quickly and little time to gather information; however, some of these emerging fisheries are now 10–15 years old and still lack adequate population knowledge. The lower knowledge reported in older fisheries (>100 years) could be partly attributed to the lower ecosystem knowledge reported in these fisheries.

We also found the overall knowledge level to be correlated to the total value of the fishery. Thus, only fisheries that reach a certain economic importance may be adequately evaluated and monitored by management agencies. This means that we miss out on collecting important baseline information on populations and the ecosystem before exploratory fisheries are expanded to higher levels of commercial fishing. Collecting baseline population information before large-scale harvesting is allowed is critical for a number of reasons. First, when funding and commitment to such management directives are not allocated from the beginning, momentum is difficult to regain later once fishing has been established (Guenette et al. 1998). Second, if populations are substantially altered before sufficient population knowledge can be gained, we will have lost vital information about their natural state and contributed to a shifting baseline syndrome (Pauly 1995).

Potential solutions

It is likely unreasonable to argue that all basic population and ecosystem knowledge should be acquired before a fishery is opened; however, to successfully manage developing and emerging fisheries, especially for species with minimal existing knowledge, a certain level of research may be necessary before the fishery begins. Perry et al. (1999) developed a framework for acquiring the necessary population, fishery, and ecosystem knowledge based on three phases (outlined in Introduction). If followed, this framework could ensure that basic knowledge parameters are acquired before and throughout the development of a new fishery.

Establishing refuges at the beginning of a fishery during Phase 0 (Perry et al. 1999) would provide information on an unfished proportion of the population that could be monitored over time, establishing important reference points of unfished parts of populations and ecosystems. None of the investigated emerging fisheries have incorporated designated marine reserves into management in which no fishing of any kind is permitted. Given our results, the relative immobility of several invertebrate and plant species, the necessity to collect information on unfished populations, and the costs and time required to gather that information, we suggest that fishing reserves would work well as part of a management strategy for emerging fisheries.

Another integral component of developing sustainable fisheries could be EBM (Pauly et al. 2002), particularly when combined with an overall management plan that incorporates quotas, effort restrictions, and gear control (Stefansson and Rosenberg 2005). Such an approach would likely incorporate the following into management: trophic interactions, evaluations of the impact of various gears on habitat, and marine reserves of suitable location and substantial size (Pauly et al. 2002). Of the emerging fisheries investigated, only the Nova Scotian sea urchin fishery has trophic interactions explicitly incorporated into management. Given the destructive impacts of bottom trawl fishing gear on marine habitat and biodiversity (e.g., Messieh et al. 1991; Hiddink et al. 2006; Tillin et al. 2006), the use of such gear in parts of the New Brunswick sea urchin fishery and the Scotian Shelf sea cucumber fishery is incongruent with EBM and the recognized importance of seafloor habitats (Department of Justice 1996).

The present study draws attention to the lack of population knowledge in emerging fisheries and the lack of ecosystem knowledge in established fisheries in Atlantic Canada. We suggest that monitoring of population and ecosystem parameters for existing emerging and established fisheries, respectively, should gain highest priority, followed by insurance measures such as area closures, precautionary quotas, effort controls, and gear restrictions where appropriate (Stefansson and Rosenberg 2005). Given their ecological roles, socio-economic value, and recent patterns of expansion and depletion elsewhere, the identified knowledge gaps may represent a risk to the sustainable development of marine resources.

Acknowledgements

We are grateful to Ransom A. Myers for input, guidance, and discussions during the initial stages of this project. He deceased in spring 2007 before the study could be completed. We thank W. Blanchard, J. Choi, C. Minto, M. Paon, D. Ricard, D. Robichaud, G. Sharp, L. Sonsini, and J. Tremblay for data and helpful discussions. Comments from B. Worm, two anonymous reviewers, and the Editor substantially improved this manuscript. Financial support is acknowledged from the Natural Sciences and Engineering Research Council of Canada and the Sloan Foundation (Census of Marine Life, Future of Marine Animal Populations) with grants to HKL.

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Appendix A

Table A1 appears on the following pages.

Table A1. Reported knowledge (1, qualitative; 2, quantitative; —, not reported) for established, developing, and emerging fisheries in Atlantic Canada.

	Fishery status																				
	Established						Developing							Emerging							
Knowledge factor*	cod	had	hal	rdf	fl	her	dg	lob	snc	shp	sca	per	rcw	rec	roc	jc	oq	arc	atc	su	sc
Population parameters																					
Metapopulations	—	—	—	1	—	1	1	1	—	1	1	—	—	—	—	—	1	—	—	—	—
Subpopulation exchange	—	1	—	1	1	1	1	—	—	1	—	—	—	—	—	—	1	—	—	—	—
Geographic range	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	2	2	1	1	1†
Degree of aggregation	—	—	—	2	—	2	1	1	1	1	1	2	—	—	—	—	—	—	—	1	—
Seasonal migrations	1	1	1	1	2	1	2	1	1	—	—	1	NR	—	1†	1	—	—	—	—	0
Preferred habitats	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1
Virgin biomass	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2	2	—	—	—
Current biomass	2	2	2	2	2	2	2	2	2	2	2	1	2	1†	—	—	2	2	—	2	—
Size–age structure	2	2	2	2	2	2	2	2	2	2	2	1	2	1†	1†	1†	2	2	—	2	—
Lifespan	—	2	—	2	2	2	2	—	2	2	2	2	2	—	—	—	1	2	—	—	—
Timing of reproduction‡	1	1	—	1	1	1	1	1	1	1	1	1	1	1	1	1	—	—	1	1	1
Size–age at maturity	2	2	1	2	2	2	2	2	2	2	2	2	NR	2	1†	1†	2	2	—	2	1
Fecundity at size	—	1	—	2	—	—	2	2	2	1	—	2	NR	—	1†	—	—	1	—	—	—
Reproductive area	1	1	1	1	1	2	2	1	2	—	—	—	NR	1	—	—	—	—	—	—	—
Length larval–egg phase	—	—	—	1	1	—	2	2	2	2	2	2	—	2	2	2	—	—	—	2	2
Type of larval–egg phase‡	—	—	—	1	1	—	1	1	1	1	1	1	1	1	1	1	—	—	—	1	1
Lifetime egg production	—	—	—	—	—	—	—	—	—	—	—	—	NR	—	—	—	—	—	—	—	—
Sex ratio	—	—	—	2	1†	2	2	2	2	1†	—	—	NR	2	—	1†	2	—	—	—	—
Growth rates	2	2	2	2	2	2	2	2	2	2	1	—	2	—	—	—	1	2	—	1	—
Recruitment rates	1	2	2	1	2	1	2	2	2	2	2	1	1	—	—	—	1	2	—	2	—
Natural mortality rates	1	1	—	—	2	1	1	2	1	2	1	—	—	—	—	—	2	2	—	1	—
Fishery parameters																					
Gear types‡	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Gear selectivity	2	2	2	—	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	—
Gear efficiency	—	—	—	—	1	—	—	1	—	—	—	—	2	—	1	1	2	2	1	1	—
Survival after capture and release	1	—	—	—	—	—	2	—	—	—	—	—	2	—	—	1	—	—	—	1	—
Specific fishery locations	1	1	2	1	2	2	2	2	2	2	1	2	1	1	2	2	1	1	1	1	—
Fishery seasons‡	1	1	1	1	1	1	1	1	1	1	1	1	1	—	1	1	—	1	—	1	—
Landings	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	2	—
Effort	1	1	1	—	2	2	1	2	2	2	2	1	1	2	2	2	—	2	1	2	—
Bycatch rate in other fisheries	1	—	1	2	2	1	2	—	1	—	—	1	—	—	1	1	—	—	1	—	1
Bycatch rate in this fishery	1	1	2	1	1	2	—	—	2	2	2	—	1	—	2	2	1†	2	—	1	—
Fishery response elsewhere	—	—	—	—	—	—	1	—	—	1	—	—	—	—	—	—	1	1	—	1	1
Market value	—	—	—	—	—	1	—	1	—	1	—	2	—	—	1	1	—	—	—	2	—
Ecosystem parameters																					
Disruption of the habitat	—	—	—	—	—	—	—	—	—	—	—	1	2	—	1	1	2	2	—	1	—
Recovery times of habitat	—	—	—	—	—	—	—	—	—	—	—	—	2	—	—	—	2	2	—	—	—
Strength of ecosystem interaction	—	—	—	—	—	—	—	—	1	1	—	1	1	—	—	—	—	—	—	2	—

Table A1 (*concluded*).

	Fishery status																				
	Established						Developing							Emerging							
Knowledge factor*	cod	had	hal	rdf	fl	her	dg	lob	snc	shp	sca	per	rcw	rec	roc	jc	oq	arc	atc	su	sc
Predator–prey species interactions	1	1	1	—	—	1	—	1	2	2	—	1	—	—	1	1	1	1	1	1	1
Competitive species interactions	—	—	—	—	—	—	—	—	2	—	—	—	—	—	—	—	—	—	1	1	1
Habitat provision or interaction	—	—	—	—	—	—	—	—	—	—	—	1	1	—	—	—	—	—	—	1	—
Role in nutrient filtration storage	—	—	—	—	—	—	—	—	—	—	—	1	—	—	—	—	—	—	1	—	1

Note: Cod, Atlantic cod; had, haddock; hal, Atlantic halibut; rdf, Atlantic redfishes; fl, yellowtail flounder; her, Atlantic herring; dg, spiny dogfish; lob, American lobster; snc, snowcrab; shp, northern shrimp; sca, American sea scallop; per, periwinkle; rcw, rockweed; rec, red crab; roc, Atlantic rock crab; jc, Jonah crab; oq, ocean quahog; arc, Arctic surfclam; atc, Atlantic surfclam; su, sea urchin; sc, sea cucumber; NR, not relevant to that fishery.

*Knowledge parameters modified from Perry et al. (1999).

†Quantitative population knowledge was not fisheries-independent, or fisheries knowledge was inferred from sources outside the fishery (bycatch rate estimated from research trawls). These instances were treated as qualitative knowledge in our analyses.

‡These parameters were only evaluated for qualitative knowledge.

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