Aquaculture Research, 2002, **33**, 95–108

Biological and technical evaluation of the potential of marine and anadromous fish species for cold-water mariculture

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Abstract

Concern about the overexploitation of wild aquatic resources, the slow recovery of the groundfish fisheries and the need to encourage the diversification of the mariculture industry of the province of Quebec (Canada) all provided strong incentive to explore the potential of a wide selection of marine and anadromous fish species for cold-water mariculture. Starting from a list of over 45 indigenous fish species of potential commercial interest, a biotechnical review was initiated. Technical sheets for each species were produced and aquaculture-based selection criteria covering three aquaculture approaches of development (complete life cycle, on-growing and stock enhancement) were examined. Species were ranked according to their degree of suitability for the given biological parameters. The final classification analysis within the complete life cycle production strategy positioned the Atlantic wolffish as the top candidate species (91%) followed by the spotted wolffish and Arctic charr (87%). Growth rate, optimal growth temperature, duration of the weaning period, minimal lethal temperature, larval size and feed requirements were the determining criteria. The on-growing scenario final results ranked Arctic charr first (84%) followed by Atlantic cod (79%) and Atlantic halibut (74%) mostly owing to their growth rate at low temperature and optimal growth temperature criteria. Stock enhancement programmes should concentrate their efforts on the striped bass (56%), the haddock (54%) and the Atlantic sturgeon (34%) based on their growth rate, fishery status, landing price and the availability of impact studies.

Keywords: species selection, aquaculture species, cold-water aquaculture, mariculture diversification

Introduction

The mariculture industry in Quebec, Canada, is at a turning point. During the 1980s and the early 1990s, efforts to establish a dynamic and profitable marine aquaculture industry failed. Lack of concerted action between the private sector and the research and development agencies, inadequate financial support and the absence of clear governmental orientations are generally the factors held responsible for this failure. In 1996, acknowledging the situation, the provincial government, with the collaboration of the industry, producers, research and university representatives, developed a strategic plan for aquaculture development (Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, 2000). The objectives of this plan were to provide increased technical and economical support to private investors and to better direct research and development of the private sector, the universities and the government. Potential mariculture sites are distributed over more than 12 000 km of coast line, whereas only 17 small and mid-sized commercial mariculture facilities are in operation. Production is limited to invertebrate cultivation (mostly mussels, *Mytilus edulis* L. and *Mytilus trossulus* L. and scallops, *Plactopecten magellanicus*, Gmelin), and it is forecasted to increase from 400 tons in 1999 to 2000 tons in 2003 (Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec, 2000). Several other invertebrates species (e.g. soft-shell clam, *Mya arenaria* L.; green sea urchins, *Strongylocentrotus droebachiensis*, Muller; snow crab, *Chionoecetes opilio*, Fabricius; American lobster, *Homarus americanus*, Milne; and the red sand shrimp, *Sclerocrangon boreas*, Phipps) are also considered for mariculture in Quebec. Out of these species, the green sea urchin and the soft-shell clam are now being evaluated on a precommercial basis. Salmoniculture in freshwater is a dynamic economic activity in the province of Quebec (rainbow trout, *Oncorhynchus mykiss*, Richardson; brook charr, *Salvelinus fontinalis*, Mitchill; Dubé & Mason 1995; Arctic charr, *Salvelinus alpinus* L.; Delabbio 1995), however, no commercial fish mariculture production facilities are in operation. Important organic load and contamination of freshwater reserves by freshwater aquaculture activities gave rise to increased public concern. The environmental standards were supplemented thereby causing a increased interest for the sustainable use of the coastal areas for fish aquaculture. Marine finfish aquaculture in Quebec has been briefly investigated through small-scale scientific projects that focused mainly on determining the potential for on-growing activities of juvenile cod (*Gadus morhua* L.) (Dutil, Munro, Audet & Besner 1992), brook charr (Besner & Pelletier 1991; Le François, Blier, Adambounou & Lacroix 1997; Le François & Blier 2000) and Arctic charr (Dumas, Audet, Blanc & de la Noue 1995; N. R. Le François, in progress) in estuarine conditions. Winter flounder (*Pseudopleuronectes americanus*, Walbaum) a small coastal flatfish species is also being evaluated (Ben Khemis, de la Noüe & Audet 2000).

Considering the collapse in the fisheries and the need to diversify the economy and the mariculture industry of the maritime region, part of the strategic plan involved the evaluation of the potential of marine finfish species for mariculture development. The objective of this evaluation was to produce a versatile, objective, large-scale study examining the three principal production strategies for development: complete life cycle (egg to egg), stock enhancement and on-growing (fattening) of juveniles. The procedure used decisive aquacultural criteria that considered our specific environmental and economical context to: (i) support the choice of the species having the best potential for cultivation; (ii) clearly assess the risk potential associated with a given species; (iii) identify research and development needs; and (iv) provide the basis for concerted action by the financial, governmental and research resources.

No studies evaluating species potential covering the different production strategies (complete life cycle, stock enhancement or on-growing) were found. Available selection studies on fish species dealt with small numbers of preselected, commercially valuable species including invertebrates and marine plants (Gardner Pinfold Consulting Economists Ltd 1998) or small number of preselected indigenous fish species (Jamu, Msiska & Costa-Pierce 1991; Legendre 1992) and were submitted to experimental trial to determine their respective degree of suitability for mariculture (Thouard, Soletchnik & Marion 1990) or to evaluate specific production strategies (Jamu *et al.* 1991). Considering the rapid developments in rearing technology, market trends and levels in fisheries landings, the present study is aimed at covering a wide range of species without preconceived market considerations and heavy reliance on past or present experience in aquaculture. Unlike computer-based analysis (Cook & Walmsley 1990), our approach involves the assembly of a large amount of information and, thus, provides a reference tool for the industry, the research and educational interests. This paper is aimed at presenting the potential evaluation procedure that was developed at the request of the governmental authorities of the province of Quebec. Thus, we included a case study of a high potential, cold-water maritime region that does not present significant mariculture activities yet, but, seeking a steady and profitable development of its mariculture potential. A demonstration of the versatility, high degree of adaptation of this analytical method is proposed and should be of interest to other parts of the world dealing with the mariculture diversification issue. A methodology that could identify the species and technologies best suited to our province's environmental attributes and level of expertise was thus conducted. This approach is governed by biological, technical and economic considerations for a share of the global market for aquaculture products and the omnipresent concern for rational use of public funds.

Quebec's maritime environment includes the river, the estuary and the Gulf of St. Lawrence that together form a semi-enclosed sea separated from

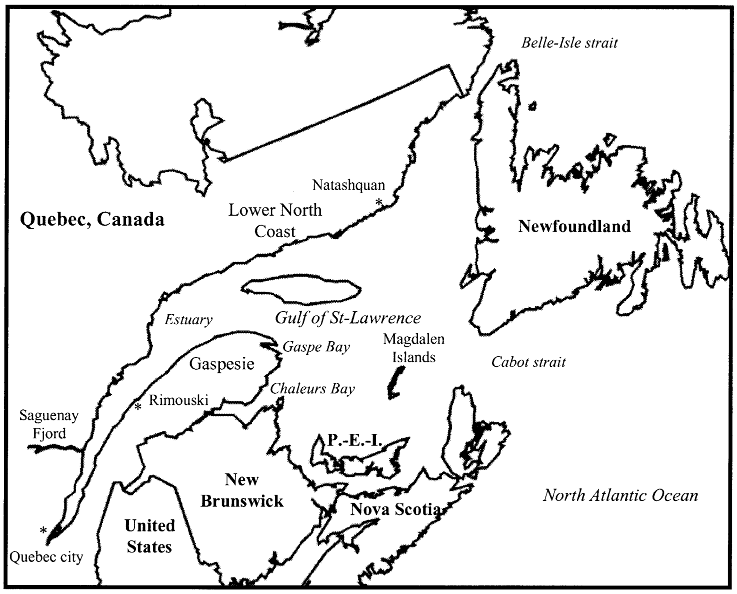

Figure 1 Potential sites for mariculture in Québec (Canada).

the Atlantic by the island of Newfoundland but connected with the former by the Cabot and Belle-Isle straits (Fig. 1). This water system is characterized by local and large-scale seasonal variations (temperature, salinity, tidal currents, etc.) along its axis and by an extensive ice coverage during the winter months (El-Sabh & Silverberg 1991; Koutikonsky & Bugden 1991). Water temperatures rarely exceed 1 °C during the six winter months but, during the summer (June–September), the range of mean temperature increases rapidly to 8–16 °C. The main areas of interest for marine aquaculture development in the province of Quebec include a fjord system (Fjord du Saguenay), a 400-km-long estuary supplied by the cold Gaspe and Labrador currents, the Chaleurs and Gaspe Bays presenting a higher surface water temperature during the summer, the North Coast with its numerous embayments but extreme environmental conditions and the Magdalen Islands, an area with shallows and lagoons, which are particularly well suited for mollusc cultivation.

Materials and methods

List of species

The first step for the evaluation of the respective potential of numerous fish species for mariculture was the elaboration of a list comprising 47 species of marine and anadromous fish (Table 1) based on the description of demersal fish assemblage for the east coast of North America by Mahon, Brown, Zwanenburg, Atkinson, Buja, Claffin, Howell, Monaco, O'Boyle & Sinclair (1998) and completed using the reference book *Atlantic Fishes of Canada* by Scott & Scott (1988). This list was then forwarded to several mariculture and fisheries experts from universities and research institutes of Quebec for validation. Far from being exhaustive, several species are absent from the list, including sticklebacks and lancetfishes. The objective of the evaluation was to submit to the proposed method of analysis, a wide array of different type of fish species including species with no apparent potential (snakeblenny, *Lumpenus lumpretaeformis*, Reinhardt; alligatorfish, *Aspidophoroides monopterygius*, Bloch) to test the outcomes of the selection procedure.

Technical sheets

Collection of relevant information regarding critical aspects of interest in an aquacultural context in either scenario (complete life cycle, stock enhancement and on-growing) was realized and these are presented in the form of technical sheets. The following information was included: growth in nature, growth in cultivation, commercial size, feeding in nature, type of food at different stages in cultivation, optimal temperature for growth, minimum and maximum lethal temperatures, temperature for

Table 1 Final list of species for the evaluation of their respective mariculture potential

Family	English name	Latin name	French name
Acipenseridae	Atlantic sturgeon	*Acipenser oxyrhynchus*	Esturgeon noir
Agonidae	Alligatorfish	*Aspidophoroides monopterygius*	Poisson-alligator atlantique
	Atlantic poacher	*Agonus decagonus*	Agone atlantique
Ammodytidae	Northern sand lance	*Ammodytes dubius*	Lançon
Anarhichadidae	Atlantic wolffish	*Anarhichas lupus*	Loup atlantique
	Northern wolffish	*Anarhichas denticulatus*	Loup à tête large
	Spotted wolffish	*Anarhichas minor*	Loup tacheté
Anguillidae	American eel	*Anguilla rostrata*	Anguille d'Amérique
Cottidae	Moustache sculpin	*Triglops murrayi*	Faux trigle armé
	Polar sculpin	*Cottunculus microps*	Cotte polaire
	Snowflake hookear sculpin	*Artediellus uncinatus*	Crochet arctique
Clupeidae	Alewife or Gaspareau	*Alosa pseudoharengus*	Gaspareau
	American shad	*Alosa sapidissima*	Alose savoureuse
	Atlantic herring	*Cuplea harengus harengus*	Hareng atlantique
Cyclopteridae	Lumpfish	*Cyclopterus lumpus*	Lompe
Gadidae	Arctic cod	*Boreogadus saida*	Saida
	Atlantic cod	*Gadus morhua*	Morue franche
	Cusk	*Brosme brosme*	Brosme
	Greenland cod	*Gadus ogac*	Ogac
	Haddock	*Melanogrammus aeglefinus*	Aiglefin
	Longfin hake	*Urophycis chesteri*	Merluche à longues nageoires
	Pollock	*Pollachius virens*	Goberge
	Red hake	*Urophycis chuss*	Merluche-écureuil
	White hake	*Urophycis tenuis*	Merluche blanche
Labridae	Cunner	*Tautogolabrus adspersus*	Tanche-tautogue
Lophiidae	Monkfish	*Lophius americanus*	Baudroie d'Amérique
Osmeridae	Capelin	*Mallotus villosus*	Capelan
	Rainbow smelt	*Osmerus mordax*	Éperlan
Percichthyidae	Striped bass	*Morone saxatilis*	Bar rayé
Pleuronectidae	American plaice	*Hippoglossoides platessoides*	Plie canadienne
	Atlantic halibut	*Hippoglossus hippoglossus*	Flétan atlantique
	Greenland halibut	*Reinhardtius hippoglossoides*	Flétan du Groenland
	Winter flounder	*Pseudopleuronectes americanus*	Plie rouge
	Witch flounder	*Glyptocephalus cynoglossus*	Plie grise
	Yellowtail flounder	*Limanda ferruginea*	Limande à queue jaune
Rajidae	Smooth skate	*Raja senta*	Raie lisse
	Thorny skate	*Raja radiata*	Raie épineuse
Salmonidae	Arctic charr	*Salvelinus alpinus*	Omble chevalier
	Atlantic salmon	*Salmo salar*	Saumon Atlantique
	Brook charr	*Salvelinus fontinalis*	Omble de fontaine
	Rainbow trout	*Oncorhynchus mykiss*	Truite arc-en-ciel
Scombridae	Atlantic mackerel	*Scomber scombrus*	Maquereau bleu
	Bluefin tuna	*Thunnus thynnus*	Thon rouge
Scorpaenidae	Redfish	*Sebaste* sp.	Sébaste
Squalidae	Spiny dogfish	*Squalus acanthias*	Aiguillat commun
Stichaeidae	Snakeblenny	*Lumpenus lumpretaeformis*	Lompénie-serpent
Zoarcidae	Ocean pout	*Macrozoarces americanus*	Loquette d'Amérique

reproduction, age and size at sexual maturity, type and duration of the spawning, spawning and reproduction control, size and number of eggs, incubation details (temperature, duration), details concerning the larval stages, survival rates (at capture, at release, at hatching, during larval stages when applicable, at the juvenile and adult stages), salinity and hypoxia tolerance, rearing density, susceptibility to disease, migration patterns, fisheries status, abundance indices, supply in juveniles, aquaculture

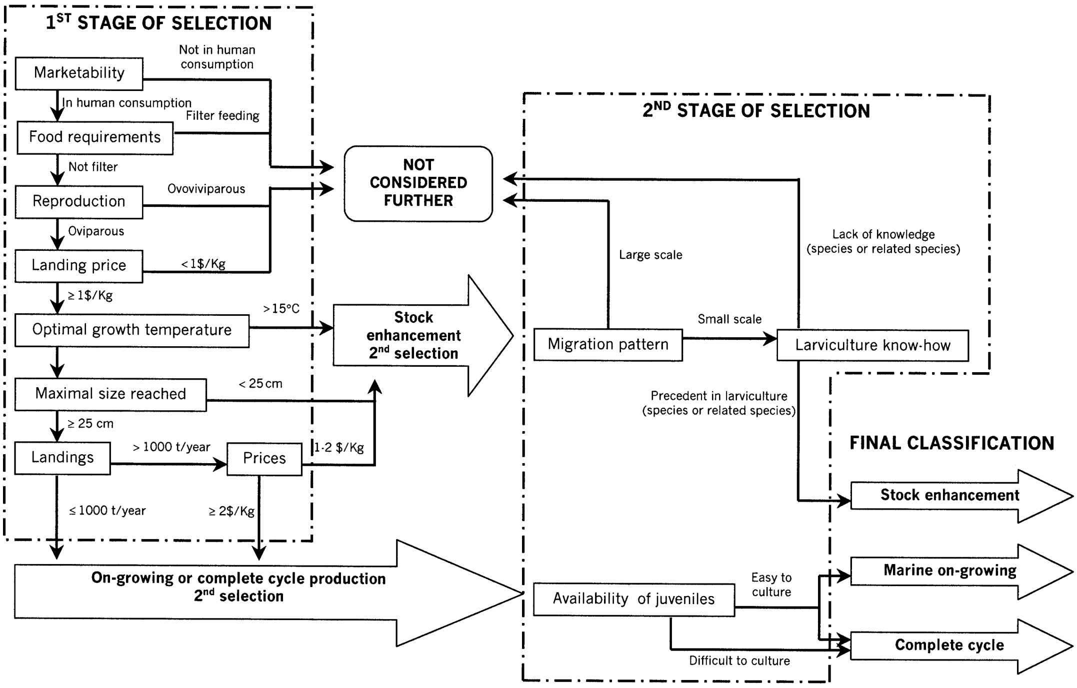

Figure 2 Schematic diagram of the selection process.

production, product characteristics (type of flesh, quality, taste, consumer relevant details), flesh and/or egg yield, other commercialization avenues (leather, biomolecules of commercial interest) and relevant information relative to aquaculture or comments from experts in the field. Unavailable information on a given species was noted as such at the end of the technical sheet. Each species was then submitted to the evaluation of its respective potential through a two-stage selection process and a final classification (Fig. 2).

First stage of selection

The first stage of selection used simple, unequivocal and discriminating criteria of primary importance in our particular environmental, technical and economical context that abide with a given situation. A discussion involving the economical and governmental authorities associated to this project was held to confirm the relevance of the chosen criteria. This first stage of selection either rejected a given species or directed it towards specific plausible scenarios (stock enhancement, grow-out and/or complete life cycle) for a second stage of selection (discussed later). The information used during the first stage of selection originates from the technical sheets. To reduce the analytical complexity, the most relevant and largely documented biological and economical characteristics of the 47 species under scrutiny were chosen. Table 1 presents the details of the 1st and 2nd stages of selection step by step. The first three criteria (marketability, food requirements and reproduction) can be qualified as binary in nature and largely applicable to any situation. The absence of current use in human consumption meant rapid rejection because of the absence of potential markets in the short term. A complete life cycle based on filter feeding and ovoviviparity also meant rejection of a given species because of the costs involved to produce live feed and clear limitation in juvenile production as a result of the small number of eggs produced per female respectively. The other criteria (optimal growth temperature, maximal size reached, landing prices and the importance of landings) are subject to a wide array of fixed range depending upon the local markets and environmental conditions that confront the users of the proposed method.

1. Optimal growth temperature. Under Quebec's environmental conditions, few areas with sea water

Table 2 Step-by-step analysis of the first and second stages of selection for the marine and anadromous fish species

Species	Marketability 1. Yes 2. No	Feeding 1. Not filter 2. Filter	Reproduction 1. Oviparous 2. Ovoviviparous	Prices (Can. $) 1. > 1$/kg 2. < 1$/kg	Growth T °C 1. < 15 °C 2. > 15 °C	Size 1. >25 cm 2. <25 cm	Landings 1. < 1000 t/year 2. > 1000 t/year	Prices 1. > 2$/kg 2. 1–2$/kg	Migrations 1. Small 2. Large	Larviculture 1. Precedent 2. No precedent	Juvenile supply 1. Easy 2. Difficult
Greenland cod	2										
Longfin hake	2										
Cusk	2										
Arctic cod	2										
Northern wolffish	2										
Northern sand lance	2										
Snakeblenny	2										
Polar sculpin	2										
Snowflake hookear sculpin	2										
Moustache sculpin	2										
Atlantic poacher	2										
Alligatorfish	2										
Atlantic herring	1	2									
Capelin	1	2									
American shad	1	2									
Alewife (Gaspareau)	1	2									
Spiny dogfish	1	1	2								
Thorny skate	1	1	2								
Smooth skate	1	1	2								
Redfish	1	1	2								
White hake	1	1	1	2 (0.82)							
Red hake	1	1	1	2 (0.27)							
Pollock	1	1	1	2 (0.77)							
American plaice	1	1	1	2 (0.86)							
Yellowtail flounder	1	1	1	2 (0.95)							
Atlantic mackerel	1	1	1	2 (0.41)							

Cunner	1	1	1	2 (0.28)							
Bluefin tuna	1	1	1	1 (16.4)	2	1	1	1	2		
American eel	1	1	1	1 (6.60)	2	1	1	1	1	2	
Rainbow smelt	1	1	1	1 (1.19)	1	2	2	1	1	2	
Atlantic cod	1	1	1	1 (1.28)	1	1	2	2	2	1	
Greenland halibut	1	1	1	1 (1.40)	1	1	2	2	2	1	
Haddock	1	1	1	1 (1.74)	1	1	2	2	1	1	
Witch flounder	1	1	1	1 (1.33)	1	1	2	2	1	1	
Winter flounder	1	1	1	1 (1.16)	1	1	2	2	1	1	
Atlantic sturgeon	1	1	1	1 (3.64)	2	1	1	1	1	1	
Striped bass	1	1	1	1 (2.45)	2	1	1	1	1	1	
Atlantic wolffish	1	1	1	1 (3.02)	1	1	1	1			2
Spotted wolffish	1	1	1	1 (3.02)	1	1	1	1			2
Ocean pout	1	1	1	1 (2.02)	1	1	1	1			2
Lumpfish	1	1	1	1 (5.03)	1	1	2	1			2
Monkfish	1	1	1	1 (2.43)	1	1	2	1			2
Atlantic halibut	1	1	1	1 (6.42)	1	1	2	1			1
Atlantic salmon	1	1	1	1 (7.65)	1	1	2	1			1
Arctic charr	1	1	1	1 (3.50)	1	1	2	1			1
Brook charr	1	1	1	1 (3.50)	1	1	2	1			1
Rainbow trout	1	1	1	1 (3.50)	1	1	2	1			1

temperature exceeding 15 °C for more than 3 months are found. Species requiring an optimal growth temperature of over 15 °C are, for production cost reasons, directed toward stock enhancement. A species for which this crucial information is unavailable, or for which optimal growth rate is achieved below 15 °C, is kept for further analysis.
2. Maximal size reached. A fish species displaying a maximal size under 25 cm is directed toward stock enhancement whereas a fish exceeding 25 cm at final size is kept for further analysis.
3. Landing price. Based on feed cost (± 1.40–1.50 Can. $ per kg) and the conversion rate higher than 1.0 for most species of fish under cultivation, a price at landing of under 1 Can. $ per kg precludes the financial viability of any fish aquaculture venture (M. Lévesque, personal communication) and such species are rejected.
4. Landings. Status of landings over 1000 metric tons per year is directed toward a price level validation. If the price at landing is between 1 and 2 Can. $ per kg, it is assumed that financial viability will be difficult to achieve and, thus, the species is directed toward stock enhancement (a strategy resulting in low production costs but, given a positive impact of a stock enhancement programme on the status of the directed fisheries, could be considered as an option). However, if the price at landing is over 2 Can. $ per kg or with landings under 1000 metric tons a year, further analysis on the complete life cycle or on-growing production strategies is needed.

Second stage of selection

The species oriented toward a specific production strategy were thereafter submitted to a closer evaluation of their respective potential by using discriminating criteria adapted to a given strategy (see second stage of selection in Fig. 2 and step-by-step analysis in Table 2). Considering the high-risk nature of the stock enhancement activities, rejection of species at this stage is still a possible scenario. The criteria for the stock enchancement were the migration pattern and the larviculture know-how. For the on-growing and/or complete life cycle production, the criteria used to specify the most suitable scenario were the availability of juveniles originating either from the wild or from hatchery productions.

Final classification

Using the results from the first and second stage of selection, the process leading to the final classification of species showing strong aquaculture potential was undertaken. Species chosen for the complete life cycle, marine on-growing and stock enhancement were submitted to the criteria presented in Table 3. Each criterion was given a maximal score that considered its relative importance under a given situation and its prospects for development. For example, optimal growth temperature is a fixed physiological characteristic and not subject to any enhancement apart from genetic improvements through selection or transgenic manipulation and was given 40 points. On the other hand, control of reproduction is a criterion that can be reasonably enhanced, given sufficient research efforts, and was thus allocated 30 points. Biological criteria presenting less impact on commercial productivity obtained 20 points. For example, incubation temperature can be tailored to accelerate or delay the timing of hatching by cost-efficient technology (owing to low flow rate requirements) and salinity tolerance can be controlled through site selection or simple technology. The total score was then reported in terms of percentage. A lack of information did not influence the final score but allowed, however, the rapid identification of areas of knowledge that could benefit from applied research efforts.

Results

The outcomes of the stepwise selection process are presented in Tables 3–6. The first stage of selection resulted in the rejection of 27 species out of a total of 47 investigated (Table 3) (see Table 1 for Latin names). The application of the first criterion (suitable for human consumption-marketability) led to the rejection of 12 species (greenland cod, longfin hake, cusk, Arctic cod, blue wolffish, northern sand lace, snakeblenny, polar sculpin, snowflake hookear sculpin, moustache sculpin, atlantic poacher, alligatorfish); the food requirements and the type of reproduction criteria resulted in the rejection of four species each (Atlantic herring, capelin, American shad, alewife and spiny dogfish, thorny skate, smooth skate, redfish, respectively). Seven species were deleted from further analysis owing to the landing price criterion (pollock, red hake, white hake, cunner, American plaice, yellowtail flounder, Atlantic mackerel). The second stage of selection

Table 3 Criteria for the final classification of finfish species within the complete-cycle, marine on-growing and stock enhancement production strategies

	40 pts	30 pts	25 pts	20 pts	15 pts	10 pts	5 pts	0 pts
Complete cycle production								
Growth rate*	⩽ 2	–	–	2–3	–	–	–	> 3
Optimal growth temperature (°C)	⩽ 8 °C	–	–	8–12	–	–	–	> 12
Larval size at hatching (mm)	> 15		10–15	–	–	5–10	–	< 5
Incubation survival (%)	–	> 75	–	60–75	–	45–60	–	< 45
First feeding survival (%)	–	> 75	–	50–75	–	25–50	–	< 25
Weaning period	–	< 2†	–	2–4	–	4–6	–	> 6
Reproduction control‡	–	Controlled	–	< 5	–	–	–	> 5
Rearing densities (kg/m^3 or /m^2)§	–	> 80	–	40–80	–	–	–	< 40
Incubation temperature (°C)	–	–	–	< 7	7–11	11–15	–	> 15
Larval feed requirements (live feed needed)	–	–	–	None	–	Size ⩾ Artemia	–	Size < Artemia
Minimum lethal temperature (°C)	–	–	–	⩽ −1	–	–	–	> −1
Minimum salinity tolerance	–	–	–	< 15	–	15–25	–	> 25
Flesh yield (%)	–	–	–	> 50	40–50	–	30–40	< 30
Egg yield (%)	–	–	–	> 25	–	15–25	–	< 15
Landing price ($/kg)	–	–	–	> 6.00	–	3.00–6.00	–	< 3.00
Ongrowing								
Growth rate in 4 years (cm/years)	> 10	–	–	5–10	–	–	–	< 5
Optimal growth temperature (°C)	⩽ 8 °C	–	–	8–12	–	–	–	> 12
Capture survival (%)	–	> 75	–	50–75	–	25–50	–	< 25
Maximal size reached (cm)	–	–	–	> 60	–	40–60	–	< 40
Minimum salinity tolerance	–	–	–	< 15	–	15–25	–	> 15
Flesh yield (%)	–	–	–	> 50	40–50	–	30–40	< 30
Egg yield (%)	–	–	–	> 25	–	15–25	–	< 15
Landing price ($/kg)	–	–	–	> 5.00	–	3.00–5.00	–	< 3.00
Stock enhancement								
Population status	Decreasing	–	Stable and weak	–	–	Abundant		Very abundant
Impact studies of stock enhancement	Effective	–	–	Doubtful results	–	–	–	Ineffective
Landing price ($/kg)	–	–	–	> 5.00	–	2.00–5.00	–	1.00–2.00

*Years to reach commercial size. †Or absence of weaning. ‡Or length of reproduction period in nature (months). §flatfish species = kg/m^2; roundfish species = kg/m^3.

resulted in the rejection of five species out of the remaining 10 species previously directed toward the stock enhancement scenario owing to their optimal growth temperature of over 15 °C (step 5, first stage of selection) (e.g. bluefin tuna, American eel, Atlantic sturgeon, striped bass, rainbow smelt, Atlantic cod, Greenland halibut, haddock, witch flounder, winter flounder). Atlantic cod, bluefin tuna and Greenland halibut were rejected because of their large-scale migration patterns. American eel and rainbow smelt did not present any adequate larviculture background to support massive juvenile production and thus were rejected. Ultimately, 15 species qualified for the final classification process and some occurred in both the on-growing and complete cycle production strategies (e.g. salmonids and Atlantic halibut). Atlantic cod (rejected in the stock enhancement scenario) was arbitrarily added in the on-growing production strategy for closer evaluation as large-scale juvenile production is a major research area experiencing steady progress in the Atlantic Canada and elsewhere in the world. This activity on a commercial scale could constitute a stable supply of juveniles and, together with inputs from the commercial fisheries, could be directed toward on-growing activities.

Table 4 presents the final classification for the complete cycle scenario with regard to the characteristics a species should, according to our standards, possess for mariculture. The Atlantic wolffish was ranked first with 91%. The spotted wolffish and the Arctic charr followed in second position with 87%.

Table 4 Final classification for the complete cycle production strategy

	Growth rate/40	Optimal growth temperature/40	Larval size/40	Incubation survival/30	First feeding survival/30	Weaning/30	Reproduction control/30	Rearing densities/30	Incubation temperature/20	Larval feed requirements/20	Minimal lethal temperature/20	Salinity tolerance/20	Flesh yield/20	Landing or eggs price/20	Results
1. Atlantic wolffish	40	20	40	30	30	30	30	30	20	20	20	20	15	10	91
2. Spotted wolffish	40	40	40	10	–	30	20	30	20	20	20	–	15	10	87
2. Arctic charr	40	20	40	30	30	30	30	30	20	20	0	20	20	10	87
3. Atlantic salmon	20	0	40	30	30	30	30	30	15	20	0	20	15	20	77
4. Rainbow trout	40	0	40	30	30	30	30	0	20	20	0	20	15	10	73
5. Brook charr	20	0	40	30	30	30	30	0	15	20	0	20	15	10	67
6. Ocean pout	20	–	40	–	30	–	0	–	15	10	20	–	–	0	61
7. Lumpfish	20	–	10	–	10	20	20	–	15	10	0	10	20	20	53
8. Atlantic halibut	0	20	10	10	5	0	30	15	20	0	0	–	20	10	38
9. Monkfish	0	–	0	–	–	–	–	–	15	–	–	–	20	0	25

The other salmonid species that remained throughout the selection process were ranked lower with an average score of 72% (Atlantic salmon, rainbow trout and brook charr). Other strictly marine species in the classification were the following: the ocean pout, *Macrozoarces americanus* Schneider, the lumpfish, *Cyclopterus lumpus* L., Atlantic halibut, *Hippoglossus hippoglossus* L. and monkfish, *Lophius americanus* Valenciennes), with scores ranging from 61% to 25%. Optimal growth temperature and minimal lethal temperature were the most decisive criteria (42.9% and 66.7% of the species obtained 0 on 20 and 40 points respectively).

The final classification for the on-growing production strategy is presented in Table 5. Arctic charr with 84% is first, followed by Atlantic cod, Atlantic halibut and Atlantic salmon with 79, 74 and 72%, respectively. Rainbow trout and brook charr obtained 59 and 47% respectively. Optimal growth temperature was again the most decisive criteria with 50% of the species receiving 0 points of a maximum of 40 points.

Table 6 shows the outcomes of the classification process examining the potential for stock enhancement. Striped bass (*Morone saxatilis* Walbaum) ranked first with 56% followed by the haddock (*Melanogrammus aeglefinus* L.), the Atlantic sturgeon (*Acipenser oxyrhynchus* Mitchill), the witch flounder (*Glyptocephalus cynoglossus* L.) and the winter flounder (54%, 34%, 33% and 16% respectively).

Discussion

Based on the complete life cycle production strategy, two species of wolffish (Spotted and Atlantic wolffish) were identified as having the highest potential in terms of biological and technical features. These species are currently under investigations in northern Norway (Falk-Petersen, Hansen, Fieler & Sunde 1999; Tveiten 2001), in the neighbouring province of Newfoundland, Canada (Brown & Wiseman 1994; Tulloch, Goddard & Watkins 1996; Wiseman 1997; Halfyard, Drover, Parrish & Jauncey 1998), Iceland (S. Gunnarsson, personal communication), Chile (Bravo 1999) and, following the results of the classification procedure presented in this paper, in Quebec, Canada (Le François, Dutil, Lord, Blier & Chabot 2001; Le François, Lemieux, Blier & Falk-Petersen 2001). Research avenues identified by the evaluation procedure and consultation of the technical sheets (reproduction, nutrition, tolerance to

Table 5 Final classification for the on-growing production strategy

	Growth rate /40	Optimal growth temperature/40	Capture survival/30	Maximal size reached/20	Salinity tolerance/20	Flesh yield/20	Landing price/20	Results
1. Arctic charr	40	25	–	20	20	20	10	84
2. Atlantic cod*	40	25	30	20	20	15	0	79
3. Atlantic halibut	40	25	10	20	–	20	10	74
4. Atlantic salmon	40	0	–	20	20	15	20	72
5. Rainbow trout	40	0	–	10	20	15	10	59
6. Brook charr	20	0	–	10	20	15	10	47

*Atlantic cod was eliminated by the first selection process but arbitrarily added to the on-growing scenario.

Table 6 Final classification for the stock enhancement production strategy

	Growth rate/40	Fishery status/40	Impact studies/40	Landing price/40	Results
1. Striped bass	20	40	20	10	56
2. Haddock	40	25	–	0	54
3. Atlantic sturgeon	0	25	20	10	34
4. Witch flounder	0	40	–	0	33
5. Winter flounder	0	25	0	0	16

environmental factors) will be addressed in future collaborations with Norway and Newfoundland.

Arctic charr and brook charr also displayed good potential. These species are currently cultured in Quebec but strickly in freshwater facilities. Seawater cultivation has been investigated under our environmental conditions (Dumas *et al*. 1995; Le François *et al*. 1997; Le François & Blier 2000). These studies confirmed the suitability of these species for rearing activities in estuarine conditions. Supported by the conclusions of the selection procedure and the presence of an industry for juvenile supply, efforts to evaluate the feasibility and the environmental impacts of seasonal marine on-growing of brook charr in sea cages in the Gaspe bay and the Chaleurs bay areas are actually underway by private interests and governmental authorities. The rainbow trout, which obtained a higher score in the final classification than the brook charr (59 and 47% respectively), is considered a non-native species in the east of the province and thus can not be considered for cultivation.

The on-growing production strategy positioned the Arctic charr and the Atlantic cod in first and second places, respectively, followed by the Atlantic halibut. Optimal growth temperature was a decisive criterion and in absence of juvenile aquacultural production, survival following capture was an important characteristic. Quebec is actually producing around 100 ton per year of Arctic charr and prospects are good for this industry given appropriate funding and research. Long-term, on-growing activities of Atlantic cod, an historical fishery, should benefit from knowledge of its larviculture requirements and from past activities of sea-pen on-growing on the lower north coast of the Gulf of St Lawrence and Newfoundland. Although the resource is showing clear signs of depletion, Canadian commercial fisheries are still in operation under strict regulation. Prices at landing are not high (1.28 Can. $ per kg) but on-growing activities of juveniles, originating from the wild or from aquaculture productions, could be profitable given a higher price for the aquaculture product (stable supply and quality). Construction of Atlantic halibut on-growing facilities in Quebec could benefit from established production facilities operating in the neighbouring province of New Brunswick, Nova Scotia of Newfoundland for stable supplies of juveniles.

Striped bass was the species presenting the highest potential under the stock enhancement production strategies. Striped bass has been, and still is, the object of stock enhancement efforts in the United States. In Canada, the possibilities of reintroduction of striped bass in the St Lawrence estuary and eastern Canada have been evaluated by governmental agencies. Ecological and management issues are still to be addressed, followed by the development of massive juvenile production facilities and evaluation of impact studies. A research programme aimed at the aquaculture production of striped bass for the retail market was realized in New Brunswick for over 10 years and ended in 1999, with the private sector taking over the development of this aquaculture species (D. Martin-Robichaud, DFO-St. Andrews, New Brunswick, Canada).

The proposed method for the evaluation of numerous marine fish species is somewhat validated by the inclusion of salmonid species currently under cultivation (Arctic charr, Atlantic salmon, brook charr, rainbow trout). It can be reasonably assumed that their persistence throughout the selection process and final order of classification are clear indications that the criteria selected for our procedure of analysis are valid under our environmental conditions. Although initially tedious, the proposed selection procedure offers interesting flexibility given periodic review of the information. In this respect, it is a powerful and durable mariculture database essential for the prioritization of species and research efforts. The database is also being integrated to college-level courses in aquaculture at the Centre Spécialisé des Pêches de Grande-Rivière, Quebec Canada (C. Levasseur, personal communication) supporting the educational value of this large-scale evaluation procedure.

Several species considered for culture elsewhere in the east coast of North America were not selected as priority species in Quebec. American eel (*Anguilla rostrata* Lesueur), yellowtail flounder (*Limanda ferruginea* Storer) and bluefin tuna (*Thunnus thynnus* L.) were rejected, whereas striped bass, haddock and sturgeon are only considered for stock enhancement. However, these species (except haddock) are all regarded as alternative species rather than priority species when compared with well established finfish mariculture research programmes (cod, halibut, salmonids). Salmonid species such as Atlantic salmon and rainbow trout (steelhead) are commercialy cultured year-round in marine cages in the neighbouring provinces (New Brunswick, Newfoundland and Nova Scotia). In Quebec, extensive ice coverage in the coastal environment and subzero temperatures limit salmoniculture cage-culture activities to a seasonal basis. Super-chill episodes, vulnerability of marine structures to ice movements and season-limited market supply confer important drawbacks in terms of competitiveness and profitability. On the other hand, commercial seasonal on-growing in sea cages of brook charr, a species not commercially grown in sea cages elsewhere in the world, is being evaluated.

General drawbacks to species selection methods are the unavoidable subjective character of the total points allocation process for the different criteria. As previously mentioned (Cook & Walmsley 1990), a careful evaluation of their relative importance in an aquaculture context is crucial and bound to present interregional variability. Relative importance of the criteria and the range of values can be readily modified to meet the particularities of the users' biological, environmental or economic context.

We acknowledge the fact that a lack of information for some species could potentially induce a ranking bias. It is, however, taken into account by the clear identification of gaps of knowledge for some selected criteria. We strongly suggest the evaluation of both the final ranking and the degree of uncertainty associated with a given species before reaching any clear conclusion on its level of interest.

The final step in the prioritization process is the evaluation of the risk level associated with a given species and of the expected delays to achieve profitability levels with regard to the production costs and market realities. A complete financial analysis is currently being conducted on only those species with a sufficient level of information on rearing technology and biological parameters and having successfully made it through the final classification process. This analysis will determine, on financial grounds, the most appropriate production technology for a given species (e.g. Atlantic halibut: land-based recirculation or marine cage technology). The evaluation of the reliance of a given species on research and development efforts should also be conducted to achieve precommercial levels. This species selection procedure is presently being adapted for the evaluation of the aquaculture potential of invertebrate species on the East coast of Canada.

Acknowledgments

The authors would like to thank: Carole Paradis for the collection of data and preliminary discussions surrounding the selection of criteria; Lucien Poirier, Francis Coulombe and Benoit Thomas of the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec and Marcel Lévesque of the Université du Québec à Rimouski for the species list and selection of criteria; and Francis Mailhot and Marie-Andrée Vaillancourt for the collection of data. We also thank Christian Nozais and Michael Patterson for comments on the manuscript. This study was supported by the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec and Développement Économique Canada.

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