Fisheries and Oceans Canada — Pêches et Océans Canada
Science — Sciences

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Canadian Science Advisory Secretariat — **Secrétariat canadien de consultation scientifique**

Research Document 2008/042 — **Document de recherche 2008/042**

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Risk Assessment for European green crab (*Carcinus maenas*) in Canadian Waters

Évaluation des risques représentés par le crabe européen (*Carcinus maenas*) dans les eaux canadiennes

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ISSN 1499-3848 (Printed / Imprimé)

Canada

ABSTRACT

Non-indigenous species continue to be dispersed to new environments and it is important for managers to understand the potential risk posed by these species. The European green crab (*Carcinus maenas*) has a rather extensive invasion history dating back over a century in North America. In order to determine the potential risk posed by this non-indigenous crab species to Canadian waters, including both the Atlantic and Pacific coasts, a formal risk assessment was undertaken. Most global introductions of crabs have been introductions attributed to commercial shipping activities. European green crab already exists in Canadian waters on both coasts with both introductions attributed to human-mediated activities. Based on impacts of green crab elsewhere owing to their extensive invasion history, there is considerable concern about the potential ecological (biological, habitat) and genetic impacts if green crab spread in Canada. Life history characteristics of green crab enhance long-distance natural dispersal. Further dispersal via ballast water is probable but a number of other anthropogenic dispersal vectors exist.

Fisheries and Oceans Canada conducted a national risk assessment to determine the potential risk posed by European green crab in Canada. This assessment included evaluating the probability of arrival, survival, reproduction and spread and potential consequences to determine a risk level. In addition, the potential risk posed by pathogens, parasites or fellow travelers (e.g. other invasive species) also was determined. These components were assessed in an expert, peer-review workshop held during February 2008 using the best available information on their biology, potential vectors of introduction, and impacts in both native and introduced ranges. The assessment concluded that European green crab generally posed a moderate to high risk on both coasts depending on the ecological endpoint assessed. For pathogens, parasites or fellow travelers the risks were deemed low. However, as little is known about many potential pathogens, parasites and fellow travelers of this crab species there was considerable uncertainty.

RÉSUMÉ

Les espèces non indigènes continuent de se disperser dans de nouveaux environnements et il est important que les gestionnaires comprennent le risque potentiel qu'elles représentent. L'invasion du crabe européen (*Carcinus maenas*) a commencé il y a déjà plus d'un siècle en Amérique du Nord. Une évaluation formelle du risque a été entreprise en vue de déterminer le risque potentiel que représente cette espèce de crabe non indigène dans les eaux canadiennes, sur les côtes atlantique et pacifique. Les introductions les plus massives de crabe sont dues à la navigation commerciale. La présence du crabe européen dans les eaux des deux côtes qui bordent le Canada est attribuée aux introductions des activités humaines. Compte tenu des répercussions qu'a eues l'arrivée du crabe européen dans d'autres régions du fait des fortes tendances envahissantes de cette espèce, on s'inquiète beaucoup des conséquences écologiques (biologique, habitat) et génétiques que sa propagation potentielle pourrait avoir au Canada. Les caractéristiques de l'évolution biologique du crabe européen renforcent sa dispersion naturelle sur de longues distances. Il est probable que la dispersion se fait également par les eaux de ballast, mais il existe plusieurs autres vecteurs de dispersion anthropiques.

Pêches et Océans Canada a procédé à une étude nationale afin de déterminer le risque potentiel que représente le crabe européen au Canada. Cette étude comportait notamment l'évaluation de la probabilité de l'arrivée, de la survie, de la reproduction et de la propagation, ainsi que des conséquences possibles, en vue d'estimer le niveau de risque. Elle a également déterminé le risque que pourraient poser les agents pathogènes, les parasites et les organismes associés (c'est-à-dire d'autres espèces envahissantes) du crabe européen. Tous ces éléments ont été évalués pendant un atelier d'experts, revu par des pairs, qui s'est tenu en février 2008. Les participants ont utilisé à cette fin la meilleure information disponible sur les aspects biologiques, les vecteurs potentiels pour l'introduction et les répercussions dans les aires de répartition, naturelles et autres. La conclusion de cette étude est que le crabe européen pose en général un risque moyen à élevé sur les deux côtes, selon l'effet écologique évalué. Les risques liés aux agents pathogènes, aux parasites et aux organismes associés ont été jugés faibles. Cependant, dans la mesure où on connaît très mal la plupart des agents pathogènes, parasites et organismes associés du crabe européen, le niveau d'incertitude est très élevé.

INTRODUCTION

Non-indigenous species (NIS) pose an enormous risk to native biodiversity and can compromise ecosystem function (e.g., Sala et al., 2000). In marine ecosystems, the European green crab (*Carcinus maenas*) has an extensive global invasion history but determining whether or not a non-indigenous species becomes invasive depends on the impact of the non-indigenous species in its newly invaded habitat. The Government of Canada (2004) defines invasive alien species as "those harmful alien species whose introduction or spread threatens the environment, the economy or society, including human health".

In order to characterize the potential risk posed by a new invader to Canadian waters or the spread of an existing invader to additional waters, a formal risk assessment is conducted. This risk assessment is adapted from the process outlined in the Canadian National Code on Introductions and Transfers of Aquatic Organisms (DFO, 2003) by considering the probability of arrival for unintentional introductions and contains two-parts. Part I evaluates the probability of establishment and consequence of establishment of an aquatic organism while Part II evaluates the probability of establishment and consequence of establishment of a pathogen, parasite or fellow traveler of the aquatic organism. Within each Part of the national framework two component ratings are determined (the probability and consequences of establishment). The final, overall ratings are high (risk is likely, or very likely, to occur), medium (there is probability of negative impact), or low (risk is considered to be insignificant). In addition, a level of certainty or likelihood also is assigned as a gradient from very certain (scientific basis), reasonably certain, reasonably uncertain, to very uncertain ("best guess").

The European green crab has an extensive global invasion history (Klassen and Locke, 2007). This document summarizes the results of a risk assessment conducted to evaluate the risk posed by this species to both Atlantic and Pacific coasts of Canada. The risk assessment process is based upon the best available information for the species of interest. The biological information was obtained from Klassen and Locke (2007) for European green crab and a draft risk assessment document was prepared and peer-reviewed at a workshop attended by international aquatic invasive species and crab experts in February 2008 (see Appendix A for workshop participants). A synopsis of the workshop will be prepared in a separate document to capture discussion at the workshop in addition to key findings. A summary of green crab's basic biology, native, non-native and potential distribution in Canada, and the risk assessment is provided. In addition, in order to gain scientific knowledge with respect to vectors and pathways and potential impacts associated with non-indigenous crab species, a formal survey of both NIS and crab experts was conducted. The results from this survey help guide the level of risk or uncertainty associated with the risk assessment.

METHODS AND MATERIALS

Risk Assessment Methodology

Risk has two components: probability and impact. The overall level of risk posed by a NIS is a combination of the probability of establishment and the consequences of that establishment. These two scores are combined in a heat matrix (Table 1) to provide an overall risk. Within the probability of establishment there are four major components with each representing a filter in the invasion process that will influence invasion success. The first step in the invasion process is determining the probability that a NIS will arrive to the geographical area being considered by the risk assessment. For example, what potential vectors exist for any given NIS and how frequently is the NIS of concern found within these vectors? The second step is determining if the NIS will survive if introduced. For example, can a NIS find a suitable environment within which to survive? The third step in the invasion process is closely linked with the second but indicates whether or not a NIS that survives the arrival to the new environment can reproduce within that environment in order to establish a sustainable population. The fourth step indicates whether or not a NIS can spread from the initial introduction location. For example, are vectors and pathways available that would allow the NIS to spread to additional suitable environments in its newly invaded range? The second component of the overall level of risk is the consequences of establishment of a NIS. For example, what are the ecological or genetic consequences on native ecosystems or populations if a NIS is able to establish? Risk is characterized both for the aquatic organism (Part I) and potential parasites, pathogens and fellow travelers (Part II).

Table 1: The following summary table was used to determine the overall risk potential by combining the probability of establishment estimate determined in Step 1 with the three consequences of establishment determined in Step 2. In the table Green = Low Risk, Yellow = Moderate Risk and Red = High Risk.

Consequence/Impact	Very High					
	High					
	Moderate					
	Low					
	Very Low					
		Rare	Low	Moderate	High	Very High
	Probability of Introduction					

Predicting Suitable Environments

The potential future range of green crab in Canada was predicted by environmental niche modeling using the Genetic Algorithm for Rule-set Prediction (GARP). Models were constructed using species presence and geo-referenced environmental data. The genetic algorithm developed iteratively a best prediction model, using 80% of occurrence points to train the data, and 20% of occurrence points to test the model. An initial model run, using all possible combinations of the environmental layers, provided each layers contribution to model accuracy. Only layers that contributed significantly to model accuracy were included in the final predictions, following Drake and Bossenbroek (2004). Environmental variables that contributed significantly to model prediction accuracy were then used to create 100 predictions using a 0.001 convergence limit and a maximum of 1500 iterations (per simulation), following the best subset procedure described by Anderson et al. (2003). The resulting predictions were converted into a map of percentage environmental match using the 'Raster Calculator' in ArcMAP 9.1.

The green crab models were based on their current North American distribution on each coast. This represents a conservative approach in that as a species' distribution increases over time additional suitable habitat will be identified. We extracted salinity, temperature and dissolved oxygen data from the NOAA World Ocean Database (http://www.nodc.noaa.gov/OC5/indprod.html) to a depth of 50m. Salinity and temperature measurements were divided into four seasons depending on the month of sampling (January-March, April-June, July-September, October-December) using Ocean Data View 3.2.0. Seasonal salinity and temperature, and annual oxygen data were converted into a continuous data layer by calculating the mean value of each variable over the 50m depth using inverse distance weighting (Geostatistical Wizard within ArcMAP 9.1). Annual surface chlorophyll *a* data were obtained from the 'Integrating Multiple Demands on Coastal Zones with Emphasis on Aquatic Ecosystems and Fisheries' project (http://www.incofish.org/). This resulted in ten environmental layers initially tested for their contribution to model accuracy: January-March temperature, April-June temperature, July-September temperature, October-December temperature, January-March salinity, April-June salinity, July-September salinity, October-December salinity, annual dissolved oxygen, and annual chlorophyll, all at 0.01° resolution. All layers except January-March salinity were included in the final model for the east coast, while the final west coast predictions retained all layers.

Additionally, we predicted the suitable range based on the environmental tolerances of green crabs according to the literature. We developed one model for adult survival, and one for successful larval development. Suitable areas for adults were defined by ocean temperatures between -2°C to 35°C (Eriksson and Edlund, 1977; Spaargaren, 1984; Hidalgo et al., 2005) and salinities between 4‰ and 52‰ (Cohen and Carlton, 2005), while larval development required temperatures between 9°C and 22°C (Dawirs et al., 1986; DeRiveria et al., 2006) and salinities of 20‰ or more (Anger et al., 1998). These limits were applied to the same oceanographic layers as used in the environmental niche models using ArcGIS 9.1 and its spatial analyst extension.

Expert Survey: Vector Importance

The importance of several potential transport vectors for the dispersal of green crab were identified through an expert web-based survey. An online questionnaire was designed and sent to 520 experts and three mailing lists associated with either crabs or invasive species. Each respondent was asked to identify their geographic and scientific areas of expertise. A total of 143 experts visited the questionnaire (but actual responses to each question were less), identifying the importance of ten potential vectors for dispersal: larval drift, directed adult migration, dispersal of adults attached to flotsam, ballast water, hull fouling on ships, movement of aquaculture gear and stock, boating (including trailering), intentional release for establishment (e.g., for food), related to fishing activities (entrapment in gear or shipping materials), via canals or other artificial waterways, as well as by "other" means (undefined). The survey was divided into two parts so that the respondents could differentiate between vectors important for primary establishment as well as for secondary spread. Respondents were asked to provide an estimate of the importance of each vector and the uncertainty associated with their estimate depending on the source of information they used to form their judgment. For both sets of questions they were provided a choice of five categories: very high, high, moderate, low, and very low. Definitions for each category were provided with each question (Appendix B), including those of uncertainty. Generally, one fifth of respondents considered there to be "moderate" levels of importance and uncertainty associated with the importance attributed to most categories and for both primary introduction and secondary spread. Vector importance and uncertainty are thus discussed in general terms of being either low (very low and low), moderate, or high (high and very high).

Transport Vectors

Literature reports have identified ballast water transport as the primary vector for global introductions of European green crab. This vector also was identified as important for secondary spread of this species. Thus, total discharge of ballast water into Canadian ports was estimated based on the Canadian Ballast Water Database Application (CBWDA), developed by Fisheries and Oceans Canada and Transport Canada. This database contains discharge coordinates and volumes obtained from ballast water reporting forms that were voluntarily submitted to the Canadian Coast Guard and individual ports, mainly by commercial vessels entering Canadian waters from outside the Exclusive Economic Zone (EEZ). Data from 2005, which provided ballast discharges for 13 587 of 25 841 ship arrivals for which forms were submitted, was analyzed. The number of arrivals and volume of ballast water discharges were categorized into three major regions (Pacific coast, Great Lakes-St. Lawrence, and Atlantic coast), tabulated and mapped.

Additional potential vectors for initial arrival or secondary spread were identified as potentially important in our survey. We gathered spatially explicit information on the distribution of these transport vectors where it existed. Aquaculture site information was gathered for both coasts from government agencies, aquaculture associations, and scientists and was converted into point data that was then transformed into density maps using ArcMAP 9.1. Thus, it was possible to reflect the density of aquaculture sites in a particular area. Similarly, we used the distribution of small craft harbors (east coast) or small craft harbors, anchorages, ports and marinas (west coast), depending on data availability, as a proxy for small craft vessel traffic. The frequency of different types of large commercial vessels, fishing boats, and barge movements on the west coast was determined based ship traffic data for 2003 (courtesy of the Canadian Marine Communications and Traffic Services [MCTS]). The frequency of vessel movements through a particular area was converted into density layers as above. Due to the unavailability of suitable data a similar analysis could not be conducted for the east coast.

Larval Drift: East Coast

To examine the potential for spread of green crab larvae by transport on oceanographic currents, a three-dimensional ice-ocean modeling system (Gulf of St. Lawrence Ocean Model) was used to hindcast ocean conditions and planktonic drift in the Estuary and Gulf of St. Lawrence and Northeast Scotian Shelf (J. Chassé, Bedford Institute of Oceanography). The horizontal resolution of the model was around 4 km and it included 32 fixed depth levels (layers) with forcing induced by tides, winds, freshwater runoff and heat flux. The model was initialized with climatological temperature and salinity fields.

In Atlantic Canada, first stage green crab zoeae were present in the water column from June to August, and megalopae were present until October (Cameron and Metaxas, 2005). The model simulated the release of 10000 larvae at sunset each day (for 7 consecutive days) on spring tides in June, July and August for a larval drift period of 90 days. Preliminary simulations were carried out for the year 2006. Drift depth switched every 12 hours between 20 and 35 m to approximate vertical migration. Where the total depth was less than 20 m, the larvae were placed at mid-depth in the water column.

Simulations commenced with larval releases at points along the 2007 green crab distribution front in eastern New Brunswick, Prince Edward Island and the southern coast of Newfoundland as well as several earlier points of invasion in Nova Scotia (Table 2).

Output consisted of geo-referenced distribution of crab larvae at 12 hour intervals during June through October.

Table 2: Starting points for the oceanographic simulation of larval drift of green crabs in Atlantic Canada.

Release point	Latitude	Longitude
Cape Jourimain, NB	46.150	-63.833
Victoria, PEI	46.200	-63.483
Savage Harbour, PEI	46.417	-62.833
Grande Entrée Lagoon, QC	47.585	-61.551
North Harbour, NL	47.860	-54.103
Tor Bay, NS	45.233	-61.316
Sandy Point, NS	43.683	-65.233
Halifax, NS	44.617	-63.567
Murphy's Cove, NS	44.783	-62.750

Larval Drift: West Coast

Velocity fields for the model region (35°N to 55°N) were calculated using a three-dimensional, diagnostic, baroclinic, finite element model. The velocities are assumed to arise from a combination of tidal, wind, and buoyancy forcing and the model computes height and current constituents in the frequency domain. The tidal components have their distinct frequencies while both the wind and buoyancy components have zero frequency; that is, they are time invariant (for more detail see Larson et al., 2002). The model was developed for an average winter and average summer scenario, both of which were seeded with larvae. The green crab larvae were seeded at ten populations along the US west coast, representing the major US green crab population centers, and at the 22 locations green crabs have been reported in British Columbia, all along the west coast of Vancouver Island (Gillespie et al., 2007). Vertical larval migration from a depth of 35m during the day to 20m at night was included in the predictions, unless the maximum depth was shallower. The larvae's position was tracked every 12 hours and imported into ArcGIS 9.1.

Potential Impacts of an Introduction: Expert Survey

The importance of several potential impacts due to green crab was evaluated via the same expert web-based survey that was used to evaluate the importance of vectors (see above). Respondents were asked to estimate the importance of each impact and the likelihood of occurrence. Respondents had a choice of six answers for effect levels: positive, very low negative, low negative, moderate negative, high negative, and very high negative, and five levels for the likelihood of an effect occurring: unlikely, possible, likely, almost certain, and certain. Definitions for each category were provided with each question (Appendix B). There were three potential areas of impact that we identified but were not explicitly considered in our expert survey. These included impacts on wildlife (or human health), habitat impacts, and genetic impacts. For these four types of impacts we relied on literature reports and personal observations and/or knowledge.

To ease interpretation and discussion, the qualitative measures used to describe the potential of various effects were assigned ordinal values ranging from -1 (positive) through 4 (very high negative). Means for each potential impact were then calculated based on the individual observations thus coded, and divided into 6 equal sized bins (0.833) for an overall score. While this does not represent the precautionary approach, it provides a balanced view of the potential impacts across the ten impact categories included in the survey. Since generating the mean of categorical variables can be problematic, we also tested the median and mode of the data. Since the mean category for each impact level was very similar independent of the method used, we present only the results of the mean values here.

RESULTS

Ballast Water

The majority of ballast was discharged on the Atlantic coast (29,390,717MT) compared to the Pacific coast (8,515,707MT) in 2005. The Great Lakes-St. Lawrence region received the lowest volume (1,817,019MT) of ballast discharge. It is important to note that mandatory reporting of ballast water (other than for vessels destined for the Great Lakes – St. Lawrence Seaway) was not initiated until June 2006, thus the 2005 likely represents incomplete reporting as this was a voluntary period. Further, there will always be some uncertainty with respect to ballast water reported and actual ballast water discharges.

On the Atlantic coast, the largest volume was discharged in Point Tupper, followed by St. John, Come-by-Chance and Sept-Iles (Figure 1), providing potential introduction sites for green crab. Roman (2006) provides genetic evidence of a green crab introduction on the Atlantic coast of Canada near Point Tupper and the recent introduction of green crab in Newfoundland occurred near Come-by-Chance (Klassen and Locke, 2007). The combined ballast water discharge in these three ports exceeds all other ballast water discharges in Newfoundland and the northern Gulf of St. Lawrence combined. Further, Come-by-Chance may see increased vessel traffic owing to proposed increases in oil production and distribution via this port. On the Pacific coast, only Vancouver and the associated Roberts Bank and Fraser Port received a large volume of ballast water (Figure 2) but with increased development of ports in northern British Columbia (e.g., container port in Prince Rupert and tanker port in Kitimat) this could change in the future (Figure 2). The main ports for ballast water discharge in the Great Lakes were in Quebec, Montreal and Sorel, all in the lower parts for the St. Lawrence River. Nevertheless the amount of ballast water discharged in these locations is an order of magnitude lower than in the major ports on both coasts (Figure 3).

Other Potential Vectors: East Coast

A number of potential secondary vectors exist on the east coast including aquaculture-related transfers, recreational or small craft traffic and commercial shipping activities, including ballast water movements. However, we were unable to quantify this vector as we did for the west coast (see below) due to a lack of data. In Atlantic Canada, the greatest density of aquaculture facilities is in waters around PEI (Figure 4). Many lower density sites exist scattered around Newfoundland, Nova Scotia, New Brunswick (both near St. Andrews in the Bay of Fundy and on the Atlantic coast) and the Magdalen Islands (Figure 4). Most of the small craft harbors exist around the island of Newfoundland (Figure 5) but this could represent an artifact in the available data as other parts of the Maritimes have much higher population densities. Other higher density areas exist around southwestern Nova Scotia and New Brunswick (mouth of the Bay of Fundy), around Cape Breton Island, PEI and the Magdalen Islands (Figure 5).

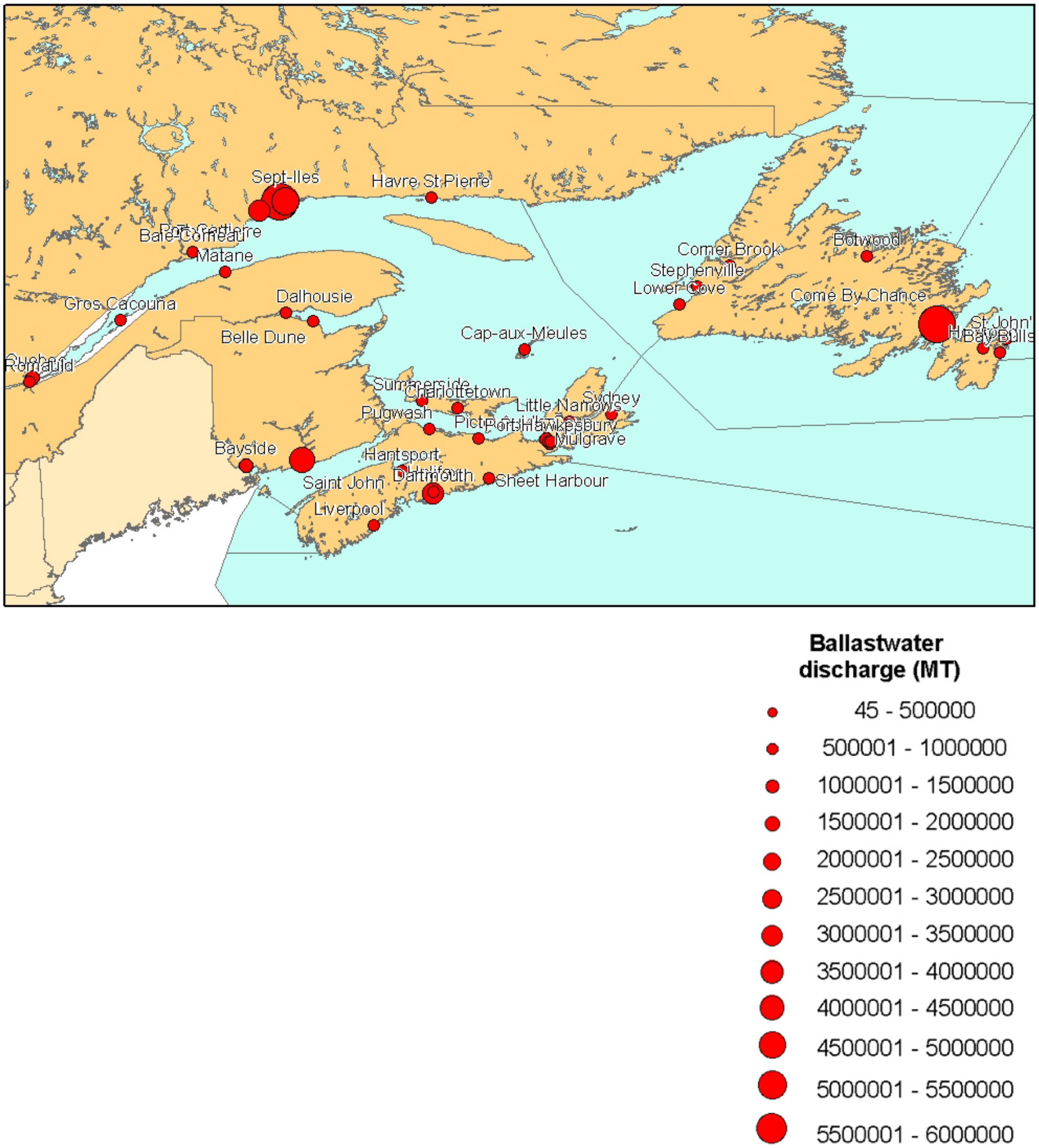

Figure 1: Total ballast water discharge volumes (in megatons, MT) on the Atlantic coast, based on 2005 CBWDA data.

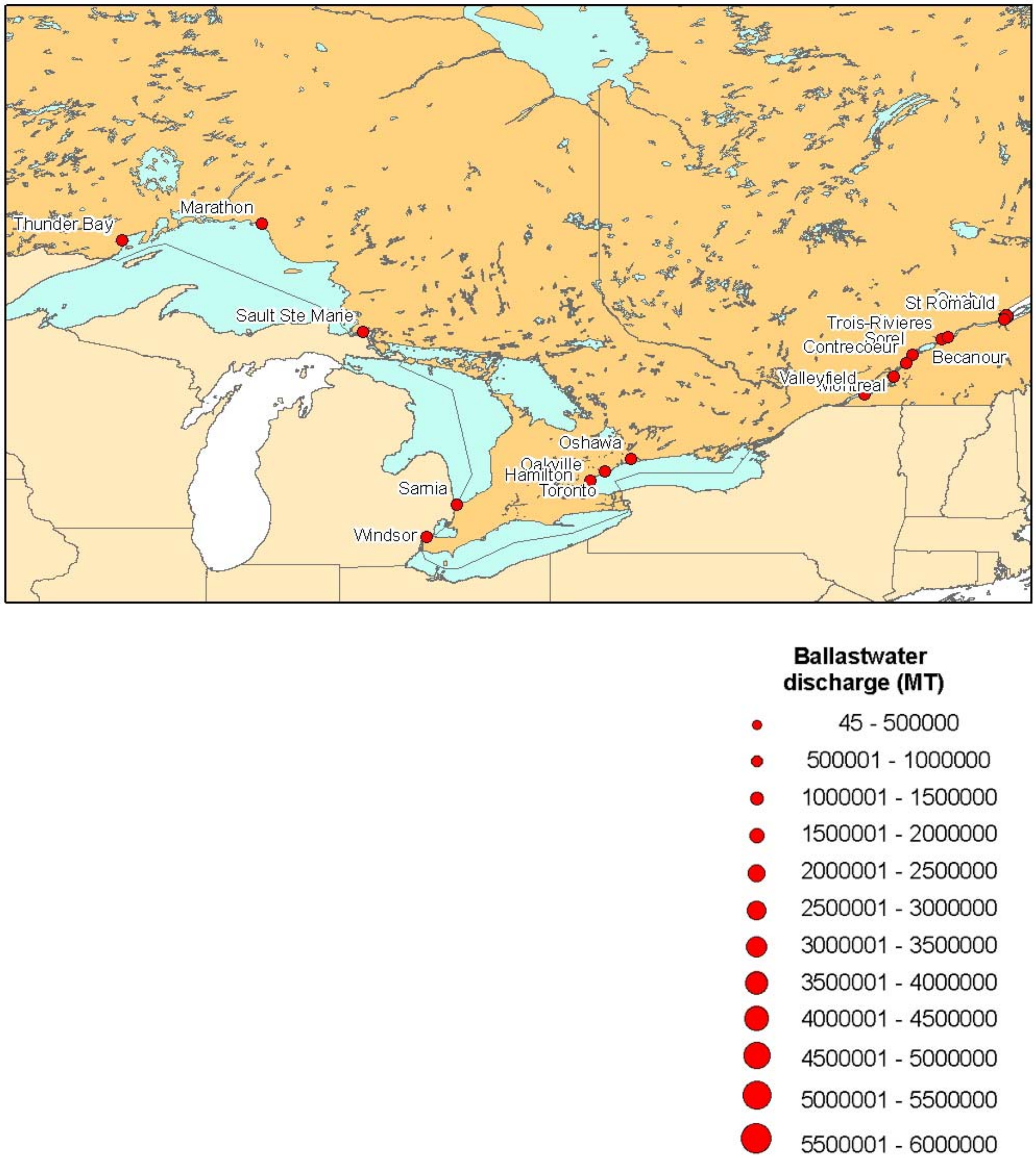

Figure 2: Total ballast water discharge volumes (in megatons, MT) in the Great Lakes-St. Lawrence, based on 2005 CBWDA data.

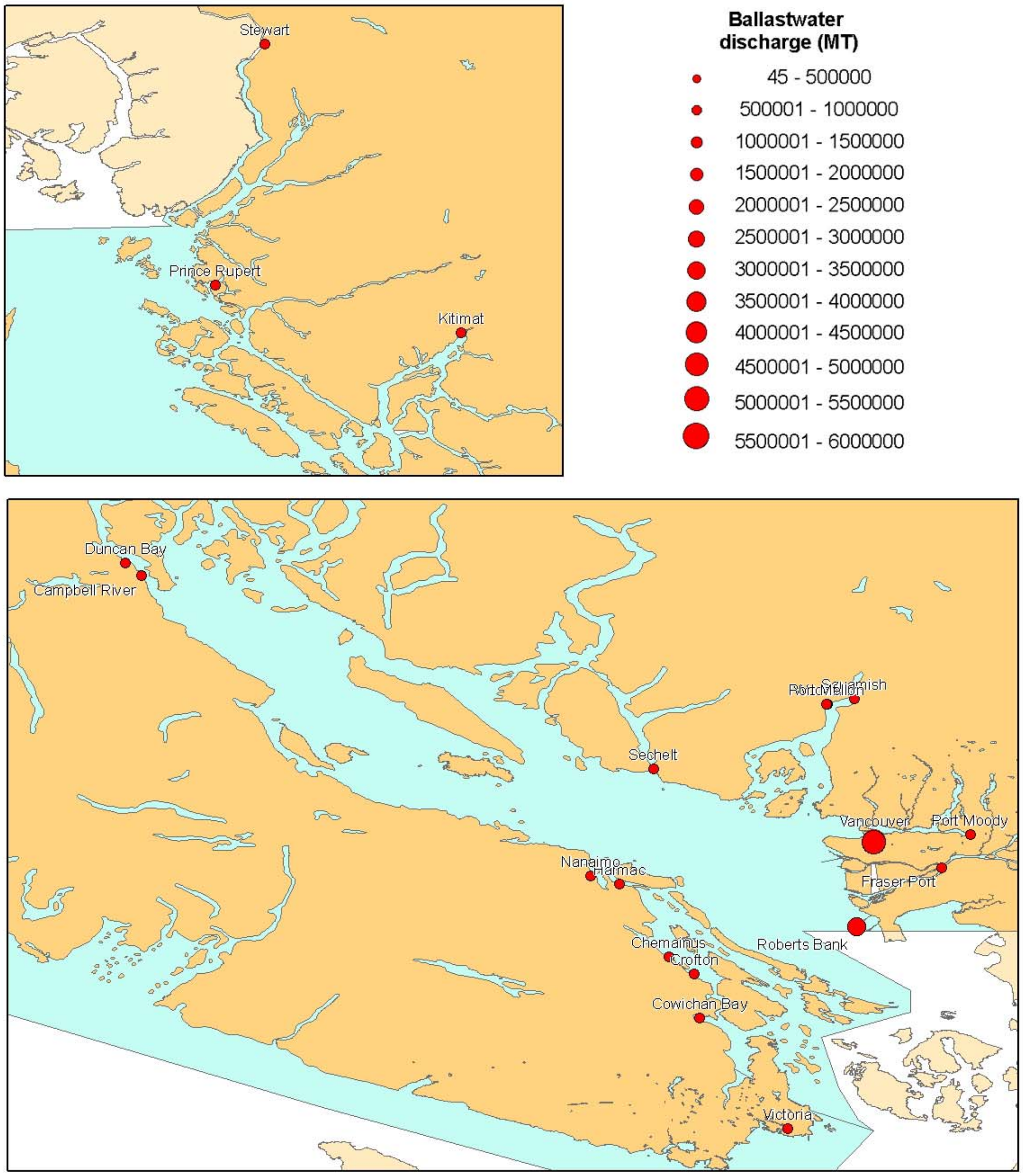

Figure 3: Total ballast water discharge volumes (in megatons, MT) on the Pacific Coast, based on 2005 CBWDA data.

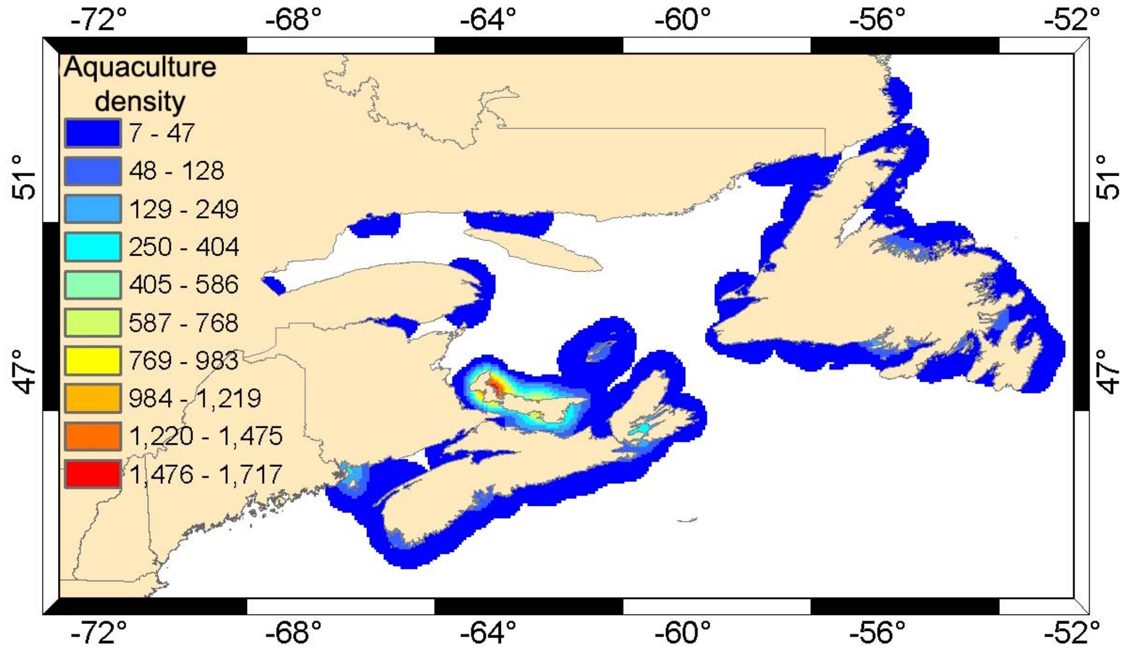

Figure 4: Relative density of aquaculture facilities around Atlantic Canada.

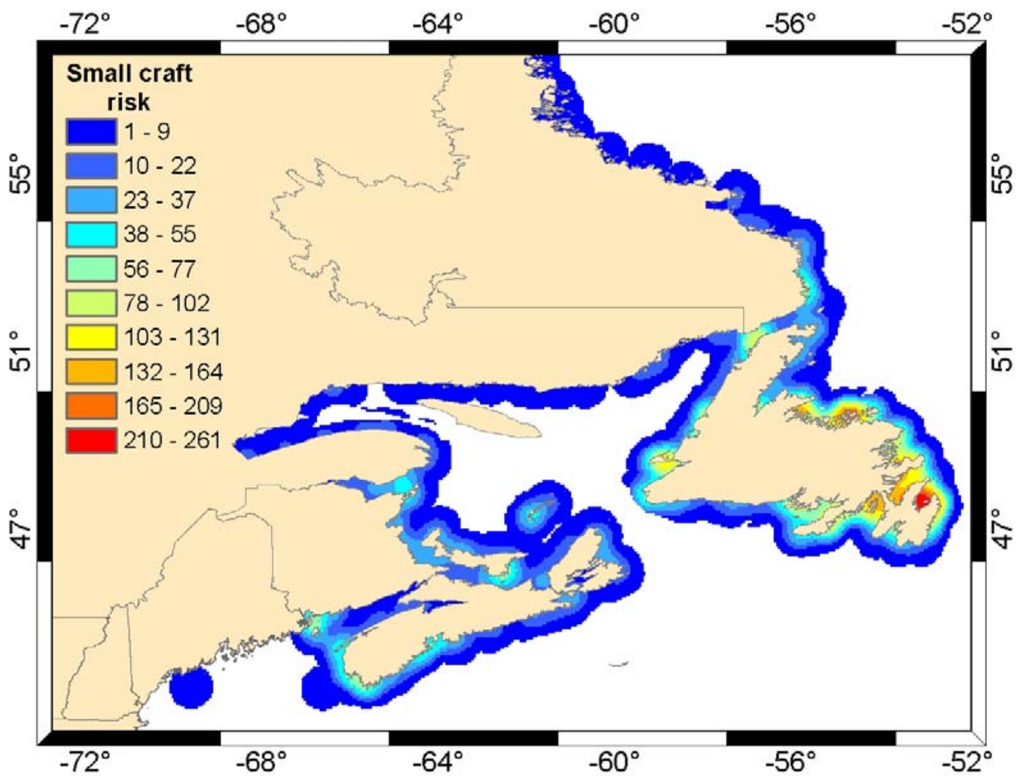

Figure 5: Relative density of small craft harbors around Atlantic Canada.

Other Potential Vectors: West Coast

A number of potential secondary dispersal vectors exist on the west coast including aquaculture-related transfers, recreational or small craft movements, and movements of commercial vessels including container ships, tankers, and fishing vessels. Most aquaculture in British Columbia (BC) is around the Strait of Georgia, notably Baynes Sound and Oekover Inlet (Figure 6). Higher than average densities also occur in the major inlets along the west coast of Vancouver Island and in Johnstone Strait (Figure 6). The highest density of small craft moorings is around the Strait of Georgia, extending through Johnstone Strait and into the Central Coast of BC (Figure 7). Additional point-source densities occur near Prince Rupert and Skidegate Inlet in the Queen Charlotte Islands (Figure 7). Most container ship activity in BC is related to international trade. These foreign vessels are entering Juan de Fuca Strait and heading to the ports of Vancouver or Delta to offload their cargo (Figure 8). Similar to container ships, most tanker traffic is into the port of Vancouver but additional tanker traffic in the north coast is destined to Prince Rupert and Kitimat, both ports recently scheduled for expansion (Figure 9). In BC, most fishing vessels are operating on inside waters. These include the Strait of Georgia, through Johnstone Strait, and along the mainland side of Queen Charlotte Sound and Hecate Strait right up to Dixon Entrance (adjacent to Prince Rupert) (Figure 10). Most of the tug and barge traffic in BC waters is within the Strait of Georgia (Figure 11). A similar level of traffic exists within Puget Sound, highlighting the interconnectedness of this inland sea. Additional tug and barge traffic exists within a relatively constrained band along the mainland coast extending from Vancouver in the south to Prince Rupert in the north (Figure 11).

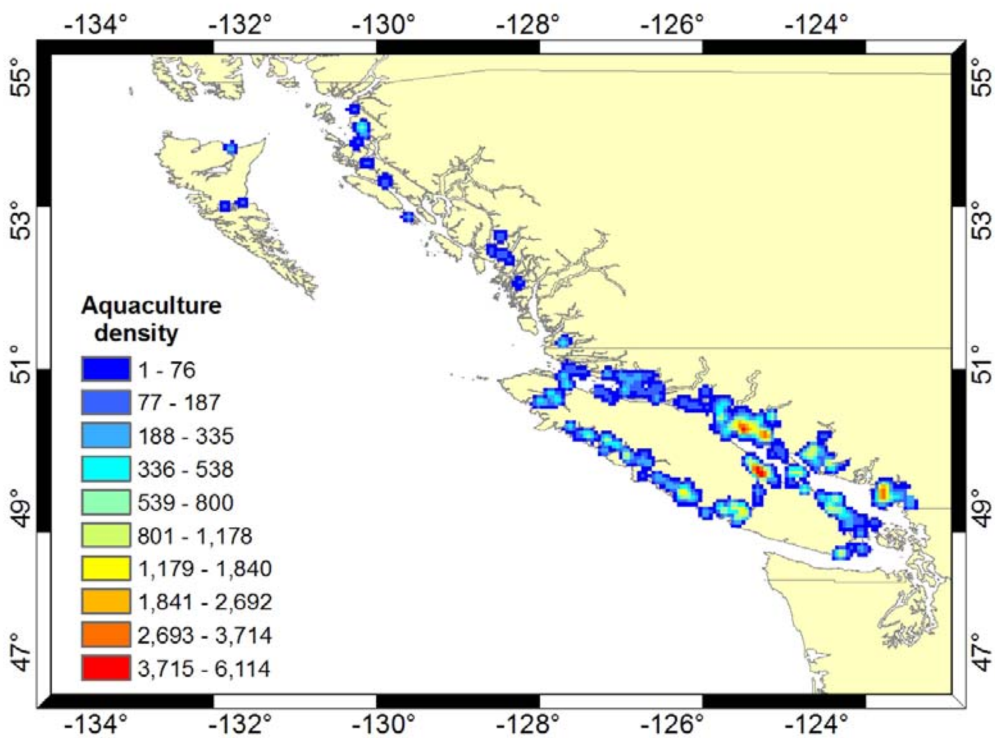

Figure 6: Relative density of aquaculture facilities in BC waters.

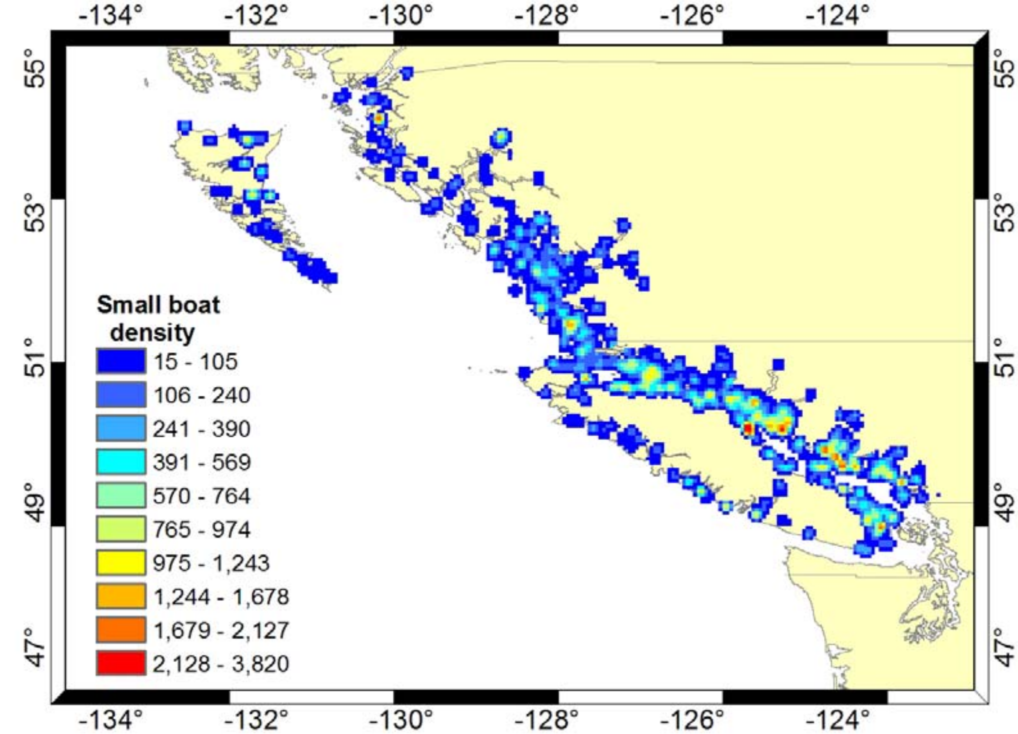

Figure 7: Relative density of small craft marinas, moorings and anchorages in BC waters.

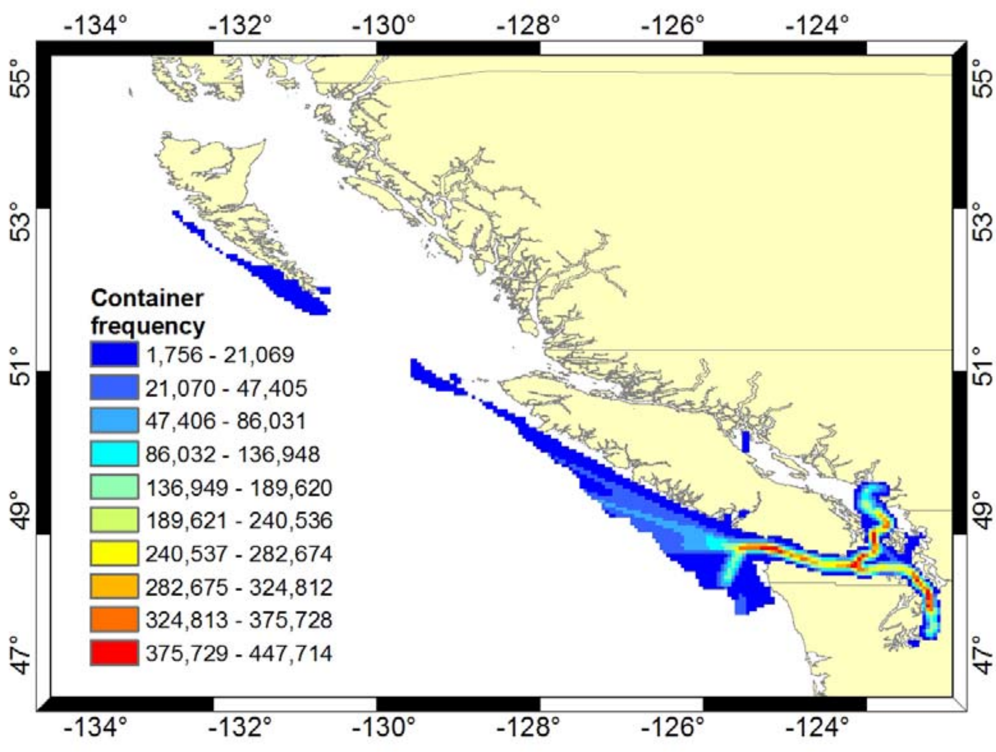

Figure 8: Relative density of container ship activity in BC waters.

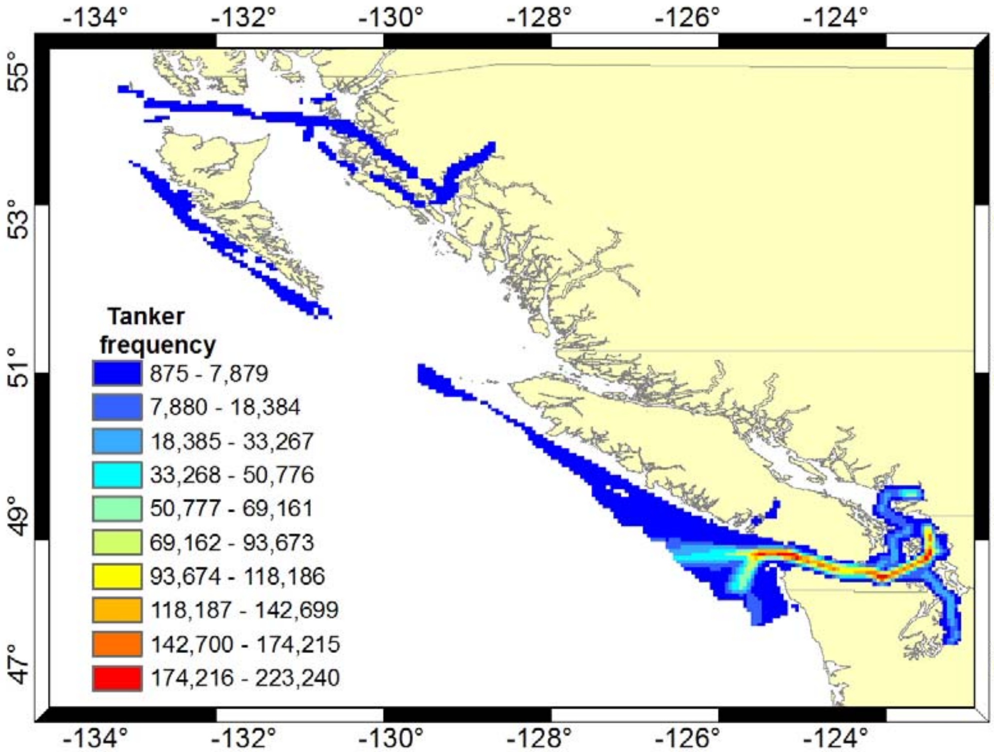

Figure 9: Relative density of tanker ship activity in BC waters.

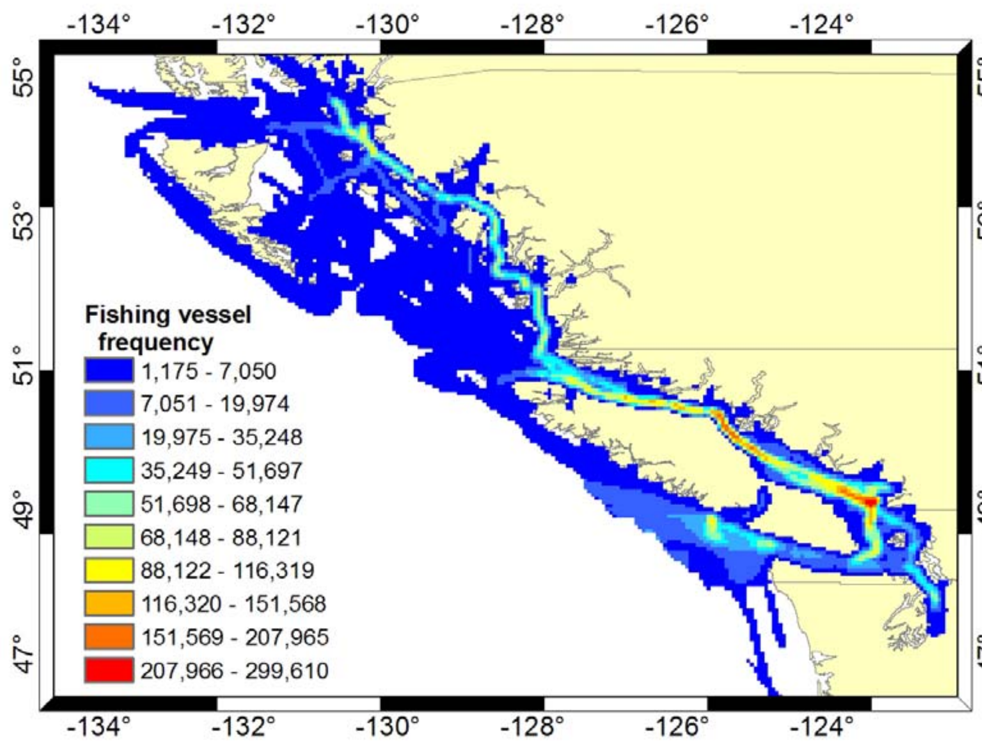

Figure 10: Relative density of fishing vessel activity in BC waters.

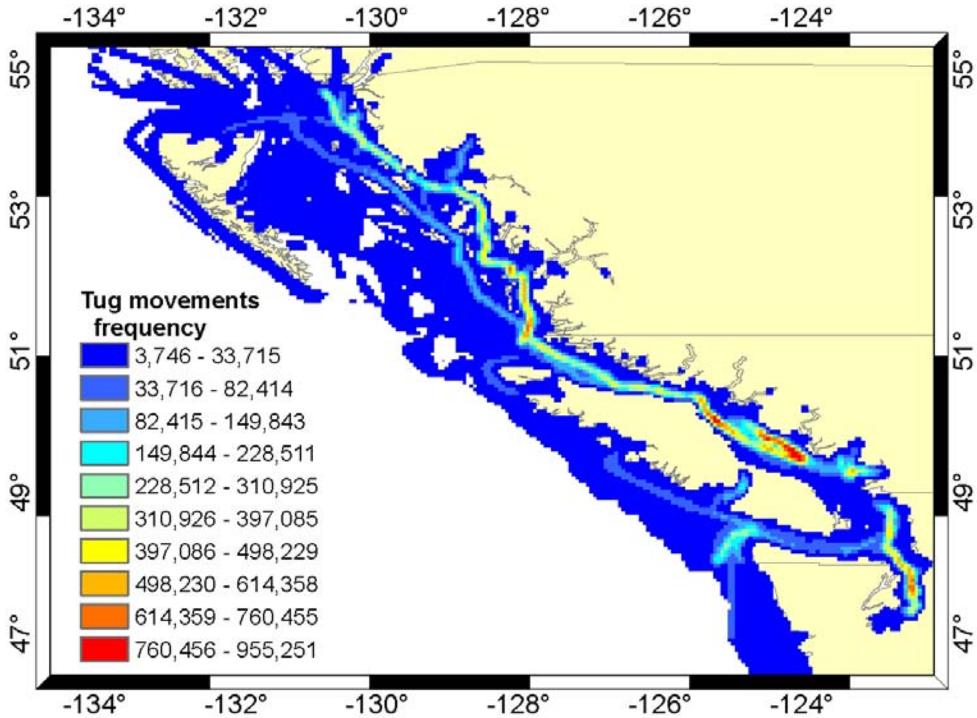

Figure 11: Relative density of tug/barge activity in BC waters.

European Green Crab (*Carcinus maenas*) Risk Assessment

Background and Biology

The European green crab or shore crab, *Carcinus maenas* (Linnaeus, 1758), is a medium-sized crab in the family Portunidae. The carapace of adult green crabs reaches about 6 cm in length and 9 cm in width. The green crab may be distinguished from native Canadian crab species by the presence of five antero-lateral spines on the carapace on either side of the rostrum, and a fifth leg which is somewhat flattened and dilated allowing the crab to swim.

Green crabs live up to 4 – 7 years (Berrill, 1982; Grosholz and Ruiz, 1996; Behrens Yamada et al., 2001). The life cycle alternates between benthic adults and planktonic larvae. One or two clutches of eggs are produced annually with females spawning up to 185,000 eggs at a time (Cohen and Carlton, 1995). Four zoeal and one megalopal larval stage develop in coastal waters for upward of 50 days, to a maximum of 82 days in laboratory experiments (Williams, 1967; DeRivera et al., 2007). Zoeae perform active vertical migrations that enhance their export from estuaries (Zeng and Naylor, 1996; Quieroga et al., 1997). Generally, larvae are found in coastal waters at depths of 20 – 25 m during the day and 30 – 45 m at twilight (Quieroga, 1996). Off Portugal, maximum distance from shore of the larvae was 45 km (Queiroga, 1996). Megalopae utilize selective tidal stream transport to return inshore to estuaries to settle and metamorphose into juvenile crabs (Quieroga, 1998).

Green crab has successfully colonized sheltered coastal and estuarine habitats and semi-exposed rocky coasts, including rocky intertidal, unvegetated intertidal, subtidal mud and sand, saltmarshes and seagrasses (Grosholz and Ruiz, 1996; Ray, 2005). Juvenile green crabs also utilize rocks, shell hash and other cover in the intertidal zone (Jensen et al., 2002). The species commonly is found from the high tide level to depths of 5 – 6 m and occasionally to 60 m.

Adult green crabs can survive temperature ranges <0^{o}C to >35^{o}C (Eriksson and Edlund, 1977; Hidalgo et al., 2005) but preferred temperatures are between 3^{o}C and 26^{o}C (Grosholz and Ruiz, 2002). Larval development was limited to 9 – 22.5^{o}C (Dawirs et al., 1986; DeRivera et al., 2007). At temperatures of 2 – 10^{o}C, feeding and growth was suppressed and most estuarine populations undertook an offshore overwintering migration to deeper, warmer coastal waters where the crabs buried in the bottom (Broekhuysen, 1936; Eriksson and Edlund, 1977; Berrill, 1982; Sharp et al., 2003). It is possible that these studies, mainly conducted on populations from the central and southern European range and from the USA, underestimate the temperature tolerance of Atlantic Canadian green crabs from northern Nova Scotia and the Gulf of St. Lawrence, which appear to originate from near the northern extent of the European range (Roman, 2006).

Adult green crabs can tolerate salinities between 4 and 52‰ (Cohen and Carlton, 1995), but prefer salinities between 10 and 30‰ (Broekhuysen, 1936; Grosholz and Ruiz, 2002). Salinities ≥20‰ were required for larval development (Anger et al., 1998). Green crab is tolerant of anoxia (Legeay and Massabuau, 2000) and readily survives at least five days out of water (Darbyson, 2006).

Planktonic larvae are filter-feeders, with early stage juveniles feeding on detritus and infauna while adults are omnivorous (Pihl, 1985). Green crabs prey on organisms from at least 104 families and 158 genera, in 5 plant and protist and 14 animal phyla (Cohen et al., 1995), including bivalves, gastropods, crustaceans and fishes, some of which may be commercially important. In many prey species, green crab predation induced adaptive responses that diverted energy from production to anti-predator strategies (e.g., cryptic behaviors, displacement to different habitat, shell thickening, stronger byssal attachments) (e.g., Hughes and Elner, 1979; Johanneson, 1986; Freeman and Byers, 2006).

Green crabs can concentrate marine biotoxins from their bivalve prey, and pass these biotoxins up the food chain. For example, at least one case of human Diarrheic Shellfish Poisoning resulted from ingestion of a large number of green crabs contaminated with okadaic acid (>32 mg/100g in a remaining sample of the meal) from razor clams (*Solen marginalis*). Domoic acid (responsible for Amnesic Shellfish Poisoning) also was present in these crabs (Vale and Sampayo, 2002).

The introduction of green crab could induce trophic changes. The diet of green crabs overlaps with that of native decapods including grapsid crabs (*Hemigrapsus oregonensis* and *H. sanguineus*), lady crab (*Ocellatus ovalipes*), Dungeness crab (*Cancer magister*) and American lobster (*Homarus americanus*) (e.g., Ropes, 1989; Jensen et al., 2002; Williams et al., 2006), but competition has not been demonstrated in nature. Also, green crab is prey for other decapods, many fish species, birds, mink, otters, and seals (e.g., Cohen et al., 1995; Hunt and Behrens Yamada, 2003).

Known Distribution

The green crab is native to European and North African coasts as far as the Baltic Sea in the east, Iceland and central Norway in the west and north, and Morocco and Mauritania in the south (Williams, 1984). It has invaded waters of both Atlantic and Pacific coasts of North America, South Africa (Cape Town), Australia, South America (Patagonia), and Asia (Le Roux et al., 1990, Thresher et al., 2003, Ahyong, 2005). Green crab has been recorded, but apparently did not successfully establish populations, in waters of the Red Sea (before 1817), Brazil (Rio de Janeiro [23˚S] in 1857 and Pernambuco [8˚S] before 1899), Panama (Pacific coast, 1866), Sri Lanka (1866-1867), Hawaii (1873), Madagascar (1922), Myanmar (1933), Perth, Australia (1965) and Pakistan (1971) (Boschma, 1972; Carlton and Cohen, 2003). In addition to European green crab, a related crab, *C. aestuarii* also has successfully invaded Japan (Geller et al. 1997; Rogers, 2001; Carlton and Cohen, 2003).

Green crabs were first observed on the east coast of North America in Massachusetts in 1817, and now occur from Newfoundland to Virginia (Grosholz and Ruiz, 1996; C. McKenzie, Fisheries and Oceans Canada, pers. comm.). Distribution of green crab in Atlantic Canada in 2007 included the Bay of Fundy, Atlantic coast of Nova Scotia, Nova Scotian coast of Northumberland Strait and most of Cape Breton Island, Baie Verte and Cape Jourimain on the New Brunswick coast of Northumberland Strait, the eastern end of Prince Edward Island (Savage Harbour and Victoria are the western boundaries of distribution on the north and south coasts, respectively), the Magdalen Islands, and Placentia Bay, Newfoundland (Paille et al., 2006; Locke and Hanson, unpub. ms.; C. McKenzie pers. comm.).

In 1989, green crab was found in San Francisco Bay, California, on the Pacific coast of the United States (Grosholz and Ruiz, 1996). It reached British Columbia in 1999, when there were two reports from southern Vancouver Island (Gillespie et al., 2007). By 2007, green crabs had established populations up the west side of Vancouver Island as far as Quatsino Sound (Winter Harbour) (Gillespie et al., 2007).

Potential Distribution in Canada

On the Atlantic coast, GARP model predictions show high environmental suitability throughout the southern Gulf of St. Lawrence, around the Atlantic coast of Nova Scotia (including around Cape Breton Island and the Bay of Fundy), and the southern shore of Newfoundland (Figure 12). Pockets of lower suitability exist around the northern Gulf of St. Lawrence (Figure 12). Based on reported temperature and salinity tolerances of adult green crab, the entire Atlantic coast could support green crab populations (Figure 13). However, based on reported temperature and salinity tolerances of larval green crab, much of the potential habitat is found around the southern Gulf of St. Lawrence, the Atlantic coast of Nova Scotia, the Bay of Fundy, and parts of southern Newfoundland (Figure 14).

On the Pacific coast, GARP model predictions show high environmental suitability along the west coast of Vancouver Island (including each of the major inlets), Queen Charlotte Sound and the Central Coast of British Columbia (Figure 15). Additionally, Puget Sound, WA (USA) also had high environmental suitability for green crab (Figure 15). Additional patches of high suitability exist around the Queen Charlotte Islands and the east coast of Vancouver Island (Figure 15). Both the model based on reported temperature and salinity tolerances of adult crabs and the model based on reported temperature and salinity tolerances of larval crabs showed virtually the entire coast of British Columbia is suitable (Figures 16 and 17).

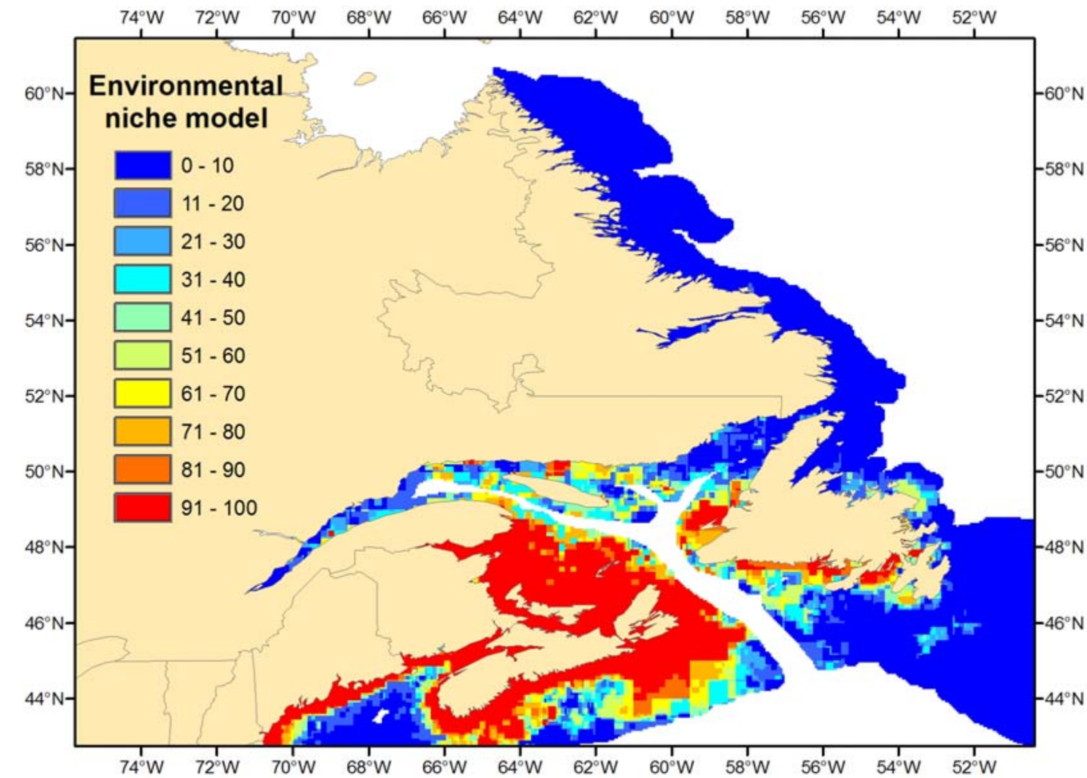

Figure 12: Potential distribution of green crab on the Atlantic coast based on GARP model predictions.

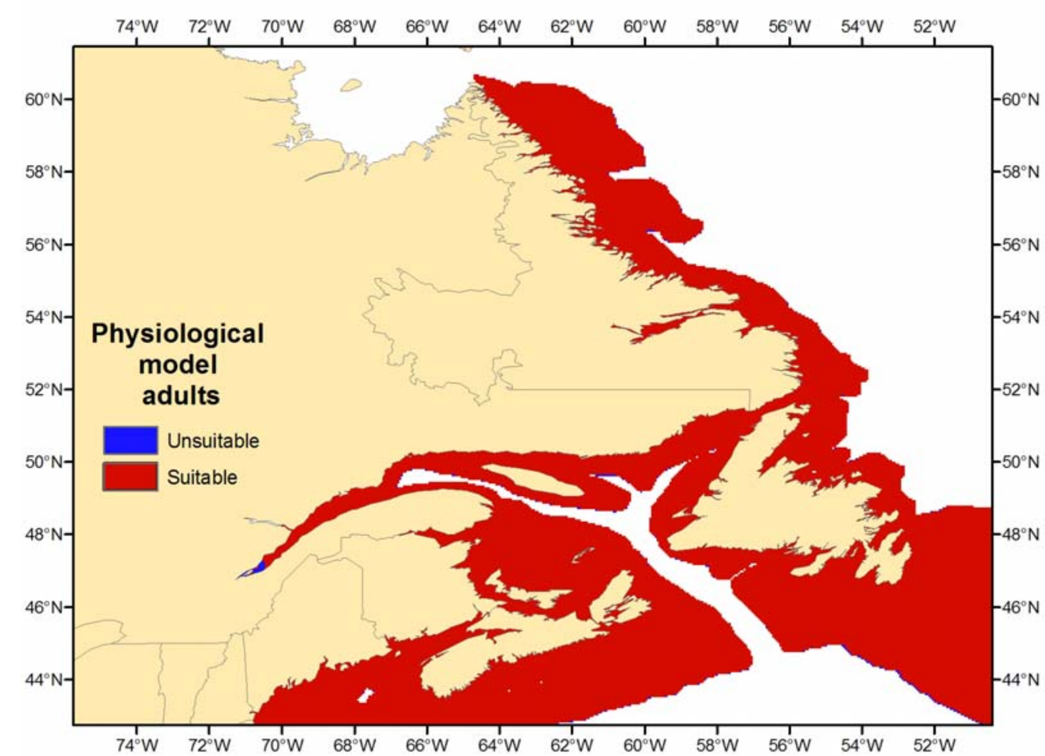

Figure 13: Potential distribution of green crab on the Atlantic coast based on reported adult tolerances for temperature and salinity.

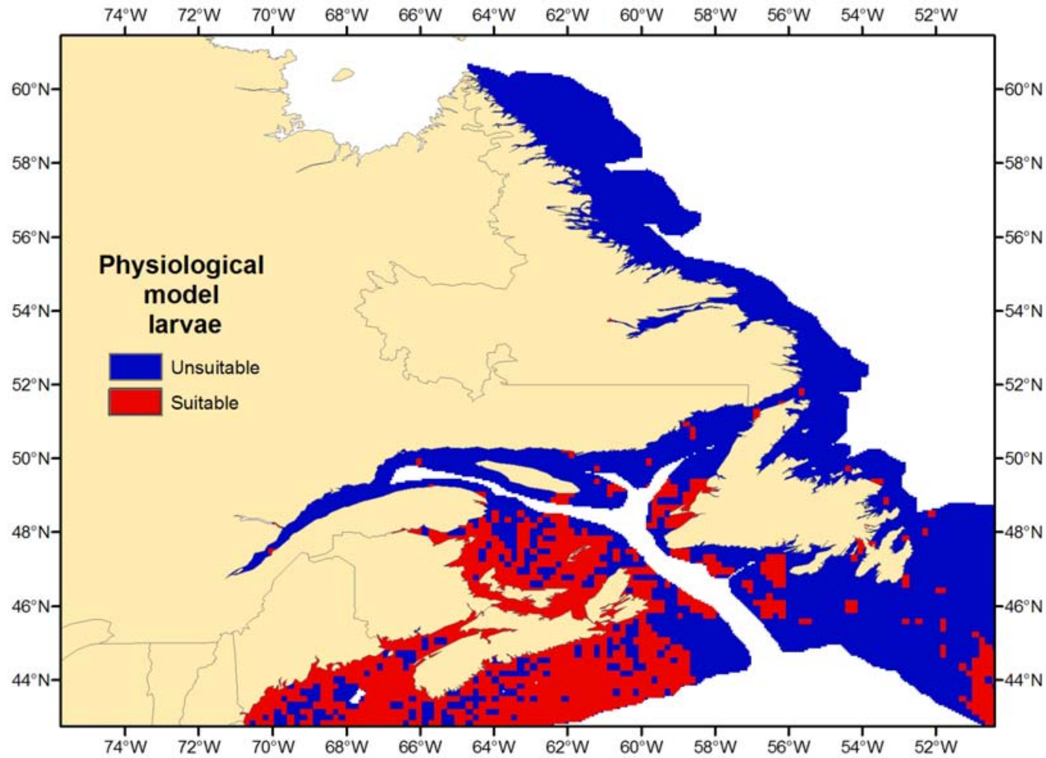

Figure 14: Potential distribution of green crab on the Atlantic coast based on reported larval tolerances for temperature and salinity.

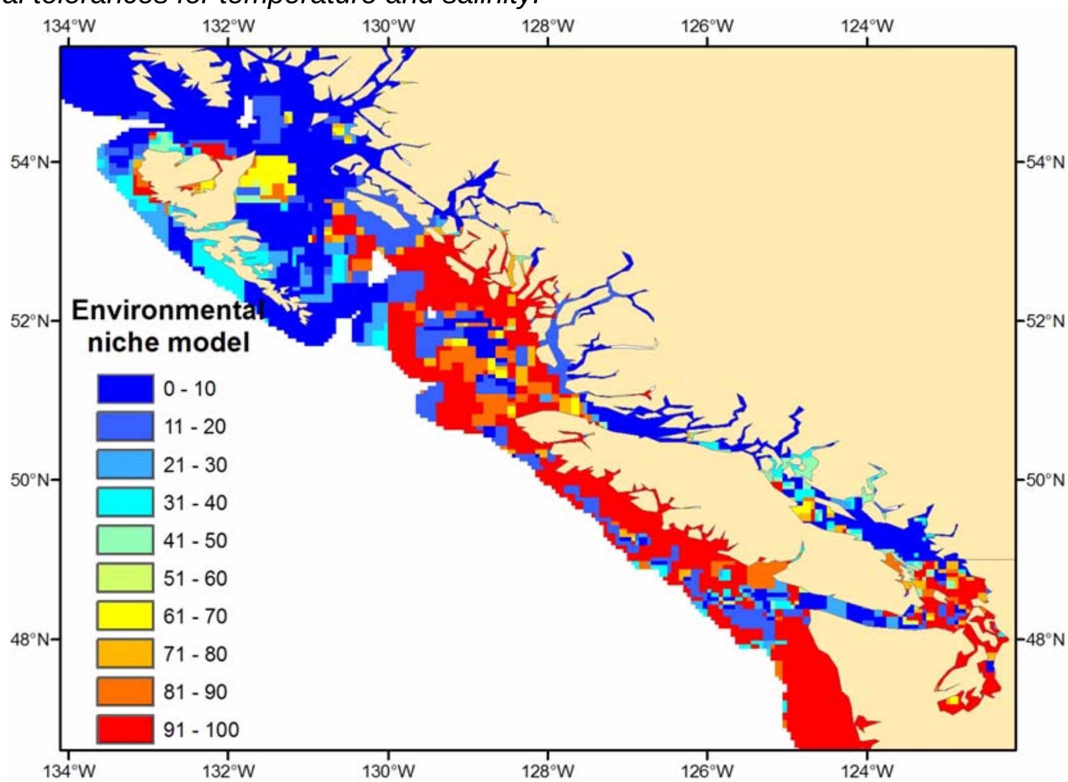

Figure 15: Potential distribution of green crab on the Pacific coast based on GARP model predictions.

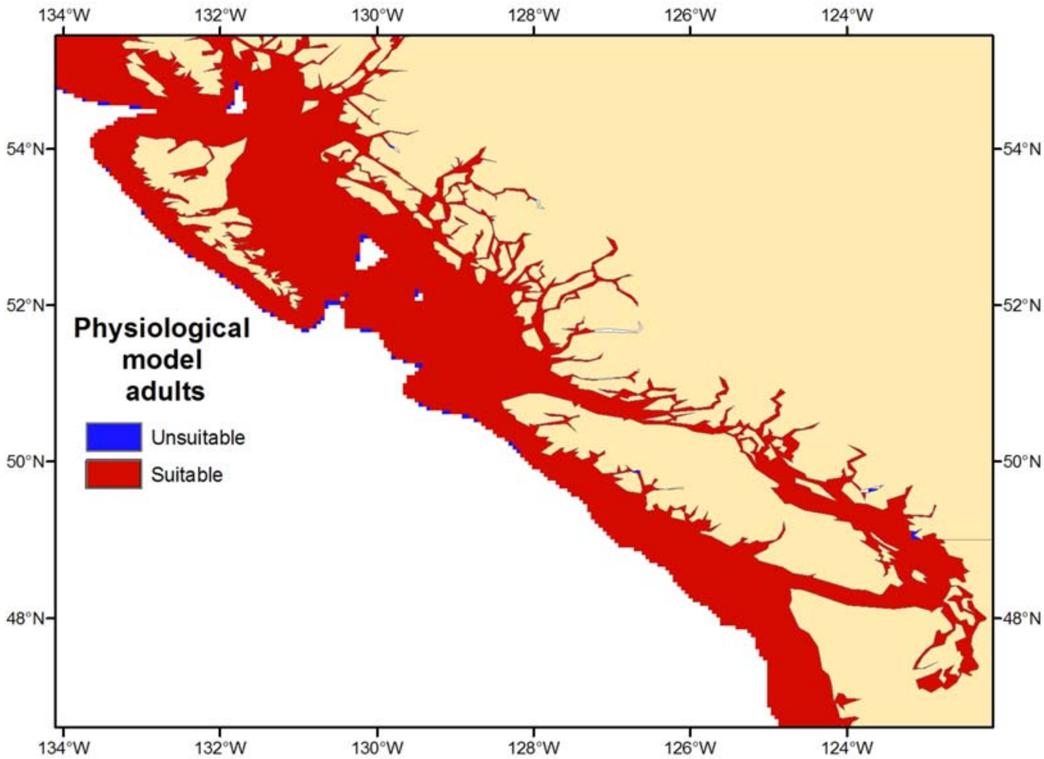

Figure 16: Potential distribution of green crab on the Pacific coast based on reported adult tolerances for temperature and salinity.

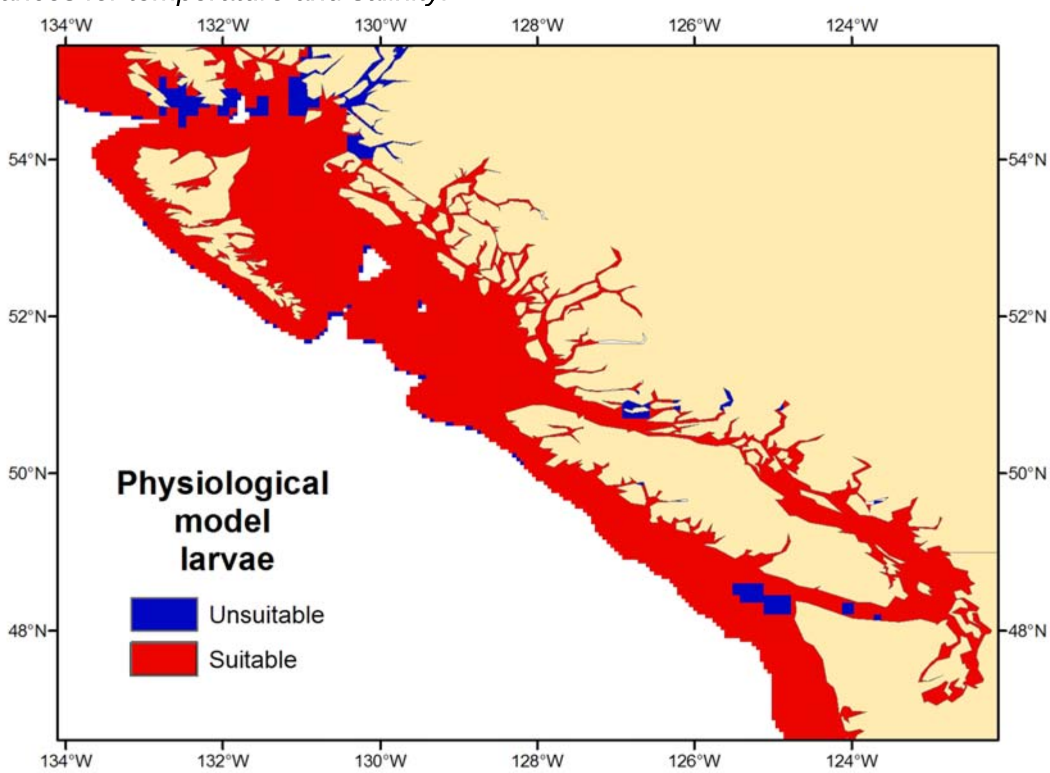

Figure 17: Potential distribution of green crab on the Pacific coast based on reported larval tolerances for temperature and salinity.

Potential Natural Dispersal

On the Atlantic coast under summer conditions, green crab larvae have the potential to disperse from locations where adults were found within a single season on oceanographic currents throughout the central Northumberland Strait, and away from bays around Prince Edward Island towards Nova Scotia (Figure 18). Summer conditions retain larvae within embayments along the Atlantic coast of Nova Scotia and in coastal areas adjacent to populations in Newfoundland and the Magdalen Islands.

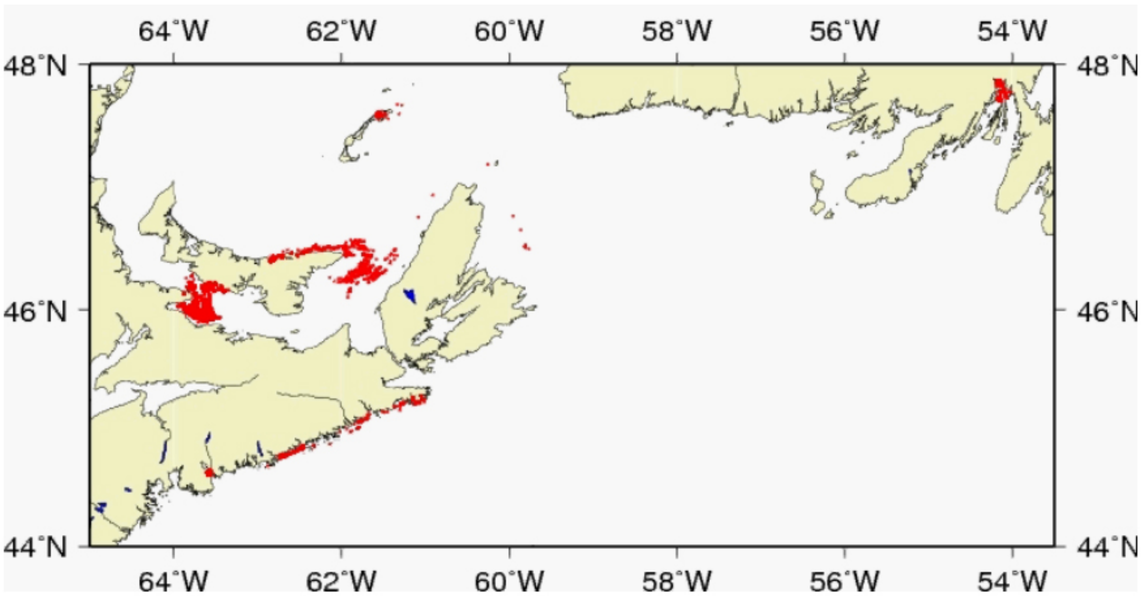

Figure 18: Potential natural dispersal of green crab larvae on the Atlantic coast based on summer oceanography and adult distribution in 2007.

In general, on the west coast under winter conditions, green crab larvae are dispersed further north. Based on the known Canadian distribution of green crab populations in British Columbia green crab could easily be transported to the central and northern coasts of British Columbia (Figure 19). Under winter El Nino conditions it appears the green crab larvae originating in British Columbia are transported further northward than under average conditions (Figure 19). However, a higher percentage of particles went offshore, rather than into Hecate Strait, and generally moved further up into the Alaskan Panhandle. Based on the known distribution of green crab populations along the west coast of the United States northward transport is possible under winter oceanographic conditions, including potential dispersal from Washington State into British Columbia (Figure 20). This provides evidence that the initial introduction of green crab into Pacific Canadian waters could have arisen due to larval dispersal from more southerly populations. In general, summer oceanographic conditions show southward particle movement (Figure 21). There are two major caveats for this type of modeling. First, these model conditions represent flows and paths for average seasonal ocean conditions. Second, storms and interannual variability could change these patterns, especially at smaller spatial scales.

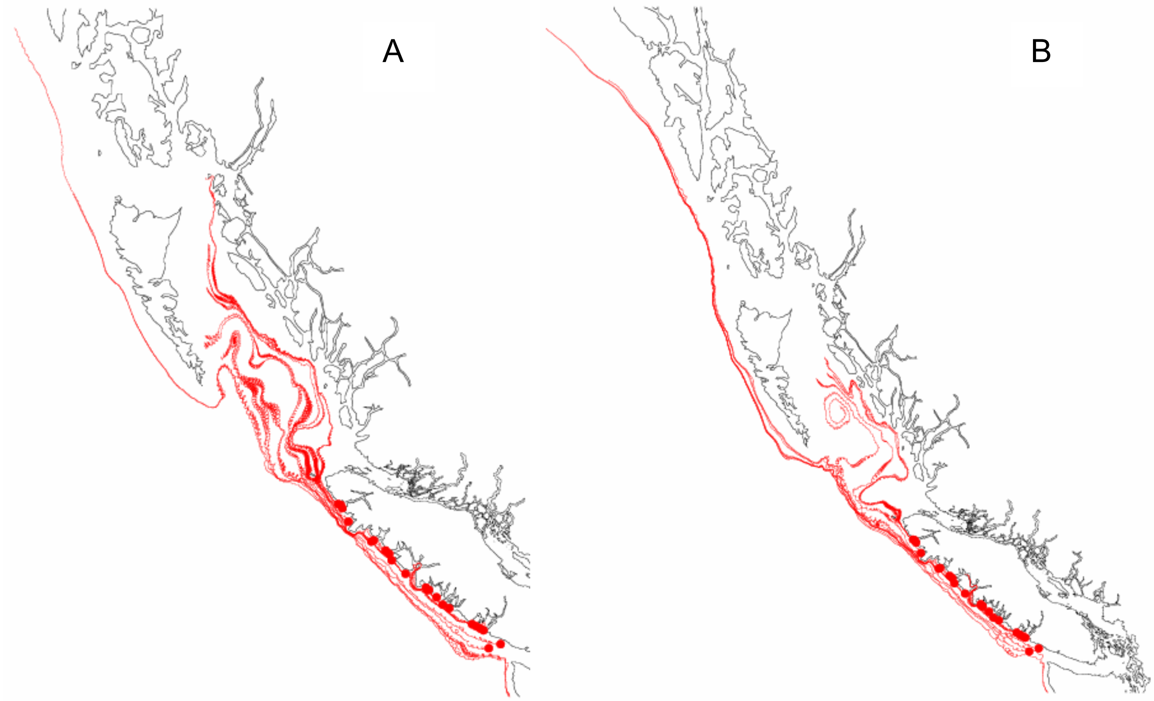

Figure 19: Potential natural dispersal of green crab larvae on the Pacific coast based on winter oceanography and the 2007 green crab distribution under A) average conditions and B) El Nino conditions.

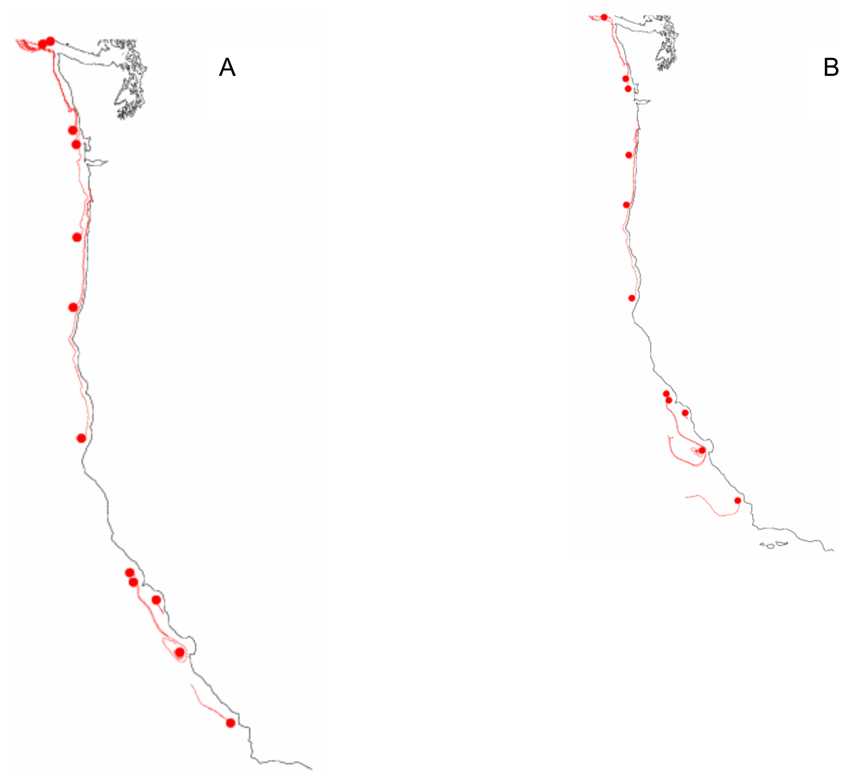

Figure 20: Potential natural dispersal of green crab larvae on the Pacific coast based on winter oceanography and the 2007 green crab distribution under A) average conditions and B) El Nino condition.

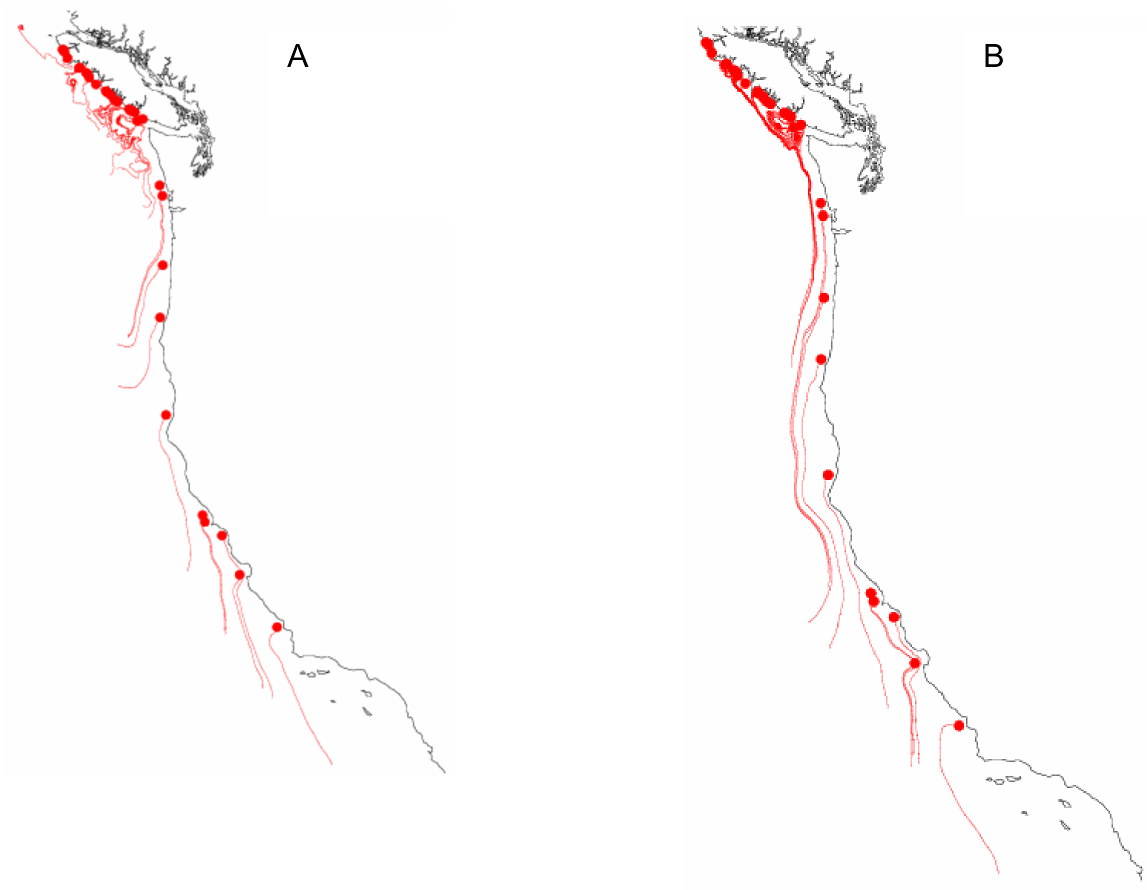

Figure 21: Potential natural dispersal of green crab larvae on the Pacific coast based on summer oceanography and the 2007 green crab distribution under A) average conditions and B) El Nino conditions.

Survey Results

The survey of crab and aquatic invasive species experts identified several potentially important vectors for the introduction of green crabs. In this discussion the category “other” is not included as the respondents did not always indicate how they defined it. Overall, ballast water was perceived by the surveyed experts to be the single most important vector for the initial establishment of green crabs (75% of respondents suggested that this vector was of high or very high importance for initial establishment) (Figure 22). This was followed by larval drift, aquaculture, and hull fouling with about 43, 29 and 24% of respondents respectively believing that these factors are of at least high importance to the initial establishment of green crabs. Other factors were largely (over 70% of all respondents) considered to be of low or very low importance. The uncertainty associated with the different vectors considered was fairly consistent among vectors. A considerable portion of the respondents indicated that there was a moderate uncertainty with respect to the various vectors considered (mean = 33%). Typically >40% of all experts surveyed had either a very low or low and <30% had a high or very high uncertainty for the importance attributed to each of the vectors considered.

In contrast, secondary dispersal was viewed to be largely related to spread via larval drift, with 83% of respondents suggesting that this mechanism was of high or very high importance for secondary spread (Figure 23). Transport via ballast water was still regarded as fairly important (35% of respondents believed this vector to be at least of high importance for secondary spread of green crabs). Transfers via aquaculture and directed adult migration also were considered to be of some importance to the secondary spread of this species as >26% of respondents believed these factors to be of at least high importance. Other factors were generally considered (as indicated by over 55% of all respondents) low or very low importance to secondary spread. An even greater proportion of respondents (mean = 39%) classified the vectors considered as moderate uncertainty with respect to the ratings they provided. The uncertainty of the experts surveyed with respect to each of the potential vectors was comparatively less consistent than with respect to initial establishment, with >40% of all experts surveyed having either a very low or low uncertainty for the importance of only four factors: larval drift, aquaculture, boating, and intentional release. The uncertainty for other factors was greater, especially with respect to the importance of directed movement by adults and fisheries activities, for which ≤25% of respondents indicated very low or low uncertainty, and fisheries-related activities, for which >40% of respondents indicated high or very high uncertainty.

These results are largely consistent with the available literature on the subject. The initial dispersal of green crab is usually linked to dispersal by commercial shipping (ballast and fouling/seachests) (Roman and Darling, 2007). Although a considerable number of respondents suggest that larval drift may be an important mechanism for initial establishment of green crabs, it is unclear how effective this mechanism would be over large spatial scales. The one possible exception is northward larval transport along the west coast of North America where green crab larvae from more southern populations could have been responsible for the establishment of populations in British Columbia (Gillespie et al., 2007). With respect to aquaculture, although this mechanism may be a historically important vector for initial establishment for exotic species in the past (McKindsey et al., 2007), current application of Introductions and Transfers regulations in North America would likely limit the introduction of green crab at this time. Most experts agreed that larval drift is a mechanism of high or very high importance to secondary spread and is consistent with the observations of a large number of eggs that can be produced (up to 185 000 eggs at a time) and the extended larval lifespan (>50 days). Ballast water and aquaculture also were considered to be mechanisms of importance, largely reflecting the observations of Cohen et al. (1995). Directed movement by adults was indicated by over one quarter of all respondents as being important to secondary spread although there is only limited direct evidence to support the notion that this species undertakes long-distance migrations. Interestingly, overall, a greater proportion of respondents had either low or very low uncertainty than high or very high uncertainty with respect to their opinions for the different potential dispersal mechanisms and this was true for both initial establishment and secondary spread.

We received 24 to 40 responses to the individual questions focusing on the potential impact of green crabs. The mean impact was estimated to be moderate on marine biodiversity, estuarine biodiversity, protected areas, shellfish aquaculture and fisheries, while the mean impact was considered as very low for freshwater biodiversity, recreational activities, flood/bank erosion, finfish aquaculture and fisheries (Figure 24). These expert opinions are supported by the literature on green crabs. Green crabs would not be expected to affect freshwater biodiversity as their effective lower salinity tolerance is approximately 10‰ (McGaw et al., 1999). In estuarine and marine habitats, they feed on a wide range of prey from at least five plant and protist and 14 animal phyla (Cohen et al., 1995), which would imply an effect on biodiversity. Indeed, unpublished data of Locke et al. indicate an adverse effect on the diversity of benthic invertebrates and

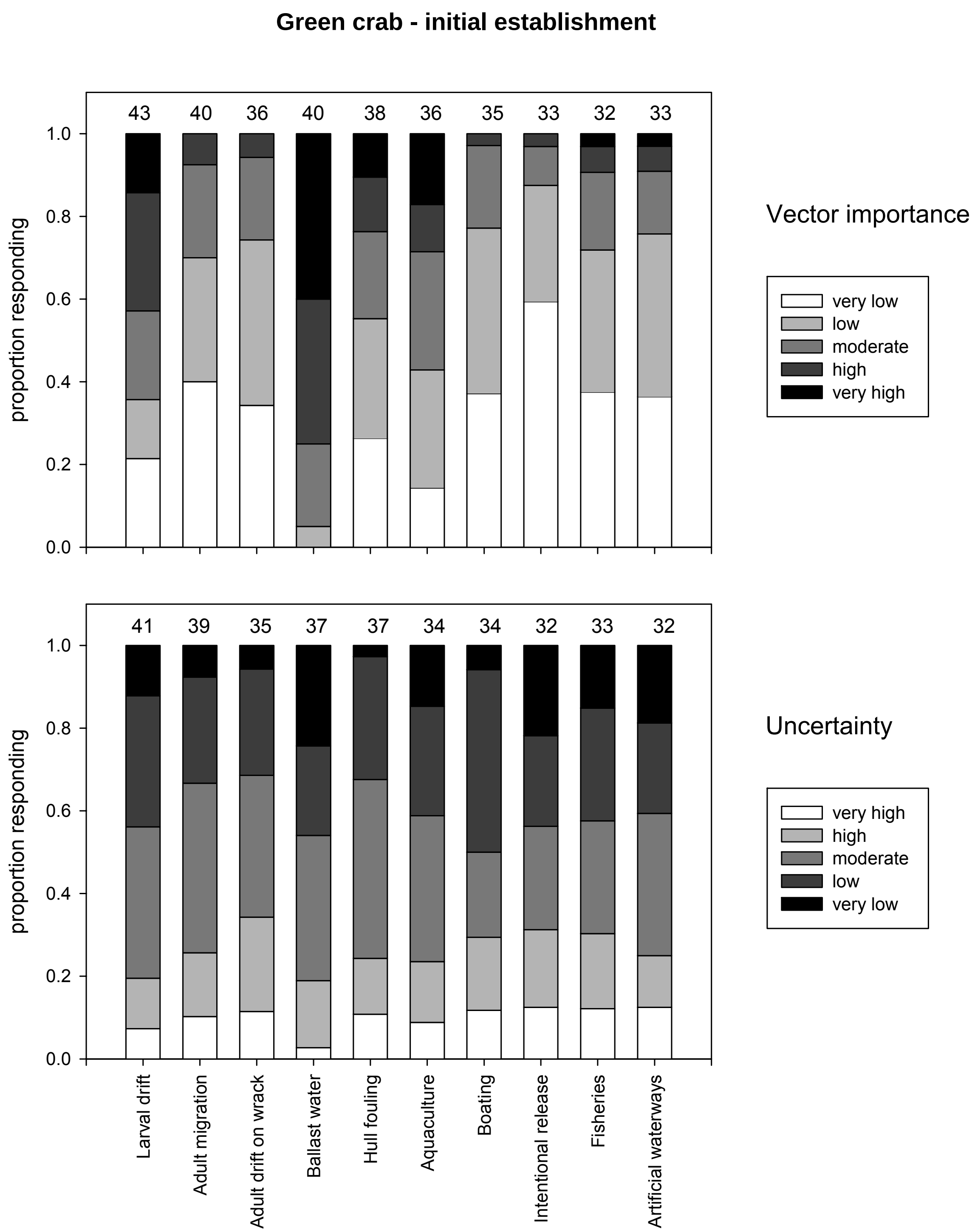

Figure 22: Relative vector importance and uncertainty for the initial establishment of European green crab as determined by experts via an online survey.

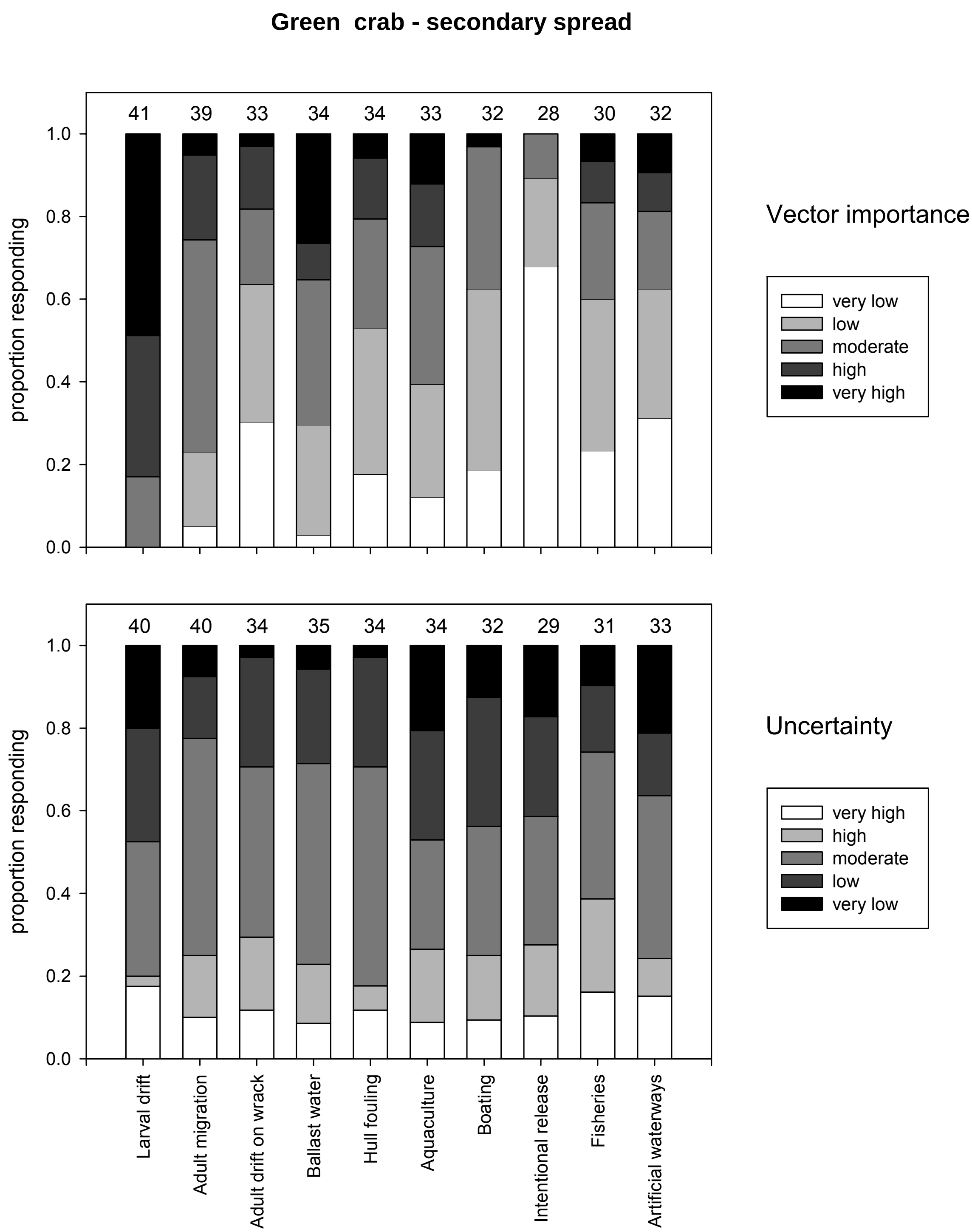

Figure 23: Relative vector importance and uncertainty for the secondary spread of European green crab as determined by experts via an online survey.

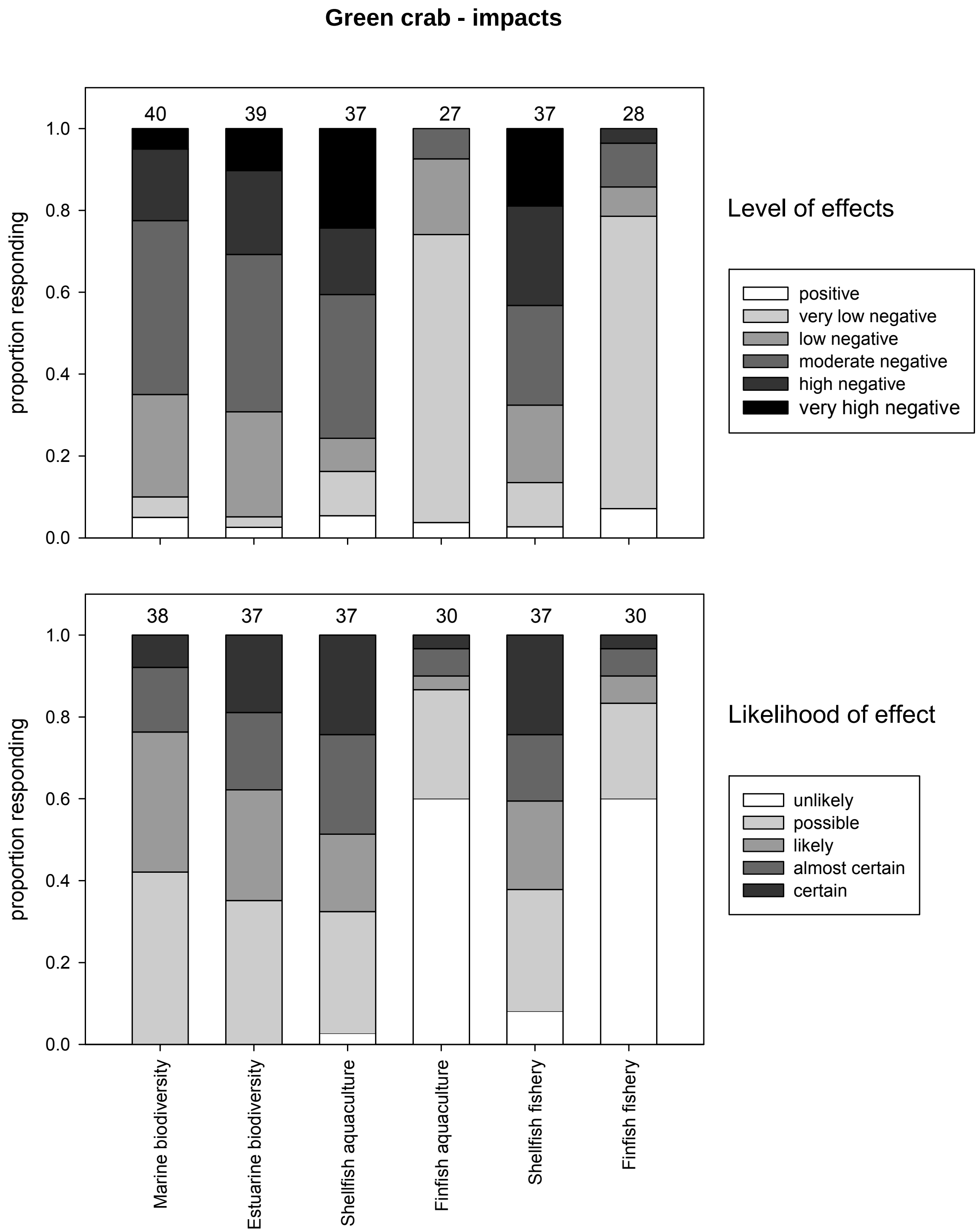

Figure 24: Potential impacts of European green crab introductions as determined by experts via an online survey that identified the level of impact and its likelihood.

nearshore fishes in Atlantic Canadian estuaries. Reductions in abundance of shellfish following the introduction of green crab have been widely reported (e.g., Ruiz et al., 1998; Walton and Walton, 2001; and other papers cited in Klassen and Locke, 2007). Evidence of direct effects on finfish aquaculture and fisheries is scarce, although green crab has adversely affected the fishery for American eel, *Anguilla rostrata*, in eastern Prince Edward Island through interference with trapping and injury or death of trapped eels (Locke, pers. obs.), and green crabs may prey on fish eggs and larvae (e.g., Ostlund-Nilsson, 2000; Taylor, 2005).

Risk Assessment Part I – Aquatic Organism Ecological and Genetic Risk Assessment Process for European Green Crab

Step 1: Determining the Probability of Establishment

(1) Estimate of probability of the organism successfully colonizing and maintaining a population if introduced.

The primary vector proposed for the introduction of green crab worldwide is commercial shipping, primarily larval transport in ballast water. Thus, the potential for new introductions to sites with high levels of ballast water discharge such as Vancouver and its associated ports and locations on the Atlantic coast like Point Tupper or Come by Chance (Figures 1 and 3) have an increased probability of new green crab arrivals. Natural dispersal from the initial introduction site via larval drift contributes to the spread of this species once established and on the Pacific coast, natural northward larval dispersal is the most probable vector for green crab populations in Pacific Canadian waters. Based on the larval dispersal modeling, green crab could be widely distributed throughout the Gulf of St. Lawrence on the east coast and into parts of central British Columbia on the west coast (Figures 18 to 21). In addition, considerable, potential suitable habitat exists on both coasts (Figures 12 to 17) suggesting further spread or additional introductions are likely.

Given that green crab has established populations on both the Atlantic and Pacific coasts, it is certain the species can arrive, survive and reproduce in Canadian waters.

(2) If the organism escapes from the area of introduction, estimate the probability of its spreading.

Given the presence of established populations on the Atlantic and Pacific coasts, suitable habitat and a variety of potential vectors (Figures 1, 3, 12 to 17), including natural larval drift (Figures 18 to 21), there is a very high probability that green crab could spread on both coasts. However, there are some geographical areas where uncertainty is slightly higher. For example, it is less clear if green crab will spread along the northern shore of the St. Lawrence River in Atlantic Canada or in the Strait of Georgia in Pacific Canada. Our uncertainty for spread is considered low given recent range expansion of European green crab on both the Atlantic and Pacific coasts. However, for areas such as the north shore of the St. Lawrence and the Strait of Georgia, additional monitoring or sampling effort could lower the uncertainty for spread to these specific areas. As suggested by the particle tracking models, much spread will be due to natural dispersal from established green crab populations.

(3) Final Rating: European green crab.

	Atlantic Coast		Pacific Coast	
Element	Rank	Uncertainty	Rank	Uncertainty
Arrival	Very High	Very Low	Very High	Very Low
Survival	Very High	Very Low	Very High	Very Low
Reproduction	Very High	Very Low	Very High	Very Low
Overall Establishment	**Very High**	**Very Low**	**Very High**	**Very Low**
Spread	Very High	Low	Very High	Low

Step 2: Determining the Consequences of Establishment of an Aquatic Organism

(1) Impacts on native ecosystems both locally and within each region.

Based on the results of its introduction throughout the world (Klassen and Locke, 2007) and input from our expert survey, there is little doubt that green crab could have significant negative impacts if introduced, including impacts on biodiversity and habitat structure, potentially altering foodweb and trophic structure of aquatic ecosystems by inducing changes in plant, invertebrate and possibly fish communities. Due to the predatory nature of this shore crab, intertidal invertebrates, primarily bivalves and gastropods, are the primary prey species. Thus, the most severe impacts are expected on shellfish aquaculture and fishery species such as clams and oysters where the survey identified high negative impacts (Figure 24) which is consistent with the literature. On the Pacific coast, especially the east coast of Vancouver Island that has a lot of intertidal shellfish aquaculture, the impacts of a green crab introduction could be very high. It is also probable that introduced green crab could encounter SARA or COSEWIC listed species and impacts on these species could be higher due to the sensitivity associated with these species. For example, on the west coast green crab would be direct predators on Olympia oyster (*Ostrea conchaphila*) and could be predators on some stickleback pairs (*Gasterosteus* sp.). It is also probable that green crab could represent potential prey for Great blue heron (*Ardea herodias fannini*) and green and white sturgeon (*Acipenser medirostris* and *A. transmontanus*, respectively). Impacts on other endpoints are generally considered moderate to low (Figure 24) with the exception of potential habitat impacts that could be high. For example, green crab activities, especially digging in soft sediment, may displace rooted macrophytes such as eelgrass and alter benthic habitats through their environmental engineering activities. As with other crustacean species, green crab is known to act as a vector (primary or secondary host) for a variety of pathogens and epibionts. Thus, green crab could have a low negative impact on wildlife health. There are no other *Carcinus* species in Canada so the genetic consequence of green crab introductions is considered very low.

(2) Final Rating: European green crab.

	Survey/Literature Results		Peer-review Results	
Element	Magnitude	Likelihood	Magnitude	Uncertainty
Biodiversity Consequences				
Marine	Moderate	Likely	High	Low
Estuarine	Moderate	Likely	High	Low
Shellfish Aquaculture	Moderate	Likely	Very High	Moderate
Finfish Aquaculture	Very Low	Unlikely	Very Low	Very Low
Shellfish Fishery	Moderate	Likely	Very High	Moderate
Finfish Fishery	Very Low	Unlikely	Low	Moderate
Wildlife Health Consequences	Low	Possible	Low	Moderate
Habitat Consequences	High	Likely	High	Low
Genetic Consequences	Very Low	Unlikely	Very Low	Low

Step 3: Summary of the Aquatic Organism Overall Risk Potential for European green crab.

	Atlantic Coast		Pacific Coast	
Element	Rating	Uncertainty	Rating	Uncertainty
Biodiversity Consequences				
Marine	High	Low	High	Low
Estuarine	High	Low	High	Low
Shellfish Aquaculture	High	Moderate	High	Moderate
Finfish Aquaculture	Moderate	Very Low	Moderate	Very Low
Shellfish Fishery	High	Moderate	High	Moderate
Finfish Fishery	Moderate	Moderate	Moderate	Moderate
Wildlife Health Consequences	Moderate	Moderate	Moderate	Moderate
Habitat Consequences	High	Low	High	Low
Genetic Consequences	Moderate	Low	Moderate	Low

Risk Assessment Part II – Pathogen, Parasite or Fellow Traveler Risk Assessment Process for European Green Crab

Step 1: Determining the Probability of Establishment

(1) Estimate the probability that a pathogen, parasite or fellow traveler may be introduced along with the potential invasive species.

Green crabs from Atlantic Canada lacked most of the parasites and symbionts associated with green crabs in Europe (Brattey et al., 1985). Even so, *Polymorphus* sp. (Acanthocephala) and *Microphallus* sp. (Platyhelminthes, Digenea) parasitized green crab ten times more frequently (prevalence) than native crabs (Brattey et al., 1985). This high prevalence in green crab, the intermediate host, could result in high rates of transmission to seabirds, the definitive host. For example, in the Dutch Wadden Sea, mass mortalities of common eider ducks partially were attributed to *Polymorphus botulis* transmitted by green crab (Camphuysen et al., 2002). However, given that ballast water transfer was the most probable vector for introduction, at least recently, the larval stages that are transported by this vector are relatively free of pathogens, parasites, or fellow travelers. Also, at least one green crab parasite appears to have transferred to a native decapod in eastern North America, the blue crab *Callinectes sapidus* (Newman and Johnson, 1975).

(2) Estimate the probability that the pathogen, parasite or fellow traveler will encounter susceptible organisms or suitable habitat.

In their native range, green crabs are known to possess a number of parasites and symbionts (Brattey et al., 1985). It is unknown how many times green crabs have been introduced to Canadian waters but genetic analyses have identified at least two separate introductions (Roman, 2006). If all introductions were via ballast water then it is not surprising that few parasites or symbionts would have been introduced at the same time. However, if some introductions were via adult transfer then at least some parasites or symbionts should have been introduced as well. Thus, at this time it is not possible to determine if European green crab parasites, pathogens or fellow travelers had difficulty encountering susceptible organisms or suitable habitat. It is probable that symbionts should encounter suitable hosts/habitats as these are generally less species-specific than parasites or pathogens.

(3) Final Rating: pathogen, parasite or fellow traveler of European green crab.

	Atlantic Coast		Pacific Coast	
Element	Rank	Uncertainty	Rank	Uncertainty
Arrival	Low	High	Low	High
Survival	Moderate	High	Moderate	High
Reproduction	Moderate	High	Moderate	High
Overall Establishment	**Low**	**High**	**Low**	**High**
Spread	Moderate	Very High	Moderate	Very High

Step 2: Determining the Consequences of Establishment of a Pathogen, Parasite or Fellow Traveler

(1) Impacts on native ecosystems both locally and within the region including disease outbreak, reduction in reproductive capacity, habitat changes, etc.

Two of the three potential parasites carried by green crab could have negative impacts on seabird or water foul populations. If these parasites were transmitted there could be moderate negative impacts on wildlife health. However, uncertainty is very high. Little is known about the parasite reportedly transmitted to blue crab and there is very little information about parasites, pathogens and fellow travelers of green crab. Thus, the potential impacts of hitchhiker organisms should be considered low but uncertainty is very high.

(2) Final Rating: pathogen, parasite or fellow traveler of European green crab.

	Literature Results		Peer-review Results	
	Magnitude	Uncertainty	Magnitude	Uncertainty
Overall Consequences	Low	Very High	Low	High

Step 3: Summary of the Pathogen, Parasite or Fellow Traveler Overall Risk Potential for European green crab.

	Atlantic Coast		Pacific Coast	
	Rating	Uncertainty	Rating	Uncertainty
Overall Risk	Low	Very High	Low	High

CONCLUSIONS

European green crab poses a variety of risks to Canadian waters. This species is already present on both coasts of Canada and environmental models show that the distribution should be expected to increase. Overall, the highest risk posed by green crab on both the Atlantic and Pacific coasts is related to biodiversity and habitat consequences. This species generally poses moderate risk to wildlife health and genetic consequences. The uncertainties about these risks were generally low to moderate.

Relatively little is known about pathogens, parasites or fellow travelers associated with European green crab. For both the Atlantic and Pacific coasts the overall risk posed by pathogens, parasites or fellow travelers is considered low but the uncertainty about this ranking is high to very high due to the paucity of available data. Also, there appears to be an inverse relationship between the level of risk and its associated uncertainty when it comes to pathogens, parasites or fellow travelers of non-indigenous green crab, due largely to limited data. These fellow organisms have not been well studied thereby increasing the uncertainty of arrival, survival, reproduction, spread and potential impacts if introduced.

Although European green crab is extensively studied in its native range there have been relatively few studies from its invaded range that have attempted to characterize the potential suite of pathogens, parasites or fellow travelers. Also there is an important data gap with respect to knowledge about larval dynamics and how this contributes to larval dispersal, including the contribution to maintenance of populations or by providing an opportunity to exploit new environments. The European green crab has used larval dispersal to invade Pacific Canadian waters and this vector has contributed to the spread of this species in Atlantic Canada.

European green crab has established populations on both the Atlantic and Pacific coasts. Recent genetic analyses have shown that the initial green crab populations along the Atlantic coast of Nova Scotia south of Halifax and the more recently established populations along the west coast of North America represent a common genotype while the more recent populations of green crab in the southern Gulf of St. Lawrence represent a second genotype, assumed to be more cold water tolerant which was introduced in the late 20th century (Roman, 2006). The larval work conducted on green crab thus far have used the initial genotype in their studies (DeRivera et al., 2007) but the purportedly "new" genotype has not been evaluated. Thus, the temperature and salinity tolerances of this genotype could be different and has serious implications for the potential distribution of this crab, especially in Atlantic Canada where it appears the initial introduced genotype had reached its maximum dispersal potential. The "new" genotype also has been spreading south into the range previously invaded by the initial genotype (J. Roman, pers. comm.), which may exacerbate impacts already experienced in those areas, especially if reduced overwintering mortality enhances green crab population abundance.

Commercial shipping, primarily ballast water, was identified as the most important vector for the initial introduction of European green crab. Commercial shipping data was available for a variety of vessel classes for the Pacific coast but no comparable data was available for the Atlantic coast. Given the large number of potential source populations for European green crab in Europe, increased resolution of shipping data would allow refinement of potential areas of new introductions based on transit locations and potential areas of ballast water discharge. Also, there was very limited riverine or estuarine data available for much of Canada. Most monitoring programs are conducted offshore in the marine environment away from estuaries. Increased monitoring of conditions in estuaries should be a priority to refine invasion predictions and better characterize the risk of this non-indigenous crab species.

Monitoring efforts for aquatic invasive species likely need to be broadened, especially to include mobile fauna such as the crab species assessed here. Recent monitoring efforts in Atlantic Canada have focused on biofouling species such as non-indigenous tunicate species while relatively little effort has been directed to crab species. Trapping for green crab has been an integral component of intertidal aquatic invasive species monitoring in Pacific Canada and the methodology would be easily transferable. Further, there is an increased need to increase stakeholder participation in monitoring programs for invasive species. For example, the shellfish aquaculture industry has been engaged in recent years to deal with non-indigenous tunicate species. Raising awareness with these stakeholders (and others) will increase our understanding of potential invasions and may allow the implementation of management measures.

The risk assessment for European green crab presented here represents a starting point. It is meant to provide scientific advice for decision makers, managers and policy makers who have to manage, control or mitigate the potential impact of these non-indigenous species. The scientific advice contained in this document is meant to inform the overall risk analysis framework that includes socio-economic considerations and should not be considered independent of this framework. The overall risk analysis framework for the Canadian Department of Fisheries and Oceans is currently under development. Also, the information contained within this document, and ancillary accompanying documents, may need to be re-visited as more information is gained and identified data gaps filled. For example, the predictions of environmental suitability for green crab were based on current distributions, therefore highlighting areas having the same environmental conditions as those the species has already been found in. One potential limitation to this approach is that it could underestimate the potential habitat available if the current invaded range is not fully representative of its potential range. As the species spreads to new areas it is possible the predicted suitable environments also will increase as the true environmental niche becomes more apparent.

The risk assessment presented here focused on the risk posed to either the Canadian Atlantic or Pacific region. If one wanted to look at the risk posed within a region, each province within the Atlantic region for example, an additional risk assessment should be undertaken. Although we used the best available data for the ecological niche modeling, it was at a larger spatial scale (i.e., Pacific Ocean, Atlantic Ocean). Further, additional smaller-scale data could be available that might better identify micro-scale habitats. For example, on the Pacific coast the risk posed to the Strait of Georgia by European green crab was not explicitly considered. The larval drift models suggested natural drift to this area was unlikely, but suitable habitat was identified both in the simple environmental models and the GARP environmental niche model. Thus, limiting the potential arrival of green crab to this area via human-mediated transport vectors should be a priority.

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APPENDIX A:
Participants at the National Peer-review Workshop for the Risk Assessment of Two Crab Species in Both Atlantic and Pacific Canadian Waters

Participant	Organization
Thomas Therriault	DFO – Pacific Region (PBS)
Leif-Matthias Herborg	DFO – Pacific Region (PBS)
Andrea Locke	DFO – Gulf Region (GFC)
Christopher McKindsey	DFO – Quebec Region (IML)
Ted Grosholtz	University of California – Davis (Reviewer)
Deborah Rudnick	Integral Corporation (Reviewer)
Graham Gillespie	DFO – Pacific Region (PBS) (Reviewer)
Joe Roman	University of Vermont (Reviewer)
Marcel Bernard	Quebec Government (MRNF)
Yves de Lafontaine	Environment Canada
David Delaney	McGill University
Trevor Floyd	DFO – NCR
Tonya Furlong	DFO – NCR
Saba Khwaja	DFO – NCR
Julie Lavallee	DFO – Quebec Region
Brian Leung	McGill University
Cynthia McKenzie	DFO – Newfoundland Region (NWAFC)
Mikio Moriyasu	DFO – Gulf Region (GFC)
Darlene Smith	DFO – NCR
Melisa Wong	DFO – Maritimes Region (BIO)
Brian Bickford	Translator

APPENDIX B:
Definitions for Vector and Impact Questions used in the Expert Survey

Vector Importance

Very low: European green crabs have not been demonstrated or believed to utilize this vector. Does not require management action.

Low: European green crabs are unlikely to spread by this vector. May require efforts to minimize spread.

Moderate: European green crabs can spread by this vector in favorable circumstances. Management could provide a reduction of spread.

High: European green crabs have extensively used this vector. Management would be important for a reduction of spread, but none has been attempted.

Very high: European green crabs have extensively used this vector despite extensive management efforts.

Vector Uncertainty Levels

Very high uncertainty: Little to no information; expert opinion based on general species knowledge.

High uncertainty: Limited information; third party observational information or circumstantial evidence.

Moderate uncertainty: Moderate level of information; first hand, unsystematic observations.

Low uncertainty: Substantial scientific information; non peer-reviewed information.

Very low uncertainty: Extensive scientific information; peer-reviewed information.

Impact Level

Positive A positive impact. Improvement of the factor in question.

Very low negative No measurable impact. Consequences can be absorbed without additional management action.

Low negative A measurable limited impact. Disruption to the factor in question, but reversible or limited in time, space, or severity. May require management effort to minimize.

Moderate negative A measurable widespread impact. A widespread disruption to the factor in question, but reversible, or of limited severity, or duration. Can be managed under normal circumstances.

High negative A significant impact. A widespread disruption to the factor in question that persists over time, or is likely not reversible. Will require effective management or adaptation of procedures.

Very high negative A critical impact. Extensive disruption to the factor in question, that is irreversible. May already be unmanageable or will become so unless effective management is immediately put in place.

Estimated Probability if Impact

Unlikely Impact will only occur in exceptions or is not expected

Possible Impact could occur in some circumstances

Likely Impact will probably occur in most circumstances

Almost certain Impact is expected to occur in most circumstances

Certain Impact has been observed to occur