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Risk Assessment of the Bloody Red Shrimp (*Hemimysis anomala*) in Canada

Évaluation du risque posé par la crevette rouge sang (*Hemimysis anomala*) au Canada

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ABSTRACT

The bloody red shrimp (*Hemimysis anomala*) is the latest non-native species to be discovered in the Great Lakes. *Hemimysis* was first identified in the Great Lakes in 2006, though anecdotal evidence suggests it has been present since 2002. A concerted sampling effort in 2007 identified 15 additional sites around lakes Michigan, Erie and Ontario with confirmed presence of *Hemimysis*. Significant food web impacts have been observed in European ecosystems invaded by *Hemimysis*. Here we present the results of an ecological risk assessment conducted to evaluate the risk from *Hemimysis* in Canada. This risk assessment was focused on two geographic areas of Canada; the Great Lakes where *Hemimysis* has been discovered and inland lakes as previous invertebrate invaders in the Great Lakes have been secondarily transported from the Great Lakes to inland lakes. This assessment concluded that the risk to the Great Lakes was moderate to high, and the risk to inland lakes was also moderate to high due to the high chance that *Hemimysis* will be unintentionally moved from the Great Lakes to inland lakes.

RÉSUMÉ

La crevette rouge sang (*Hemimysis anomala*) est la plus récente espèce exotique découverte dans les Grands Lacs. *Hemimysis* a été identifiée dans les Grands Lacs en 2006 bien que sa présence ait été suggérée depuis 2002. En 2007, une campagne d'échantillonnage concertée a permis d'identifier 15 sites d'occurrence dans les lacs Michigan, Érié et Ontario. En Europe, des effets significatifs associés à l'invasion de *Hemimysis* ont été observés sur les réseaux trophiques. Ce document présente les résultats d'une analyse de risques posés par *Hemimysis* au Canada. L'analyse de risque est basée sur deux régions du Canada : Les Grands Lacs où *Hemimysis* a été découverte, et les lacs intérieurs susceptibles d'être envahis par transport en provenance des Grands Lacs. Cette évaluation conclue que le risque pour les Grands Lacs est modéré à haut et le risque pour les lacs intérieurs est aussi modéré à haut à cause de la forte probabilité d'une introduction non intentionnelle en provenance des Grands Lacs.

INTRODUCTION

Aquatic invasive species (AIS) are a growing problem estimated to cost the economy billions of dollars a year (Colautti *et al.* 2006), have been identified as one of the lead threats to native biodiversity (Sala *et al.* 2000) and species at risk (Dextrase and Mandrak 2005), and have potentially wide ranging indirect impacts on ecosystems through effects such as trophic disruption (Shuter and Mason 2001). The Great Lakes are known to have been invaded by at least 182 non-native species (Ricciardi 2006). While not all these species have had impacts on the ecology or economy of the Great Lakes, some have had significant impacts (e.g., zebra mussels). In addition, some AIS (e.g., *Bythotrephes longimanus*; MacIsaac *et al.* 2004) that initially invaded the Great Lakes have secondarily invaded inland lakes with subsequent impacts to these ecosystems (e.g., Compton and Kerfoot 2004, Yan and Pawson 1997, 1998). The bloody red shrimp (*Hemimysis anomala*) was identified as a species that would potentially be introduced to the Great Lakes with possible significant impacts (Ricciardi and Rasmussen 1998), and is the latest non-native species to be discovered in the Great Lakes (Pothoven *et al.* 2007).

The purpose of a risk assessment is to use the best available scientific knowledge (factual information and scientific theory) to provide technical support for decision making under uncertainty (Suter 2007). The purpose of an ecological risk assessment is to assess risk to non-human organisms, populations, and ecosystems. While AIS are associated with potential social and economic impacts, which can be included in risk assessments, the risk assessments conducted as science advice within Fisheries and Oceans Canada (DFO) do not include socio-economic impacts (e.g., Mandrak and Cudmore 2004, Cudmore and Mandrak 2005), instead focussing on the potential ecological risks of AIS.

Here we present an ecological risk assessment of the bloody red shrimp (*Hemimysis anomala*) in Canada. The available biological information on the bloody red shrimp (hereafter referred to as *Hemimysis*) has been compiled by Marty (2008). This document presents the parameter estimation, results of the risk assessment, and uses the risk assessment to identify important knowledge gaps.

METHODS

We used the Quantitative Biological Risk Assessment Tool (QBRAT), developed by Fisheries and Oceans Canada (Moore *et al.* 2007), to organize and frame the risk assessment of *Hemimysis*. The QBRAT framework models invasion as a four step process: arrival, survival, establishment and spread. Represented as an event tree (Fig. 1), the invasion process has four event nodes and five end points. Each event node is associated with a probability of occurrence, and each end point is associated with a potential impact. The four probabilities are p1 the probability of arrival, p2 the probability of survival, p3 the probability of establishing a self-reproducing population, and p4 the probability of spreading. The five potential impacts are I1 the impact if the AIS does not arrive, I2 the impact if the AIS arrives but cannot survive in the receiver ecosystem, I3 the impact if the AIS arrives, can survive, but cannot establish a reproductive population, I4 the impact from a locally established population, and I5 the impact from a widespread invasion.

The Quantitative Biological Risk Assessment Tool requires users to estimate each of the four probabilities and five impacts plus estimates of the uncertainty associated with each estimate. Probabilities are expressed on a zero to one scale. Impacts can be expressed as either continuous or categorical impacts. QBRAT can handle continuous impacts ranging from -10^{100} to $+10^{100}$, or up to five categorical impacts. All impacts must be of the same form (either continuous or categorical). Uncertainties can be expressed as either relative or absolute uncertainties. Relative uncertainties are defined as ± x%. Absolute uncertainties are expressed as standard deviations and can be described with one of the following: a uniform, normal, lognormal, or beta (for probabilities only) distribution. When impacts are expressed categorically, uncertainties are not expressed with a distribution, but instead the user expresses the probability of each impact category for each potential impact (end point on the event tree).

For this risk assessment, categorical impacts will be defined on a scale of 1 to 5: negligible, low, moderate, high or extreme impacts (Table 1). A relative uncertainty (Table 2) will be associated with each probability. QBRAT then uses the distribution of values described by these uncertainties to run Monte Carlo simulations. Each simulation run randomly draws a parameter value from the uncertainty distributions and calculates the risk; this is repeated 5000 times. The results provide an integrated estimate of risk and uncertainty. Sensitivity analyses on the Monte Carlo simulation results identify the parameters that have the strongest influence on the estimation of risk. Results of the sensitivity analyses in association with the parameter uncertainties are used to identify the key uncertainties and knowledge gaps.

Table 1. Impact categories and descriptions.

Impact Category		Description
1.	Negligible	Undetectable change in the structure or function of the ecosystem. No management action required.
2.	Low	Minimally detectable change in the structure of the ecosystem, but small enough that it would not change the functional relationships or survival of species. Unlikely to affect management of the ecosystem.
3.	Moderate	Detectable change in the structure or function of the ecosystem that would require consideration in the management of the ecosystem.
4.	High	Significant changes to the structure or function of the ecosystem leading to changes in the abundance of native species and a need for management to adapt to the new food web. May have implications beyond the extraction or use of ecosystem resources.
5.	Extreme	Impacts that restructure the ecosystem resulting in, for example, the extirpation or extinction of at least one species and the need for significant modification of the management of the ecosystem. Will probably have implications beyond the extraction or use of ecosystem resources.

Table 2. Relative uncertainty categories.

Level	Uncertainty Category
± 10%	Very high certainty (e.g., extensive, peer-reviewed information)
± 30%	High certainty
± 50%	Moderate certainty
± 70%	Low certainty
± 90%	Very low certainty (e.g., little to no information; expert opinion)

RESULTS

ARRIVAL

There are a number of pathways through which *Hemimysis* could potentially have been introduced to the Great Lakes. These include the aquarium trade, intentional introductions, boat bilge water, and ballast water. Live mysids have been observed in the import trade and in pet stores (B. Cudmore, DFO, unpubl. data). *Hemimysis* is too small to be desired as an aquarium species on its own. While it is a lipid rich organism that could be a good food source for aquarium fishes, *Hemimysis* is not known to be in the import or aquarium trade.

Hemimysis was intentionally introduced into a number of ecosystems of the former Soviet Union for the purpose of enhancing fish production. However, nearshore fish production is not currently identified as a concern within the Great Lakes (see the Great Lakes Fishery Commission research priorities) and no agencies are known to be introducing species to the Great Lakes for the purposes of enhancing fish production.

Hemimysis has invaded lakes in the English Midlands (Holdich *et al.* 2006). While the pathway is unknown for this invasion, one of the sites hosts international rowing competitions, and it is considered a possibility that the pathway of introduction was in the bilge water of boats transported between waterbodies. This is unlikely to be the trans-oceanic pathway of invasion, though it could be a pathway for secondary transport within the Great Lakes or to inland lakes.

Hemimysis is thought to have been introduced into the Great Lakes from the Ponto-Caspian region through ballast water (Kipp and Ricciardi 2007, Ricciardi 2007). Live mysids (a marine species, not *Hemimysis*) have been sampled from the ballast tanks of trans-oceanic ships (S. Bailey, DFO, unpubl. data). *Hemimysis* is a euryhaline organism, originally known as an estuarine or marine species (Marty 2008), and can be expected to be tolerant of the salinities found in ballast tanks.

SURVIVAL

The collection of *Hemimysis* from numerous locations around the Great Lakes suggests that it has been present in the Great Lakes for a number of years. Anecdotal evidence suggests that *Hemimysis* may have been present at the Oswego (Lake Ontario) site as early as 2002, and it was collected from the Muskegon Canal (Lake Michigan) in both

2006 and 2007. Persistence across multiple years at sites suggests that *Hemimysis* can survive in the Great Lakes.

While little is known of temperature tolerances, *Hemimysis* has been sampled from locations with temperatures as low as 2°C, suggesting that they can survive winter water temperatures in Canada. However, while they are found at these temperatures, how long they can survive low temperatures is unknown, and substantial mortality may be incurred by low winter temperatures (Dumont 2006). In Europe, *Hemimysis* has invaded locations as far north as the northern Baltic Sea, suggesting that *Hemimysis* will be able to survive at least in southern Canada.

ESTABLISHMENT

Anecdotal reports that *Hemimysis* swarms have been present at Oswego (Lake Ontario) as early as 2002, and the presence of males, females (some in reproductive condition) and juveniles in lakes Michigan and Ontario suggests that reproductive populations have already established in the Great Lakes. Temperatures in aquatic ecosystems in southern Canada are not expected to prevent reproduction as *Hemimysis* has been observed to swarm under low water temperatures (down to 3°C).

Bailey *et al.* (2009) estimated the probability of cladocerans to establish at up to 0.4 with inoculations of 1.5 females/L (see estimates under Spread and assuming an even sex ratio). However, this assumes that populations need to reach a critical density before winter to produce resting eggs, an assumption that does not apply to *Hemimysis*, instead, individual *Hemimysis* that are introduced could survive the winter to reproduce the following year. While *Hemimysis* may not need critical densities to produce resting eggs, they may still need critical densities for reproduction if swarming is essential for successful reproduction, though this is currently unknown. The cladoceran modelling also assumes that the species is parthenogenic which also does not apply to *Hemimysis*. If inoculation densities are low, we can expect the probability of establishment for *Hemimysis* from a single inoculation to be low. If instead, a transport event occurs at a time when *Hemimysis* are swarming, then the inoculation density can be expected to be much higher, and the probability of establishment could be significant. Furthermore, the probability of establishment could be moderate with low inoculation densities if there are multiple sequential inoculations of a site within a short time period.

SPREAD

Hemimysis has already spread within the Great Lakes to lakes Michigan, Erie and Ontario (original point(s) of invasion unknown). Sampling in the Huron-Erie Corridor, Lake Huron and Lake Superior failed to detect any *Hemimysis* in these locations. If *Hemimysis* was originally transported to the Great Lakes in ballast water, then secondary transport within the Great Lakes in ballast water is a possibility. However, only half of the sites where *Hemimysis* was detected receive ballast water from either ‘salties’ or ‘lakers’, suggesting that ballast water is not the sole, and probably not the main, means of secondary spread in the Great Lakes. Another possible means of secondary spread within the Great Lakes is through dispersal, either actively swimming or passively if *Hemimysis* is picked up by lake currents.

Sampling for *Hemimysis* in 2007 found that the most consistent location to catch *Hemimysis* was next to docks (J. Gerlofsma, DFO, unpubl. data), and *Hemimysis* seems to prefer structure. *Hemimysis* are usually found at low densities (< 6 individuals/L), however, they do exhibit swarming behaviour at which time they are found at very high densities (> 1500 individuals/L; Pothoven *et al.* 2007). This suggests that activities around docks that will pick up and move water represent a higher risk of secondary transport of *Hemimysis*. Two possible activities that will be considered are (1) recreational boating and (2) the transportation of live bait.

Recreational Boating

Recreational boats are often moved from one location to another by trailering. Water associated with recreational boats includes bilge water, live wells, and engine cooling systems (Johnson *et al.* 2001). Based on estimates from Johnson *et al.* (2001) for zebra mussel larvae, the probability that a recreational boat from the Great Lakes will transport *Hemimysis* to an inland lake can be estimated as 1.15×10^{-5} (Table 3). In 2000, it was estimated that there were approximately 1.2 million recreational boats in Ontario, and that 65% (780 000) were used in the Great Lakes and St. Lawrence River (GLC 2000). This suggests 9 potential introductions per year from the Great Lakes to inland lakes (1.15×10^{-5} x 780 000). Based on Johnson *et al.*'s (2001) estimate for zebra mussel larvae introductions from recreational boat bilge water, we can expect each event to introduce 2 *Hemimysis*. When *Hemimysis* swarm, however, any water picked up in a recreational boat will potentially transport a significant number of individuals.

Table 3. Estimates associated with the probability of spreading *Hemimysis* through recreational boating (based on Johnson *et al.* 2001).

Estimate	Description
0.089	Probability that a recreational boat from the Great Lakes will be heading to an inland lake
0.27	Probability that boaters heading to an inland lake will use that boat within one day
0.006	Probability that *Hemimysis* will be picked up if present
0.8	Probability of exposure (educated guess)
0.1	Probability of survival in bilge water (educated guess, Johnson *et al.* assumed low survival)
1.15×10^{-5}	Probability that any recreational boat on the Great Lakes will transport *Hemimysis* to an inland lake

Bait Buckets

When anglers transport live bait, there is the possibility of secondary transport of *Hemimysis* in the water of bait buckets (bags, live wells or coolers). The probability that *Hemimysis* will be successfully spread by commercial bait harvesters is very low. Commercial harvesters sort and transfer bait fishes numerous times, and then the fishes are held in tanks before sale. At this point the fishes are expected to settle enough to consume any zooplankton that may have been transferred in the water, especially since these holding tanks offer little refuge for *Hemimysis*. When the bait is sold to anglers, the fishes are transferred again. It is highly unlikely that *Hemimysis* would be transferred through this pathway.

Anglers, however, also collect their own bait. These fishes are then transported live in water. While these fishes are live, they are also stressed and unlikely to feed even if zooplankton were present in the bait bucket, thereby providing the opportunity for any *Hemimysis* picked up in the water to be transported with the bait. Based on a voluntary survey of anglers in Ontario (A. Drake, University of Toronto, unpubl. data), a number of factors associated with the probability that *Hemimysis* may be transported in a live bait bucket can be estimated (Table 4). From this survey, we estimate that there is a 1% chance that anglers will introduce water from the Great Lakes to an inland lake on any trip where they collect their own bait from the Great Lakes.

Table 4. Estimates concerning live bait practices of anglers in Ontario from a voluntary survey (A. Drake, University of Toronto, unpubl. data). All estimates are specific to survey respondents who live next to the Great Lakes and are considered to be the anglers most likely to collect live bait from the Great Lakes.

Estimate	Description
0.34	Probability that a licensed angler lives next to the Great Lakes.
0.34	Probability that anglers living next to the Great Lakes sometimes or always catch their own bait.
0.76	Probability that anglers living next to the Great Lakes catch their bait by minnow traps, which is the gear most likely to be used near docks. Bait harvest has been observed near docks at locations where *Hemimysis* were present (J. Gerlofsma, DFO, personal observation).
0.38	Probability that anglers living next to the Great Lakes who catch their own bait use their bait in waters other than where it was caught (i.e., they transport live bait to other waterbodies).
0.8	Probability that anglers living next to the Great Lakes move to inland locations to fish.
0.83	Probability that anglers living next to the Great Lakes who catch their own bait have bait left over (unused bait).
0.46	Probability that anglers living next to the Great Lakes who catch their own bait release unused bait.
0.01	Probability that an angler will introduce Great Lakes water to an inland lake on any one trip where they collect their own live bait from the Great Lakes (assuming that water from a bait bucket is only dumped into an inland lake when unused bait is released).

Based on water samples, Johnson *et al.* (2001) estimated that the probability of a bait bucket picking up zebra mussel larvae was 0.024. Zebra mussel larval densities in donor water were estimated to be 4-5 times higher (24 zebra mussel larvae versus max 6 *Hemimysis* per L) than observed *Hemimysis* densities (except when *Hemimysis* are swarming). Based on this, we will assume that the probability of a *Hemimysis* being picked up in a bait bucket, if present, to be 0.006. We now have a $6x10^{-5}$ (0.006 x 0.01) probability that a bait bucket will pick up *Hemimysis* if present. Given that there are 500 000 licensed anglers in Ontario, and that anglers living next to the Great Lakes use live bait an average of 8.3 days per year (A. Drake, University of Toronto, unpubl. data), there are 249 ($6x10^{-5}$ x 500 000 x 8.3) opportunities per year when water will be transported from the Great Lakes to an inland lake in a bait bucket. If *Hemimysis* is present in more than 0.4% of the Great Lakes locations where bait buckets are filled by anglers, then *Hemimysis* will be transported from the Great Lakes to other waterbodies multiple times every year. If we assume a 50% chance of surviving transit (Johnson *et al.* assumed a moderate chance of zebra mussel larvae surviving transit), each transport will on average introduce 3 individuals. We assume that anglers are unlikely to pick up *Hemimysis* when they swarm as a bucket of water collected through a swarm of *Hemimysis* would look unappealing for the maintenance of bait.

POTENTIAL IMPACTS

Ricciardi and Rasmussen (1998), Kipp and Ricciardi (2007), and Ricciardi (2007) forecasted several potential ecological impacts of *Hemimysis* such as food web disruptions, altered nutrient and contaminant cycling which are likely to occur if the species becomes abundant. These effects may occur sooner than otherwise expected given that the distribution of *Hemimysis* is more widespread than was originally reported (Pothoven *et al.* 2007, Reid *et al.* 2007, Ricciardi 2007).

Observed impacts, based on European invasions (Ketelaars et al. 1999), have affected all trophic levels (Fig. 2). *Hemimysis* has a high feeding rate and declines in zooplankton biomass occur due to predation and competition. Smaller zooplankton (e.g., cladocerans, rotifers, ostracods) have been observed to disappear due to heavy predation. Larger, predatory zooplankton (e.g., *Leptodora*, *Bythotrephes*) have been observed to disappear due to a combination of competition and direct predation.

Once zooplankton decline, grazing release seems to lead to an increase in phytoplankton biomass. There is the potential here to interact with the eutrophication process leading to algal blooms. Significant effort has been invested in the Great Lakes to reverse eutrophication and algal blooms in nearshore areas. However, *Hemimysis* is omnivorous, and if zooplankton production is insufficient, *Hemimysis* will switch to feeding on phytoplankton. There is also a potential interaction with dreissenid mussels. Ecosystem modelling of the Bay of Quinte (Lake Ontario) suggests that phytoplankton production is almost entirely consumed due to the presence and high consumption rates of dreissenid mussels (Koops *et al.* 2006). If the current abundance of dreissenids is limited by the availability of phytoplankton, then an increased availability of phytoplankton due to *Hemimysis* predation on zooplankton, may not lead to algal blooms, but may instead be consumed by dreissenids. Any increase in production of dreissenids will potentially benefit round goby (*Neogobius melanostomus*), the main consumer of dreissenids in the Great Lakes, which also have impacts on native fishes (summarized in Cudmore and Koops 2007).

Declines in the abundance of zooplankton in nearshore areas will have significant impacts on larval, young of the year (YOY), and planktivorous fishes. While *Hemimysis* have been intentionally introduced to enhance fish production in Europe, and *Hemimysis* has been found in the stomachs of Great Lakes fishes such as white perch (*Morone americana*), yellow perch (*Perca flavescens*), and alewife (*Alosa pseudoharengus*), if *Hemimysis* out competes larval fishes for smaller zooplankton, then the net impact can be negative even if survivors to the YOY stage benefit from the presence of *Hemimysis* as a lipid rich prey.

In general, mysid introductions have been associated with higher trophic level impacts. In many cases this involves decreased growth, abundance and productivity of pelagic fishes, but benefits to benthic fishes (see description and references in Ricciardi 2007). With its high consumption rates, diurnal hiding under rocks, and nocturnal emergence, the same impact pattern may be associated with *Hemimysis*, namely, a negative impact on pelagic fishes and a benefit to benthic fishes.

Mysid introductions have also been associated with lengthening of the food chain and altered contaminant cycling. This is a possibility for *Hemimysis*, but the extent to which this will impact the Great Lakes depends on the ability of *Hemimysis* to integrate the food web, which is currently unknown.

The potential for impacts associated with fellow travellers (e.g., viruses, bacteria, diseases, parasites) is unknown. It is thought that a parasite plays an important role in reducing *Hemimysis* abundances in native locations where *Hemimysis* is endangered (J. Wittmann, Department of Ecotoxicology, Medical University of Vienna, pers. comm.). If disease or parasites were introduced to the Great Lakes with *Hemimysis*, then there is the possibility that these same afflictions could infect the native mysid, *Mysis diluviana* (formerly *Mysis relicta* Audzijonyte and Väinölä 2005). *M. diluviana* is considered to be an important food source in the Great Lakes and because of its role in the food web has been used as an indicator species. *M. diluviana* inhabits deeper areas, but there is potential for some overlap with *Hemimysis*, making it possible for diseases and parasites to be transferred. If this happened and it affected *M. diluviana* abundance, the impact on the Great Lakes food web could be significant.

RISK ASSESSMENT

Great Lakes

Arrival, Survival, Establishment: Estimating the probabilities that *Hemimysis* will arrive, survive and establish a reproductive population in the Great Lakes are not necessary given the evidence that these events have already occurred. As outlined above, we know this has occurred with very high certainty.

Spread: Monitoring for *Hemimysis* in 2007 confirmed that *Hemimysis* are found at multiple sites around three of the Great Lakes suggesting that this event has also already occurred. There is very high certainty around this estimate.

Impacts of Non-Arrival, Non-Survival and Non-Establishment: Due to the observed occurrence of *Hemimysis* around three of the Great Lakes, the main impact of concern is the impact of a widespread invasion of *Hemimysis* in the Great Lakes. Impacts of non-arrival, non-survival, and non-establishment are negligible.

Impacts of a Local Population: The impact of a locally established population could be low to moderate, but with some chance of high impacts, particularly if the location is an important nursery for fishes.

Impacts of a Widespread Invasion: As outlined above (see Potential Impacts section), there is a real possibility that widespread establishment of *Hemimysis* in the Great Lakes will alter the food web, and may require management to adapt to a new food web structure in nearshore areas. There is a much smaller possibility that the impact will be more extreme or that the impact will be low.

Based on these estimates (Table 5), *Hemimysis* poses a moderate to high risk to the Great Lakes. Uncertainties around parameter estimates bound the risk between low and extreme. The key uncertainty in this analysis is the impact of a widespread invasion (see Appendix A for full QBRAT results for the Great Lakes).

Table 5. Parameter estimates for the risk assessment of *Hemimysis* in the Great Lakes.

Parameter		Estimate	Certainty
p1	Probability of Arrival	1	Very High
p2	Probability of Survival	1	Very High
p3	Probability of Establishment	1	Very High
p4	Probability of Spread	1	Very High
I1	Impact of Non-arrival	Negligible	Very High
I2	Impact of Non-survival	Negligible	Very High
I3	Impact of Non-establishment	Negligible	Very High
I4	Impact of Local Invasion	Low - Moderate	High
I5	Impact of Widespread Invasion	Moderate - High	Moderate

Inland Lakes

This risk assessment of *Hemimysis* in inland lakes will focus on inland lakes of Ontario. As far as we know, *Hemimysis* only occurs in the Great Lakes. Based on the spread patterns of other invertebrate AIS that first invaded the Great Lakes (e.g., *Bythotrephes*), any potential spread will occur first to the inland lakes of Ontario, then to other parts of Canada. If *Hemimysis* does start to spread inland from the Great Lakes, then an additional assessment may be needed to evaluate risk to areas beyond the inland lakes of Ontario.

Arrival: Based on the estimates for movement of *Hemimysis* from the Great Lakes to inland lakes by either bilge water or in bait buckets, the probability that *Hemimysis* will arrive in inland lakes is 1, however, the certainty is only moderate.

Survival: The probability of survival is just as high in inland lakes as in the Great Lakes. Certainty is high.

Establishment: Even though the probability of establishment is expected to be low (< 0.4) from a single inoculation event based on the low estimate of propagule pressure, the potential for a relatively large number of annual events suggests that the cumulative probability of establishment is high (close to 1). The certainty associated with this estimate is low.

Spread: The probability that *Hemimysis* will become widespread in inland lakes will depend on which inland lakes are initially invaded. MacIsaac *et al.* (2004) built a gravity model to predict the spread of *Bythotrephes* from the Great Lakes to inland lakes. This gravity model predicted that the spread was relatively contained until lakes Muskoka and Simcoe were invaded, and that particularly the successful invasion of Lake Simcoe led to the invasion of many inland lakes due to the pattern of angler and recreational boat traffic. The main source of invasion to inland lakes was from Lake Huron. Muirhead (2007), building a model for the spread of *Bythotrephes* at a later phase in its invasion, found that Lake Ontario contributed the greatest flow of propagules from the Great Lakes. So far, we do not know of any invaded sites within Lake Huron, however, multiple sites have been identified within Lake Ontario suggesting that the immediate probability of spread is high (we assume p4 = 0.75), however, only 5 sites in Lake Huron have been sampled for *Hemimysis*, so the certainty associated with this estimate is very low.

Impacts of Non-Arrival, Non-Survival and Non-Establishment: The impacts of non-arrival, non-survival, and non-establishment are negligible. Due to their relatively short lifespan, if *Hemimysis* does not establish a population, the impacts from a few individuals consuming zooplankton would be undetectable. Certainty is very high.

Impacts of a Local Population: The impact of a locally established population will be moderate, but with some chance of either low or high impacts. In this case, a local population is defined as an inland lake.

Impacts of a Widespread Invasion: As outlined above (see Potential Impacts section), there is a real possibility that establishment of *Hemimysis* in inland lakes will alter the food web, and may require management to adapt to new food web structures. There is a much smaller possibility that the impact will be more extreme or that the impact will be moderate to low.

Based on these estimates (Table 6), *Hemimysis* currently poses a moderate to high risk to inland lakes. Uncertainties around parameter estimates bound the risk between low and high. The key uncertainty in this analysis is the probability of establishment (see Appendix B for full QBRAT results).

Table 6. Parameter estimates for the risk assessment of *Hemimysis* in inland lakes.

Parameter		Estimate	Certainty
p1	Probability of Arrival	1	Moderate
p2	Probability of Survival	1	High
p3	Probability of Establishment	0.4	Low
p4	Probability of Spread	0.75	Very Low
I1	Impact of Non-arrival	Negligible	Very High
I2	Impact of Non-survival	Negligible	Very High
I3	Impact of Non-establishment	Negligible	Very High
I4	Impact of Local Invasion	Moderate	Moderate
I5	Impact of Widespread Invasion	High	Moderate

KEY UNCERTAINTIES AND KNOWLEDGE GAPS

The sensitivity analysis based on the Great Lakes estimates (Appendix A) indicates that the risk assessment is most sensitive to the impact of a widespread invasion. The risk assessment is also sensitive to estimates of the probabilities of arrival, survival, and establishment, however, our uncertainty about these estimates is low, so there is relatively little value in refining these estimates.

Most of the predicted effects of a *Hemimysis* invasion are related to food web disruption. The relatively early detection of the invasion in the Great Lake basin allows for comparisons of the food web dynamic between invaded and non-invaded sites. Stable isotope analysis could represent a useful tool to make such comparison, as already shown for other invaders (e.g., Vander Zanden *et al.* 1999). This research area is currently poorly represented in the literature for *Hemimysis*. The carbon and nitrogen isotopic composition of the main levels of the food web (particulate matter, zooplankton and planktivorous fishes) would allow identification of carbon pathways fuelling the food web and food web structure. This type of research could easily be added to existing monitoring programs already in place in the Great Lakes.

The Great Lakes ecosystem differs substantially from other invaded ecosystems. Future work should evaluate how these differences may moderate the impacts of *Hemimysis*. For example, if nearshore temperatures exceed thermal preferences during the summer, *Hemimysis* may move offshore, moderating the predation on nearshore zooplankton communities. A better understanding of *Hemimysis* thermal preferences and potential for seasonal movements is needed.

Sensitivity analysis of the inland lakes estimates (Appendix B) indicates that the risk assessment is most sensitive to the probability of establishment. If estimates of the probability of establishment can be resolved, the next most sensitive parameter is the probability of arrival. These results suggest that further work should be conducted on the potential for *Hemimysis* to spread to and establish in inland lakes.

Understanding the factors that will control the abundance of *Hemimysis* will be important for predicting the probability of establishment. For example, *Hemimysis* is currently endangered in some of its native localities, and one hypothesis is that this is possibly due to fish predation (J. Wittmann, Department of Ecotoxicology, Medical University of Vienna, pers. comm.). Can fish predation limit *Hemimysis* abundances? Understanding what may limit *Hemimysis* abundances will also help to refine estimates of potential impacts.

Additional efforts should be placed in detecting *Hemimysis* and developing standard sampling methods adapted for this organism. The behaviour of this organism makes detection difficult and sampling methods must be developed to take into account the daily migration of *Hemimysis*. New techniques based on optical counter or echosounder may overcome these issues in large systems such as the Great Lakes.

Finally, we need to understand why *Hemimysis* swarm and what conditions trigger swarming. The probability that *Hemimysis* will be picked up and spread will be higher during swarming due to high densities around docks. Better understanding the reasons and mechanisms for swarming may help to identify efforts that could mitigate the risk of spread.

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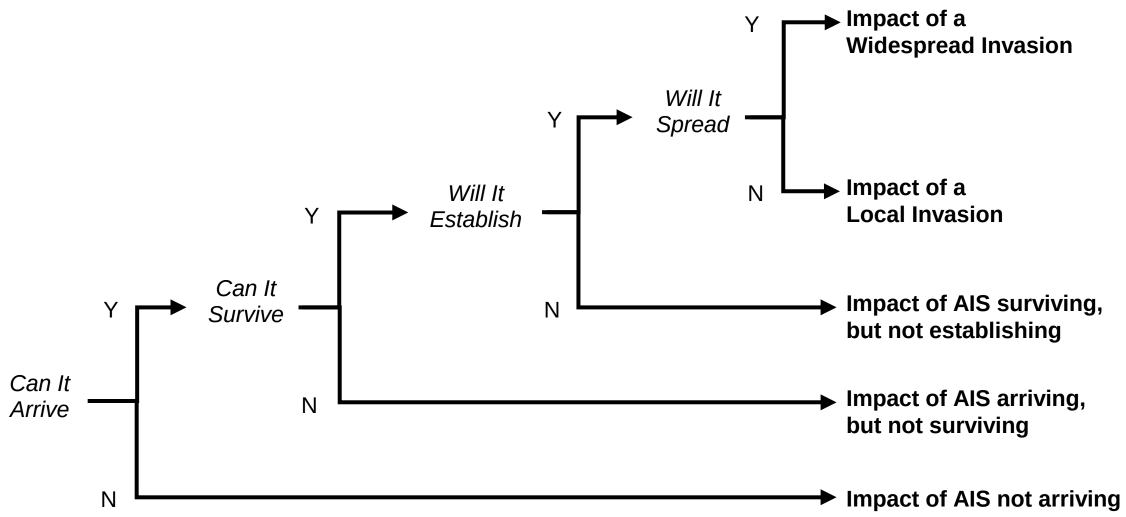


Figure 1. An event tree representation of the four step (arrival, survival, establishment, spread) invasion process modelled by the Quantitative Biological Risk Assessment Tool (QBRAT). The four event nodes (italicized text) represented by questions are associated with probabilities of occurrence. The five end points (bold text) represent potential impacts.

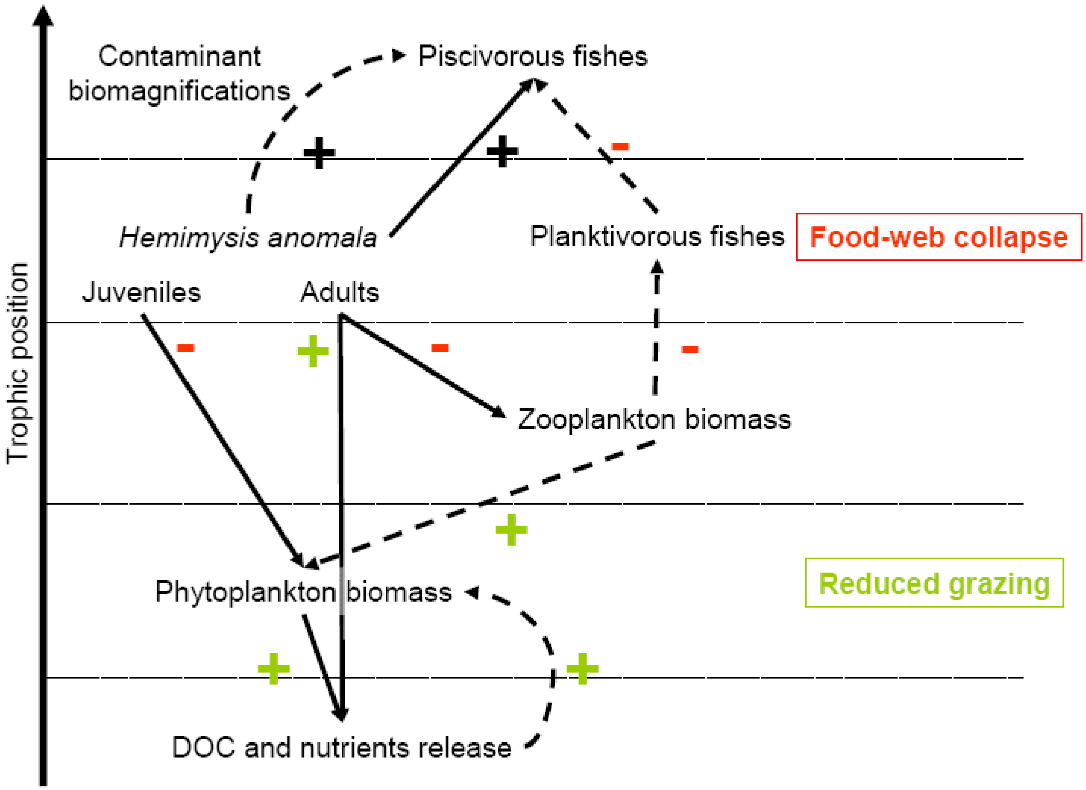
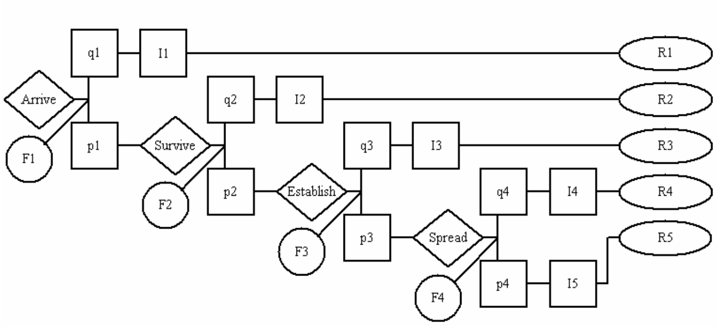


Figure 2. Trophic position of *Hemimysis anomala* in the food web and potential impacts (food web collapse, eutrophication and contaminant bioaccumulation) predicted for the Great Lakes (from Marty 2008).

Appendix A: Biological Risk Assessment Report – Great Lakes

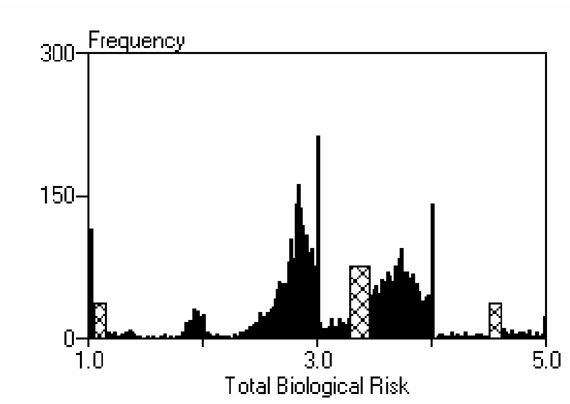


Species: *Hemimysis anomala*

Location: Great Lakes

Date: 30-Jan-2008

Monte Carlo Simulation Results: Biological Risks [PRNG=VB,Const=N,Tails=2]

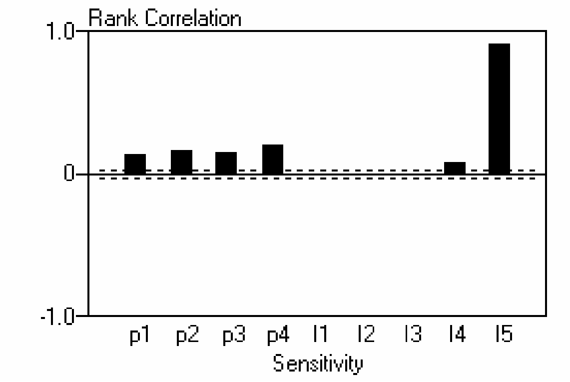


Probabilities
p1 = 1.00 (0.05774,U)
p2 = 1.00 (0.05774,U)
p3 = 1.00 (0.05774,U)
p4 = 1.00 (0.2598,U)

Calculated Risks
R1 = 0
R2 = 0
R3 = 0
R4 = 0
R5 = 3.375
Rb = 3.375

Impacts
I1 = 1 (*)
I2 = 1 (*)
I3 = 1 (*)
I4 = 2.5 (*)
I5 = 3.375 (*)

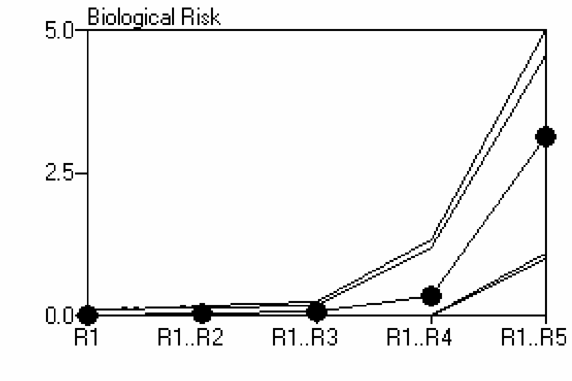
Simulation Stats
N = 5000
Mean = 3.123
SD = 0.7335



Sensitivities
p1 = 0.134*
p2 = 0.162*
p3 = 0.141*
p4 = 0.202*

I1 = -
I2 = -
I3 = -
I4 = 0.081*
I5 = 0.910*

R2 (Raw) = --
R2 (Ranked) = --



Cumulative Risk (CI = 95 %) [Sx = Sum R1 to Rx]

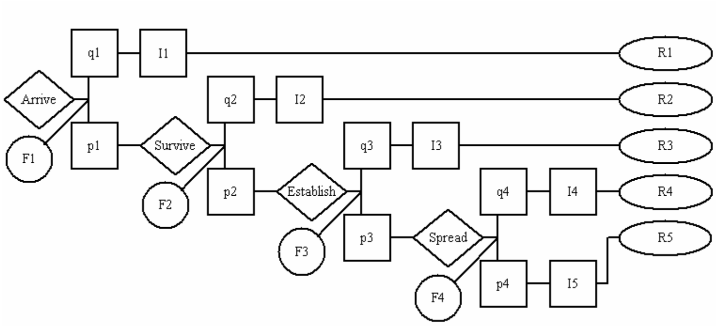
	Mean	Min	Max	Lower CI	Upper CI
S1	0.02462	0	0.09996	0	0.0951
S2	0.04961	0	0.1867	0	0.1493
S3	0.07266	0	0.2575	0	0.184
S4	0.3364	0	1.344	0	1.212
S5	3.123	1	5	1.094	4.561

Appendix A: Biological Risk Assessment Report (cont’d)

Categorical Impact Data

I1	P(0-1)	I2	P(0-1)	I3	P(0-1)	I4	P(0-1)	I5	P(0-1)
1	1.0	1	1.0	1	1.0	1	0.0	1	0.05
2	0.0	2	0.0	2	0.0	2	0.5	2	0.05
3	0.0	3	0.0	3	0.0	3	0.5	3	0.425
4	0.0	4	0.0	4	0.0	4	0.0	4	0.425
5	0.0	5	0.0	5	0.0	5	0.0	5	0.05

Appendix B: Biological Risk Assessment Report – Inland Lakes



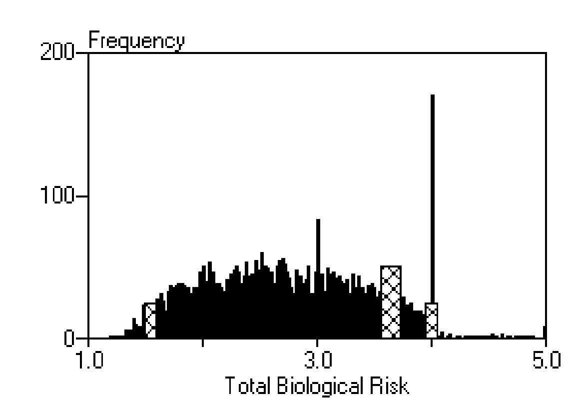
Species: *Hemimysis anomala*

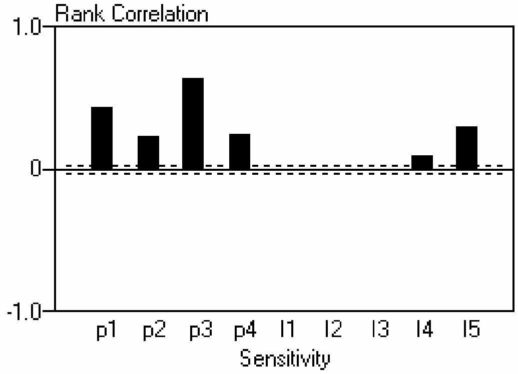
Location: Inland Lakes

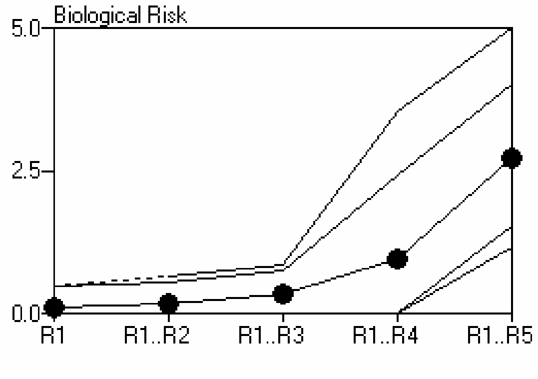
Date: 30-Jan-2008

Monte Carlo Simulation Results: Biological Risks

[PRNG=VB,Const=N,Tails=2]







Probabilities
p1 = 1.00 (0.2887,U)
p2 = 1.00 (0.1732,U)
p3 = 0.99 (0.4001,U)
p4 = 0.75 (0.3897,U)

Calculated Risks
R1 = 0
R2 = 0
R3 = 0.01
R4 = 0.7425
R5 = 2.896
Rb = 3.648

Impacts
I1 = 1 (*)
I2 = 1 (*)
I3 = 1 (*)
I4 = 3 (*)
I5 = 3.9 (*)

Simulation Stats
N = 5000
Mean = 2.731
SD = 0.7069

Sensitivities
p1 = 0.428*
p2 = 0.229*
p3 = 0.640*
p4 = 0.234*

I1 = -
I2 = -
I3 = -
I4 = 0.087*
I5 = 0.289*

R2 (Raw) = --
R2 (Ranked) = --

Cumulative Risk (CI = 95 %) [Sx = Sum R1 to Rx]

	Mean	Min	Max	Lower CI	Upper CI
S1	0.1263	0	0.4998	0	0.4758
S2	0.1922	0	0.6444	0	0.5411
S3	0.3358	0	0.867	0	0.7653
S4	0.9667	0	3.543	0	2.427
S5	2.731	1.177	5	1.534	4

Appendix B: Biological Risk Assessment Report (cont’d)

Categorical Impact Data

I1	P(0-1)	I2	P(0-1)	I3	P(0-1)	I4	P(0-1)	I5	P(0-1)
1	1.0	1	1.0	1	1.0	1	0.0	1	0.0
2	0.0	2	0.0	2	0.0	2	0.05	2	0.05
3	0.0	3	0.0	3	0.0	3	0.9	3	0.05
4	0.0	4	0.0	4	0.0	4	0.05	4	0.85
5	0.0	5	0.0	5	0.0	5	0.0	5	0.05