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Using the Quantitative Biological Risk Assessment Tool (QBRAT) to predict effects of the European green crab, *Carcinus maenas*, in Atlantic Canada

Utilisation de l'Outil de quantification du risque biologique (OQRB) pour prédire le coût potentiel du crabe vert, *Carcinus maenas*, dans l'Atlantique canadien

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ABSTRACT

The European green crab or shore crab, *Carcinus maenas* (Linnaeus) is ranked among the "100 worst alien invasive species" in the world. It initially invaded Atlantic Canadian waters in 1951 via Passamaquoddy Bay, where the subsequent failure of fisheries for infaunal bivalves was attributed to predation by the green crab. In the 1990s, green crabs spread into the Gulf of St. Lawrence and British Columbia. There has been considerable interest in forecasting their eventual effects on these ecosystems and their fisheries. Green crab was therefore selected as a candidate for a case study for the National Workshop on the Evaluation of a Quantitative Biological Risk Assessment Tool (QBRAT) Through Various Case Studies, 29-30 November 2006. The objective was to evaluate QBRAT v. 2 by assessing the risk of green crab invasion to Atlantic Canada, over a temporal scale of 30 yr, and by estimating environmental impacts (on a probabilistic scale between 0 and 1) and economic impacts (as dollar values according to scenarios we devised as approximations of the cost over 30 yr).

QBRAT was a useful device for structuring and quantifying assumptions about each step in the invasion process. It was also valuable in identifying where more work was required in order to provide an adequate estimate of a variable. Many of the values we assigned to steps in the invasion were estimated with a high level of uncertainty. We did establish with reasonable certainty that there was a high risk of continued establishment and spread of the species throughout Atlantic Canada. The calculated economic risk, based on hypothetical scenarios of commercial fishery and aquaculture losses in bivalve harvests in the Gulf of St. Lawrence, averaged just over $1 million annually. We stress, however, that this value should not be quoted as a definitive estimate of economic impacts of green crabs in Atlantic Canada. Indeed, we consider that no valid estimates of economic impacts of this species exist for these waters.

RÉSUMÉ

Le crabe vert *Carcinus maenas* (Linné), aussi appelé crabe enragé, est classé parmi les « cent pires espèces exotiques envahissantes » au monde. L'invasion de cette espèce dans les eaux canadiennes de l'Atlantique a commencé dans la baie Passamaquoddy en 1951. L'échec subséquent de la pêche des bivalves endofauniques avait alors été attribué à leur prédation par le crabe vert. Au cours des années 1990, l'invasion du crabe vert s'est étendue au golfe du Saint Laurent et à la Colombie Britannique. Ses répercussions éventuelles sur ces écosystèmes et les pêches qui y sont pratiquées suscitent un intérêt considérable. Ainsi, cette espèce a été sélectionnée en vue de la réalisation d'une étude de cas à présenter à l'Atelier national, tenu les 29 et 30 novembre 2006, sur l'évaluation d'un outil de quantification du risque biologique (OQRB) à l'aide de diverses études de cas. L'Atelier avait pour objectif d'évaluer la deuxième version de l'OQRB en déterminant le risque que pose l'invasion du crabe vert dans l'Atlantique canadien sur une échelle temporelle de 30 ans, ainsi qu'en évaluant les conséquences environnementales (sur une échelle probabiliste de 0 à 1) et les impacts économiques (en dollars, selon des scénarios correspondant à des approximations de coûts sur 30 ans).

L'OQRB est utile pour structurer et quantifier les hypothèses formulées pour chacune des étapes du processus d'invasion. Il se révèle un outil tout aussi précieux pour déterminer à quel stade l'évaluation appropriée de certaines variables exige un travail plus approfondi. Bon nombre des valeurs attribuées à chacune des étapes de l'invasion résultent d'évaluations fortement teintées d'incertitude. Nous avons cependant établi avec un degré de certitude raisonnable que les risques de progression de l'invasion et de la propagation du crabe vert dans l'Atlantique canadien sont élevés. Le calcul des risques économiques, fondé sur des scénarios hypothétiques des pertes de captures de bivalves dans le cadre des pêches commerciales et de l'aquaculture dans le golfe du Saint Laurent, dépasse légèrement, en moyenne, le million de dollars par année. Nous tenons cependant à souligner que cette donnée ne doit pas être citée comme une évaluation définitive des répercussions économiques de la présence du crabe vert dans l'Atlantique canadien. En fait, nous jugeons que, pour l'heure, il n'existe, pour ces eaux, aucune évaluation valide de ces impacts.

1. INTRODUCTION

The European green crab or shore crab *Carcinus maenas* (hereafter, "green crab") is ranked among the 100 'worst alien invasive species' in the world (Lowe et. al. 2000). A native of coastal and estuarine waters of Europe and Northern Africa, it has colonized the Atlantic and Pacific coasts of North and South America, as well as South Africa, Australia, and Asia. In many ways it could be considered a model invader. It is a voracious omnivore and aggressive competitor with a wide tolerance for salinity, temperature, oxygen, and habitat type. A large number of planktonic larvae are produced, and dispersal occurs at all life history stages.

Green crab was first detected in Canadian waters in 1951 as a range extension of the introduced New England population into Passamaquoddy Bay in the Bay of Fundy (Leim 1951). It subsequently expanded its range throughout the Bay of Fundy and up the Atlantic coast of Nova Scotia (Audet et al. 2003). Green crab reached the Gulf of St. Lawrence, most likely through the Canso Causeway, in 1994 (Locke and Hanson unpub. ms.). Its invasion of the Atlantic coast north of Halifax, and the Gulf of St. Lawrence, probably resulted from the *de novo* introduction of at least five lineages not previously found in North America; several of these apparently originated from the North Sea (Roman 2006). On the west coast, green crab was first reported from Vancouver Island in 1998, as a range extension from the population introduced to the northwestern USA. Genetic studies have shown that the west coast invasion originated from the lineage that has been present on the east coast of the USA since the 1800s (Bagley and Geller 1999).

A substantial area of both the east and west coasts of Canada is most likely vulnerable to future invasion, as green crab distributions continue to expand northwards (Locke and Hanson unpub. ms.). Chmura and colleagues predicted, from physiological thermal limits, that the northern limit of green crab in eastern Canada is near Ungava Bay (www.geog.mcgill.ca/climatechange/results.htm, accessed 22 Nov 2006). By contrast, a model based on the relationship of temperature to larval duration predicts that the St. Lawrence Estuary is too cold for larval development (DeRivera et al. 2006). The latter prediction, however, is based on New England green crabs, which may be less well adapted to cold weather than the lineages found in the Gulf of St. Lawrence. It has been suggested that the northern limit of green crab in the northeastern Pacific is in Alaska (Gray Hitchcock et al. 2003, DeRivera et al. 2006).

In all areas where the green crab has invaded, its potential for significant impacts on fisheries, aquaculture, and the ecosystem has caused concern. During the early stages of invasion of the green crab in Canada, Hart (1955) wrote: "The green crab (*Carcinides maenas*), which has entered and spread throughout the Bay of Fundy since 1950, has become our most serious clam predator. It destroys adult clams as well as those of seed size. Feeding experiments conducted this year have demonstrated that it will also destroy young oysters and quahaugs. Studies of its spread show that there is serious risk of its extending its range to the Gulf of St. Lawrence where it might do enormous damage." Numerous studies have shown the potential for green crab to adversely affect many ecosystem components, directly and indirectly, by predation, competition and habitat modification (Grozholz and Ruiz 1996). Because green crab has the ability to modify entire ecosystems, it is considered an "ecosystem engineer" (Crooks 2002).

1.1. Scope and objectives of this study

This study was undertaken as a case study for the National Workshop on the Evaluation of a Quantitative Biological Risk Assessment Tool (QBRAT) Through Various Case Studies, 29-30 November 2006 (Cudmore et al. 2007). The objective was to evaluate the Quantitative Biological Risk Assessment Tool, QBRAT, version 2 (Moore et al. 2006), by examining a case study of green crab.

We defined the spatial scale of the study to be Atlantic Canada; the temporal scale to be 30 yr; and the scope of the study to be the risk posed by the future spread of green crabs to bivalve aquaculture and fisheries, including both environmental (ecological) and economic risks. We limited the geographic scope of the study to Atlantic Canada instead of including both coasts because more complete information was available on which to base model decisions. Following their initial introduction in Passamaquoddy Bay, green crabs spread through the Bay of Fundy, Atlantic coast of Nova Scotia, and into the southern Gulf of St. Lawrence within 40 yr (Klassen and Locke 2007), therefore we judged that 30 yr might be a sufficient time frame for them to accomplish their potential distribution in Atlantic Canada. In deciding the nature of the risk to be assessed, the scientific literature consistently indicates a strong potential for negative effects of green crab on ecosystems, commercial fisheries and aquaculture (see Biological Synopsis). In particular, there is a long history of adverse effects on bivalve fisheries and aquaculture. We decided to use the QBRAT software to examine two sets of impacts: (a) environmental impacts, which we estimated on a probabilistic scale between 0 and 1; and (b) economic impacts, which we estimated as dollar values according to scenarios we devised as approximations of the costs over 30 yr.

2. BIOLOGICAL SYNOPSIS

A comprehensive biological synopsis is available in Klassen and Locke (2007). Here, we present only a summary of relevant portions of the synopsis.

2.1. Life history

The life cycle of green crab alternates between a benthic adult, and planktonic larval stages. Females can spawn up to 185,000 eggs at a time (Cohen and Carlton 1995). Four zoeal and a megalopal larval stage develop in open waters for upward of 50 days, to a maximum of 82 days in laboratory experiments (Williams 1967, DeRivera et al. 2006). Planktonic larval abundances can reach ~150 individuals/m^3 (Quieroga et al. 1997). Zoeae perform active vertical migrations that enhance their export from estuaries (Quieroga et al. 1997). Megalopae return inshore to settle and metamorphose into juvenile crabs (Cameron and Metaxas 2005).

The seasonal timing of events in the life cycle of green crab varies greatly across its range (Sharp et al. 2003). In Basin Head Lagoon, PEI, females are ovigerous in July through September and larvae are released from August until December, with the peak in September (Sharp et al. 2003). The reproductive season in northern Nova Scotia, based on ovigerous females, was June-October. Zoea I stage larvae were in the water column from June until August, and megalopae were present from August through October (Cameron and Metaxas 2005).

At Basin Head, size at maturity is 49 mm for males, and 44 mm for females (Sharp et al. 2003).

Green crab has a life span of 6 yr in Maine, 5 yr in Europe, but only 3-4 yr in Oregon, perhaps related to higher growth rate in the invaded as compared to the native environment (Grosholz and Ruiz 1996, Yamada et al. 2001). Maximum size is 9-10 cm in carapace width in Oregon, but 8.6 cm in Europe.

2.2. Ecology

Green crabs have invaded estuarine and coastal environments of much of the temperate world. They are commonly found from the high tide level to depths exceeding 5 m (Elner 1981). Green crabs inhabit a wide range of habitats in sheltered areas including rocky intertidal, unvegetated intertidal, subtidal mud and sand, saltmarshes and seagrasses (Ray 2005). The highest abundances, especially of juveniles, often occur in seagrass beds, relative to adjacent unvegetated sandy areas (Polte et al. 2005).

Diet preference and ecological impact are similar among Europe, eastern North America, and South Africa, but habitat usage appears to be more site-specific (Grosholz and Ruiz 1996). For example, while green crabs are typically less abundant in high-energy environments, they do occur in moderate numbers in such habitat in their native range. By contrast, they have (to date) colonized only sheltered habitats such as estuaries in several invaded areas, including South Africa, the Pacific USA, and Gulf of St. Lawrence (Griffiths et al. 1992, Grosholz and Ruiz 1996, Locke pers. obs.).

Green crab preys on a variety of marine organisms including species from at least 104 families, 158 genera, in 5 plant and protist and 14 animal phyla (Cohen and Carlton 1995). Larvae filter-feed on particles as small as bacteria, early stage juveniles feed primarily on detritus then switch to infauna as they get older, and adults prefer to prey on bivalves (Pihl 1985). Green crab is in turn eaten by various predators including herring gulls *Larus argentatus*, mink *Mustela vison*, and striped bass *Morone saxatilis* (Dumas and Witman 1993, Dunstone and Birks 1987, Nelson et al. 2003).

Adult green crabs tolerate a wide range of salinities and temperatures, but prefer mesohaline to polyhaline salinities (10-30 $^{o}/_{oo}$) and temperatures between 3ºC and 26ºC (Grosholz and Ruiz 2002). Green crabs can tolerate salinity as low as 4 $^{o}/_{oo}$, but their physiology, particularly the ability to adapt to hypoxia, is compromised below 10 $^{o}/_{oo}$ (Legeay and Massabuau 2000). Green crab readily survive several days out of water (Darbyson 2006).

Larvae are less tolerant and, in the laboratory, complete development only at temperatures between 10 and 22.5ºC (DeRivera et al. 2006). Freshly hatched larvae can survive at salinities < 15 $^{o}/_{oo,}$ but do not develop beyond the zoea stage, while metamorphosis to the megalopa stage requires salinities greater or equal to 20 $^{o}/_{oo}$ (Anger et al. 1998).

2.3. Native range

The green crab (*C. maenas*) 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. It is one of the commonest crabs throughout much of its range.

In the Mediterranean Sea, it is replaced by the congeneric species *Carcinus aestuarii* (also known as *C. mediterranae*). Following much discussion in the scientific literature as to whether the two taxa are distinct species or subspecies (see Clark et al. 2001), Roman and Palumbi (2004) have identified a clear genetic break between Mediterranean and Atlantic forms, supporting their species-level status.

2.4. Introduced range

Green crabs were first observed on the east coast of North America in Massachusetts in 1817, and now extend from Prince Edward Island to Virginia. In 1989, *C. maenas* was found in San Francisco Bay, California, its first occurrence on the Pacific coast of the United States. It started extending its range in 1993 and reached Oregon in 1997, Washington state in 1998 and British Columbia in 1999 (Grosholz and Ruiz 1996).

In Australia, *C. maenas* was first reported in the late 19th century, in Port Phillip Bay, Victoria. It has since spread along the coast of Victoria, reaching New South Wales in 1971, South Australia in 1976 and Tasmania in 1993. One specimen was found in Western Australia in 1965, but *C. maenas* has not been seen in the area since (Thresher et. al. 2003, Ahyong 2005). *C. maenas* first reached South Africa in 1983, near Cape Town (Le Roux et. al. 1990). In 2003, *C. maenas* was recorded from Argentinian Patagonia (Hidalgo et. al. 2005).

It has been recorded but has not established viable populations in Brazil, Panama, Hawaii, Madagascar, the Red Sea, Pakistan, Sri Lanka and Myanmar (Carlton and Cohen 2003, Rogers 2001).

2.5. Range in Atlantic Canada

The green crab has established reproducing populations in the Bay of Fundy, the Atlantic coast of Nova Scotia north to Ingonish Beach, the Nova Scotia coast of the Gulf of St. Lawrence from Pleasant Bay to the New Brunswick border, Baie Verte and Cape Jourimain, NB, the eastern end of Prince Edward Island (east of Savage Harbour and Victoria on the north and south coasts, respectively), and in Placentia Bay, Newfoundland (Locke and Hanson, unpub. ms.). Adult green crabs have been found in the Magdalen Islands since 2004, but no evidence of successful reproduction has been found to date (Paille et al. 2006).

2.6. Impacts

The green crab significantly decreases the densities of a wide range of prey species (Grosholz and Ruiz 1995). Some of the strongest evidence relates to its effects on bivalves. Of particular concern are its direct economic impacts in Canada, these include several species that are commercially fished or grown in aquaculture: blue mussels *Mytilus edulis*, quahogs *Mercenaria mercenaria*, eastern oysters *Crassostrea virginica*, soft-shell clams *Mya arenaria,* and bay scallop *Argopecten irradians irradians* (Clark et al. 2004, Gardner and Thomas 1987, Floyd and Williams 2004, Miron et al. 2002). Effects on these species include both the consumption of individuals, and the redirection of energy from production to anti-predator strategies (e.g., cryptic behaviours, shell thickening, stronger byssal attachments) (Freeman and Byers 2006). While its effects on bivalves are most commonly cited, green crab also preys on many other commercially important species. Green crab prey on settling juvenile lobsters *Homarus americanus* in some habitats such as salt marshes (Barshaw et al. 1994) as well as in laboratory experiments (Rossong et al. 2006) although there is no documentation to indicate that this occurs in natural habitats found in Atlantic Canada. Green crabs are also well known predators on eggs and juveniles of winter flounder (Taylor 2004).

The predatory effects of green crabs may cascade through the food web and affect community dynamics (Trussell et al. 2004). Green crab may compete for prey with other decapods, for example the rock crab *Cancer irroratus*, lady crab *Ovalipes ocellatus*, and sand shrimp (*Crangon septemspinosa*) (Ropes 1989, Taylor 2004). Another area of concern is the effect on migrating shorebirds due to the reduction in abundance of small invertebrates they depend on for food (Jamieson et al. 1998).

Green crabs also affect the suitability of habitat for other species. Mechanical disturbance of sediment by the digging activities of green crab adversely affects infaunal species (Le Calvez 1987). Digging also damages eelgrass *Zostera marina*, which provides a critical habitat for many species, by cutting off the shoots and loosening the sediments in which the plant is rooted (Davis et al. 1998, D. Garbary pers. comm.).

In commercial fisheries, green crabs may interfere with the trappability of rock crabs (*Cancer irroratus*) (Miller and Addison 1995). In PEI, they have been a major nuisance species in the American eel (*Anguilla rostrata*) fishery, as green crabs either prevent the entry of eels to fyke nets, or damage eels captured in the nets so that they are unmarketable.

2.7. Benefits

In its native range, green crab is an important scavenging species, especially of commercial fishery discards (Catchpole et al. 2006, Moore and Howarth 1996). Green crab was a dominant species contributing to the removal of 3.4 kg dry weight/m^2/7d of fish feed pellets from under marine fish farms (Smith et al. 1997).

Green crab may be of use in controlling biofouling on aquaculture sites. It preys on mud crabs feeding on bay scallops on spat bags, although green crab does eat bay scallops as well (Turner et al. 1996). It has been used to remove mussels fouling oyster nets, although it also eats the oysters (Enright et al. 1993). Its utility as an anti-biofouler is greatest when the chelae are neutralized to prevent destruction of the target crop, but overall it was found to be less effective than other species such as hermit crabs (Enright et al. 1993).

Green crab may have some limited utility as a species that can control invasive tunicates fouling aquacultured bivalves. However, rock crabs appear to be more effective predators on the vase tunicate, *Ciona intestinalis* (Carver et al. 2003). Green crab does not eat golden star tunicate, *Botryllus schlosseri* (Teo and Ryland 1994). Its efficacy against other invasive tunicates now present in Canada has not, to date, been evaluated.

There has been a commercial fishery for green crab for many years in Europe, and indeed overharvesting of green crabs has apparently occurred in several countries (Gomes 1991). There has been some examination of the potential for commercial fisheries in Atlantic Canada and New England (e.g., chemical analyses of meats and shell discards, product testing) (Naczk et al. 2004, Skonberg and Perkins 2002, Food Science Centre of the University of Prince Edward Island pers. comm.). In the Maritimes Region, a small commercial fishery had been planned to take place in 2006 off the Atlantic coast of Nova Scotia, but has been delayed, apparently because of the lack of a market (J. Tremblay, DFO, pers. comm.).

2.8. Management

Mitigation methods that have been considered or attempted for green crabs include sound pulses, air exposure/desiccation, chemical control, biological control ("guarding" bivalve seed with toadfish *Opanus tau*), genetic manipulations, local physical barriers (nets, rafts), altered fishery practices (overwintering seed so it is larger when planted, closed areas), manual removal, commercial harvesting, trapping, and parasitic castrators (Walton 2000, Walton and Walton 2001, McEnnulty et al. 2001). Harvest programs as typically carried out in New England do not seem to reduce abundance, but abundance can be controlled by intensive and frequent trapping within restricted embayments (Walton 2000).

Exclusion of green crab from sites seeded with soft-shell clams in Massachusetts is apparently successful, using 1/6 inch plastic webbing (Buttner et al. 2004). However, lease sites are quite large, on the range of 1-5 acres, which makes exclusion quite difficult.

Control strategies often rely on baited traps, but these are relatively ineffective because ovigerous females are less mobile and unresponsive to bait. Therefore trapping primarily captures males, which has little effect on propagule pressure (McDonald et al. 2004). Quahog growers who supported trapping noted reductions in green crab density, however others had given it up as ineffective, or because of attraction of predators to the area, the large acreage involved, and negative effects on nontarget species including endangered species (Walton and Walton 2001).

Delayed outplant has been recommended as a strategy to reduce losses to green crab predation in commercial production of Manila clams (*Venerupis philippinarum*) (Grosholz et al. 2001). Similarly, modifications of timing, size and density of seeding of quahog *Mercenaria mercenaria* in Martha's Vineyard have been tried in order to develop an optimum seeding strategy to minimize predation (Walton et al. 1999). Biological control by parasites, particularly the castrator *Sacculina carcini* has been proposed, but the parasite is not specific to the green crab and readily transfers to several native crabs (Thresher et al. 2000, Goddard 2001).

3. SUPPORTING EVIDENCE FOR QBRAT BIOLOGICAL RISK ASSESSMENT

3.1. Arrival (p1)

In their native habitat, green crabs tend to expand their range by a few kilometers per year punctuated by periodic long-distance expansions associated with unusual oceanographic conditions or human-mediated introductions (Thresher et al. 2003). The vast majority of primary invasions throughout the world are attributable to transport by human agents, mostly in ships ballast but also on hull fouling and in seaweed used to pack marine products. (Carlton and Cohen 2003). Secondary invasions (intraregional dispersal) may also involve a combination of larval and adult dispersal mechanisms. Larval dispersal may be particularly important in intraregional dispersal as green crab larvae may be carried great distances by surface currents.

Rates of range expansion have been quite variable among green crab invasions (Grosholz and Ruiz 1996).In most invaded locations, rates of range expansion (secondary invasion) are typically only a few km per year, despite the long larval duration (>50 d), punctuated by rare episodes of long-distance and large-scale spread. The latter appear to be related to either unusual oceanographic conditions or to human assistance (Thresher et al. 2003). On the west coast of Canada and the USA, green crabs dispersed northward about 1500 km in 12 yr (Jamieson et al. 2002). The strong recruitment event and major range expansion that took place in 1998 is believed to have been the result of unusually strong northward-moving coastal currents of up to 50 km/day, which occurred between November 1997 and February 1998 (Jamieson et al. 2002, Yamada and Becklund 2004). In contrast, following its arrival in western North America in 1989, green crab remained limited to San Francisco Bay until 1993, when it spread 80 km northward, and 1994, when it spread 125 km southward (Grosholz and Ruiz 1996). Mean annual range expansion over the five years of 20 km/yr northward and 31 km/yr southward are close to the mean range of range expansion for marine species generally (Grosholz and Ruiz 1996). Northward expansion of green crab from New England to Nova Scotia averaged 63 km/yr, but was very episodic (Grosholz and Ruiz 1996). In South Africa, range expansion averaged 16 km/yr from 1983 to 1992 (Grosholz and Ruiz 1996).

We tabulated the dates and locations of records of range expansion of green crabs in Atlantic Canada since 1951 (Table 1), and determined the straight-line distances (by water) between locations using the "ruler" tool in MapInfo Professional 6.5. The median rate of dispersal was 23 km/yr (range 1.5-101 km/yr, N=26). If we define Atlantic Canada as the area south of Ungava Bay and seaward of Quebec City, then it would take about 70 and 40 yr, respectively, for green crabs to arrive at these locations at the median rate of range expansion in Canada. We decided to look at the probability of dispersal of green crab throughout its possible range in Atlantic Canada within the next 30 yr.

As a first approximation, we set the probability of "arrival" within the next 30 yr as:

$$p1 = ((30/70)+(30/40))/2 = 0.59$$

We are "reasonably uncertain" of this value.

3.2. Impact (I1 – does not arrive)

We assume that if the species does not arrive, then impact I1=0. We are "very certain". The same I1 value would apply to both the environmental and economic impacts. The only situation where I1>0 would be in the case where the benefits of having the species present exceed the costs. Despite the potential benefits of green crabs (section 2.7), it is our view that these are not sufficient to justify assigning I1>0.

3.3. Survival (p2)

We assume that p2 refers to survival without reproduction, therefore in developing a value for p2 we focused on the conditions required for the survival of adult crabs.

We postulate that the eventual distribution of green crabs in Canada will be limited by temperature and salinity. Green crabs can inhabit most coastal habitats, but have been more successful in invading sheltered estuaries. Since most ports are located in embayments or estuaries, these are logical points of inoculation for ship-borne taxa. Hidalgo et al. (2005) consider green crabs to be eurythermic, being able to survive temperatures from <0 to >35^{o}C. Green crabs are euryhaline, tolerating salinities ranging from 4 to 52$^{o}/_{oo}$, although their effective lower limit for longer-term survival is more likely 10$^{o}/_{oo}$ (Cohen and Carlton 1995). Thus in Canada the distribution of adult crabs will be limited by the lower salinity rather than the higher salinity.

Chmura et al. estimated the northern thermal limit of green crab in Canada, based on mean monthly February temperature (usually the coldest month of the year), as being about 250 km south of Ungava Bay. We consider DeRivera et al.'s (2006) more conservative model under the section on "Establishment", as it is based on larval development.

If Chmura and colleagues are right, the green crab could spread up the St. Lawrence estuary. In that case, we consider that salinity will limit its survival in the St. Lawrence estuary to areas with salinity ~10 $^{o}/_{oo}$ or greater. The lowest salinity values in the St. Lawrence estuary occur in May, and vary between 22 $^{o}/_{oo}$ on the north shore and 15 $^{o}/_{oo}$ on the south shore in the vicinity of Mont-Joli, QC (El-Sabh 1979). We conservatively suggest this area as an approximate upstream limit of green crab in the St. Lawrence estuary.

The northeastern limit in Canada (250 km south of Ungava Bay) would be 87% of the distance to Ungava Bay from the nearest green crab at present, using the most direct water route. The northwestern limit (Mont-Joli) would be 90% of the distance to Quebec City from the nearest green crab (northern PEI).

Therefore, we estimate the value of p2 as the average of these percentages,

$$p2 = (0.87+0.9)/2 = 0.885$$

We are “reasonably uncertain” of this estimate.

3.4. Impact (I2 – arrives but does not survive)

If the species arrives but does not survive, there is no impact, either environmental or economic. Therefore we set I2=0. We are “reasonably certain”. The element of uncertainty is the potential cost if a disease or parasite were spread to native species. The probability of this occurring with a larval introduction is very low. The probability of this occurring with an adult introduction is higher, but may still be near zero if the introduction is of only a few crabs which survive only a very short period.

3.5. Establishment (p3)

Establishment requires successful reproduction. Larvae of green crab are more sensitive to temperature and salinity than the adults. Larval development appears limited to the range from 10 to ~25^{o}C (Cohen and Carton 1995). Larval stages can survive salinities as low as 17$^{o}/_{oo}$ (Hidalgo et al. 2005), but metamorphosis to the megalopa stage required salinities greater or equal to 20 $^{o}/_{oo}$ (Anger et al. 1998).

The model of DeRivera et al. (2006) predicts that Baie-Comeau would be too cold for larval development. The latter estimate is based on New England crab physiology, these animals having originated from very near the northern limit of green crab in Europe (Roman 2006). We speculate that the Gulf of St. Lawrence populations are more temperature-tolerant. Unfortunately, DeRivera et al. did not evaluate survival at many sites in Atlantic Canada; the only others were the Magdalen Islands and Halifax, both of which were judged suitable (and where green crabs currently occur). We assume that the temperature regime of Baie-Comeau probably typifies most of the Northern Gulf, which would imply that sites to the northeast of the Gaspé Peninsula would be unsuitable as well, by DeRivera et al.’s model.

The northeastern and northwestern limit in Canada based on this prediction would be Gaspé. This would represent 16% of the distance to Ungava Bay and 30% of the distance to Quebec City from the nearest green crab at present. We averaged these two percentages to estimate p3.

$$p3 = (0.16+0.30)/2 = 0.23$$

We are “reasonably uncertain” of this value.

3.6. Impact (I3 – arrives, survives, but does not establish)

If the species were to survive but not establish, this would imply the absence of reproduction. Adult green crabs live a minimum of 4-6 years (see above). The estimate of impact must therefore take into consideration the effects of adult crabs on the receiving environment during up to 6 years. However, if the population is not reproducing the “founder population” of crabs will probably be quite small.

Green crab is a voracious predator on a variety of marine organisms including species from at least 104 families, 158 genera, in 5 plant and protist and 14 animal phyla (Cohen and Carlton 1995). Patterns of ecological impacts have been consistent through multiple invasions. High impacts are indicated for bivalves, moderate to high impacts on other crabs. Impacts on fishes and birds are suspected but poorly documented (Grosholz and Ruiz 1996).

For this risk assessment, we focused on effects on bivalves, as these are the best documented. Green crabs at ambient density (1 crab/m^2) removed ~80% of soft-shell clams <17 mm in field experiments in Pomquet Harbour, NS. The rate of consumption was 3.1 – 21.8 clams/crab/day (Floyd and Williams 2004). In laboratory experiments in PEI, the mortality over 4 d was 5-10% of quahogs, 10% of oysters (<15 mm size class only), 75% of mussels (15-25 mm size class only), and 30% of soft-shell clams (>25 mm size class) (Miron et al. 2002). In New England, laboratory and field experiments with a duration up to 2 d found the mortalities of mussel to be 75% (no control) and 44% (compared to 25% in the control) (Tyrrell et al. 2006).

The probability that green crabs will have an impact on bivalve populations seems fairly high, given the above, but in the absence of a reproducing and spreading population, the impact would be localized and presumably only a small number of crabs would be involved. We therefore set environmental I3=0.1, and are “reasonably uncertain” that this is appropriate.

This scenario assumes episodic and very sporadic passive transport of crabs to the area. The costs of survival are likely to be quite small, probably undetectable if the species were distributed in a non-vulnerable area. As a “worst case” scenario, we considered an inoculation of 100 crabs, which all survived for 6 years, in an estuary where there was an aquaculture operation rearing softshell clams over 1 hectare of soft-bottom habitat. Assuming each crab eats x clams per day for y days during the growing season for 6 years, that is a loss of z clams to the grower, perhaps a value of $1000. We assumed that 100 crabs would not do enough damage to the more widely dispersed wild populations of native species to assign an economic value.

The value assigned to economic I3=$1000. This estimate is “very uncertain”.

The cost of survival would be continuous if introduction occurred through active migration of crabs into an area or through continuous anthropogenic inoculation, but only short-term as above if introduction was episodic and infrequent.

3.7. Spread (p4)

Given the highly efficient nature of dispersal of green crabs, we consider the probability of spread to be high. We set the probability of “Spread” at p4=0.9. This estimate was not based on a literature value, but reflects our perception that the spread of green crab is practically inevitable. We are “reasonably certain” that this is appropriate, as the green crab range in Atlantic Canada continues to spread.

3.8. Impact (I4 – arrives, survives, establishes in a localized area)

The probability of impact on a limited area is relatively high if certain kinds of activities are undertaken in that area (e.g. bottom culture of softshell clam, quahogs etc.). Impact may be lower on other kinds of habitat or fishery activities. We suggest environmental I4 = 0.4 with a certainty of “reasonably uncertain”.

It might be possible to better quantify this estimate based on the proportion of estuaries in which bottom culture, or fisheries for benthic bivalves, are commercially important.

Assuming that the green crab established locally in an area where vulnerable economic activities take place, the associated costs could be substantially greater than those assigned to I3. Assume in the worst case scenario, that green crabs totally prevent recruitment of cultured and wild benthic bivalves in five estuaries. That could translate to a value of $50,000 per year, in perpetuity. In the case of risks over the next 30 years, the total cost of establishment in this limited area would be economic I4= $50,000/yr x 30 yr = $1,500,000. The certainty of this estimate is “very uncertain”.

We recognize that there are also ecosystem costs (direct and cascading trophic interactions, including those associated with the loss of ecosystem services provided by the bivalves) in this scenario which we are unable to estimate at this time.

3.9. Impact (I5 – arrives, survives, establishes and spreads)

If the green crab spreads, the probability of it encountering vulnerable areas increases. Therefore we set the probability of impact at environmental I5=0.6 with a certainty of “reasonably uncertain”.

Colautti et al. (2006) used economic losses attributed to 21 NIS to empirically determine appropriate cost projections for other NIS. They proposed median (52% loss), quartile (25%) and half-quartile (20%) cases were appropriate maximum, mid-range and minimum cost projections.

Applying these projections to fishery and aquaculture landings (year 2000), Colautti et al. (2006) projected the economic impact of green crabs in Atlantic Canada (Table 2).

For consistency with our above scenarios, we use only the bivalve portion of this estimate. We used Colautti et al.’s “midrange” values:

Economic I5 = $8,750,000/yr x 30 yr = $262,500,000.

We are “very uncertain” of this estimate. For one thing, this is only a projection for effects in the Gulf of St. Lawrence, and does not take into account the past loss of production of bivalves in the Bay of Fundy or Atlantic shoreline, or any ongoing loss of fisheries revenue in those areas due to the limitations imposed by the presence of green crab. We also had reservations about the means by which Colautti and colleagues determined the range of “typical” cost projections, the calculation of which contained at least one misquoted value (Locke is cited as having indicated a 50% loss associated with tunicate invasions in PEI, whereas the value she gave to Colautti et al. during a telephone interview was 15%).

4. RESULTS

Using the environmental impacts values, the QBRAT analysis determined the biological risk was 0.1099 (Table 3; Appendix 1). This risk value was difficult to interpret in isolation, but perhaps would have been useful as a means of comparison of several possible invasion scenarios. Within the single calculated value, it was feasible to investigate the relative contribution of different stages in the invasion process. The biggest portion of the risk was associated with establishment and subsequent spread of the species, which is what we would have predicted *a priori*.

Our estimates of the probabilities of survival, establishment, etc., are probably very conservative, i.e., biased in favour of failure of an invasion, because of the reliance on literature based on more southerly genotypes (Table 3). Green crabs from the southern Gulf of St. Lawrence and northern Europe may be more likely to survive in the northern Gulf than those from the Bay of Fundy and New England. However, the models we cited (e.g., the thermal limits model of DeRivera et al. 2006) are based on the latter. Inoculations of green crabs into the northern Gulf and Labrador are likely to come from southern Gulf populations because they are closer, have more local traffic, active dispersal of adults, and easier oceanographic transport of larvae.

The calculated risk, using hypothetical economic costs as the inputs to “impacts”, was $30,170,000 over 30 yr, or just over $1 million annually (Table 3; Appendix 2). The risk was primarily associated with the spread of the species; costs of localized invasions were smaller, but could still be substantial.

We consider our estimates of costs to be conservative. We examine the potential costs on bivalve harvests only, and only for the Gulf of St. Lawrence. We did not take into account any of the large number of possible effects of green crabs on ecosystem services, biodiversity, non-bivalve commercial fisheries and other values that could potentially be affected by green crabs. Within the bivalves alone, one important function is the removal of nutrients from eutrophic coastal systems. Rice (2001) estimated that for every kg of shellfish tissue harvested, 16.8 g of nitrogen is removed from the water body.

Taking into consideration our reservations about Colautti et al.’s (2006) model, and the limitations of our present study (with its primary goal of serving as a trial of QBRAT rather than a comprehensive study on green crabs) we consider that there are no valid estimates of the economic impacts of green crabs in Atlantic Canada. It must be stressed that the values we have used as QBRAT impacts are extremely hypothetical, based on our guesswork rather than actual economic data. A widely cited estimate of actual costs of green crab in Atlantic Canada and New England ($44 million) attributed to Pimentel (2000), has been shown to be in error (Carlton 2001, Hoagland and Jin 2006). It is based on Pimentel’s incorrect citation of work by Lafferty and Kuris (1996), who estimated potential, not actual, costs of green crab and conducted this exercise for the west coast of the USA between California and Puget Sound, not for New England.

5. RECOMMENDATIONS FOR QBRAT

We found that working through QBRAT was an interesting “thought experiment”, which forced us to structure and quantify our assumptions about each step in the process. It was also valuable in indicating to us where our data were weak and more work would be required to strengthen an estimate.

We had some difficulties with the online manual (Moore et al. 2006) and recommend clarification of the meaning of the inputs to the elements on the “Ps and Qs tab”. For example, what is the rationale for I1, the cost of non-arrival? We interpreted it as 0 in the case that costs > benefits of arrival of the species, but it is open to various interpretations. It was obvious that probabilities P1 through P4 had to be expressed on a scale of 0 through 1 (and indeed this was explicitly stated in the manual), but the appropriate scaling for impacts I1 through I5 was not clear. For environmental impacts, we expressed these also on a scale of 0 through 1, but used dollar values for economic impacts, thus the two QBRAT outputs were scaled differently and not comparable. We noted at the workshop that different presenters used a wide variety of scaling options for the “I” values. Retaining this flexibility is a valuable asset to QBRAT as it allows for further research on assigning impact scales, but it should be explained more clearly in the manual. A further source of confusion is the determination of economic costs of management vs. the economic costs of invasion. In our presentation to the QBRAT workshop, we misunderstood the meaning of the “fixed costs” elements, F1 through F4, and incorrectly used these to input our “economic impacts” estimates.

In our initial calculations we also found that the “report” function consistently produced an empty file and we had difficulties in outputting the results, but this was corrected by re-installing the QBRAT program.

Although we did not make use of this feature of QBRAT, the ability to compare the costs and benefits of management is a valuable aspect of the program. This will be an essential step in the estimating the costs and benefits that are required for any Rapid Response protocol.

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Table 1. History of the dispersal of green crab in Atlantic Canada.

Region	Site	Year	Notes	Reference
Bay of Fundy	Digdeguash R.; Passamaquoddy Bay	1951		Leim 1951
Bay of Fundy	Lepreau Basin, NB ; Sandy Cove (St. Mary Bay), NS	1953		MacPhail 1953
Atlantic shore NS	Wedgeport, NS	1954		MacPhail and Lord 1954
Atlantic shore NS	Lockeport, NS	1960		Audet et al. 2003
Atlantic shore NS	Peggy's Cove, NS	1964		Audet et al. 2003
Atlantic shore NS	Prospect Bay, NS	1966		Audet et al. 2003
Atlantic shore NS		1965-1973	Not present between Halifax and St. Marys River	Audet et al. 2003
Atlantic shore NS	Whitehead, NS	~1978	~600 km N of known distribution; possible *de novo* introduction	Audet et al. 2003
Atlantic shore NS	Marie-Joseph, NS; Tor Bay, NS	1982-1983		Audet et al. 2003
Atlantic shore NS	Chedabucto Bay, NS	~1985		Audet et al. 2003
Atlantic shore NS	Bras d'Or Lake, NS; Ingonish, NS	1997		Audet et al. 2003
Atlantic shore NS		1997-2001	Not present at South Harbour (Aspy Bay, NS)	Audet et al. 2003
Gulf of St. Lawrence	Aulds Cove (at Canso Causeway), NS	1994	1st observation in Gulf of St. Lawrence; from Atlantic side of Canso Causeway via ship lock	M. Dadswell, pers. comm.
Gulf of St. Lawrence	Margaree Harbour, NS	1994 or 1995		Audet et al. 2003
Gulf of St. Lawrence	St. Georges Bay	1997		Audet et al. 2003
Gulf of St. Lawrence	Pleasant Bay (Cape Breton I.), NS; Malignant Cove (St. Georges Bay), NS	1997		Audet et al. 2003
Gulf of St. Lawrence	Merigomish, NS	1998		Locke et al. unpub. data
Gulf of St. Lawrence	Caribou River, NS	1999		Locke et al. unpub. data
Gulf of St. Lawrence	Tatamagouche Bay, NS	2000		Locke et al. unpub. data
Gulf of St. Lawrence	Wallace Bay, NS	2001		Locke et al. unpub. data
Gulf of St. Lawrence	Gaspereau River (Baie Verte), NB	2002		Locke et al. unpub. data
Gulf of St. Lawrence	Cape Jourimain (Northumberland Strait), NB	2006		R. Hart, pers. comm.

Table 1 (continued). History of the dispersal of green crab in Atlantic Canada.

Region	Site	Year	Notes	Reference
Gulf of St. Lawrence	Georgetown, PEI	1996		N. MacNair, pers. comm.
Gulf of St. Lawrence	Naufrage, PEI; Vernon Bridge, PEI	1998		N. MacNair, pers. comm.
Gulf of St. Lawrence	North Lake, PEI ; Gascoigne Cove (Wood Island), PEI	1999		N. MacNair, pers. comm.
Gulf of St. Lawrence	Charlottetown Harbour, PEI	2000		Locke et al. unpub. data; N. MacNair pers. comm.
Gulf of St. Lawrence	Savage Harbour, PEI; Victoria, PEI	2001		N. MacNair, pers. comm.
Gulf of St. Lawrence		2002-2005	No spread in PEI.	N. MacNair, pers. comm.
Gulf of St. Lawrence	Grande Entrée Lagoon (Magdalen Islands), QC	2004		N. Simard, pers. comm.

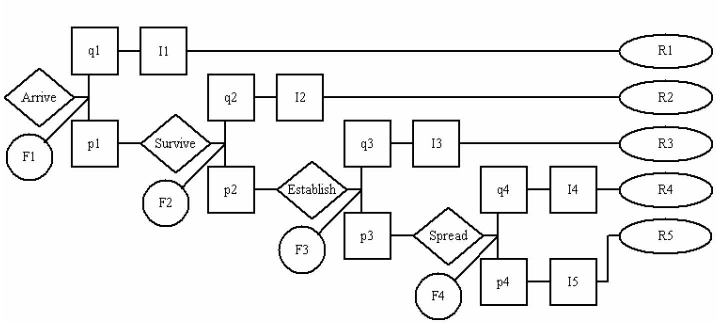
Table 2. Projected annual costs of green crab to established fishery industries in the Gulf of St. Lawrence, from Colautti et al. (2006).

Resource	Locality	Annual value (x $1,000)	Projected annual impact (x $1,000)		
			Min. (20%)	Mid. (25%)	Max. (52%)
Soft-shell clams, blue mussels, American oysters	Gulf of St. Lawrence	35,000	7,000	8,750	18,200
Lobster and rock crab	Southern Gulf, Newfoundland	175,000	35,000	43,750	91,000

Table 3. Summary of values input to QBRAT for determination of risks associated with expansion of green crabs in Atlantic Canada.

Step	Variable	Value	Uncertainty
Arrival	p1	0.59	Reasonably uncertain
	I1 (environmental)	0	Very certain
	I1 (economic)	$0	Very certain
Survival	p2	0.885	Reasonably uncertain
	I2 (environmental)	0	Reasonably certain
	I2 (economic)	$0	Reasonably certain
Establishment	p3	0.23	Reasonably uncertain
	I3 (environmental)	0.1	Reasonably uncertain
	I3 (economic)	$1,000	Very uncertain
Spread	p4	0.9	Reasonably certain
	I4 (environmental)	0.4	Reasonably uncertain
	I4 (economic)	$1,500,000	Very uncertain
	I5 (environmental)	0.6	Reasonably uncertain
	I5 (economic)	$262,500,000	Very uncertain

Appendix 1. Biological Risk Assessment Report: Environmental.

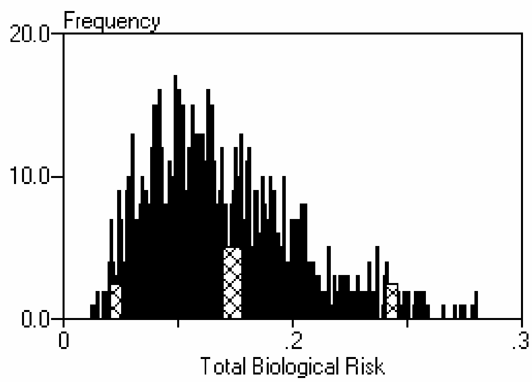


Species: green crab

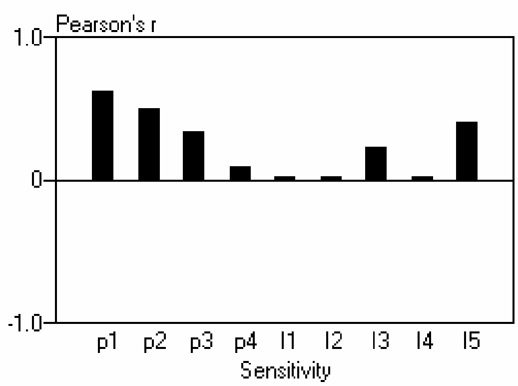
Location: Atlantic (environmental)

Date: 24-Jul-2007

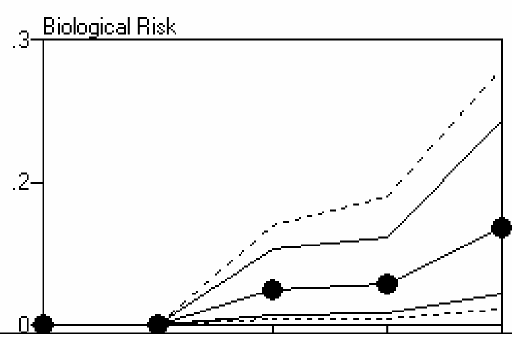
Monte Carlo Simulation Results: Biological Risks [PRNG=VB]



Probabilities	Calculated Risks
p1 = 0.59 (0.1703,U)	R1 = 0
p2 = 0.89 (0.2555,U)	R2 = 0
p3 = 0.23 (0.0664,U)	R3 = 0.04021
p4 = 0.90 (0.1559,U)	R4 = 0.004804
	R5 = 0.06485
	Rb = 0.1099
Impacts	Simulation Stats
I1 = 0 (0,U)	N = 1000
I2 = 0 (0,U)	Mean = 0.103
I3 = 0.1 (0.02887,U)	SD = 3.596
I4 = 0.4 (0.1155,U)	
I5 = 0.6 (0.1732,U)	



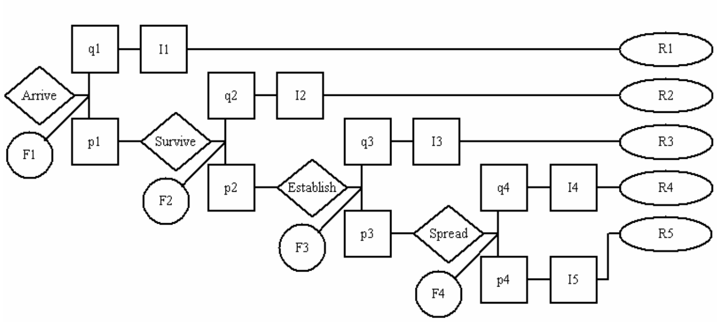
Sensitivities	
p1 = 0.626	
p2 = 0.496	
p3 = 0.331	
p4 = 0.088	
I1 = 0.028	
I2 = 0.028	
I3 = 0.222	
I4 = 0.026	
I5 = 0.406	



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

	Mean	Min	Max	Lower CI	Upper CI
S1	0	0	0	0	0
S2	0	0	0	0	0
S3	0.03756	0.007084	0.1038	0.01119	0.08031
S4	0.04323	0.007337	0.1344	0.01303	0.09225
S5	0.103	0.01718	0.2701	0.03334	0.2141

Appendix 2. Biological Risk Assessment Report: Economic.

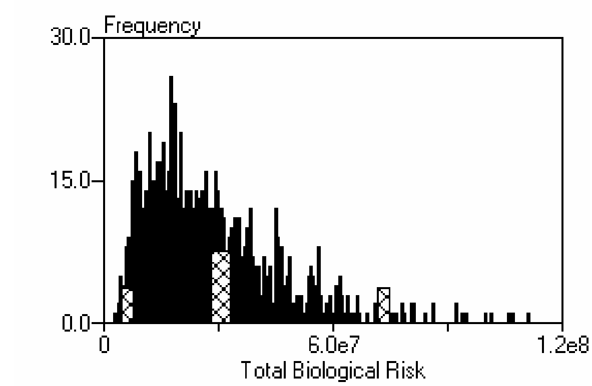


Species: green crab

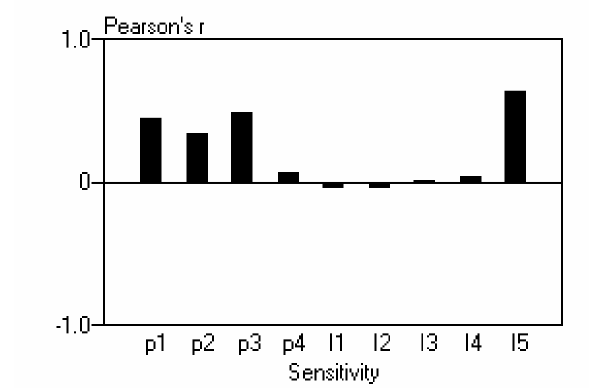
Location: Atlantic (economic)

Date: 24-Jul-2007

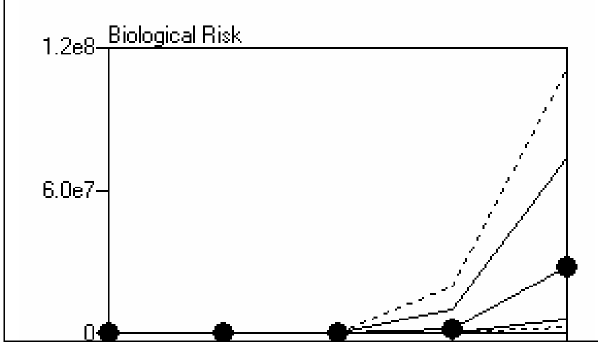
Monte Carlo Simulation Results: Biological Risks [PRNG=VB]



Probabilities	Calculated Risks
p1 = 0.59 (0.1703,U)	R1 = 0
p2 = 0.89 (0.2555,U)	R2 = 0
p3 = 0.23 (0.0664,U)	R3 = 402.1
p4 = 0.90 (0.1559,U)	R4 = 1801000
	R5 = 28370000
	Rb = 30170000
Impacts	**Simulation Stats**
I1 = 0 (0,U)	N = 1000
I2 = 0 (0,U)	Mean = 27550000
I3 = 1000 (404.1,U)	SD = 1.035e09
I4 = 1.500e08 (60620000,U)	
I5 = 2.625e08 (1.061e08,U)	



Sensitivities	
p1 = 0.439	
p2 = 0.330	
p3 = 0.480	
p4 = 0.058	
I1 = -0.031	
I2 = -0.031	
I3 = 0.012	
I4 = 0.030	
I5 = 0.633	



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

	Mean	Min	Max	Lower CI	Upper CI
S1	0	0	0	0	0
S2	0	0	0	0	0
S3	368.7	48.79	1162	87.87	893.6
S4	2106000	50.84	20140000	110.2	9931000
S5	27550000	2459000	1.113e08	5939000	73290000