Schizophrenic fisheries management
– the case of the red king crab management

Jannike Falk-Petersen and Claire W. Armstrong
University of Tromsø, Department of Economics and Management,
Jannike.Falk-Petersen@nfh.uit.no

Abstract

The red king crab (*Paralithodes camtschaticus*) is an alien invasive species in the Barents Sea representing a value as well as a potential pest. A bio-economic model is applied analysing the economics of the king crab in relation to the costs it represents to traditional fisheries as well as the income from catching the king crab itself. Since the impact of the king crab on the native species is not known, bycatch costs in traditional fisheries were used as a proxy for cost related to the invasion. The model suggests that the king crab stock (X) should be harvested close to maximum sustainable yield (MSY) in order to optimize the profit of the total fishery. The model was robust to changes in input parameters. A lack of quantitative information on ecosystem functioning excludes their contribution to the economy in the initial analysis. To account for the potential costs related to long-term ecological impacts of the invasion the existence of exponential cost functions and threshold values were incorporated in the model. The king crab biomass at which large negative impacts on benthic communities have been observed was used as a proxy of a threshold value. Accounting for non-linearity in the relationship between king crab biomass and cost to traditional fisheries gave an optimum crab stock size substantially below Xmsy. The analysis illustrates the importance and challenges of capturing the often unpredictable costs of ecosystem changes following alien invasions or other disturbances.

Key words: alien invasives, red king crab, bio-economic analysis, threshold values

Introduction

Since its introduction to the Kola fjord in North-West Russia by scientists in the 1960s, the red king crab (*Paralithodes camtschaticus*) population has grown and expanded its distribution down the Norwegian coast (Figure 1) (Orlov and Ivanov 1978, Sundet 2005). The king crab represents both a value as well as a potential pest in the Barents Sea ecosystem. The crab has been a nuisance in traditional fisheries, getting entangled in gear and eating the bait as well as the catch. Being an alien species to the Barents Sea it may also severely impact the ecosystem and thereby the economic basis for resource exploitation. However, the crab is also an important source of income with the total landed value of king crab being close to NOK 100 million in 2005 (FID 2005). The king crab fishery has made it possible for small fishing communities to persist and grow along the Norwegian coast (Monsen 2004). In addition to the commercial fishery, the king crabs attract tourists who want to see and taste the monster crab (www.varanger.com). The benefits to those allocated crab quotas are evident as the high market price of the crab contributes significantly to the income of the fishers (Wessel 2004). Apart from a study on bycatch costs of the crab (Sundet and Hjelset 1999) however, the full cost related to the invasion, including impact on commercial fish stocks, has not been documented due to a lack of biological data (Falk-Petersen et al *submitted*). Invaded areas do show signs of stress including reduced diversity, size and biomass of benthic organisms (Falk-Petersen submitted). According to the Total Economic Value concept (Pearce 1994) these observations indicate that indirect use values related to functional benefits (ex resilience and habitat availability) of the ecosystem are negatively affected by the crab.

This paper analyses the economics of the king crab fishery in relation to the costs it represents to traditional fisheries as well as the income of the king crab fishery itself. A theoretical model by (Skonhoft 2005) is applied to economic and biological data from the Varanger fjord where the king crab first established (see Figure 1). To account for loss of functional benefits of the ecosystem the model is modified by a) assuming an exponential relationship between king crab biomass and cost to the fisheries and b) assuming a threshold value beyond which the king crab biomass has extremely high/ irreversible impact on the ecosystem. The optimal king crab stocks for the three scenarios are determined, and sensitivity analysis of this stock size to input parameters explored and discussed.

The paper is laid out as follows: The next section presents the biology of king crab and their interaction with other species. This is followed by a description of the king crab fishery. The bioeconomic model is then introduced followed by the data input used in the model analysis. Results are presented, and finally discussed.

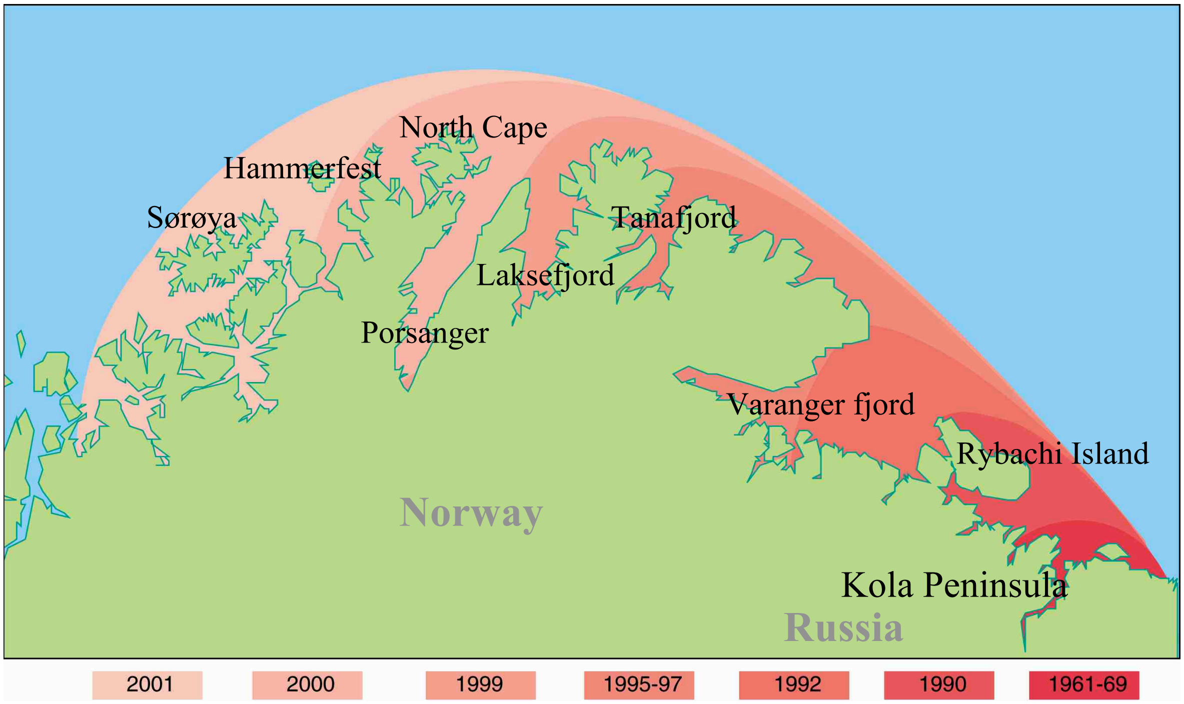

Figure 1. Generalised distribution and spread of the red king crab from area of release on the Kola Peninsula and westward expansion down the coast of Finnmark (Sundet 2002).

Background

King crab biology and interactions with native species

The red king crab (*Paralithodes camtschaticus*) is one of few large, higher trophic level marine organisms that have successfully established in a new geographical region (Jamieson 1998). The crab reaches sexual maturity at about the age of 5 at 100 mm carapace length (Otto 1990; Rafter, Nilssen et al. 1996) and in Norway commercial crabs have on average been about 4 kg (Anonymous 2007). It is a generalist predator feeding on the most available, benthic prey, in addition to collecting and filtering out small invertebrates from the substratum (Cunningham 1969; Bright 1994; Sundet, Rafter et al. 1998). Both juvenile and adult crabs feed on epibenthic organisms that are believed to play an important role in the functioning of benthic systems (Hagen 1995; Piepenburg 1996; Rzhavsky 2006). Reduced benthic biomass and diversity, in particular with respect to large epibenthic organisms such as echinoderms and bivalves, confirms that the king crab has altered community structure as well as the physical appearance of native benthos (Haugan 2004; Pavlova 2004; Rzhavsky 2004; Anisimova 2005; Jørgensen 2005; Pavlova 2008). Biogenic structures, such as the structurally complex scallop beds, influence benthic architecture and represent important habitat, feeding and nursery areas for a number of species ((Sjøtun 1995; Christie 2003; Wallentinus and Nyberg 2007).

While the crab clearly affects native benthos, knowledge is limited with respect to their impact on the fisheries the Barents Sea ecosystem supports (Falk-Petersen submitted). The crab predates on the Icelandic scallop as well as on the eggs of three commercial species (capelin, haddock and Arctic lump sucker) (Gerasimova 1997; Haugan 2004; Jørgensen 2005; Anonymous 2007; Jørgensen 2007). Declines in local Icelandic scallop populations has been reported ((Jørgensen 2005), but the fishery is commercially insignificant. The capelin stock plays a key role in the Barents Sea ecosystem. It is preyed upon by commercially important fish stocks, seals, whales and sea birds and has supported a fishery of annual catches up to 3 million tonnes (Gjøsæter and Bogstad 1998). The significance of egg predation on population dynamics is difficult to quantify due to generally high levels of mortality at earlier life stages. In years of small capelin populations egg mortality due to crab predation could have population level consequences if the capelin spawns in high density crab areas. Arctic lumpsucker is believed to be particularly vulnerable to egg predation by the king crab (Mikkelsen, N., University of Tromsø, pers com). Although locals report that the fish is almost gone from some fjords, fishery statistics for eastern Finmark does not suggest that traditional fisheries have declined following king crab invasion (Anonymous 2007).

The king crab fishery

The king crab was managed collaboratively by the Norwegian and Russian authorities until 2007 (Anonymous 2007). Due to an initial ban on fishing the crab[1], fishers were previously forced to throw over board the crabs caught as bycatch in other fisheries. After negotiations between the two countries, a research fishery was opened in 1994, where a limited number of fishing vessels

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[1] The Russian authorities were originally vehemently negative to any Norwegian harvest of king crabs.

were involved. In 2002 the fishery was opened to commercial harvesting of large males with the management objective of exploiting the crab at maximum economic yield. King crab quotas were given as compensation to boats between 8-15 m in lenght that had been negatively affected by bycatch of crabs in other fisheries (Anonymous 2007). Since 2004 there have been two management regimes for the king crab on the Norwegian side of the Barents Sea. East of 26°E (North Cape) the king crab was until 2007 managed in cooperation with Russian authorities as a resource that should be harvested at a sustainable level, and all catches are regulated by quotas. Damaged, female and undersized crabs are discarded within this management area. West of 26°E the management goal is to stop, or to as far as possible limit, the expansion of king crab. In this area an open access fishery of the king crab has been implemented where it is illegal to throw out king crabs that could survive (Anonymous 2007).

According to the fishers, the king crab fishery is light work and most vessels take their quota in a short period of time. The crab cages are set in the morning and in the evening the fishers return to empty them. The cost lies in buying the cages, which are used for many years and repaired by the fishers themselves. The cages require bait, as for many other fisheries, but they need fewer fishers onboard (Wessel 2004). The quality of the king crab is at its best in the fall. In 2005 the season was from 19th of September to 31st of December, while by 2010 it has been extended from 21st of June to 31 March 2011 (Ministry of Fisheries and Coastal Affairs, http://www.regjeringen.no/nb/dep/fkd.html?id=257).

The king crab market

The king crab is a well known and highly valued delicacy on the international market. The Japanese in particular are willing to pay for king crabs of high quality. The criteria for good quality include weight, meaty legs and a nice colour. Although some crabs are delivered whole to the marked, it is only the legs that are edible (Damsgård, Siikavuopio et al. 1999). The main product is clusters of the three legs and the claw of the crab that are attached to each other (Monsen 2004). The king crab fishers have obtained a high landing price for the king crab, but in the past years the price has declined due to increased landings in Alaska, Norway and North-West Russia. The average price per king crab has gone down from NOK 341 in 2001 to NOK

245 in 2005, though the overall trend from 1994 shows a rise in price (Figure 4) (Anonymous 2006). King crab is a luxury product and the prices of such products are often sensitive to changes in supply. The market is very sensitive to a change in size of the crabs (Seipajærvi 2003). The average individual weight of landed king crabs in the Norwegian part of the Barents Sea has decreased from 5.4 kg in 1999 to 4.2 kg in 2005 (Sundet 2005), presumably due to overpopulation (E. Nilssen, pers com).

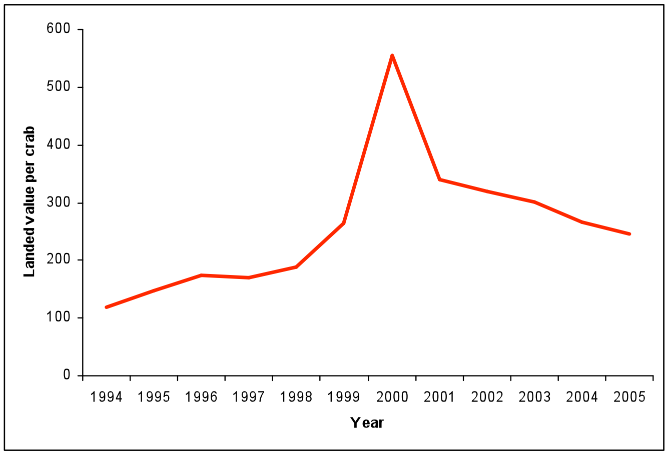

Figure 4: Landed value per crab from 1994 to 2005[2].

The model

The bioeconomic invasive species model applied here is developed by (Skonhoft 2005) for a nuisance species[3]. The profit of resource utilisation from the area, A, is affected by the population of the invasive species, X. This damage is given by $N=N(X)$, with $N(0)=0$ and $dN/dX=N_X>0$. When normalizing the damages to crop profit (see e.g. Carlson and Wetzsten 1993 as in (Skonhoft 2005)), the net profit given the presence of the invasive species is:

1) $U = A(1 - N(X)) \geq 0$

In our case A would be the profit in the area prior to the king crab invasion. The profit is

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[2] Local competition between two landing facilities gave abnormally high landing price in 2000.

[3] An alternative modelling approach could be to use a two-species model with bycatch. The focus in this paper is however the red king crab, and not other interacting species, hence the chosen model seems most suitable.

negatively affected by the costs related to the king crab invasion.

The population of the invasive species is assumed to grow according to:

2) $$\frac{dX}{dt} = F(X) - h = rX(1 - \frac{X}{K}) - h$$

where h is the number of harvested king crabs. The natural growth function is considered a logistic-type model with $F(0) = F(K) = 0$, where $K>0$ is the carrying capacity and $F_{XX}<0$. F_X is positive for a stock size below X^{msy} and negative when $X>X^{msy}$. The maximum specific growth rate is given by $r>0$, and K is the carrying capacity for the invasive species. The crab also represents a value with market price and harvesting costs;

3) $$B = \left[p - c(X)\right]h = b(X)h$$

where $b(X)$ is the unit profit, increasing in the stock size, $b_X = -c_X > 0$. The unit harvest price is p and the unit trapping cost function is specified as $c(X)=a/X$, where $a>0$. The unit profit can be either positive or negative. In the case where the invasive is a pure nuisance $b(X)=-c(X)<0$, while when it has a value $b(X)=p-c(X)\geq 0$.

Maximizing present value overall is given by:

4) $$\underset{<X>}{\text{Max}}\, PV = \int_0^\infty \left[A(1 - N(X)) + b(X)h\right] e^{-\delta t} dt$$

subject to (2), where $\delta>0$ is the discount rate, i.e. the return on alternative investment.

Solving the maximisation problem gives a modified golden rule equation:

5) $$\delta = \frac{-AN_x(X^*) + b_X(X^*)F(X^*) + b(X^*)F_X(X^*)}{b(X^*)}$$

where the first term on the right hand side is the addition to the standard golden rule equation due to the damage effect of the invasive species.

The optimal stock level of the invasive species, X^* given three different relationships between crab stock size (X) and damage (α) was explored. Case I assumes a linear damage function (N(X)=αX), Case II an exponential relationship (N(X)= αX^2) and Case II a threshold level ▯ beyond which the damage function in Case I will increase by a constant α_0 (Figure 2).

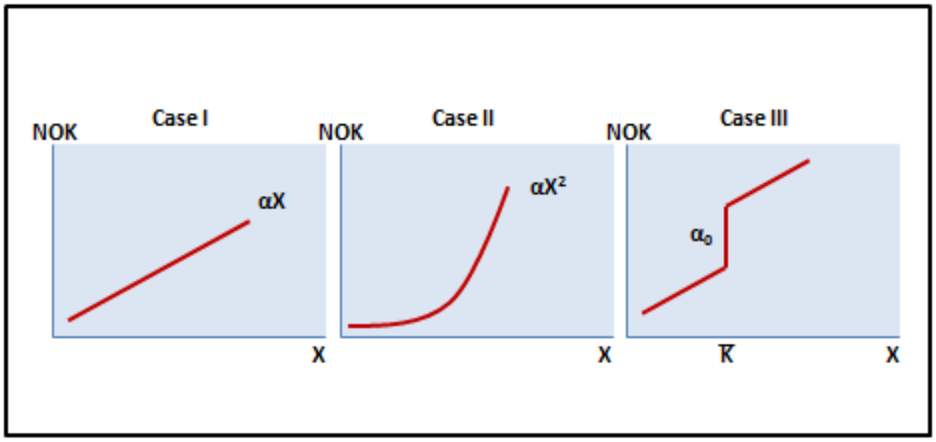

Figure 2: Illustration of how a linear (Case I) and exponential (Case II) relationship between damag cost and invasive stock size X, as well as a threshold value ▯ (Case III) could affect the cost curve.

Case I

Solving the golden rule equation in (5) for the optimal stock level of the invasive species, X^*, given a linear damage function $N(X)=\alpha X$, where α is the unit damage cost normalised to profits A, results in:

$$6)\quad X_1{}^* = \frac{K\left(\left[\frac{ra}{K} - \alpha A + (r-\delta)p\right] + \sqrt{\left[\frac{ra}{K} - \alpha A + (r-\delta)p\right]^2 + \frac{8rpa\delta}{K}}\right)}{4rp}$$

Hence we observe the optimal stock size of the invasive species depends on both the economic and the biological parameters of the model.

Case II

Non-linearity between disturbance and impact, as well as discontinuity around thresholds, exists in ecological systems (Perrings 1994). The damage function in the model was therefore modified by assuming an exponential relationship between damage costs and stock size *X*. Solving the golden rule equation given $N(X)= \alpha X^2$ gives an optimal stock level of the invasive species X_2*

$$7)\ X_2{}^* = \frac{K\left(\left[\frac{ra}{K}+(r-\delta)p\right]+\sqrt{\left[\frac{ra}{K}-(r-\delta)p\right]^2+8(A\alpha K\delta a-\delta apr)}\right)}{4(rp+A\alpha K)}$$

Case III

The existence of a threshold value ▯ where the ecosystem loses resilience and flip from one state to another will be incorporated in the model. When $X\varepsilon$ (0, ▯) a proportional relationship between *X* and damage cost will apply as in Case I. When $X\varepsilon$ [▯, ∞) the threshold is exceeded and $N(X)=\alpha_0+ \alpha X$. Because α_0 disappears from the golden rule equation (as $AN_x(X) = A(\alpha_0 + \alpha X)' =A \alpha$), X^* is given by equation 6), for $X\varepsilon$ [▯, ∞).

Sensitivity analysis was run for a 10% increase in the value of the input parameters for the optimal stock sizes for the three cases.

Data

Economic

Varanger was chosen as a case study due to reasonably good biological data on the adult male stock size and because a study on bycatch costs to vessels <13 m in length was carried out in this area in 1998 (Sundet and Hjelset 1999). Accounts from 1998 for vessels between 8-12.9 m in length from Finnmark county (Anonymous 1999) were used and assumed to be representative for the fisheries in Varanger (see Appendix 1). Out of 198 small vessels registered in Finnmark, 24 were assumed to operate in Varanger as they were based in surrounding fishing villages

(Anonymous 1999). These vessels form the basis for the calculation of the profit, A, from resource utilisation in the area.

Bycatch costs

Only direct costs to traditional fisheries in terms of bycatch costs were included in α (damage cost) when X^* was calculated. In the year of the bycatch cost study (1998) the legal king crab male population was assumed to be 800 000 individuals (see Figure 3). At this crab population size an estimated 1-5% of the cod gill nets had to be replaced per season due to entanglement of the king crabs. The bycatches increased the time needed to tend the nets by about 10%. In the line fishery an estimated 40% of the bait and 10% of the catches were believed to be eaten by the crabs. In the lumpsucker fishery only a few reported that fishing nets were destroyed or catches eaten by the crab. The season of this fishery was very short in the year of the investigation due to problems related to the sales. In all the fisheries many fishers reported increased fuel expenses as they had to leave traditional fishing grounds to find "crab free" fishing areas The total catches, and thereby the income, from other fisheries seems to be unaffected by bycatch of the king crab as the fishers compensate for the losses by spending more time fishing (Sundet and Hjelset 1999). Based on these estimates the cost of maintenance and replacement of gear was assumed to have increased by 3% after arrival of the crab. Fuel costs increased by about 10% regardless of fishing gear employed to reach alternative fishing grounds. Since the total catches from other fisheries are unaffected by the bycatch (Sundet and Hjelset 1999), it was assumed that in a given year the income from the traditional fisheries (A) remains the same, but the costs of fishing increases due to king crab bycatch. In 1998 the income of an average vessel between 8-12.9 m in Finnmark was NOK 663 904, operating costs NOK 576 127 and profit before taxes 87 777. Subtracting the cost of gear replacement and maintenance (NOK 1195), extra fuel use (NOK 2 127) and subtracting the income of the king crab (NOK 12 000) gives an annual profit per vessel of NOK 71 996 (see Appendix). The total profit in absence of the king crab (A) for the fleet of 24 vessels in Varanger is therefore NOK 1 727 910 (see Table 1) (Anonymous 1999).

From the fisheries statistics it is not possible to differentiate the costs involved in catching the various target species. It was therefore assumed that the cost of trapping one ton of a species is equal across target catches. This gave a trapping cost (a) of king crab of NOK 2 275 per vessel per year (see Appendix X). The total cost of bycatch divided by an assumed 800 000 legal male king crabs in 1998, gave a damage cost per thousand large male king crabs of 100. Normalized to profit the damage cost (α) is 103.67. The average price per crab in 1998 was NOK 189 (Anonymous 2006). A market discount rate (δ) of 5% was assumed.

Biological

Data on king crab population dynamics suggests that the carrying capacity of legal male king crabs in Varanger is 3 million individuals (Carsten Hvingel, IMR, *pers. com.*). Models describing the population growth of the king crab in the Barents Sea are under development by The Institute of Marine Research (IMR). Preliminary values have been provided for this model based on population estimates in Varanger where the estimates are believed to be the most accurate (Carsten Hvingel, IMR, *pers. comm.*). The population of legal male crabs (>137 mm carapace length) is believed to be representative for the population of large crabs. Although the population growth model needs to be refined, the values are believed to be representative for the stock. The natural growth rate of the stock (r) was estimated to 0.227, which is in the same range (r=0.212) as for king crab males in their natural area of distribution (Zhou, Shirley et al. 1998).

Table 1 summarises the values of the input parameters of the model for calculation of X*.

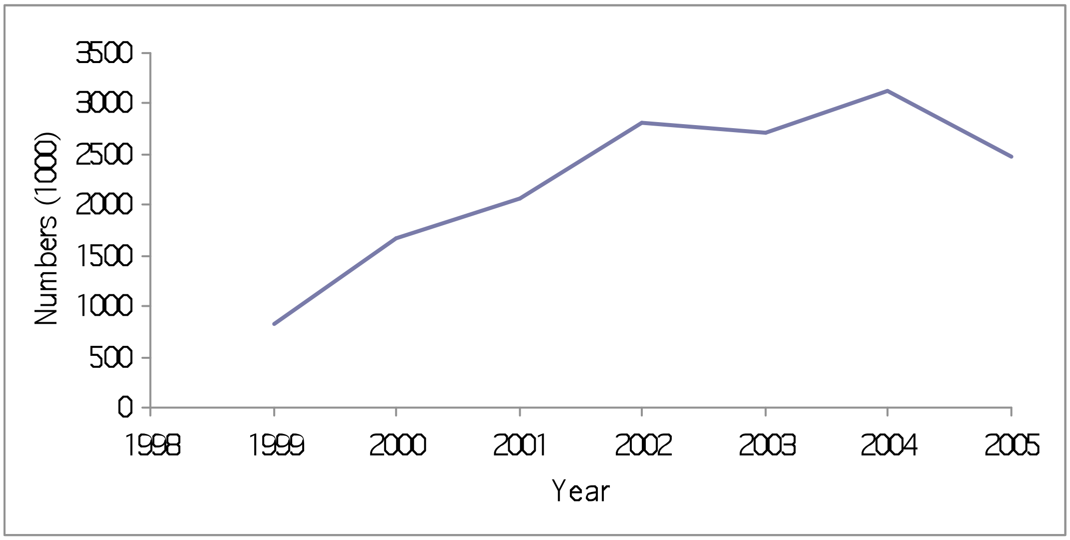

Figure 3: Population growth of red king crab in Varanger from 1999 to 2005.

Table 1: Initial value of input parameters (*A, p, a,* α, *r, K, δ)* for the model estimating optimal size of king crab population (*X**) for Varanger fjord in 1998.

Profit in absence of king crab (*A*)	Price per 1000 crab (*p*)	Trapping cost of king crab (*a*) per vessel per year	Damage cost per thousand crab (*α*) normalized to profit	Maximum intrinsic growth rate of king crab stock (*r*)	Carrying capacity of king crab stock (*K*)	Discount rate (δ)
1 727 910	189000	2275	103.67	0.2267	3 mill ind.	0.05

Optimal X given non-linear relationship between N(X) and X

The majority of the estimates of carrying capacity with respect to how many crabs the benthic production can sustain (corresponding to *K* in the model) have not considered biodiversity issues. Gerasimova (1997) calculated *K* of crabs larger than 80 mm CW to be 2.74 ton km^{-2}. Estimates of benthic carrying capacity suggest that the Barents Sea can sustain a biomass of 1.2 ton km^{-2} small (<100 mm CL) and 2.8 ton km^{-2} large crabs (>100 mm CL) (Falk-Petersen 2004). Assuming half the population of large crabs are males, *K* for large males is 1.4 ton km^{-2}. The biomass of large males divided by their numbers gave an average size of large males of 2.31 kg (0.00231 t). 1.4 ton crabs of 0.00231 ton gives a *K* of 606 large males per km^2.

The way management authorities currently define carrying capacity of the Barents Sea with respect to king crab ignores biodiversity considerations. Ecological surveys warn about severe impacts of the king crab on Barents Sea benthic systems (Haugan 2004; Pavlova 2004; Rzhavsky 2004; Anisimova 2005; Pavlova 2008), but it has not yet been established at what biomass levels of crabs these changes are seen. Thus, estimates of at what level of biomass the king crab has major impacts on benthic communities, defined by ▯ in this model, do not exist. (Pavlova 2008) suggested that juvenile king crab densities over 5 individuals per 100 m^2 may deteriorate both their own food resources as well as those of fish in benthic communities with a biomass lower than 50 g per m^2. Epi-benthic productivity in Porsanger fjord, close to Varanger, is on average 22 g per m^2 (Jørgensen 2009). Assuming that consumption per biomass of adult crabs is 67% of that of juvenile crabs (Falk-Petersen 2004) and half of the biomass is male crabs, densities of about 1.5 male crabs per 100 m^2 will exceed ▯. This would correspond to 15 000 crabs per km^2, while the highest estimated density in Varanger fjord is 606 large males/km^2 at a population close to 3 million individuals (Table 2). Clearly the ▯ estimated for juveniles cannot be applied to large, male crabs feeding in the less productive deep water areas. Preliminary studies by (Jørgensen 2009) calculate that on average it takes an average sized crab 1-200 days to eat all the epibenthos within a 1000 m^2 area in a North-Norwegian fjord. Large spatial variations with respect to epibenthic production result in differences in how many crabs an area can sustain. Depending on the productivity of the area carrying capacity can range from 4-20 crabs per km^2 (or 2-10 male crabs/ km^2 assuming half the population is males)(Jørgensen, L.L. pers. Com). Being preferred prey of the crab epibenthos is a good indicator of disturbance (Falk-Petersen submitted). Assuming that 1/3 of the male population is mature the epibenthos in Varanger could sustain a population of between 0.67 and 3.3 crabs/km^2. The area of the Varanger fjord is about 3500 km^2 (wikipedia.org). Thus the corresponding ▯ for Varanger is between 2345-11 550 commercial males.

Table 2. Absolute biomass and density of males >137mm CL in the Varanger fjord 1999-2009

Year	Absolute biomass	Number of crabs per km^2
1999	822,45	
2000	1665	198
2001	2064	153
2002	2821,5	400
2003	2716,5	613,8
2004	3132	461,8
2005	2482,5	186,29
2006		130,14
2007		156,91
2008		112,23
2009		78,06

Results

Assuming a linear relationship between damage (bycatch costs) and crab population size, the optimal king crab stock size (X^*) is 1.169 million individuals without and with a threshold value ▯ (Case I and Case III). An exponential relationship between damage and crab population size (Case II) gave a steady-state crab stock of 31 individuals (Case 2).

Table 3: Estimation of percentage change in optimal king crab stock size (X^*) for a 10% increase in the value of input parameters*.

Input parameters	r	a	K	α	A	δ	p
Case I and III	-2,61	0,00	-10,00	0,03	0,00	2,84	-0,03
Case II	-0,02	-4,87	-4,87	4,66	4,66	-4,87	-0,02

*r- maximum intrinsic growth rate of crab stock, a- trapping cost of king crab, K- carrying capacity of crab stock, α-damage cost of crab, A- profit in traditional fishery, δ- discount rate, p- price of crab.

As can be seen in Table 3, the Case I and III models are sensitive to the carrying capacity (K). They are quite robust with respect to the other parameters, although it is most sensitive to growth rate (r) as well as the discount rate (Table 3). The Case II model is less sensitive to K compared to Case I/III, but more sensitive to changes in a, α, A and δ.

Discussion

This attempt at determining the optimal biomass of an alien species given that it represents a valuable resource as well as a potential threat to the ecosystem, illustrates the challenges of conducting bio-economic analysis when the knowledge of ecological impact is scarce. The initial analysis (Case I) shows that the direct use value of the king crab fishery far outweighs the low costs related to bycatch of crabs in traditional fisheries. However, the model is sensitive to the carrying capacity (K), which is estimated from the observed biomasses of crabs in Varanger fjord. Being a new predator in the region, the crab could be expected to initially overshoot the carrying capacity in the fjord before a new equilibrium between the crabs and their prey is established (Williamson and Fitter ; Bohn, Sandlund et al. 2004). Although the Varanger fjord crab population has been affected by harvesting, indications of biodiversity losses (Haugan 2004), suggests that the K used in the biological model is too high. The establishment of the true value of K could make it possible to harvest the crab at a level where the large population fluctuations (boom and bust cycles) associated with invasive species (Bohn, Sandlund et al. 2004) could be reduced, thereby making the crab fishery more stable.

Assuming an exponential relationship between the crab population size and damage (Case II) reduced the optimal crab size drastically. The optimal crab stock size, X^*, is less sensitive to changes in the intrinsic growth rate of the stock and the carrying capacity (K) because X^* is far left on the X-axis. The cost of catching the crab (a) is fairly low. This can explain why the model is not very sensitive to an increase in a. It is not intuitive that the optimal stock size is reduced when a increases in Case II. This result will be explored further. Higher sensitivity of the Case II model to damage costs, profit to the traditional fisheries and the discount rate can be explained by the optimal crab stock size being close to zero. Increased discount rate implies impatience with respect to taking out profit, explaining a reduction in the optimal crab stock size in Case II. In Case I, however, the optimal crab stock size increases. The impact of δ will be explored further.

Introduction of a threshold level (Case III) did not change the optimal crab stock size compared to when the relationship between crab biomass and damage was linear (Case I) for $X^*>$ ▯. This is because the optimal crab stock size is determined by the point where the slope of the total income function equals that of the total cost function. The optimal crab stock size will only change if the cost function changes at population levels beyond ▯.

For the purpose of this study the ecological threshold value was determined by the king crab biomass that the Barents Sea epibenthic productivity can sustain. The estimates of benthic carrying capacity, however, only consider the capacity of the benthic community to produce biomass and do not take into account other qualities such as maintaining biological and structural diversity. Furthermore, the full impact of alien invasive species on native systems is often not immediately apparent. In the long run the costs to the ecosystem and subsequently the economy may be significant (Elton 1958; Galil 2007). We are therefore operating with the lower bound with respect to the biomass at which the crab can cause severe damage to the ecosystem. Fishers, environmental organizations, local politicians and individual scientists have voiced their concern about the impact the crab may have on the ecosystem. Ecological threshold values, defined in this paper by ▯, cannot be accurately determined. Bio-economic analysis must therefore be accompanied by ethical judgements on the socially acceptable level of environmental impact (Perrings 1994). The main concern of crossing the threshold is the consequence, or the size of α_0. Thus, a risk analysis of the king crab invasion should include the probability of crossing a threshold value as well as the probability of severe consequences.

In the management area west of 26°E, the expansion of the king crab is meant to be stopped or limited through an open access fishery. However, low landing prices of the crab (NOK 10-30 per kg depending on quality) (Anonymous 2004) in combination with an apparently low cost of the crab to traditional fisheries, results in the economic incentives for fishing the crabs currently being low. Thus if the open access stock size of the crab is higher than ▯, subsidies are needed to keep the stock at an acceptable level if $X^*<$ ▯. Norwegian authorities have recognised that the king crab invasion may result in ecosystem losses and have allocated money to fishing down the crab. Alien invasive species are rarely eradicated once established (Mack, Simberloff et al. 2000). Control efforts must therefore be sustained it aims are to reduce or limit the expansion of the crab stock. To complicate the matter further, the management area East of 26°E, where the crab is managed as an economic resource, will function as a source of king crab into the western management area. Expanding the model to take into account the immigration of crabs could illustrate the biological and economic challenges in reaching the management goal of eradication when the adjacent area represents a constant supply of king crabs.

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