# A Cost-Benefit analysis of introducing the non-native species signal crayfish*

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July 6, 2004

**Abstract**

This article uses a simple bioeconomic model to measure the net benefits associated with the signal crayfish introduction. The introduction of signal crayfish is considered as a deliberate change of species in the ecosystem, where the noble crayfish gets replaced by the signal crayfish. Replacement is considered for watercourses where the noble crayfish extinct immediately given introduction of signal crayfish. The resource stock is valuable to sole-owner only because of it's productive potential. That is, the value of the noble- respectively signal crayfish population equals the present value of the net future revenues that the respective species will yield. The model is applied to empirical data for the lake Halmsjon in Sweden. Biological equilibrium (MSY), economic optimum (MEY) and economic equilibrium(OAE) are calculated for the signal crayfish in Lake Halmsjon. The net benefits of introducing the signal crayfish is found positive, which can explain the private economic incentives to introduce the signal crayfish, threatening the noble crayfish to extinction. Moreover this study suggests that the net benefits of an introduction will only be positive if the intrinsic growth rate of the noble crayfish is more than 40 percent lower than for the signal crayfish.

Keywords: Bioeconomics, fisheries management, competing species, invasive species.

## 1 Introduction and overview

In the beginning of the twentieth century, Sweden had a relative big population of the noble crayfish (Astacus Astacus). Unfortunately, the crayfish plague reached Swedish watercourses. As a consequence, the population of the noble crayfish decreased dramatically. Repeated attempts were done up to 1960, trying to restore the population of noble crayfish by plant outs. But, as the crayfish plague periodically came back, this strategy became less successful. In 1960, a decision was taken to import and implant the signal crayfish, Pacifastacus leniusculus, (Hamrin, 1993). This seemed as a good idea since the signal

*I gratefully acknowledge comments on early versions of this paper from Ing-Marie Gren, Clas Erikson, Dennis Collentein and Karin Larsen, the financial support of AquAliens, and lucrative discussions about the crayfish industry with Nils Fors and Carl Nilsson.

crayfish is resistant against the crayfish plague. However, as the signal crayfish also can work as a host for the crayfish plague, the action taken has become the definitive threat against the existence of the noble crayfish.

Putting it in a bigger perspective, the signal crayfish is the most widespread non-native crayfish in the northern Europe. Since 1960s, the signal crayfish has been introduced into more than 20 countries in Europe. Europe has five native species of crayfish, which all have been affected by the introduction of non-native species, (Bubb et al., 2004). Several European countries have taken very strong regulatory and management steps to reduce further ecological disruptions from nonnative crayfishes, (Lodge et al., 2000). In the present position the Swedish authorities doesn't approve signal crayfish introduction in watercourses where the nobel crayfish can be found. This in order to preserve the threaten population of noble crayfish.

The primary purpose of this article is to identify and measure the social net benefits associated with the signal crayfish introduction. Net benefits of an introduction will be defined as the additional economic value gained by introducing the signal crayfish compared to preserving the noble crayfish, and will from now on be denoted as $NB$. $NB$ will also reflect the cost of preserving the noble crayfish in terms of forgone profits. Note that the sign of $NB$ is not predetermined. A working assumptions of this paper is that the resource-stock is valuable to the sole-owner only because of it's productive potential. It is by this assumption we will be able to measure the $NB$-value. It should be carefully noted that this is just a working assumption, used to measure the $NB$-value and identify economic forces which can lead to extinction of the native noble crayfish.

A model of the economic impact of biological invasion must be based on two principles. First, the economic impact by the invader will depend on the nature of the interspecific competition with the native species. Secondly, the correct measure of these impacts should be based on a comparison of the ex post and ex ante invasion scenarios, (Barbier, 2001). That is, the economic impact should be measured be relating the ex-ante economic performance of the watercourse with ex-post the biological introduction. The problem will be addressed for those watercourses where the signal crayfish replaces the noble crayfish. An underlying thought throughout the analysis is that species competes for water resources provided by humans, who manage this portfolio of biological assets, (Swanson, 1994). Introductions to watercourses with no preexisting crayfish populations are assumed to always be successful.

Economic theory of open-access resources was initially developed by Gordon (1954), which together with Schaefer (1954), are considered as the two seminar papers in fisheries economics. Ever since then, the simple stock-growth models has been the core of fisheries economics. The dynamic aspects was first discussed by Scott (1955). While the single species production surplus models are well investigated both theoretically and empirically, empirical studies for multispecies models are quite scare in the literature. To name some empirical studies, Clarke et al. (1992) evaluated different single species models for the Northwestern Hawaiian Island Lobster fishery. Conrad and Adu-Asamoah (1986) examined management policies for the commercial tuna fisheries from both a single and multispecies perspective. Considerations of the statistics of catch and effort data can be found in Schnute (1977) and Uhler (1980), to name a few. This paper follows up on Barbier (2001) suggestion on how to evaluate the economic impact of a biological invasion. As far as the knowledge of the author, very few attempts have been made to actually estimate the economic impact of species introductions. To name one, Knowler and Barbier (2000) estimated the economic impact on the Black Sea anchovy fishery from the Mnemmiopsis (comb-jelly) introduction. While the main concern of Knowler and Barbier (2000) was to estimate the structural change of productivity of the native species, defining the invading species as a pest, this paper will consider the case when both the invading and the native species has a commercial value. We thereby recognize a possible trade-off between the value of preserving the native species, and introducing the new species. The essence of this paper is captured by the following figure.

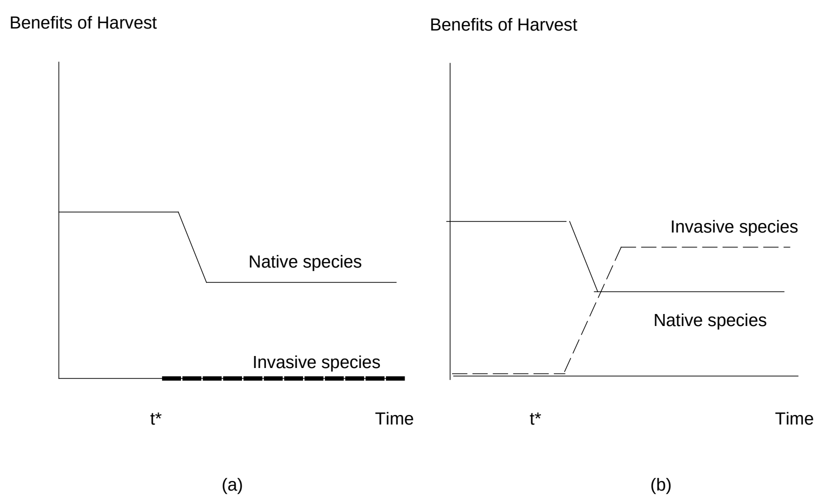


Figure 1: Structural change of the productivity of the native species because of invasive species: (a) simple case; (b) when the invasive species have a harvesting value as well. The time of invasion is denoted as t*. The net benefits will be the vertical sum of the benefits of the native and invasive species ex-post biological invasion, minus the benefits of the native species ex-ante biological invasion. Given that the net benefits are positive, we have a trade-off between the value of preserving the native species and introducing the non-native species.

The outline of the paper is as follows. The paper starts of with a brief description about the noble- as well as the signal crayfish, and the crayfish plague. In section 3 the theoretical model with assumptions will follow. Section 4 will specify the empirical model which is used to estimate the parameters of the theoretical model. Finally, using these empirical findings the net benefits of introducing the signal crayfish will be presented in section 5, followed by discussion and conclusions in section 6.

## 2 Brief description about noble-, signal crayfish and the crayfish plague

Swedish experience of the signal crayfish introduction has shown that it is in long-term impossible to maintain noble crayfish populations in the same watercourse as the signal crayfish. Hence, introduction of the signal crayfish will almost always lead to an outcome where the crayfish plague becomes frequently established, (Johansson and Odelstrom, 1999). Furthermore, the signal crayfish seems to be superior to the noble crayfish in many different aspects. Taking a few examples, the signal crayfish grows faster, reaches sexual maturity earlier, is more aggressive and has the ability to dominate the use of many important factors like food and hiding places. The signal crayfish have also shown to have a relatively higher population growth than the noble crayfish. Even in watercourses where the signal crayfish is free from plague, it seems likely that the signal crayfish will crowd out the noble crayfish, in the long term. In a short-term however, a co-existing state with both noble- and signal crayfish is possible, (Hamrin, 1993). This will thus not be considered as a steady-state.

A fungus called Aphanomyces Astaci causes the crayfish plague. Aphanomyces Astaci is a parasite, which for survive is dependent on its host. Aphanomyces Astaci is spread from uninfected to infected crayfish by the so-called zoospores. Zoospores can only live for a day without finding a host. Most suitable hosts seem to be the noble and the signal crayfish. When the noble crayfish population is exposed of the crayfish plague, the entire population will extinct within a given time period. As the crayfish plague is dependent of it's host, the crayfish plague will disappear short after it's host disappears. Given the presence of signal crayfishes however, the crayfish plague can survive because of the additional amount of hosts, (Hamrin, 1993).

The noble crayfish occurs in 1518 watercourses in Sweden, while the signal crayfish occurs in 3042 watercourses, (Hamrin, 1993).

## 3 The theoretical model

The present values of the flows of net revenues that the respective species will yield, will depend on the growth rate of the respectively species, as well as the costs of harvesting, the prices of the specimens and the discount rate. This section is divided into two parts. In the following part, a simple biological model will be presented, capturing the main features of the growth rate of the species. Prices, management policies and harvesting costs of the specimens will be introduced in the next part.

The assumptions of the biological model is as follows. The signal crayfish will always serve as a host for the crayfish plague. Introducing the signal crayfish will instantaneously imply a total extinction of the noble crayfish. The instantaneous extinction of noble crayfish will be a result of the crayfish plague. That is, co-existence of the two species in the same watercourse is not feasible in the very simplified version of the model that we present here. Using the well known logistic function, (Schaefer, 1957), we specify the growth function for the respectively species independently of each other.

$$\dot{x} = r_x \cdot x \left(1 - \frac{x}{K_x}\right) \tag{1}$$

where $x$ denotes the mass of noble crayfish, $r_x$ the intrinsic growth rate and $K$ the environmental carrying capacity.

Correspondingly for the signal crayfish we have,

$$\dot{y} = r_y \cdot y \left(1 - \frac{y}{K_y}\right) \tag{2}$$

where $y$ denotes the mass of signal crayfish, $r_y$ the intrinsic growth rate.

The model assumes that the biological mass can't grow forever with an exponential rate. Possible restrictions in an ecosystem could be due to for instance food scarcity, space scarcity etc. The logistic function is strictly concave from below and exhibits positive growth for all positive values of $x < K$. Such functions is said to be purely compensatory. The coming part will combine the biological model as presented here, with management as well as price and cost information. This sets up the basic bioeconomic model, referred as the Gordon-Schaefer Model, (Clark, 1990).

The change of species in the ecosystem will be considered given that the crayfish industry follows an optimal management, where the fiction of a sole owner will be adopted. The resource stock is valuable to the sole-owner only because of it's productive potential. This per definition makes the resource management problem of the species signal- and noble crayfish a capital theoretical problem. Abstaining from fishing can be seen as an investment in the stock, while fishing is considered as a disinvestment in the stock. Also note that introduction of the signal crayfish, automatically implies disinvestment in the noble crayfish stock. Since these two species cannot coexist, the introduction of signal crayfish will be evaluated by comparing the possible net future revenues of signal crayfish, with net future revenues of noble crayfish. Then the economic optimum derived from the sole-ownership management (MEY), will be compared with the economic equilibrium in an open-access economy (OAE), and the biological equilibrium (MSY). We assume the following production function as commonly used in fishery management,

$$H_x(t) = q_x \cdot E_x(t) \cdot x(t) \tag{3}$$

where $H(t)$ denotes harvest, $E(t)$ the effort and $q$ a constant, the catchability coefficient representing the fishing technology. This function is derived from the following two assumptions, (Clark, 1985)

1. catch per unit effort ($H/E$) is directly proportional to the density of fish in the lake, and
2. the density of fish is directly proportional to the abundance $x(t)$.[1]

We also assume that the total effort cost is

$$C = cE \tag{4}$$

[1] For alternative specifications and discussion of the production function, read Coppola and Pascoe (1998).

where $c$ is a constant representing the average as well as the marginal cost of effort. Equation (3) and (4) implies that the harvesting cost is linear in effort, and decreasing of biomass $x$. Assumption of the constant cost of effort is usually justified because it allows for concentration on the physical production problems without significantly altering the generality of the results, (Anderson, 1982). All prices are considered as exogenous given by infinitely elastic demand curves of the respectively species. That is, the fishermen are price-takers, and cannot set the price as a monopolist.

There are two scenarios. The first is the status quo where there is no introduction of signal crayfish, so that the noble crayfish is preserved. In the second scenario the signal crayfish is introduced, which immediately wipes out the total stock of noble crayfish. We will consider this two scenarios when the fishery is managed as capital good maximizing net present value, (Clark and Munro, 1975). Maximization of the present value of net revenues for Noble crayfish entail maximization of

$$\Pi_x = \int_0^\infty \left( p_x \cdot H(t) - \frac{c}{q_x \cdot x(t)} H(t) \right) \cdot e^{-\delta t} dt \tag{5}$$

$$\text{s.t } \dot{x}(t) = r_x \cdot x(t) \left( 1 - \frac{x(t)}{K_x} \right) - H(t) \tag{6}$$

$$x(0) = x^*$$

It will be assumed that the noble crayfish population initially takes its optimal and steady-state value $x^*$. The discount rate is denoted by $\delta$. Correspondingly, the maximization of the present value of net revenues for signal crayfish entail maximization of

$$\Pi_y = \int_0^\infty \left( p_y \cdot H(t) - \frac{c}{q_y \cdot y(t)} H(t) \right) \cdot e^{-\delta t} dt \tag{7}$$

$$\text{s.t } \dot{y}(t) = r_y \cdot y(t) \left( 1 - \frac{y(t)}{K_y} \right) - H(t) \tag{8}$$

$$y(0) = y^*$$

$y^*$ is the initial and steady-state amount of signal crayfish introduced.

These problems will be solved using the maximum principle. Here we will solve for the noble crayfish population, but of course the same solution applies for the signal crayfish as well.

The Current-value Hamiltonian of our problem is

$$J = p_x \cdot H(t) - \frac{c}{q_x \cdot x} \cdot H(t) + \lambda \left( r_x \cdot x \left( 1 - \frac{x}{K_x} \right) - H(t) \right) \tag{9}$$

Using the maximum principle (details are given in Appendix 1) we find that singular control $H^*$ arises when

$$\lambda = p_x - \frac{c}{q_x \cdot x} \tag{10}$$

and

$$H(t) = 0 \text{ if } \lambda > p_x - \frac{c}{q_x \cdot x}$$
$$H(t) = H_{\max} \text{ if } \lambda < p_x - \frac{c}{q_x \cdot x}$$

The condition above simply states that the resource should be harvested only if the net revenue per unit harvest exceeds the shadow price of the resource stock. Further, going ahead with the calculations we will find the well known equation called the "Golden rule of capital accumulation".

$$\delta = r - \frac{2}{K_x} \cdot r_x \cdot x + \frac{\frac{c \cdot r_x}{q_x \cdot x} \cdot \left(1 - \frac{x}{K_x}\right)}{p_x - \frac{c}{q_x \cdot x}} \tag{11}$$

where the firsts part of this equation,

$$r_x - \frac{2}{K} \cdot r_x \cdot x \tag{12}$$

is the instantaneous marginal physical product of the capital, and the second part,

$$\frac{\frac{c \cdot r_x}{q_x \cdot x} \cdot \left(1 - \frac{x}{K_x}\right)}{p_x - \frac{c}{q_x \cdot x}} \tag{13}$$

is the marginal stock effect, (Clark and Munro, 1975). The golden rule of capital accumulation states that the optimal stock level is such that the rent earned by the stock equals the social rate of discount. The optimal stock solution considering the positive root of the quadratic equation is as follows.

$$x^* = \frac{1}{4}\left(x_\infty + K_x\left(1 - \frac{\delta}{r_x}\right) + \sqrt{\left(x_\infty + K_x\left(1 - \frac{\delta}{r_x}\right)\right)^2 + 8K_x \cdot x_\infty \cdot \frac{\delta}{r_x}}\right) \tag{14}$$

where

$$x_\infty = \frac{c}{p_x \cdot q_x} \tag{15}$$

$x_\infty$ will be the limiting position of x as $\delta \longrightarrow \infty$. Further $x_\infty$ is also the bionomic biomass equilibrium under open-access, Clark (1985).

The optimal stock depends on the bioeconomic parameters $c$, $p$, $q$, $\delta$, $r$, and $K$. That is, to be able to measure the economic impact of the signal crayfish introduction, the net benefits, we have to quantify these parameters for the noble as well as for the signal crayfish. This will be done in section 4. The signal crayfishes relatively higher population growth and more aggressive nature will be reflected in the biological parameters. The complete solution for our problem is

$$H(t) = 0 \text{ when } x(t) > x^*$$
$$H(t) = H_{\text{max}} \text{ when } x(t) < x^*$$
$$H(t) = \dot{x} \text{ when } x(t) = x^*$$

Using the equilibrium stock level, the equilibrium harvest will be found for the respectively species, also denoted as the maximum economic yield (MEY). Using the equilibrium harvest level it is then straight forward to calculate the equilibrium profits for the respectively species.

Profits of nobel crayfish in each period is,

$$\pi_x \left(c, p_x, q_x, r_x, K_x, x*\right) = p_x \cdot H_x^* - \frac{c}{q \cdot x^*} \cdot H_x^* \tag{16}$$

and correspondingly the profits of signal crayfish in each period is,

$$\pi_y \left(c, p_y, q_y, r_y, K_y, y*\right) = p_y \cdot H_y^* - \frac{c}{q \cdot y^*} \cdot H_y^* \tag{17}$$

The net benefits of introducing the signal crayfish as well as the costs of preserving the noble crayfish per period is given by the following expression

$$NB = \pi_y - \pi_x \tag{18}$$

The present value of the flow of profits for the two species is given by,

$$V_x = \int_0^\infty \left(\pi_x\right) e^{-\delta t} dt = \frac{1}{\delta} \pi_x \tag{19}$$

for the nobel crayfish, and

$$V_y = \int_0^\infty \left(\pi_y\right) e^{-\delta t} dt = \frac{1}{\delta} \pi_y \tag{20}$$

for the signal crayfish. Given that the sole-owner only values the productive potential of the crayfishes, the choice of introducing the signal crayfish or not, will be equivalent of a choice between investing in one of the two arbitrary bonds $V_x$ or $V_y$. The bond which yields highest return will be preferred.

A static formulation of the Gordon-Schefer model is derived in comparatively purposes to the dynamic model, and can be found in Appendix 2.

# 4 The empirical model

The parameters of the Schaefer model was estimated from catch and effort data, catch per unit effort denoted as $U$, using the finite difference approximation, Schaefer (1957).

$$\frac{dU}{dt} \approx \frac{U_{t+1} - U_{t-1}}{2} \tag{21}$$

A period is defined at yearly basis. Many bioeconomic studies incorporate biological parameters estimated by Schaefer model. However, Schnute (1977) suggests a modified version of the Schaefer model using an integration procedure. This article follows Uhler (1980) which evaluated different bioeconomic models by Monte Carlo Simulation and found Schaefer model to perform relative well and useful for economic analysis. The equation to be estimated is given by equation 8. Using that catch per unit effort is proportional to $x(t)$ we get

$$\frac{\dot{U}}{U} = r - \frac{r}{q \cdot K} \cdot U - q \cdot E \tag{22}$$

Using the finite difference approximation, we get

$$\frac{U_{t+1} - U_{t-1}}{2U_t} = r - \frac{r}{q \cdot K} \cdot U_t - q \cdot E_t \tag{23}$$

A linear regression of $\frac{U_{t+1}-U_{t-1}}{2U_t}$ against the two variables $U$ and $E$ is used to estimate the parameters $r$, $K$ and $q$ in equation 8, yielding the following econometric specification,

$$Y = \beta_1 + \beta_2 \cdot U_t + \beta_3 \cdot E_t + \varepsilon \tag{24}$$

where $Y = \frac{U_{t+1}-U_{t-1}}{2U_t}, \beta_1 = r, \beta_2 = \frac{r}{q \cdot K}$ and $\beta_3 = q$. Lake Halmsjon is the object of our study. Lake Halmsjon is eutrophic, has an area of 38 hectares and situated in Stockholm. It is a fairly good crayfish habitat. The former inhabitant of Lake Halmsjon, the noble crayfish, was struck by plague in 1950. Before the plague, about 1500 specimens were probably harvested annually. The lake was threaten with rotenon in the 1950s. The signal crayfish was introduced in 1971. After the signal crayfish introduction, some specimens of Noble crayfish were caught during the period 1972-1975, after which they disappeared. This is a common pattern in Swedish lakes, (Fjalling et al., 1991). Lake Halmsjon was managed by the Swedish national board of fisheries between the years of 1971-1993.

Noble respectively signal crayfish is usually caught by traps called mjarde. Since crayfish are active at nights, the traps are put out during night. The fishing season is normally between August and September, when the crayfishes are active and easier to catch. Effort is standardized to measure traps/night. Catch and effort data between 1972-1990 for signal crayfish in the Lake Halmsjon was provided by the Swedish national board of fisheries and can be found in Fjalling et al. (1991). Bait and fishing technique is considered homogenous throughout the time period. The population dynamics for noble crayfish will be simulated by altering the intrinsic growth rate of the noble crayfish from 10-50 percent lower levels than for the signal crayfish. To keep the empirical results simple and trackable, the other parameters will be kept constant.

Fishermen was considered price takers and 1999 they got between 300-400 SEK per kg for noble crayfish and 100-300 SEK for signal crayfish, Ackefors (1999). Median price of 1999 price level adjusted for inflation to 2002, was used to calculate the revenue function of noble respectivey signal crayfish. In average some 20 specimens >10 cm, suited for consumption, equals 1 kg crayfish. This was used to calculate the price per specimens of the crayfish.

The cost function was approximated by conversing with professional crayfish fisherman in Sweden. A proxy wage level of 136,5 SEK/h was then used, representing a minimum average wage rate in Sweden 2002. In the remainder of this study, the average and marginal cost of 14,14 SEK/effort will be used.[2]

# 5 Results

The Schaefer production surplus model was estimated using OLS with 1972-1990 catch and effort data for Lake Halmsjon. Modified Durbin-Watson test for autocorrelation was applied, and the model showed significant evidence of negative autocorrelation for the 5 percent level. The Cochrane-Orcutt procedure was then applied as a correction to the model. Statistical properties are summarized in Table 1.

**Table 1: Estimation of the Schaefer production surplus model**

| Variable | Coefficient | Std.error | t-Statistics | P-value |
|---|---|---|---|---|
| $\beta_1$ | 0,58706 | 0,05709 | 10,28 | 0,0000 |
| $U_t$ | -0,022679 | 0,006387 | -3,551 | 0,0030 |
| $E_t$ | $-7,51 \cdot 10^{-5}$ | $3,472 \cdot 10^{-5}$ | -2,162 | 0,048 |

| | |
|---|---|
| R-squared | 0,7010 |
| Durbin h statistics | -1,4913 |
| White's Het.sked. test | $n \cdot R^2 = 5,327$ |

The model have coefficients [3] with the proper signs, and t-statistics with reasonable levels. Whites Heteroscedasticity test was applied and detected no heteroscedasticity in the regressed model. Using this parameter values from the regression, the following constants of the Gordon-Scaefer model are obtained.

**Table 2: Intrinsic growth rate, carrying capacity and catchability coefficient for signal crayfish in Lake Halmsjon**

| r | K | q |
|---|---|---|
| 0,58706 | 344880 | $7,51 \cdot 10^{-5}$ |

Static biological equilibrium (MSY), economic optimum (MEY) and economic equilibrium for open-access fisheries (OAE), are presented in Table 3, using the constants from Table 2.

[2]To put out 200 cages takes two hours. Then to collect and sort these 200 cages with it's contents takes 4 hours. The cost of the boat with fuel, is approximated to 150 SEK per trip and 200 cages. Bait is accounted to cost 1,5 SEK/cage. A proxy wage level of 97,5 SEK is used, representing a minimum average wage rate in Sweden 2002. The employment tax 2002 was 33 percent, which is added on the wage cost.

[3]Durbins h statistics is actually best suited for large samples, but will be used as an approximation for the finite sample.

**Table 3: MSY, MEY and OAE for the signal crayfish in Lake Halmsjon**[4]

| | MSY | MEY | OAE |
|---|---|---|---|
| **H** | 50616 | 50481 | 9922 |
| **E** | 3911 | 3709 | 7417 |
| **Profits** | 479711 | 481145 | 0 |

The result confirms relative well with a MSY value between 50000-60000 speciemens for Lake Halmsjon as suggested by Fjalling et al. (1991). Incorporating intertemporal time substitution, that is dynamics into the model, we obtain the result's presented in Table 4.

**Table 4: Optimal values for biomass, effort, harvest and profits for signal crayfish in Lake Halmsjon for different discounting rates**

| $\delta$ | y | E | H | Profits |
|---|---|---|---|---|
| 0 | 181352 | 3709 | 50481 | 481145 |
| 0,01 | 178702 | 3768 | 50550 | 481019 |
| 0,05 | 168221 | 4006 | 50586 | 478043 |
| 0,10 | 155348 | 4298 | 50119 | 468979 |
| $\infty$ | 17823 | 7417 | 9922 | 0 |

The MEY value for the dynamic model with a zero discounting rate confirms with the MEY value for the static model, and using infinite discounting rate for the dynamic model we obtain the OAE value in the static model, as expected. As the crayfish fishing seem to be a relatively low cost fishing, we see that open-access yields considerable low catches and biological overfishing. Simulating the optimal values for the noble crayfish for different intrinsic growth rates and using a 5 percent discount rate yields the following result.

**Table 5: Optimal values for biomass, effort, harvest and profits for noble crayfish in Lake Halmsjon simulating with different intrinsic growth rates and using a 5 percent discounting rate**

| r | x | E | H | Profits |
|---|---|---|---|---|
| 0,53 | 162238 | 3728 | 45395 | 786986 |
| 0,47 | 160348 | 3348 | 40294 | 697989 |
| 0,41 | 157905 | 2968 | 35180 | 608746 |
| 0,35 | 154666 | 2588 | 30047 | 519198 |
| 0,29 | 150151 | 2208 | 24885 | 429094 |
| 0,045 | 37697 | 534 | 1511 | 20398 |

The first five values are simulated for 10, 20, 30, 40 and 50 percent less intrinsic growth rate than the signal crayfish. The last observation is simulated to fit a annual harvest rate of some 1500 specimens, as suggested for Lake Halmsjon before the crayfish plague. The results suggest that the intrinsic growth rate for the noble crayfish most be more than 40 percent lower than for the signal crayfish, to yield positive net benefits ($NB$). The annual economic profits

[4]Harvest is expressed in number of specimens, effort in traps/night and profit in SEK.

of noble respectively signal crayfish using a five percent discount rate is, 20398 SEK and 478043 SEK. The annual net benefits of introducing the signal crayfish in Halmsjon as well as the annual costs of preserving the noble crayfish is given by

$$NB = \pi_y - \pi_x = 457645 \quad SEK \tag{25}$$

The present value of the noble crayfish stock using a 5 percent discount rate and again a annual harvest of 1511 specimens for the noble crayfish is,

$$V_x = \int_0^{\infty} (\pi_x)\, e^{-\delta t} dt = \frac{1}{\delta}\pi_x = 407960 \quad SEK \tag{26}$$

The present value of the signal crayfish stock using a 5 percent discount rate is,

$$V_y = \int_0^{\infty} (\pi_y)\, e^{-\delta t} dt = \frac{1}{\delta}\pi_y = 9560860 \quad SEK \tag{27}$$

Meaning that given the sole-owner only values the productive potential of the crayfishes, the signal crayfish will be introduced.

# 6 Discussion and conclusion

This study begun with distinguishing between two cases of biological invasion. The simple case when the invasive species is a pest, from the more complex case when the invasive species has a commercial value as well. While the net benefits of the invasive species in the simple case always will be negative, because of the downward structural productivity shift of the native species, the more complex case can yield positive as well as negative net benefits. The net benefits will be the sum of the profits of the native and invasive species ex-post biological invasion minus the profits of the native species ex-ante biological invasion. This is the core of this study, compressed and captured by figure 1.

A simple bioeconomic model is then applied to catch and effort data, to consider the net benefits (the sign as well as the value) of the signal crayfish introduction in Lake Halmsjon. The estimated MSY for lake Halmsjon of 50616 specimens confirms relative well with the approximation of Fjalling et al. (1991). The huge difference in yield between the noble and signal crayfish in Lake Halmsjon is according to Fjalling et al. (1991), mainly influenced by the higher population resilience of the signal crayfish. This study suggests that the net benefits of an introduction will only be positive if the intrinsic growth rate of the noble crayfish is more than 40 percent lower than for the signal crayfish.

Assuming an annual harvest rate of some 1500 noble crayfishes in lake Halmsjon as before the plague, the net benefits of introducing the signal crayfish, or putting it differently the costs of preserving the noble crayfish, is estimated to 457645 SEK per year. Moreover, the present value of the noble crayfish stock is 407960 SEK, while the present value of the signal crayfish stock is 9560860 SEK. This huge difference could explain the private economic incentives to introduce the signal crayfish, which threatens the noble crayfish to extinction. This could also explain the unauthorized introductions of signal crayfish, as been suspected in Sweden.

One of the working assumptions of this study, was that the resource stock is valuable to the sole-owner only because of it's productive potential. Policy implications to preserve a species primary takes into consideration other values than the species productive potential. In the case of the crayfishes, it is the value of saving the noble crayfish from extinction. This paper estimated the cost of such a policy and identified the active economic forces and private incitements of the sole-owner which could be valuable in order to save the noble crayfish from extinction. That is, to avoid an unwanted asset substitution in the biological portfolio in favor to the species generating highest returns.

There are however limitations of this study, like uncertainties in the biological parameters and the economic approximations. When a species enters new habitat it could exhibit a higher growth rate initially, and the data series may be to short to reflect a ecological equilibrium. The results should therefore be interpreted with some caution. Further, this study do not consider the initial costs of an introduction, and uncertainties involved of an introduction. More research considering different watercourses and for longer time periods, is needed to appreciate the magnitude of the economic impact of the signal crayfish introduction.

# 7 Appendix 1

$$\begin{aligned} \Pi_x = \int_0^\infty \left( p_x \cdot H(t) - \frac{c}{q \cdot x(t)} \cdot H(t) \right) e^{-\delta t} dt \\ \text{s.t } \dot{x}(t) = r_x \cdot x(t) \left( 1 - \frac{x(t)}{K} \right) - H(t) \\ x(0) = x^* \end{aligned} \tag{A.1.1}$$

The Current-value Hamiltonian of our problem is

$$J = p_x \cdot H - \frac{c}{q \cdot x} \cdot H + \lambda \left( r_x \cdot x \left( 1 - \frac{x}{K} \right) - H \right) \tag{A.1.2}$$

F.O.C

$$\begin{aligned} \frac{\partial J}{\partial H} = p_x - \frac{c}{q \cdot x} - \lambda \\ \lambda = p_x - \frac{c}{q \cdot x} \end{aligned} \tag{A.1.3}$$

Differentiate $\lambda$ with respect to $t$.

$$\dot{\lambda} = \frac{c}{q \cdot x^2} \cdot \frac{dx}{dt} \tag{A.1.4}$$

$$\dot{\lambda} = -\frac{\partial J}{\partial x} + \delta \cdot \lambda \tag{A.1.5}$$

$$\dot{\lambda} = \delta \cdot \lambda - \frac{c}{q \cdot x^2} \cdot H - \lambda \cdot r_x + r_x \cdot x \cdot \left(\frac{2}{K}\right) \cdot \lambda$$

$$\dot{x} = \frac{\partial J}{\partial \lambda} = r_x \cdot x \left(1 - \frac{x}{K}\right) - H \tag{A.1.6}$$

Solving for steady-state

$$H = r_x \cdot x \left(1 - \frac{x}{K}\right) \tag{A.1.7}$$

Equating the two expressions with $\dot{\lambda}$, that is (A.1.4) and (A.1.5) yields,

$$\frac{c}{q \cdot x^2} \cdot \frac{dx}{dt} = \delta \cdot \lambda - \frac{c}{q \cdot x^2} \cdot H - \lambda \cdot r_x + r_x \cdot x \cdot \left(\frac{2}{K}\right) \cdot \lambda \tag{A.1.8}$$

$$\delta = \frac{\frac{c}{q \cdot x^2} \cdot H}{\lambda} + r_x - r_x \cdot x \left(\frac{2}{K}\right) \tag{A.1.9}$$

Use equation (A.1.3) and (A.1.7) in equation (A.1.9) we get the golden rule of capital accumulation

$$\delta = r - \frac{2}{K} \cdot r_x \cdot x + \frac{\frac{c \cdot r_x}{q \cdot x} \cdot \left(1 - \frac{x}{K}\right)}{p_x - \frac{c}{q \cdot x}} \tag{A.1.10}$$

Collecting x-terms yields

$$x^2 \left(\frac{2}{K} \cdot r_x \cdot p_x\right) + x \cdot \left(\delta \cdot p_x - r_x \cdot p_x - \frac{c \cdot r_x}{q \cdot K}\right) - \delta \cdot \frac{c}{q} = 0 \tag{A.1.11}$$

Use

$$\alpha = \left(\frac{2}{K} \cdot r_x \cdot p_x\right), \beta = \left(\delta \cdot p_x - r_x \cdot p_x - \frac{c \cdot r_x}{q \cdot K}\right), \gamma = -\delta \cdot \frac{c}{q} \tag{A.1.12}$$

Then,

$$x_{12} = \frac{-\beta \pm \sqrt{\beta^2 - 4 \cdot \alpha \cdot \gamma}}{2\alpha} \tag{A.1.13}$$

$$x_{12} = \frac{(r_x - \delta)p_x + \frac{c \cdot r_x}{q \cdot K} \pm \sqrt{\left(p_x(\delta - r_x) - \frac{c \cdot r_x}{q \cdot K}\right)^2 + \frac{8 r_x \cdot p_x \cdot \delta \cdot c}{K \cdot q}}}{4\frac{r \cdot p_x}{K}} \tag{A.1.14}$$

$$x_{12} = \frac{1}{4} \cdot K\left(1 - \frac{\delta}{r_x}\right) + \frac{1}{4}\frac{c}{p_x \cdot q} \pm \sqrt{\left(\frac{1}{4}\frac{K}{r_x \cdot p_x}\right)^2 \left(p_x(\delta - r_x) - \frac{c \cdot r_x}{q \cdot K}\right)^2 + \left(\frac{1}{4}\frac{K}{r_x \cdot p_x}\right)^2 \left(\frac{8}{K}\frac{r_x \cdot p_x \cdot \delta \cdot c}{q}\right)} \tag{A.1.15}$$

The positive root of the quadratic equation yields following solution.

$$x^* = \frac{1}{4}\left(x_\infty + K\left(1 - \frac{\delta}{r_x}\right) + \sqrt{\left(x_\infty + K\left(1 - \frac{\delta}{r_x}\right)\right)^2 + 8K \cdot x_\infty \cdot \frac{\delta}{r_x}}\right) \tag{A.1.16}$$

where

$x_\infty = \frac{c}{p_x \cdot q}$

# 8 Appendix 2, Social economic optimum, open-access and biological equilibrium derived from a static formulation

At equilibrium, we have the following catch-effort relationship for the Schaefer model,

$$H = q \cdot K \cdot E\left(1 - \frac{q \cdot E}{r}\right) \tag{A.2.1}$$

Using the catch-effort relationship we derive the static version of the social economic optimum (MEY). At the static MEY,

$$\frac{dTR}{dE} = \frac{dTC}{dE} \tag{A.2.2}$$

Simplifying the expression above we get

$$E_{(MEY)} = \frac{r}{2q}\left(1 - \frac{c}{p \cdot q \cdot K}\right) \tag{A.2.3}$$

Using equation (A.2.3) in the catch-effort relationship, we obtain,

$$H_{(MEY)} = q \cdot K \cdot E_{(MEY)}\left(1 - \frac{q \cdot E_{(MEY)}}{r}\right) \tag{A.2.4}$$

The catch-effort relationship is used again together with the zero profit definition for OAE, to derive the effort and harvest rate at open-acess.

$$E_{(OAE)} = \frac{r}{q}\left(1 - \frac{c}{p \cdot q \cdot K}\right) \tag{A.2.5}$$

Using equation (A.2.5) in the catch-effort relationship, we obtain,

$$H_{(OAE)} = q \cdot K \cdot E_{(OAE)}\left(1 - \frac{q \cdot E_{(OAE)}}{r}\right) \tag{A.2.6}$$

The biological equilibrium, maximum sustainable yield (MSY), is derived by differentiating the catch-effort relationship with respect to effort,

$$E_{(MSY)} = \frac{r}{2q} \tag{A.2.7}$$

Using equation (A.2.7) in the catch-effort relationship, we obtain,

$$H_{(MSY)} = \frac{rK}{4} \tag{A.2.8}$$

## References


Hans Ackefors. Development of crayfish culture in sweden during 1980s and 1990s. *National board of fisheries*, 1:59–81, 1999.

Lee G. Anderson. Optimal utilization of fisheries with increasing cost of effort. *Canadian Journal of fisheries and aquatic sciences*, 39:211–214, 1982.

Edward B. Barbier. A note on the economics of biological invasions. *Ecological Economics*, 39:197–202, 2001.

Damian H. Bubb, Timothy J. Thom, and Martyn C. Lucas. Movement and dispersal of the invasive signal crayfish pacifastacus leniusculus in upland rivers. *Freshwater Biology*, 49:357–368, 2004.

C. W. Clark. *Bioeconomic modelling and Fisheries management*. Wiley Interscience, first edition, 1985.

C. W. Clark. *Mathematical bioeconomics: The optimal manegemnet of renewable resoursces*. Wiley Interscience, New York, 2nd edition, 1990.

C.W Clark and G.R Munro. The economics of fishing and modern capital theory: A simplified aprroach. *Journal of enviromental economics and manegement*, 2:92–106, 1975.

R.P Clarke, S.S Yoshimoto, and S.G Pooley. A bioeconomic analysis of the northwestern hawaiian island lobster fishery. *Marine resource economics*, 7: 115–140, 1992.

J.M Conrad and R. Adu-Asamoah. Single and multispecies systems: The case of tuna in the eastern tropical atlantic. *Journal of Enviromental Economics and Management*, 3:50–68, 1986.

Gianluigi Coppola and Sean Pascoe. A surplus production model with a nonlinear catch-effort relationship. *Marine Resource Economics*, 13:37–50, 1998.

Arne Fjalling, Magnus Furst, and Gunnar Furst. Population resilience of pacifastacus leniusculus in sweden. *Finnish fisheries Research*, 12:165–177, 1991.

H.S Gordon. The economic theory of a common property and resoursce: the fishery. *Journal of Political Economy*, 62:124–142, 1954.

Stellan.F Hamrin. Mojligheter att oka flodkraftbestand i svenska vatten. 1993.

Soren Johansson and Tommy Odelstrom. Flodkraftodlingen i norrland - biologiska och ekonomiska forutsattningar. 1999.

Duncan Knowler and Edward B. Barbier. *The economics of an invading species: a theoretical model and case study application*. In C.Perrings, M.Williamson and S. Dalmazzone (eds.), The Economics of Biological Invasions. Edward Elgar, 1 edition, 2000.

David M. Lodge, Christopher A. Taylor, David M. Holdich, and Jostein Skurdal. Nonindigenous crayfishes threaten north american freshwater biodiversity, lessons from europe. *Nonindigenous species*, 25:7–20, 2000.

M.B Schaefer. Some aspects of the dynamics of populations important to the management of marine fisheries. *Bulletin of the Inter-America Tropical Tuna Commission*, 1:25–56, 1954.

M.B Schaefer. Some considerations of population dynamics and economics in relation to management of marine fisheries. *Journal of the fisheries Research board of Canada*, 14:669–681, 1957.

J Schnute. Improved estimates from the schaefer production model: theoretical considerations. *Journal of the Fisheries Research Board of Canada*, 34:583–603, 1977.

A.D Scott. The fishery: the objectives of sole ownership. *Journal of Political Economy*, 63:116–124, 1955.

T.M Swanson. The economics of extinction revisited and revised: a generalised framework for the analysis of the problems of endagered species and biodiversity losses. *Oxford Economic papers*, 46:800–821, 1994.

R. S Uhler. Least squares regression estimates of the schaefer production model: some monte carlo simulation results. *Canadian Journal of Fisheheries and Aquatic Sciences*, 37:1284–1294, 1980.