Valuation of coastal habitats sustaining plaice fisheries

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Abstract
This paper presents a model to attempt to economically value changes in shallow soft bottoms along the west coast of Sweden in terms of their impact on plaice fisheries in Kattegat and Skagerrak. An ecological model links the quality of the habitat to changes in the plaice population which, in turn, are likely to be of importance for the opportunities for fishermen to harvest plaice. An economic dynamic model connects fish recruitment with fisheries profits over time, suggesting a shadow price for plaice nursery grounds. Using the results – under the assumptions and restrictions – of the model, the presence of algal mats in the Swedish west coast could "cost" from 30% up to 40% of the total profits of the plaice fishing industry, i.e., between 7.6 and 12.5 billion Danish kroner, depending on the recruitment level and the discount rate used for the simulation.

1. Introduction

The majority of the world's population lives in coastal areas and, in the last few decades, these areas have been seriously affected by all kinds of human activities, such as destruction of wetlands for agriculture, tourism and recreation, and waste disposal. The impact of human activities in coastal zones is causing habitat deterioration, affecting spawning grounds, nurseries and feeding grounds of marine resources, thereby representing an increasing threat to global food security (UNEP, Agenda 21: Protection of Oceans (Ch. 17)).

Problems related to coastal zone management and the deterioration of our fish resource basis are subject to public policies, and measures must often be taken in agreement among several countries. Measures are costly and it is therefore important to know their potential benefits. Thus, it is important to know the connections among human activities, habitat deterioration, and effects on social welfare. This paper contributes to an increased knowledge of such connections by an economic valuation of habitat changes that affect plaice populations in the sea

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areas of Kattegat and Skagerrak. In these areas, plaice (*Pleuronectes platessa*) is the most important flatfish from an economic point of view. It is also a fish whose reproduction shows a close dependence on available coastal habitats where young individuals can grow before they leave the coast and become part of the fishable stock. Juvenile plaice have spatially restricted nursery grounds located in shallow soft bottom areas. Such nursery grounds along the Swedish west coast account for 77% of the total plaice recruitment in the areas of Kattegat and Skagerrak (Wennhage et al. 2006).

The problem is that there has been an increasing presence of filamentous algae on the Swedish west coast and seasonal algal blooms cover some of the areas where plaice larvae settle. This is one of several effects of marine eutrophication, with increasing phytoplankton production and coastal sedimentation, as a result of an increasing nitrogen loading together with the characteristic small tides of the region, see, e.g., the review by Boesch et al. (2006). The nitrogen loading into the west coast waters at the end of the 1990s is estimated to be equivalent to four times the amount of loading in the 1930s (Troell et al. 2005). This eutrophication process is also observed in phytoplankton blooms, reduced oxygen in bottom waters and increased presence of filamentous algae as mats covering shallow soft bottoms. Since the 1970s, this coverage has increased from 3% to 50% of the total shallow soft bottoms on the Swedish Skagerrak coast (Pihl et. al. 2005)

These coastal shallow soft bottom ecosystems are ideal nursery grounds for several commercial fish species, including plaice. Since the settlement of plaice larvae in soft bottom areas is crucial for recruitment and population increase, increasing algae coverage implies a decrease in habitat quality, thereby affecting the stock of plaice available at sea and, consequently, the fisheries.

In this paper, I present a dynamic optimization model to connect habitat quality, plaice population growth, and the plaice fishing activity. The model explicitly, quantitatively and empirically links ecological and economic aspects of plaice fisheries and the paper thus makes a contribution to the increasing literature on building ecological-economic models[2]. This allows the model to be an instrument for economic valuation of an environmental change (presence of algal blooms) when the environment (soft bottom areas) is an input in the production process (plaice production), cf. e.g., Ellis and Fisher (1987), Lynne et al. (1981) and Freeman (1991).

The purpose of the paper is thus to show how plaice fisheries are affected when algae coverage of the settlement areas increases, and the economic impact of this particular ecosystem degradation on the Swedish west coast. The paper is organized as follows. The next section (2) gives a background to plaice ecology and fisheries. Section 3 presents the fisheries model, and a discrete dynamic version of this model is developed in Section 4. Results from simulations of this model and a sensitivity analysis are found in Section 5. A concluding discussion follows in Section 6.

[2] See, for example, Knowler (2002) and Knowler et. al (2003).

2. Plaice: ecology and fisheries

2.1. Plaice population dynamics

Sea currents transport plaice larvae from spawning areas in the sea to the Swedish west coast, where they settle on the nursery grounds during the spring. The larvae stay in these shallow areas until the autumn, when they move into deeper waters to spend the winter and continue their life cycle (Pihl et al. 2005). After two years in the deeper sea, these 0-group juvenile fish are recruited to the adult population. There are no clear stock-recruitment relationships in plaice population dynamics. As for other fish species, the size of the stock typically determines the growth of the population. In contrast, only at very low stock levels is the stock of plaice a constraining variable for population growth. At "normal" stock levels, the habitat – the quantity and quality of shallow soft bottom areas available – is the bottleneck. This situation is roughly illustrated in Figure 1, where B^N is the level of spawning biomass where the available habitats are fully utilized. At levels greater than B^N, an increase in spawning biomass does not influence annual recruitment because there are no suitable spaces left for larvae to settle.

The important aspect here is population density dependent growth and mortality in the nursery grounds (Pihl et. al. 2000). If the available habitat decreases, the density is higher, leading to higher mortality due to predation and lower growth due to food limitation.

The stock of plaice available at sea is kept at a relatively low level by the fishing pressure, meaning that factors such as carrying capacity are not constraining population growth. An individual plaice stock is assumed to be mature after the age of two years, which thus is the age at which an individual is recruited to the fishable stock.

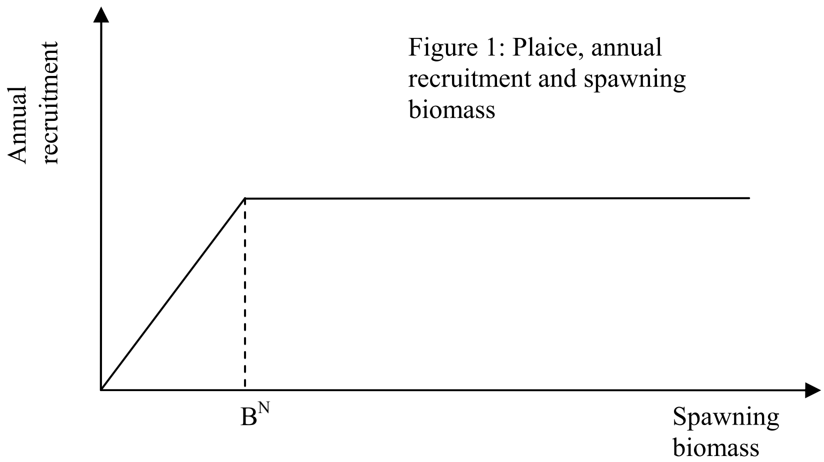

Figure 1: Plaice, annual recruitment and spawning biomass

As previously mentioned, the ecological problem that concerns us in this paper refers to the fact that, in some of the bays in the west coast of Sweden, seasonal algal blooms cover the areas where plaice larvae settle. Since the settlement of plaice larvae in soft bottom areas is crucial for recruitment and population increase, increasing algae coverage implies a decrease in habitat quality, thus affecting the stock of plaice available at sea and, consequently, the fisheries.

The effect of algae on plaice recruitment has been modeled by Pihl et. al. (2005). They have found that the relationship between vegetation coverage and recruitment of juvenile plaice depends on the behavior of the larvae in the presence of algae. Their model takes into consideration two different options for the behavior of young fish in the settlements. In the first option ("stay"), the plaice that settle in vegetated areas remain there and perish, while the other settlers in non-algae areas are exposed to the "normal" mortality rate. The second option ("move") considers the possibility of fish moving from vegetated to non-vegetated areas. Instead of having its initial number reduced in direct relation to the algal mats, the fish would be exposed to a higher density dependent mortality in this second option. The basis for the analysis in this paper is the "stay" option, but it is perfectly possible to change the equation for the vegetation-recruitment relationship to instead study the effect of the "move" option.[3]

Pihl et al. describe the recruitment of 0-group juvenile plaice No_t (number of individuals) as a function of the density dependent and density independent mortality rates (M), the size of the nursery area (A , expressed in square meters), the settlement density (D , individuals per square meter) and the vegetation cover (V , percentage):

$$No_t = A * D(1-V) * e^{(-M*t)}, \quad (1)$$

with mortality related to the concentration of plaice in the following way:

$$M = 0.008 + 0.0008 * D. \qquad (2)$$

Based on this model, the authors obtain results for the recruitment of two-year-old plaice in relation to the presence of algal mats.

For the time being, we leave the biological aspects of plaice population to discuss the fisheries model that serves as the basis for the exercise presented in this paper. These aspects will later be used for building different scenarios for how algae coverage affects the fishing economic activity.

2.2 Plaice fisheries

Plaice is the most important flatfish in Kattegat and Skagerrak from an economic viewpoint. Figure 2 gives a general picture of how plaice landings and estimated plaice biomass (stock) in Kattegat and Skagerrak have changed in the period 1978-2000. It can be noted that in 2000, the levels of landings and biomass were less than half of those in 1978. However, a major decrease in landings and biomass took place already in 1979-1982.

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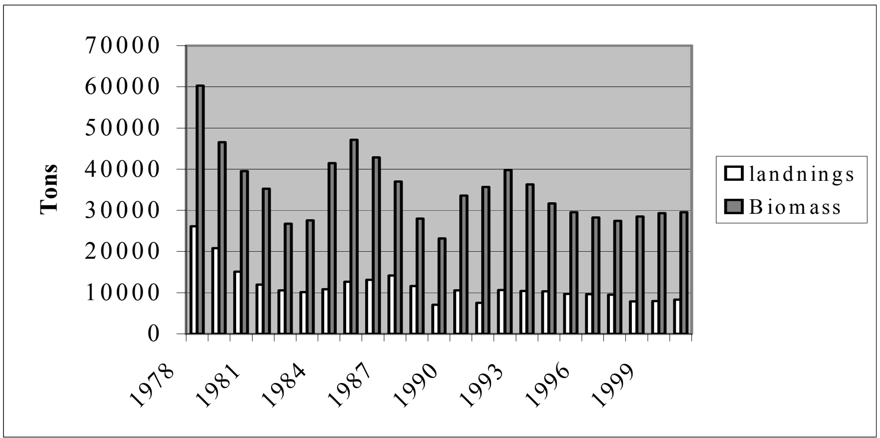
[3] Both the move and the stay option are likely to occur in nature. For simplicity, this paper only presents the "stay" option, since it implies a simpler relation between the initial numbers of plaice and the area available without algal mats. Cf. Phil et al, 2005.

Figure 2. Total biomass and landings of plaice in Skagerrak and Kattegat.



Source: ICES (2001)

Danish fishermen dominate plaice fishery on the Swedish west coast, as can be observed in Table 1. Danish landings account for more than 90% of the total and the catch of plaice is carried out by three vessel categories: seiners, otter-trawlers and gillnetters.

Table 1. Plaice landings (ton) from Kattegat and Skagerrak in 2000.

	Denmark	Sweden	Germany	Norway
Kattegat	1 644	184	10	0
Skagerrak	6 680	230	5	67
Total	8324	414	15	67

Source: ICES (2001)

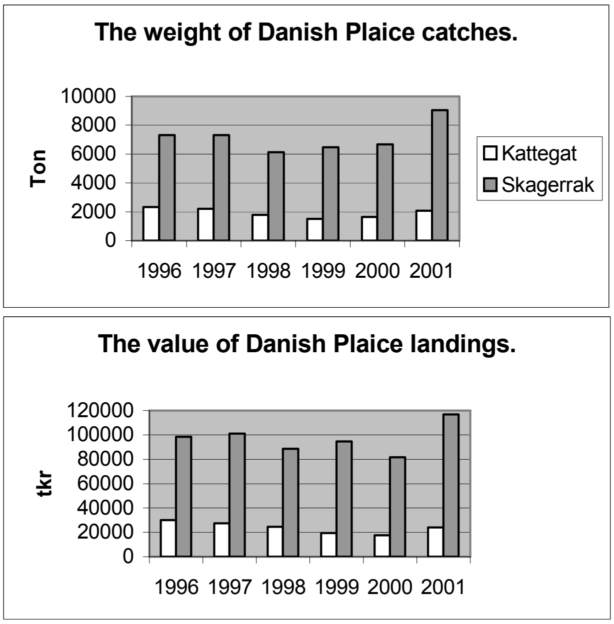
Plaice is an important species in the Danish fishing industry: in 2001, plaice accounted for about 10 per cent of the total value of Danish fish catch. In the same year, the value of plaice catches in Kattegat and Skagerrak represented about 41 per cent of the total value of Danish plaice fishery (Fiskeridirektoratet 2005). Figure 3 shows the weight and value of Danish catches of plaice in Kattegat and Skagerrak for the period 1996-2001.

Plaice catches in Kattegat and Skagerrak areas are regulated by the European Commission. The regulation is based on the scientific reports prepared by ICES[4],

[4] The ICES, the International Council for the Exploration of the Sea, is the organization that coordinates and promotes marine research in the North Atlantic. It produces scientific information and advice about the marine ecosystem which are published in reports, publications, and at their website http://www.ices.dk/indexfla.asp.

whose recommendations are based on the evolution of fish biomass and the marine ecosystem over the years. Establishing quotas is a result of a political process that does not necessarily and always follow ICES recommendations. However, it would be reasonable to think that there is or should be a close relationship between plaice catches and plaice stocks, as suggested by Figure 2 above.

Figure 3. The weight (tons) and value (thousands of DKK) of the Danish plaice catches in Kattegat and Skagerrak.



Source: Fødevareøkonomisk institut (2002).

For the period 1996-2001, the values of Danish landings of plaice have been rather stable and the same is true for the price level. As shown by Table 2, there is a trend of rising prices for most important fish species. Decreasing landings imply that revenues might still show a negative trend, but this is not true for plaice fishery, cf. Figure 3.

On the cost side, there is scarce information and we only had access to cost data for the period of 1996-2001 thanks to fishery accounts compiled by the Danish Research Institute of Food Economics. These data constituted the basis for the estimation of the cost function used in this paper.[5]

[5] For more detailed information about the estimation of the cost function, see Söderqvist and Norling (2003).

Table 2. Average price of selected fish species (DKK/kilo whole fish)

	Plaice	Cod	Sole	Norway lobster	Herring	Mackerel
1996	12.70	7.60	59.44	43.57	1.30	5.37
1997	12.89	9.20	75.77	50.49	1.51	6.92
1998	13.90	12.12	72.38	52.96	1.55	4.45
1999	14.05	13.12	59.19	62.36	1.31	3.70
2000	11.97	14.45	58.89	63.88	1.17	4.68
2001	12.74	15.45	72.46	70.23	2.41	6.31

Source: Fødevareøkonomisk institut (2002)

Because of the short time series available (six years only), the data were combined with different types of fisheries that include plaice: i. Cod, plaice, sole (CPS), ii. Flatfish (F), and iii. Norway lobster, cod and flatfish (LCF). The resulting 36 observations are the combination of six time series observations, for each of the three types of fisheries, in the two different areas (Kattegat and Skagerrak), as shown in Table 3. The resulting cost function is presented and discussed in section 4.1.

Table 3. Plaice fisheries for three segments of Danish commercial fisheries

Segment[a]	Catch of plaice per year[b] (tons)					
	Kattegat			Skagerrak		
	mean	std.dev	range	mean	std.dev	range
CPS	719	269	369-1177	1561	751	855-2832
F	2572	1367	651-4239	1240	463	730-1826
LCF	449	145	259-647	271	108	96-376
Segment[a]	Total variable costs per year for fishing plaice[b] (millions of DKK in 1996 prices)					
	Kattegat			Kattegat		
	mean	mean	mean	mean	mean	mean
CPS	5.9	5.9	5.9	5.9	5.9	5.9
F	21.6	21.6	21.6	21.6	21.6	21.6
LCF	3.6	3.6	3.6	3.6	3.6	3.6

Source: Födevareökonomisk Institut (2002) and Söderqvist and Norling (2003).

[a] CPS: Segment focused on cod, plaice and sole. F: Segment focused on flatfish. LCF: Segment focused on Norway lobster, cod and flatfish.

[b] Data were available for the period of 1996-2001.

3. The Beverton-Holt fisheries model

The most common model used in fisheries is the Schaefer model[6], based on the logistic growth curve which postulates an average relationship between the growth and size of the fish population. It is a simplified model that does not consider individual year classes of fish and, hence, does not allow for gear selectivity in fishing. We are interested in analyzing how changes in habitat, through their effect on fish yearly recruitment, affect the fisheries. For that reason, the model used in this paper is a more complex model based on the Beverton-Holt fisheries model as presented by Clark (1990). This model first appeared in 1957 and was a seminal work for the modern age structured approach to optimal fisheries management[7].

The Beverton-Holt model describes the fish population as different cohorts for each year, resulting from the annual recruitment (R , the new additions to the fish stock). To follow the life-span of one cohort, we have the number of fish in the cohort ($N(t)$) varying over time ($t \geq 0$) according to both the natural mortality rate ($\mu > 0$) and the fishing mortality rate ($F \geq 0$), in the following way:

$$\frac{dN}{dt} = -(\mu + F)N \qquad (3)$$

$$N(0) = R \qquad (4)$$

Natural and fishing mortality are assumed to be independent of each other and in the simplest version presented by Clark, recruitment R is given.

The total biomass of each cohort is given by the total number of fish in a cohort multiplied by the average weight of a fish (*w*) at age t . Clark uses the well-known von Bertalanffy weight function:

$$w(t) = a(1 - be^{-ct})^3 \qquad (5),$$

where a, b, and c are positive constants.

The total biomass of a cohort ($B(t)$) is then given by $B(t) = N(t)w(t)$.

Following Clark, the state equation for the dynamic problem is equation (4), slightly modified for allowing fishing mortality to be the control variable (harvest at different points in time):

$$\frac{dN}{dt} = -(\mu + F(t))N \qquad (6)$$

6 Schaefer (1954) is probably one of the most cited articles in fisheries economics. See, for example, Eggert, 1998, Knowler, 2002 and Quinn, 2003.

7 The Beverton-Holt model assumes natural growth to be a function of the age classes of the fish stock, and not only a function of the total stock, as in the simpler Schaefer model. It is this feature of the former model that allows for fishing gear selectivity. Their original investigations were carried out between 1947 and 1953 and the models then described were actually applied to North Sea plaice. See Beverton and Holt (1993), cf. authors' acknowledgements, p. 7.

The objective function is the present value of the stream of profits that a fisherman can get out of fishing:

$$PV = \int_0^{\infty} e^{-\delta t}\left[p(t)N(t)w(t) - C(t)\right]F(t)dt \qquad (7)$$

where $p(t)$ is the price of fish, $w(t)$ is the average weight of a fish of age t, δ is the discount rate and C is a cost function.

Clark shows that the dynamic analysis of the multiple cohort Beverton-Holt model is much more complicated than the dynamics of the typical Schaefer fisheries model[8]. This is true even if simplifying assumptions such as constant costs of fishing were to be used, which makes it difficult to find analytical general results. My approach to handle this fact is to build a discrete version of the Beverton-Holt model and use the software GAMS (General Algebraic Modelling System) for simulating optimal plaice harvest, taking the population dynamics into consideration.

4. The GAMS model

The discrete Beverton-Holt model will establish the optimal harvest of plaice through time that maximizes the profits from the fishery, subject to fish population dynamics. Assuming fishery to be at this optimum, we then analyze different scenarios for habitat quality and the effect on the benefits for the fishery of changes in habitat. The objective function is presented in the next subsection (4.1) and fish population dynamics in subsection 4.2. Some important model characteristics are discussed in subsection 4.3.

4.1 Objective function

Denoting harvest in kg at time t by $H(t)$, average cost of harvest at time t by $C(t)$ and the price per kg harvested plaice by p the constant per kg price of fish, the objective function to be maximized is the discrete flow of net benefits (*NB(t)*) from the fishery: [9]

$$NB(t) = \sum_{t=2000}^{2054} \frac{1}{(1+r)^{t-2000}} (p(t).H(t) - C(t)) \cdot \qquad (8)$$

The maximization is carried out given the following assumptions in the main scenario; see also the GAMS code in the appendix. The consequences of using other assumptions are studied in the sensitivity analysis in Section 5.

[8] See, for example, p. 292.

[9] If we assume that the fishermen (the industry, not the individual fisherman) face a downward sloping demand curve and have a convex cost function, as is done in this model, the maximization of profits is equivalent to maximizing a concave utility function. For a more complete explanation, see Mäler (mimeo).

a) The fishing industry decision variable is *H(t)* and *p* is assumed to be an internationally determined nominal price constant over time and equal to DKK 13/kg (Danish Crowns) in the main scenario. This figure roughly corresponds to the average price for plaice between the years 1996 and 2001, see Table 2.

b) The time horizon used is 55 years, from 2000 to 2054, t is the current time and a discount rate of 1 per cent is used in the main scenario.[10]

c) The cost function used in the main scenario is specified as:

$$C(t) = e^{2,494} * H(t)^{0,9898} * TotB(t)^{-0,146} \quad (9).$$

As already mentioned, this cost function was estimated by Söderqvist et al. (2003) based on cost data about the Danish commercial plaice fisheries for the period 1996-2001, compiled by the Danish Food and Resource Economic Institute.

4.2 Fish population dynamics

The objective function is maximized subject to the dynamics of the fish population: what is fished today, i.e., the harvest, affects what can be fished tomorrow, because it reduces the stock of fish available for the following periods, and so on.
Harvest is determined as:

$$H(t) = \sum_{k=1970}^{t} Q(k,t) * W(k,t) \quad (10)$$

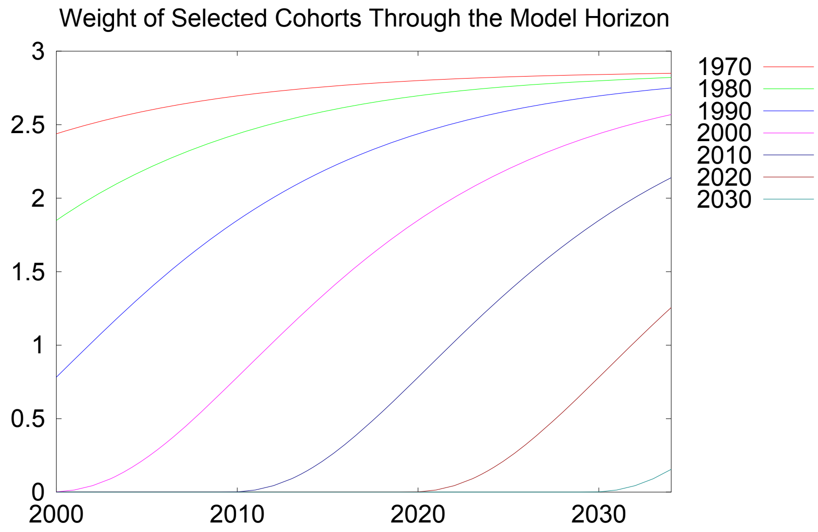
where $Q(k,t)$ corresponds to the number of fish from cohort k harvested at time t. k denotes the cohort time, the year the fish was born. The model includes fish born since 1970, so that $1970 \leq k \leq$ 2054. t - k is then the age of the fish. I assume that an individual plaice lives 30 years if it does not die from fishing or natural mortality. The natural mortality parameter in use is equal to 0.1, which means that every year, 10% of the fish population disappear due to natural causes (diseases, predation, etc.). H(t) is total harvest at time t, which is the sum of all harvested biomass from all cohorts at time t. W(t) is a von Bertalanffy weight function described above by equation 5. It is used for obtaining the average weight of a fish at age t-k as:

$$W(k,t) = a(1 - be^{-c(t-k)})^3 \quad (11).$$

[10] Notice that the choice of time horizon is a tricky one, since the "true" time horizon for our problem is actually infinite. I could have chosen 100 years, or 30. When defining a starting and an ending time for the model, I am incurring problems related to handling the initial and final years. I need a sufficiently long time horizon to allow for observing the dynamics during a certain number of years, and sufficiently short not to generate too many interactions and infeasibility.

This function is bounded and increasing, with the proportional rate of increase in weight decreasing over time, as is shown in Figure 4. The maximum weight (in kg) of a plaice individual when times goes to infinity is given by the constant a, which I assume, as does Clark, to be equal to 2.867.[11] The constant b is assumed to be equal to 1 and c is assumed to be equal to 0.095.

Figure 4



Fish stock grows in weight but, through recruitment, it also grows in numbers. The number of fish in a cohort (N(k,t)) when t>k, i.e. when that specific cohort is alive, is determined as:

$$N(k,t) = N(k,t-1) - Q(k,t-1)\,. \qquad (12)$$

When k>t, the number of fish in the cohort is $N(k,t) = 0$.

The fish population increases through yearly recruitment R(k). The number of fish in a given cohort the year that cohort is born (k=t) is the recruitment that year: $N(k,t) = R(k)$. The potential yearly recruitment of 0-group plaice from Skagerrak and Kattegat nursery grounds along the Swedish west coast was estimated to be around 88 million individuals[12]. This results in 62 to 76 million two-year old individuals entering the plaice population every year, depending on the assumed natural mortality rate during these two years (Wennhage et al. 2006). Those are the numbers in use in the model as recruitment at time k.

[11] This assumption, as well as the values for constants b and c, is based on the original work of Beverton and Holt for the North sea plaice population, cf. Clark, p. 285.
[12] Wennhage et. al. 2006.

The equation

$$B(k,t) = N(k,t) * W(k,t) \quad (13)$$

gives the fish biomass for the kth cohort, while the total fish biomass is given by

$$TotB(t) = \sum_{k}^{t} B(k,t) \cdot \quad (14)$$

4.3 Some important model characteristics

As already discussed before, analytically solving the theoretical dynamic model that constitutes the basis for this exercise is not possible without several simplifying assumptions. Even for this numerical exercise, a number of assumptions are necessary for building the model. Here, we discuss some of the model assumptions and characteristics and their consequences for the results.

The first important assumption relates to the time horizon. As already mentioned, the true time horizon for our problem is infinite. For dealing with this problem, a 55-year time horizon was defined for the fisheries activity, while another horizon of 30 years was defined for allowing the fishing stock to build up without fishing activity. The assumption used is that there was no harvest previous to the year 2000. The consequence of this is that the model assumes there to be a whole stock of fish accumulated to be harvested by the year 2000. The result is that during the first fishing year, the initial year 2000, the quantity harvested is extremely and abnormally high. During the following years, the harvest follows the optimal path, according to the evolution of fish stocks and population dynamics. After the year 2050, close to the end of the time horizon in the model, there is, according to the optimization problem and given the time horizon and the objective function, no longer any reason to preserve the fish stock , and that is the reason why the whole remaining stock is fished in the last year. This feature brings the problem of an abnormally high harvest which, in turn, produces artificially high profits.

Another assumption in the model is related to perfect cohort selectivity. The way the model is built, every fisherman uses a fishing gear that perfectly selects which fish cohort will be harvested. What the fisherman does in the model is that she waits for the individual fish to grow until it reaches the optimal size. Then she harvests the whole cohort that has reached that size. The effect of this assumption can be observed in the next section, where we show some diagrams to illustrate the functioning of the model.

Pulse fishing occurs when there are nonlinearities in the cost function[13]. In our case, the cost function is almost linear in harvest and fish stocks, but there is an obvious nonlinearity produced by the fact that there is a perfect selection of which

[13] A definition of pulse fishing is "harvesting a stock of fish, then moving on to other stocks or waiting until the original stock recovers". Cf. FishBase glossary, http://filaman.ifm-geomar.de/Glossary/Glossary.cfm?TermEnglish=pulse%20fishing. For a discussion about pulse fishing, cf. Clark (1990), pp. 144-145 and p. 152.

cohort to harvest. This is equivalent to establishing a maximum harvest, which introduces a simple kind of nonlinearity into the model, and results in pulse fishing and oscillating stocks.

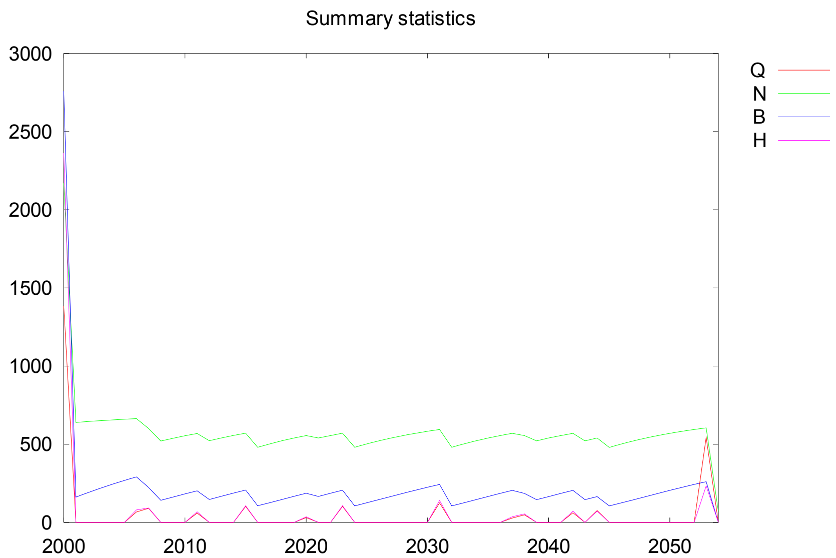
5. Results

The results are here presented in three steps: (1) GAMS output illustrating optimal fishery (subsection 5.1), the estimated shadow price of plaice recruitment (5.2), and the estimated value of reduced algae coverage of shallow soft bottoms (5.3). The sensitivity of the results for some different parameter values is analyzed in subsection 5.4.

5.1 GAMS output

Figure 5 summarizes the most important outputs from the GAMS model. Both the fish biomass (B) and the number of individuals (N) are very high in the first year of the time line because of the fish stock accumulation over 30 years without fishing activity, and they approach zero at the end of the time horizon.

Figure 5 – Summary output of GAMS model



Harvest, both in numbers and in weight, shows the pulse fishing effect. This oscillating path can be better observed in Figure 6, which once more illustrates the effect of the initial year in the time horizon, when the accumulated fish stocks allow for an abnormally high harvest, and the final year, when there would be no economic reason for keeping fish stock in the sea.

Figure 6

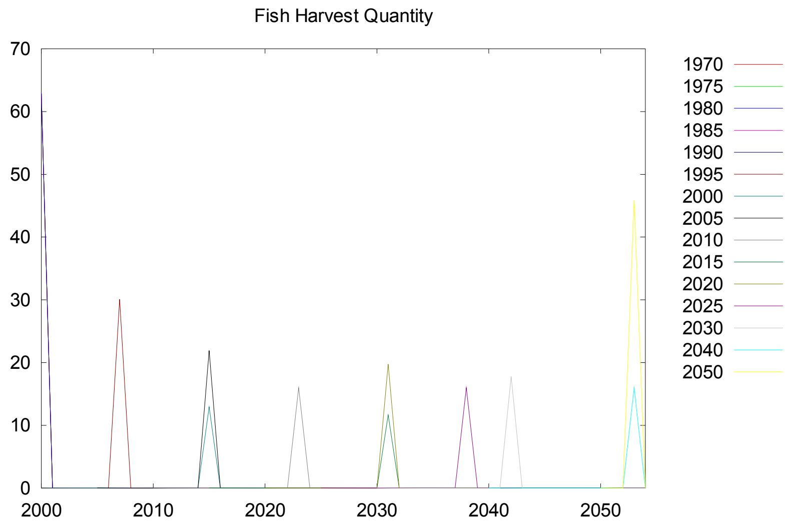
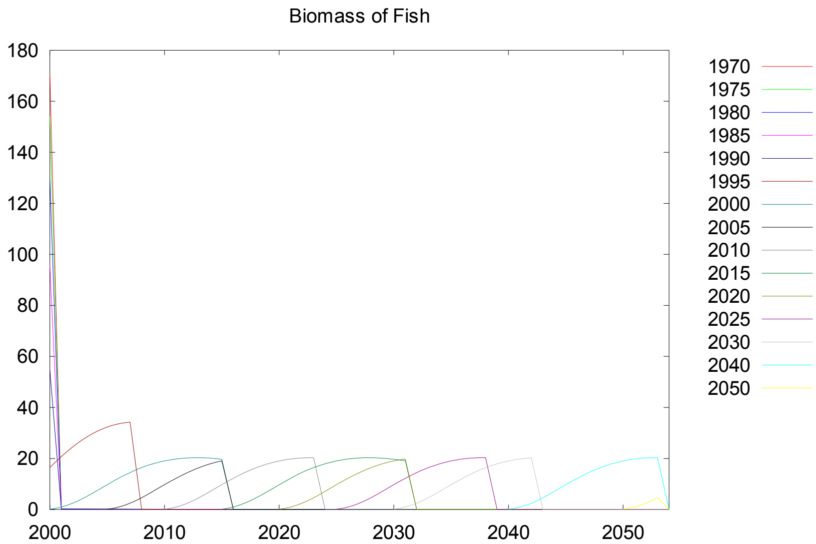


Figure 7 below, showing the evolution of the fish biomass, illustrates the dynamics of the model in more detail. As we can see there, every fish cohort grows in weight, following a path that is given by the von Bertalanffy growth function, and then decreases almost instantaneously with the harvest, when that cohort becomes the optimal cohort to harvest.

Figure 7



5.2. The shadow price of plaice recruitment

Table 3 reports the estimated values of the objective function for various levels of recruitment, given a harvest of the resource that follows the optimal path suggested by the model. As expected, the greater the fish recruitment, the greater the present value of the stream of profits over the time horizon between 2000 and 2054. The end-points of a recruitment level of 62 million and 76 million individuals per year correspond to profits in the plaice fishing industry amounting to a present value of about DKK 25000 and 32000 million, respectively.

As shown by Table 4, using a yearly discount rate of 1% over the time horizon, one additional unit of fish recruitment (recall that the unit here is millions of individuals) implies an average of around DKK 456 million increased profits for the industry over the time horizon. This could be interpreted as the shadow price of plaice recruitment in the west coast of Sweden. This result allows us to make a valuation of a change in habitat quality in economic terms.

Table 4: Plaice recruitment and different results for the fisheries profits

Value of Rk (In millions of individuals)	Value of the objective function (in millions of DKK) r= 0,01
62	25336
63	25970
64	26236
65	26680
66	27110
67	27730
68	27972
69	28424
70	28838
71	29294
72	29758
73	30155
74	30595
75	31271
76	31726

5.3 The value of reduced algae coverage

The GAMS model results are now linked to information available on how recruitment is affected because of algae coverage of the nursery grounds. Pihl et al. (2005) study an area of four regions corresponding to 67 km^2 of the total of 157 km^2 of the plaice nursery grounds on the Swedish west coast. In their paper, the authors depart from a baseline situation of potential recruitment from 4 regions in the study area, each of these with a mean algal coverage of 60, 27, 30 and 29%, respectively. The reduction in recruitment in each region is predicted in comparison to their potential, for three different settlement scenarios (high, medium and low larval supply) of juvenile plaice. Pihl et al. conclude that the reduction in the output of juvenile plaice from nurseries can reach 29 to 45%, assuming a medium recruitment year[14].

Based on these results, the following assumptions are used for valuing the contribution of the nursery grounds to plaice fisheries:

a) The value of the marginal increase in plaice recruitment (in one million individuals) is equal to the estimated shadow price of DKK 456 million over the time horizon of 55 years used in this paper;

b) The total area of nursery grounds producing juvenile plaice in the Swedish west coast is 157 km^2 and it is this area that is responsible for the estimated recruitment of 62 to 76 million two-year old individuals per year used in the model;

c) The current situation of habitat quality is assumed to be an average vegetation coverage of the nursery grounds varying between 30 and 60% of the total area. This situation is compared to the ideal situation of no algal mats and the whole potential recruitment being realized;

d) Only the nursery grounds without algae coverage are supposed to be available as nursery areas[15].

For different levels of recruitment algae coverage, Table 5 presents the estimated marginal value of an additional square kilometer of plaice nursery grounds not covered by algal mats. For example, in the case of a recruitment of 62 million individuals per year, and with an average of 30% of the nursery grounds affected by algal mats, a marginal increase in the availability of nursery grounds would give an increase in profits from plaice fishery amounting to DKK 257 million as a present value over the time horizon of 55 years. This is the estimated marginal contribution of the ecosystem to plaice production.

The marginal values in the table are the result of the following calculation:

$$MgV = \frac{SP * R}{TA * (1 - V)} \qquad (15)$$

where:

MgV is the marginal value of a square kilometer of plaice nursery ground

SP is the shadow price of recruitment

R is recruitment

TA is the total area of 157 km^2

V is the percentage of the total area covered by vegetation (algae)

[14] Cf. Pihl et al. (2005), Table 3, p. 1189.

[15] The implicit assumption here is that the juvenile plaice that settle in areas covered by algae die, i.e., the “stay” model. In the move model, the individuals would move to “clean” areas and the reduction in recruitment would happen through the increase in the density dependent mortality in the areas to which the fish moved.

Table 5: The marginal value of shallow soft bottom areas in the Swedish west coast (million DKK/km2)

Recruitment in millions of individuals	Algae coverage (%)				
	0	30	40	50	60
62	180	257	300	360	450
63	183	261	305	366	457
64	186	266	310	372	465
65	189	270	315	378	472
66	192	274	319	383	479
67	195	278	324	389	486
68	198	282	329	395	494
69	200	286	334	401	501
70	203	290	339	407	508
71	206	295	344	412	516
72	209	299	349	418	523
73	212	303	353	424	530
74	215	307	358	430	537
75	218	311	363	436	545
76	221	315	368	441	552

The economic significance of algae coverage can also be expressed as the profit loss caused by the resulting reduction in recruitment. As mentioned above, Pihl et al. (2005) concluded that the present 30-50% algae coverage might imply a 30-40% reduction in recruitment. The GAMS model suggests that this would, in turn, cause a 30-40% profit reduction, which according to Table 3 corresponds to a loss of about DKK 7600-12500 million as a present value over the 55-year time horizon.

It is important to emphasize here that all the estimated economic values only reflect the contribution of soft bottom shallow areas to Danish commercial plaice fisheries. Other contributions, such as to other commercial fisheries, recreational plaice fisheries, other recreational fisheries and other ecosystem services provided, are not included in this estimation.

5.4 Sensitivity analysis

The results presented in the previous section are directly connected to the values of the different parameters used in the simulation with GAMS. Below, the sensitivity of the value of the objective function is illustrated for different values of three important parameters: the discount rate, the fish price and the shape of the cost function.

Table 6 illustrates the fact that the smaller is the discount rate, the greater is the value of the objective function. The choice of a discount rate is an unavoidable issue whenever economic magnitudes in different time periods are to be compared. However, the choice involves difficult technical and ethical issues[16] and the use of a discounting factor in analyzing courses of action involving an eventual extinction of a biological resource has been controversial, especially among ecologists and other natural scientists.[17] The relatively low discount rate of 1% used in the main scenario might be motivated from arguments about having a prescriptive approach to discounting in the case of relatively long time perspectives, such as the 50-year time horizon used in this paper (cf. Arrow et al. 1996).

Table 6: The effect of the discount rate on industry profits

r	p	Rk	m	Value of the objective function
0.00	13	62	0.1	27489
0.01	13	62	0.1	25336
0.02	13	62	0.1	23963
0.03	13	62	0.1	22847

The results of having different prices for plaice than the base case of DKK 13/kg are illustrated in Table 7. For example, a price reduction of about 60% to DKK 5/kg would result in almost a 90% decrease in industry profits. However, based on the current evolution of the population of plaice in Kattegat and Skagerrak[18], and assuming that flatfish farming will not have any dramatic impact in terms of production increase, we should not expect a decrease in the price of plaice in the near future. The base case of DKK 13/kg was constructed using the mean for the six years for which we had cost data available to feed the model[19].

Table 7: The effect of fish price on industry profits

P	r	Rk	M	Value of the objective function
5	0.01	62	0.1	3049
10	0.01	62	0.1	17093
13	0.01	62	0.1	25336
20	0.01	62	0.1	45260

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16 See, for example, Mäler (mimeo).
17 See, for example, Ludwig et. al. (2005).
18 http://www.regeringen.se/sb/d/119/a/62575, ”Allvarligt läge för rödspättan i Nordsjön”.
19 Cf Table 2 above.

Several different specifications of the cost function were tried in the process of building the model, including theoretically desirable convex non-linear functions. Having the cost function estimated from available data in the base case is a natural choice, and Table 8 shows that applying a perfectly convex, but fictional, cost function results in a greater industry profit.

Table 8: The effect of different cost functions on industry profits

Cost function	R	Rk	m	Value of the objective function
$C(t) = e^{2,494} * H(t)^{0,9898} * TotB(t)^{-0,146}$	0,01	62	0,1	25336
$C(t) = H(t)^{1,4} * TotB(t)^{-0,3}$	0,01	62	0,1	32596

6. Discussion and further questions

The results in this paper rely on a number of assumptions already presented and used in the model. The conclusions are also dependent on the assumptions that current ecological conditions will remain the same in the future. The same is true for future economic conditions for the fish industry, including prices and the institutional setting under which the economic agents take their decisions, for example, national or individual fishing quotas, maximum allowable catch, mesh restrictions, and other restrictions affecting fishing effort.

However, the model developed in this paper allows us to see the clear connection between plaice population dynamics and the benefits from the fisheries industries. At the same time, through the link between the availability of soft bottom nursery grounds and annual plaice recruitment, it is possible to value the changes in habitat quality in terms of changes in the profits of the fisheries throughout the time horizon. It is shown that the increasing eutrophication on the Swedish west coast can cost up to 30% of the profits of the Danish plaice fishing industry. It is also shown that an additional available square kilometer of “clean” shallow soft bottom bay can contribute up to DKK 552 million to the industry profits over the time horizon used in the analysis.

In principle, these estimated economic values underestimate the economic significance of the habitats in question, since they do not , for example, include habitat support to recreational fisheries. However, they are likely to overestimate the effects on fishery industry profits because of the assumptions and characteristics of the GAMS model used. In particular, adjusting for the abnormally high harvests recommended by the GAMS optimization at the beginning and end of the 55-year time horizon, Figures 5 and 6 suggest that the harvest level predicted by the model could be up to 40% larger than more realistic harvest levels. The abundant fish biomass at the beginning of the time horizon of the model might also produce an artificial reduction of the costs of fishing, also contributing to an overestimation of the industry profits and, therefore, an overestimation of the contribution of the coastal ecosystem to plaice production. Another aspect which should be taken into consideration, though, is that, since "a sizeable fraction of the overall net present value of profits stems from the first year's harvest" [20], eutrophication levels later on will not affect the profits as they should. This means that the habitat deterioration might cost even more in terms of total production, if this production is more realistically smoothly distributed throughout the time horizon. This means that great caution is necessary if the above value estimates are used for policy purposes. A next step in the research process is to correct the model for these problems, to get better estimates of the costs of eutrophication for the fisheries.

The model developed offers, in fact, rich opportunities for refinements that could, for example, approach this overestimation issue. One type of refinement could be to model the beginning and the end of the time period under study in a more advanced way. Another would be to introduce the possibility of using selective gear to avoid perfect cohort selectivity and the infinite catch assumption for every cohort of optimal age. At this point, this assumption was used to avoid additional difficulties, since the model is already quite complicated to solve numerically as it is. But there will be further efforts to make the model more realistic. It would also be possible to use the model for studying the consequences of different institutional arrangements. While these issues are here left as suggestions for further research, the model presented in this paper would constitute a suitable point of departure for such work.

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[20] Even though the author was already conscious about this issue, an anonymous referee whose comments are acknowledged here suggested this more explicit discussion of this aspect.

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Appendix - GAMS code

```
$title  Optimal Fish Harvesting subject to the von Bertalanffy weight function

$onupper

SETS    k       Time in which the kth cohort enters the fishery /1970*2054/
        t(k)    Time period of the model  /2000*2054/,
        tf(t)   First period of the model,
        tl(t)   Last period of the model,
        a(k,t)  Tuple indicating which cohorts are alive at time t;

*       Set up logic for the first and last period:

tf(t) = yes$(ord(t) = 1);
tl(t) = yes$(ord(t) = card(t));

SCALARS     p          Price of plaice         /13/
            r          Discount rate           /0.01/
            Rk         Recruitment at time k (millions)  /62/
            m          Natural fish mortality          /0.1/;

PARAMETER      yr(k)        Year corresponding to cohort k,
               w(k,t)       Weight of a cohort k fish in year t,
               pv(t)        Present value price;

yr(k) = ord(k)-1;
pv(t) = 1/(1+r)**ord(t);
w(k,t)$(yr(t) ge yr(k)) = 2.867 * (1 - EXP(-0.095*(yr(t)-yr(k)+1)))**3;

VARIABLES
        OBJ     Objective function;

POSITIVE VARIABLES
        N(k,t)  Number of fish belonging to the kth cohort at time t,
        B(k,t)  Fish biomass of the kth cohort,
        C(t)    Cost of fishing,
        Q(k,t)  Harvest in numbers,
        H(k,t)  Harvest biomass of fish from cohort k;

EQUATIONS
        EQNB          Defines the objective function
        EQN(k,t)      Equation for number of fish belonging to the kth cohort at time
t,
        EQB(k,t)      Equation for the fish biomass of the kth cohort,
        EQH(k,t)      Harvest biomass for a given cohort,
        EQC(t)        Equation for the cost function,
```

```
    QLAST(k,t)      Limit on harvest in final period;

EQNB ..               OBJ =E= SUM(t, pv(t) * (p * sum(a(k,t),H(k,t)) - C(t)));

EQN(k,t+1)$a(k,t)..    N(k,t+1) =E= N(k,t) - Q(k,t) - m * N(k,t);

QLAST(k,tl)$a(k,tl)..   N(k,tl) =g= Q(k,tl);

EQB(k,t)$a(k,t) ..      B(k,t)   =E= N(k,t) * w(k,t);

EQH(k,t)$a(k,t) ..      H(k,t)   =E= Q(k,t) * w(k,t);

*       Cost function

EQC(t)..        C(t) =E=  SUM(a(k,t), exp(2.494)* H(k,t))**(0.9898) *
                          SUM(a(k,t), B(k,t))**(-0.146);

*       Introduce fish into the active population only when their biomass is
nonneglible:

a(k,t) = yes$(yr(k) le yr(t));

N.L(k,t)$a(k,t) = RK;

*        Assuming that fish cannot live more than 30 years:

B.L(k,t) = 0$(yr(t)- yr(k) ge 30);

*       Assume that no harvesting has occurred prior to the first year:

N.FX(k,tf)$a(k,tf) = RK;
N.FX(t,t) = RK;

B.L(k,t)$a(k,t) = N.L(k,t) * w(k,t);
H.L(k,t)$a(k,t) = RK/10;

*       Avoid divide by zero errors:

H.LO(k,t) = 0.0001;
B.LO(k,t) = 0.0001;

MODEL PLAICE/ALL/;
SOLVE PLAICE USING DNLP MAXIMIZING OBJ;
DISPLAY OBJ.L;

$if not exist "%gams.sysdir%wgnupl32.exe" $exit

*       Produce some graphical output using GNUPLOT:
```

```
PARAMETER     wvalue(t,k)    Weight of Selected Cohorts Through the Model
Horizon;

set   kplot(k)       Cohorts to be plotted
/1970,1980,1990,2000,2010,2020,2030,2040,2050/;

wvalue(t,kplot) = w(kplot,t);

set   tlbl(t) Time periods to label in plots /2000,2010,2020,2030,2040,2050/;

$setglobal gp_opt0 'set key outside width 3'
$setglobal domain t
$setglobal labels tlbl
$libinclude plot wvalue


PARAMETER     QH(t,k)       Fish Harvest Quantity,
              NF(t,k)       Numbers of Fish
              BF(t,k)       Biomass of Fish
              HF(t,k)       Harvest biomass,
              SUMMARY(t,*)   Summary statistics;

SUMMARY(t,"Q") = sum(k, Q.l(k,t));
SUMMARY(t,"N") = sum(k, N.l(k,t));
SUMMARY(t,"B") = sum(k, B.l(k,t));
SUMMARY(t,"H") = sum(k, H.l(k,t));
$libinclude plot summary

set  ksol(k)  Cohort solutions to plot

/1970,1975,1980,1985,1990,1995,2000,2005,2010,2015,2020,2025,2030,2040,20
50/;

QH(t,ksol) = na;
QH(t,ksol)$a(ksol,t) = Q.L(ksol,t);
$libinclude plot qh

NF(t,ksol) = na;
NF(t,ksol)$a(ksol,t) = N.L(ksol,t);
$libinclude plot nf

BF(t,ksol) = na;
BF(t,ksol)$a(ksol,t) = B.L(ksol,t);
$libinclude plot BF

HF(t,ksol) = na;
HF(t,ksol)$a(ksol,t) = H.L(ksol,t);
$libinclude plot HF
```