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Sustainable Marine Resource Management: Lessons from Viability Analysis

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Abstract: Marine natural resources are under pressure worldwide. Management and surveillance systems are often inappropriate to guarantee a sustainable resource utilization since the knowledge on fisheries and/or stocks is limited. Additionally, institutional failures, e.g. unsuitable regulatory policies, have accelerated resource exploitation in several cases. Modelling is often considered as a very effective tool for studying the behaviour of complex systems, but a variety of difficulties arise if one has to deal with uncertain knowledge or inhomogeneous data of different quality. In this paper we present a method that is capable both for (i) integration of sparse or limited knowledge from different disciplines and (ii) provides a test-bed for an assessement of different management regimes.

Keywords: fisheries management; imprecise knowledge; qualitative modeling; viability theory

1 INTRODUCTION

Following sustained interest from policy makers, recent years have seen a number of modelling efforts examining the effects of commercial fisheries. The issue is recognized as highly important, as stated also by the FAO [2001]. In their report on the state of world fisheries the FAO mentioned that 50% of the world's fish resources are fully exploited, 20% overexploited and 10% depleted. Even though overfishing has been a fact since historical times [Jackson et al., 2001] the problem has gained a new quality due to the industrialization of fisheries. The activities of highly capitalized fishing companies have reduced community biomass by 80% within 15 years of exploitation [Myers and Worm, 2003]. In many cases the fishing industry can only be sustained at an economic level by paying high amounts of subsidies, while at the same time increased capitalization and efficiency put additional pressure on the stocks [Banks, 1999; Gréboval and Munro, 1999; Munro, 1999; Pauly et al., 2002; Pauly, 2003]. As a consequence of this intricate situation an ongoing debate on adequate control and management instruments is taking place. Especially the following questions are discussed frequently:

1. Do fishery management strategies focus too much on the ecological system part, an approach sometimes coined “ichthyocentrism” [Lane and Stephenson, 2000]?
2. How to deal with inherent uncertainties in the dynamics of the fishing industry as well as those of the fish stocks [Whitmarsh et al., 2000]?
3. What are potential benefits and risks of so-called co-management strategies [Potter, 2002]?

In our paper we address the issues mentioned above by applying a technique which considers inhomogeneous and uncertain knowlege from the biological, economic and political domain. The framework of viability theory [Aubin, 1991] can be used to assess management strategies and highlights the role of fish stock estimates in the recommendations for catch quota allocations. It allows normative sustainability criteria, e.g. for employment or environmental protection, to be included into systems analysis. All possible trajectories can be computed and checked concerning their properties violating these normative settings or not. Analytical frameworks like this are used to an increasing extent in sustainability sciences [Bene et al., 2001; Eisenack and Kropp, 2001; Aubin and Saint-Pierre, 2004].

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2 MANAGEMENT REGIMES IN FISHERIES AND MODELLING METHODS

In this section we briefly introduce some concepts from fishery management and viability theory.

Co-management is implemented to increase participation of fishermen in the management of marine resources [Jentoft et al., 1998; Charles, 2001]. By introducing a degree of responsibility for the resource, it is expected that the compliance with regulations, e.g. catch quota, gear type, etc., will be higher [Mahon et al., 2003]. This is in contrast to the prevalent type of management, where a governmental authority imposes restrictions on the fishery. We refer to this strategy as top-down management, since fishing firms have no direct influence on the regulatory measures.

The problem of ichthyocentrism focuses on scientific institutions which play an essential part in both management regimes. Typically, these institutions provide biomass estimates which are an important basis for catch restrictions or quotas. It is often claimed that such an approach – in comparison to research efforts on the behaviour of resource users – puts too much emphasis on the resource itself. The question is whether we need a deeper understanding of the fisheries as a whole, or if it is sufficient to have better knowledge on the behaviour of fish stocks.

Viability theory [Aubin, 1991] investigates whether trajectories of a controlled dynamical system will stay within a prescribed region of the phase space given by the sustainability criteria (the so-called constrained set). This allows management targets to be formalized and takes into account the limitations of knowledge. A trajectory respecting the criteria is called viable or sustainable. However, not just a single trajectory is tested for viability, but the set of all trajectories which result from possible control paths (management decisions). The set of all initial conditions for which there exists at least one control path keeping the resulting trajectory in the constrained set forever is called the viablity kernel. The shape of the kernel depends on the management regime, and thus the approach can be used to identify sustainable management regimes.

3 THE MODEL

The change of biomass x of a fish stock depends on the recruitment $R(x)$ and the total catch h, given by $\dot{x} = R(x) - h$. We study the fish stock above a threshold $\underline{x} > 0$ assuming that its density is sufficiently low to allow an accelerating growth if there are no activities of fishing firms, i.e. $\forall x > \underline{x}$: $R(x) > 0$ and $D_x R(x) > 0$, where D_x denotes the partial differential operator with respect to x. Below $\underline{x}$ our knowledge about the recruitment behaviour is uncertain, and therefore we ignore this part of the phase space.

Co-management is exercised by a fishery council, where representatives from different groups (fishing firms, authorities, and scientific institutions) participate and negotiate about the allocation of catch quotas q_i to the groups $i = 1, \ldots, n$. The resulting total harvest is $h = \sum_i q_i$. When the members agree on their quota, the decision of the council is approved by a governmental authority. The resulting restrictions are executed by a management organization which works in close collaboration with local fishermen. The negotiations are opened by the scientific institution, which provides a preliminary recommendation h_0 for the total catch. Subsequently each group of the fishing industry tries both (i) to get a large share of the total harvest h and (ii) to increase h above the catch recommendation h_0 in order to improve profits. The profit π_i of group i depends on the quota q_i and on the available amount of fish x, which is the same for all fishing firms. It also depends on the efficiency of boats, fishing gear and technological equipment which varies between the groups [Scheffran, 2000]. Furthermore deviation costs d_i have to be considered which result from an exceeding of the scientific recommendation. They are due to public perception, the risk of being excluded from the co-management framework and a stronger need for good public relations. We define $\pi_i(q_i, x) = p\, q_i - c_i(q_i, x) - d_i\left(\sum_{j=1}^{n} q_j - h_0 \right)$. Here, the market price p is assumed to be exogeneous. The cost function c_i depends on a realized harvest q_i and the biomass of fish. It increases in q_i since more effort is needed for a larger catch, and decreases in x due to higher densities of the exploited stocks. If $\sum_j q_j - h_0$ becomes negative, d_i vanishes because deviation costs do not come into play if the sum of all quotas is below the scientific recommendation. It is reasonable to assume that d_i is a monotonicly increasing function. Each group of fishing firms can propose a quota allocation to obtain an optimal profit for a given price and fish stock. At Nash equilibrium the quota allocation assigns an individual quota q_i to each group i that maximizes π_i with respect to q_i for given p, x and quotas of the other participants. Assuming that all π_i are concave and continuously differentiable with respect to q_i, the equilibrium is provided by solving

$\forall i = 1,\dots,n : D_{q_i}\pi_i = 0$. In our analysis we study the case of two fishery groups and specify c_i and d_i as

$$c_i(q_i,x) := \frac{{}_iq_i + \beta_i q_i^2}{x};$$

$$d_i(q_1+q_2-h_0) := \begin{cases} 0 \quad \text{if} \quad q_1+q_2<h_0 \\ \kappa_i(q_1+q_2-h_0)^2 \quad \text{otherwise.}\end{cases}$$

The parameters ${}_i,\beta_i$ $(i=1,2)$ are positive and represent the technical efficiency. The political power of each group i is expressed by the positive parameter κ_i. Both functions are continuously differentiable (x is positive), and the resulting profit functions π_i are concave with respect to q_1, q_2. The Nash equilibrium for given a p, x, h_0 is obtained by solving
$D_{q_1}\pi_1 = p - \frac{{}_1+2\beta_1 q_1}{x} - 2\kappa_1(q_1+q_2-h_0) = 0$,
$D_{q_2}\pi_2 = p - \frac{{}_2+2\beta_2 q_2}{x} - 2\kappa_2(q_1+q_2-h_0) = 0$,
for q_1, q_2.
From this, the total harvest resulting from the negotiations evaluates to

$$h(x,h_0) = q_1+q_2 = \frac{upx + wxh_0 - v}{\beta_1\beta_2 + wx}, \qquad (1)$$

where $u := \frac{1}{2}(\beta_2+\beta_1) > 0$, $v := \frac{1}{2}({}_1\beta_2 + {}_2\beta_1) > 0$, and $w := \beta_1\kappa_2+\beta_2\kappa_1 > 0$. It is below the profit optimum in the case of absent deviation costs and above the initial scientific recommendation. The impact of h_0 on h is

$$D_{h_0}h(x,h_0) = \frac{wx}{\beta_1\beta_2 + wx} > 0, \qquad (2)$$

and

$$D_xh(x,h_0) = \frac{vw + (up + wh_0)\beta_1\beta_2}{(wx+\beta_1\beta_2)^2} > 0, \qquad (3)$$

i.e. the negotiation equilibrium increases with the abundance of fish. The difference between the initial recommendation and total harvest increases with abundance too, because $D_x\big(h(x,h_0) - h_0\big) = D_xh(x,h_0)$.

4 VIABILITY CONSTRAINTS

For the assessment of recommendation strategies, i.e. for controls $h_0(t)$, we will specifiy sustainability criteria in the form of a constrained set (cf. Sect. 2). We will emphasize that these criteria are normative, i.e. they are not solely defined by scientists, but they are outcomes of the public debate which shall be analysed in this contribution. Here, we exemplarily investigate the following constraints:

(i) Prevent a decline of the fish stock, i.e. the condition $\dot{x} \ge 0$ has to be fulfilled at any time.

(ii) Ensure that $\forall t : x(t) \ge \underline{x}$, i.e. that situation exists with a relatively certain recruitment estimate.

(iii) Require a minimum harvest $\underline{h}$ covering fixed costs and that employment and/or food safety is sustained.

We rewrite $\dot{x} = R(x) - h(x,h_0)$, where R is monotonicly increasing for $x \ge \underline{x}$, and the function h has the form given in eq. (1). Then, constraint (i) implies

$$h_0 \le \frac{R(x)(wx+\beta_1\beta_2)+v}{wx} - \frac{up}{w} =: \bar{h}_0(x). \qquad (4)$$

Its differential is $D_x\bar{h}_0(x) =$

$$D_xR(x) + \frac{\beta_1\beta_2(xD_xR(x) - R(x)) - v}{wx^2}. \qquad (5)$$

Observe that the expression may become negative. By definition, $R(x) \equiv h(x,\bar{h}_0(x))$, and therefore $D_xR(x) \equiv D_xh(x,\bar{h}_0(x))$. This implies that $D_x\bar{h}_0(x) = \frac{D_xR(x) - D_xh(x,h_0)}{D_{h_0}h(x,h_0)}$, where $D_{h_0}h(x,h_0) > 0$ (cf. eq. 2). If the negotiation result $h(x,h_0)$ increases in x faster than the recruitment $R(x)$, e.g due to high prices p (cf. eq. 3), the maximal viable harvest recommendation $\bar{h}_0(x)$ decreases in x.

For viability constraint (ii) it is sufficient that the derivative $\dot{x}$ is non-negative only for $x = \underline{x}$, i.e. $h_0 \le \bar{h}_0(\underline{x})$. Constraint (iii) requires a minimum harvest $\underline{h}$ at each time, yielding

$$h_0 \ge \frac{\underline{h}(wx+\beta_1\beta_2)+v}{wx} - \frac{up}{w} =: \underline{h}_0(x). \qquad (6)$$

The partial derivative of $\underline{h}_0(x)$ with respect to x simplifies to $D_x\underline{h}_0(x) = -\frac{\underline{h}\beta_1\beta_2+v}{wx^2} < 0$. Thus, for increasing fish stocks lower initial recommendations can guarantee economic viability. Constraints (ii) and (iii) hold at the same time if $x > \underline{x}$ and $h_0 \ge \underline{h}_0(x)$, or if $x = \underline{x}$ and $\underline{h}_0(\underline{x}) \le h_0 \le \bar{h}_0(\underline{x})$, which implies $\underline{h} \le R(\underline{x})$. Hence, the compatibility of the viability constraints (ii) and (iii) depends only on the recruitment function and the desired harvest. When recruitment at the minimum stock size $\underline{x}$ is higher than the required harvest, there is no contradiction between economic and ecological targets. Otherwise, when the stock attains $\underline{x}$, it must be decided whether to sacrifice conservation or harvest objectives. In the first case the viability kernel, i.e. the set of initial conditions allowing sustainable control, is the space $\{x \mid x \ge \underline{x}\}$, while

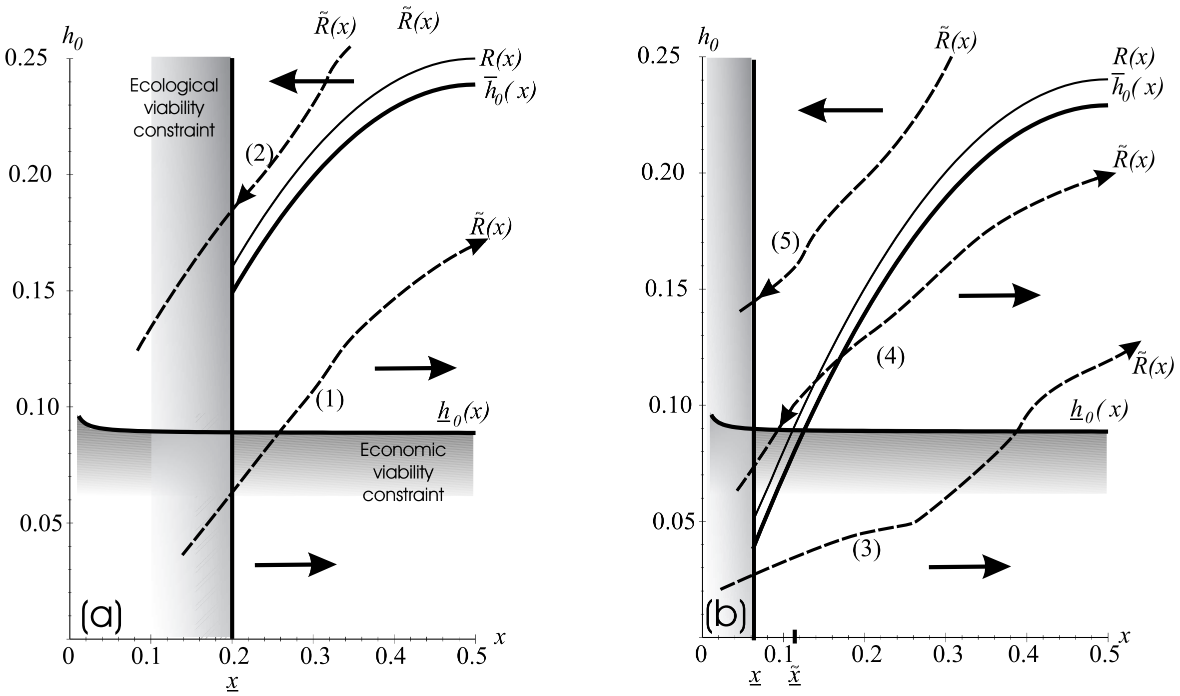

Figure 1: Phase space representation for five possible outcomes of ichthyocentric control. The shaded areas indicate the boundaries of the constrained set, the dashed lines represent possible “real world” realizations of estimated recruitment $\tilde{R}$. The bold arrows indicate how the stock evolves. Note that the dashed lines provides an additional information: the arrows signify the trajectories resulting from the corresponding recruitment estimate. (a) corresponds to the case where $R(\underline{x}) > \underline{h}$, and (b) to $R(\underline{x}) < \underline{h}$.

in the second case the viability kernel is the subset $\{x \mid x \geq \tilde{\underline{x}}\}$, where $\tilde{\underline{x}}$ is defined by the unique solution of $R(\tilde{\underline{x}}) = \underline{h}$.

5 ASSESSMENT OF RECOMMENDATION STRATEGIES

Whilst the system remains in the viability kernel it is *possible* to find harvest recommendations that guarantee viability forever. However, this does not imply that such a strategy is necessarily chosen. We assess whether this is the case for an ichthyocentric or for a qualitative recommendation strategy (see below). For the ichthyocentric strategy, the harvest recommendation h_0 is assumed to be identical to the estimated recruitment $\tilde{R}(x)$, assumed to be increasing with x (for possible realizations of $\tilde{R}(x)$, see Figure 1). We observe that under the presumption that recruitment is estimated exactly ($R = \tilde{R}$), the fishery is exposed to a high risk:

The permanent endeavour of fishing companies during the negotiations to accomplish higher catch quotas has the consequence that the stock will *necessarily* decrease below $\underline{x}$, since $h(x, R(x)) > \bar{h}_0(x)$, and thus $\dot{x} < 0$.

Only in the cases of strongly underestimated recruitment (cases (1) and (3)) is the resource within safe limits. For the cases (2) and (5) the recruitment is overestimated leading to a decrease of stocks and a violation of the ecological constraint. Finally, case (4) partly overestimates and partly underestimates the recruitment. Only if $R(\underline{x}) < \underline{h}$, a rapidly decreasing recruitment estimate leads to an economically non-sustainable state before the ecological criterion is violated.

The qualitative control strategy takes into account uncertainties and is performed in the sense of qualitative reasoning concepts, where systems dynamics is only characterized in terms of thresholds and trends [for details see, Kuipers, 1994; Kropp et al., 2002]. Assume that the values of $x, R, \underline{h}_0$ and $\bar{h}_0$ are not exactly known, but that we can observe whether x is decreasing or increasing and whether the total catch h exceeds $\underline{h}$ or not. In such a situation a control rule can only contain qualitative directives implying an increase or decrease of h_0 (see Table 1). A fast change (rule #1) means that h_0 is set to a level where x increases instantaneously. If the change is slow (rules #3 and #4), we only increase the harvest recommendation if x has been increasing for a longer time. If rule #2 or #3 come into

rule #	observed situation	response
(1)	x decreases and $h > \underline{h}$	decrease h_0 fast
(2)	x decreases and $h < \underline{h}$	decrease h_0 fast
(3)	x increases and $h < \underline{h}$	increase h_0 slow
(4)	x increases and $h > \underline{h}$	increase or decrease h_0 slow

Table 1: Qualitative control strategy consisting of four rules. If the surveillance authority, e.g. the scientific institution, observes the situation shown in the second column it can provide policy advice as indicated in the third column.

play, viability is already violated. Thus they have to be interpreted as crisis management. In Figure 2 the regions corresponding to the different rules are shown. They are separated by the graph of the function $\bar{h}_0(x)$ where $\dot{x} = 0$, and $\underline{h}_0(x)$ where $h = \underline{h}$. Horizontal arrows denote changes in the stock size resulting from the recommendation h_0. Vertical arrows represent the reaction of the scientific institution. Trajectories evolve in the directions given by the arrows. If rule #3 is applied the viability constraint (iii) is not fulfilled. Economic viability can be achieved by increasing h_0 and as a result region (2) or (3) can be entered. Indeed, if stocks are at a very low level and h_0 increases too fast, region (2) is more likely. Thus, an increase of h_0 should be slow, although this keeps the system economically unprofitable for a longer time. Otherwise a sharp cut in harvests is necessary in order to avoid the risk of crossing the threshold $\underline{x}$. When region (4) is approached, the associated rule prevents the system from leaving it. In this region of the phase space additional steering options are possible which not only meet economic and ecological constraints, but also allow a adjusted extension of the harvest in order to improve the profits.

If catches decrease below $\underline{h}$, rule #3 forces the system back. The same holds if catches increase too strongly: when x starts to decrease, rule #1 forces the system back to region (4). If h_0 is far above $\bar{h}_0(x)$ the decrease has to be fast to avoid a transition to region (2). For the same reasons h_0 must be changed slowly in region (4) to prevent it from exceeding $\bar{h}_0$ too much. The qualitative strategy is still risky in region (1) if we do not reduce harvest recommendations fast enough. However, once region (4) is entered, the qualitative strategy guarantees viable recommendations.

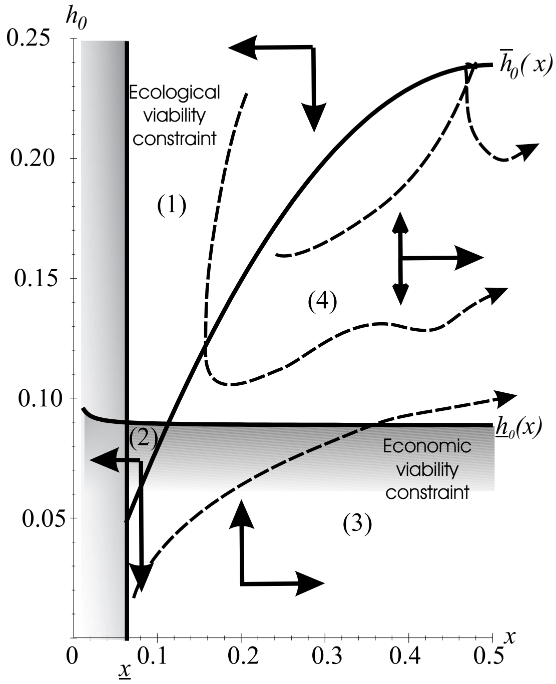

Figure 2: Phase space portrait for qualitative control: The shaded lines represent the viability constraints, the dashed arrows indicate trajectories in accordance with the control strategy. The numbers correspond to the control rules (cf. Table 1, right panel).

6 CONCLUSIONS

Management objectives in fisheries are rarely achieved in practice and the debate on adequate strategies is ongoing. Although it is not expected that a unique solution exists, the need for cross-disciplinary analyses taking into account uncertainties still remains. Our analysis shows that the outcome of co-management regimes depend on biological, *as well as* on economic and political factors. In particular, participatory management strategies, such as co-management, are not *per se* sustainable Recommendations purely based on the observation of fish stocks expose the fishery to a high economic and the resource to a high ecological risk. More flexible strategies, e.g. based simply on qualitative information on the state of the fishery, can guarantee minimum harvest levels and an increasing fish stock.

In summary, much more research is needed, but we hold that the presented methodology opens a promising road towards a better understanding of the intrinsic processes – including ecological, economic, and social issues – in fisheries. The viability concept supply a valuable tool for risk assessments in fisheries prone to non-sustainable developments. Therefore, future work will be directed to the introduction of additional viability constraints focussing on the profits realized by fishing firms and different capital stocks.

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