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Viability analysis of management frameworks for fisheries

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The pressure on marine renewable resources has rapidly increased over past decades. The resulting scarcity has led to a variety of different control and surveillance instruments. Often they have not improved the current situation, mainly due to institutional failure and intrinsic uncertainties about the state of stocks. This contribution presents an assessment of different management schemes with respect to predefined constraints by utilizing viability theory. Our analysis is based on a bio-economic model which is examined as a dynamic control system in continuous time. Feasible development paths are discussed in detail. It is shown that participatory management may lead to serious problems if a purely resource-based management strategy is employed. The analysis suggests that a less risky management strategy can be implemented if limited data are available.

Keywords: co-management, decision support, environmental constraints, fisheries management, inverse technique, viability analysis

1. Introduction

Marine fish stocks are under extreme pressure worldwide [1,2]. Two divergent but closely related developments are observable [3,4]. On the one hand increasing surveillance efforts, limited entries, or marine protected areas are established for mitigating overfishing, whilst on the other hand the fishing industry can be sustained at an economic level only by high amounts of subsidies from the public sector [5–7]. This is, in particular, remarkable since there has been an awareness of these problem for decades and most fisheries are subject to management measures. The general situation in marine capture fisheries can be characterized by the following statements:

- Several authors argue that research as well as management instruments are overly biased toward the ecological viewpoint, while economic driving forces or the role of political decisions are rarely considered [8,9].
- Fisheries are per se associated with inherent uncertainty, which is related to the partial opaqueness on both the ecological and the economic systems [10].
- It is often mentioned that model approaches used to provide policy advice are based on unrealistic basic assumptions and/or inappropriate methodological concepts (cf. [11]).

However, one-sided views, distinct sources of vagueness, and unsuitable assessment techniques not only restrict what can be modeled, but they also impose severe limitations regarding the explanatory power of the results. Thus, the basic question concerning the possibilities for a sustainable development in fisheries still remains: How can we manage fisheries in a way that avoids 'hazardous developments'? Recently, so-called co-management schemes have been introduced in order to mitigate the consequences of fishery mismanagement, but currently systematic assessments of control schemes regarding their effectiveness are rarely employed. Considering this situation, it seems impossible to define safe management options for fisheries.

One focal point of our examination is the inability to anticipate exactly what will happen in the future of fisheries and marine stocks. Thus, we do not strive to determine 'optimal paths' for the co-evolution of fisheries and marine resources, but rather for desirable corridors.[1] These corridors are constrained by measures representing our knowledge of what should at least be avoided in order to achieve sustainability or prevent catastrophic developments (for an example from climate research, cf. [13]). We make use of these ideas by applying viability theory, which was developed by Aubin [14], because it enables us to formally define the corridor boundaries. Such an analytical strategy allows to provide knowledge for decision-making, although constraints are normative and an outcome of public discussions. In addition, it shifts attention from the whole set of options to a constrained set of options leaving space for adjustments acceptable in political frameworks. Additionally, we have combined the viability approach with game-theoretic assumptions about the socio-economic mechanisms constituting typical management frameworks. The management schemes we are analysing are an issue of

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[1] The conceptual ideas how these corridors can be used for policy advice and how judicious strategies for the management of development processes shall be designed, have been discussed in, e.g. [12]. Inverse techniques (target-oriented approaches), such as viability analysis, solve many analytical problems posed by the intricacy of the policy-bioeconomic complex.

the current debate and are discussed briefly in the next paragraphs.

Without any regulation it is likely that in the future fish stocks will be further depleted as long as overexploitation is profitable for the individual fisherman. The revenues from catches are private, while the costs induced by a reduced resource stock are shared between all participants in the fishery (tragedy of the commons, cf. [15]). Competing fishing firms base their decisions on deployable capital, necessary efforts, and on the observed state of the target species (see dashed core in figure 1A,B). The latter is rather critical, because the catch is commonly used as an estimator for the abundance of biomass. This situation changes when a management authority introduces measures imposing restrictions on the fishery (e.g. on gear type, allowable catches, amount of effort, etc.). Such limitations change the decisions made by fishing firms (top-down management, cf. figure 1A). Nevertheless, in many cases the results are disappointing, because restrictions are perceived as constraining economic opportunities. Thus, fishing firms act as opponents to management authorities, often resulting in illegal landings or mis-reported catches [16–19]. Moreover, scientific stock estimates are often not as reliable as required. Hence, when a fishery reaches a state of crisis, scientific institutions come under pressure in the public debate, i.e. for putting too much stress on conservation objectives and neglecting economic sustainability.

One solution to avoid these shortcomings is offered by co-management schemes, i.e. by including fishing firms in the decision-making process [20–23]. If fishermen are involved in the decision-making process, it is assumed that economic objectives will complement conservational goals of governmental organizations. It is the aim of this strategy that all actors in marine capture fisheries participate actively with respect to the overall target to keep the utilization of marine resources sustainable. Self-governance within a legal framework constituted by governments is a basic principle of this strategy. As a result, the fishing industry represents economic objectives in a negotiation process with agents pursuing conservational goals. Before such a situation comes into play, a variety of conflicts often have to be resolved, e.g. conflicts over who owns and controls access, how policy and control mechanisms should be carried out, or conflicts between local stakeholders (for a nomenclature of common conflicts in fisheries, cf. [24]). Typically, this type of management is exercised via a fishery council where the representatives of fishing firms, processing firms, scientific institutions and policy negotiate, e.g. about the total allowable catch for each different species. This plan has to be approved by a governmental authority and is executed by a management organization which operates in close collaboration with local fishermen (see figure 1B). A plausible conjecture is that under co-management fishermen will show higher compliance with the resulting constraints (cf. [25,26]).

However, an additional problem occurs if management regimes consider only biological measures as steering targets. Such a strategy has been claimed as 'ichthyocentrism', indicating that scientific advice puts too much emphasis on the resource itself (the various fish stocks, in particular their biomass) [8,9] compared with efforts to examine the behaviour of the resource users, their economic settings, and aims. In such a case, the management success cannot depend on an exact stock assessment, which is impossible, due to insufficient measurement and sampling methods.

Our study applies viability analysis in order to assess different management schemes in marine fisheries. Recent studies have shown that this methodology is valuable for determining completely unacceptable outcomes and defining judicious measures for mitigation [13,27–29]. Therefore, we try to find out how management in fisheries should be designed under defined constraints in order to achieve safe limits.

Pursuing this goal we have defined a model including stock dynamics as well as economic and political decision-making. We motivate the viability constraints and use the

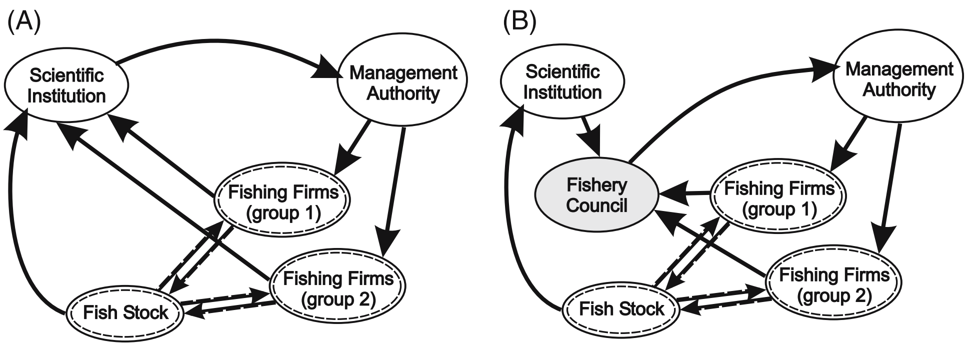

Figure 1. Sketch of management schemes in fisheries: (A) Top-down strategy: a scientific organization collects data from fishing firms and own scientific trawls and estimates the stock size. Resulting reports are delivered to a management authority for decision support. The authority imposes restrictions on the fishing firms. (B) For a co-management a fishery council is introduced, in which representatives from science and the fishing industry negotiate for appropriate catch or effort restrictions. If they agree the resulting plan is provided to the management authority, who approves it. An unmanaged fishery is represented by the dashed cores. Here the firms calculate their efforts independently and only related to the current stock status (measured by the catch from the previous years, etc.).

catch recommendations of the scientific institution participating in the co-management process as control variable. The viability criteria are imposed on the model in order to assess and develop different control strategies. A discussion of the results and a summary concludes the paper.

2. The dynamic model

The basic state variable of the model is the biomass of a fish stock x, which is influenced by the total harvest h in the fishery. If we introduce a recruitment function R which assigns the growth of the biomass to a given stock, we obtain

$$\dot{x} = R(x) - h$$

as ODE for the stock dynamics. As usual, R is assumed to be of the Schaefer type [30] producing logistic growth with maximum $\overline{R}$ at x_{MSY} and $R(0) = 0$.

$$\forall x \in [0, x_{\mathrm{MSY}}] : R(x) > 0 \quad \text{and} \quad D_x R(x) > 0,$$

where D_x denotes the differential operator with respect to the argument x. For $x > x_{\mathrm{MSY}}$ we have $D_x R(x) < 0$. Due to the complexity of ecosystems (embedding of target species into several food webs, large scale impacts such as ENSO, etc.) we have to deal with limited knowledge about the behaviour of a fish stock. Thus, no additional assumptions about R are introduced.

The next step is to determine the amount of total harvest h. In the presented model we concentrate on output-management, i.e. the negotiation process is about the allocation of catch quotas q_i to groups of fishing firms $i = 1, \ldots, n$. We assume that it is profitable for each firm to realize a harvest which it is allowed to catch. Thus, the resulting total harvest is $h = \sum_i q_i$. To model the negotiation process a game theoretic approach can be applied where the fishing actors agree on particular limits for harvest and the allocation of efforts (cf. [31]). Expanding this approach, a scientific institution and representatives from the fishing industry 'bargain' for the total harvest h and the individual quotas q_i. When these pressure groups agree on an allocation, the result is transformed into practice by the management authority. It is further presumed that the negotiations are opened by the scientific institution, which makes a recommendation $r \geq 0$ for the total catch. Each group of the fishing industry tries both (i) to get a share as high as possible of the total harvest h and (ii) to increase h above the catch recommendation r in order to improve their profits.

The optimal quota and optimal increase h–r may differ among the groups, e.g. due to their capitalization or technical efficiency (artisanal vs. industrial fishery). But there is also a trade-off between higher profits resulting from higher quotas and deviation costs d_i imposed by exceeding the scientific recommendation. These costs are linked to the legitimation of bargaining positions challenging the scientific advice and increasing transaction costs of fierce negotiations (time, expertise, human and social capital, data retrieval, public relations, etc.). How strong this trade-off is depends i.a. on reputation, the political influence, and the availability of information – all of which may differ between the pressure groups. We further assume that the fishing groups act myopically, which is realistic if the influence of single fishing firms on the resource is neglectable [6,32] and if they push their representatives for higher quotas. This entails that they only account for short-term deviation costs. Myopic behaviour can also be observed if the burden of long-term responsibility is shifted to the scientific institution (allowing fishing firms to reduce subjective uncertainties).

We denote the profit of a group i as π_i. It depends on the quota q_i and the available amount of fish x (which is the same for all fishing firms). This function also represents the efficiency of boats, fishing gear, technological equipment, etc. In a situation without deviation costs, the function has the form

$$\pi_i(q_i, x) = pq_i - c_i(q_i, x).$$

The first term represents revenues on markets, where p corresponds to the market price (which is assumed to be exogenous), while c_i is a cost function assigning variable costs to a realized harvest q_i. It is economically reasonable to assume that c_i is increasing in q_i, since more labour, time, fuel, etc., is needed for a larger catch. On the other hand, costs are decreasing in x due to higher densities of fish. Each firm individually selects catch q_i to obtain an optimal profit for a given price and target species. However, in a co-management framework the profit function is modified by deviation costs:

$$\pi_i(q_i, x) = pq_i - c_i(q_i, x) - d_i\left(\sum_{j=1}^{n} q_j - r\right).$$

It should be noted that the deviation costs not only depend on the individual decision q_i, but also on the quota allocated to the other pressure groups. If $\sum_j q_j - r$ becomes negative, we assume that d_i vanishes, since deviation costs do not apply if the sum of all quotas is below the scientific recommendation. It is reasonable to presume that each d_i is a monotonic increasing function.

Now, the Nash equilibrium of the negotiation process is given by a quota allocation which assigns an individual quota q_i to each group i that maximizes π_i with respect to q_i for given p, x and the quotas of the other participants. The resulting total harvest is the sum of all quotas. By applying basic calculus it is shown that all π_i are concave and continuously differentiable with respect to q_i. Solutions of the equation system

$$\forall i = 1, \ldots, n : D_{q_i} \pi_i = 0$$

are such negotiation equilibria.

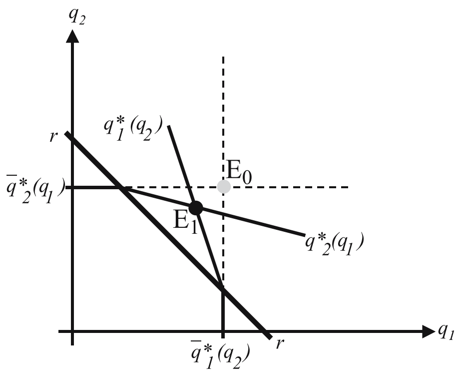

Figure 2. Negotiation equilibrium of the quota setting game. q_1^* and q_2^* denote the optimal catch for both groups if there were no management (i.e., deviation costs $d_i \equiv 0$). In this case the choice of the groups is independent from each other (indicated by dashed lines), and will result in the equilibrium E_0. By introducing a catch recommendation r all points to the upper right of the diagonal are associated with positive deviation costs. Therefore, the optimal choice of each group depends on the choice of the other (indicated by *solid lines*) and results in the equilibrium E_1.

In the following analysis we restrict this general approach to the case of two specific fishery groups and provide a possible functional specification for variable and deviation costs:

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

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

The parameters α_i, β_i, κ_i (i = 1, 2) are not completely known, but positive.

First assume that we are in the case of non-vanishing deviation costs. If x is positive and since $q_i \geq 0$ the resulting profit functions π_i are continuously differentiable and concave with respect to q_1, q_2. Thus, the Nash equilibrium (for given p, x, r) is obtained by solving

$$D_{q_1}\pi_1 = p - \frac{\alpha_1 + 2\beta_1 q_1}{x} - 2\kappa_1(q_1 + q_2 - r) = 0,$$

$$D_{q_2}\pi_2 = p - \frac{\alpha_2 + 2\beta_2 q_2}{x} - 2\kappa_2(q_1 + q_2 - r) = 0,$$

for q_1, q_2. The latter equations define a total (binding)[2] harvest

$$h_b(x, r) = q_1 + q_2 = \frac{upx + wxr - v}{\beta_1\beta_2 + wx}, \tag{1}$$

where

$$u := \frac{1}{2}(\beta_2 + \beta_1) > 0,$$

$$w := \beta_1\kappa_2 + \beta_2\kappa_1 > 0,$$

$$v := \frac{1}{2}(\alpha_1\beta_2 + \alpha_2\beta_1) > 0.$$

The binding harvest varies according to

$$D_r h_b = \frac{wx}{\beta_1\beta_2 + wx} > 0, \tag{2}$$

and

$$D_x h_b = \frac{vw + (up + wr)\beta_1\beta_2}{(wx + \beta_1\beta_2)^2} > 0. \tag{3}$$

If the catch recommendation r is so high that it is not profitable for fishing firms to exceed it, then no deviation costs apply in the Nash equilibrium. This special case κ_i = 0 results in a total harvest (associated with a non-binding recommendation)

$$h_n(x, r) = \frac{upx - v}{\beta_1\beta_2} =: \hat{r}(x). \tag{4}$$

Thus, for $r \geq \hat{r}(x)$, we have $h = h_n(x, r)$, i.e. the industry catches voluntarily less fish than recommended and therefore, no deviation costs apply.

For $r < \hat{r}(x)$ the harvest is $h = h_b(x, r)$. Summarizing we obtain the total harvest function[3]

$$h(x, r) = \begin{cases} h_b(x, r) & \text{if } r \leq \hat{r}(x) \text{ and } h_b(x, r) \geq 0, \\ h_n(x, r) = \hat{r}(x) & \text{if } r \geq \hat{r}(x) \geq 0, \\ 0 & \text{if } \hat{r}(x) \leq 0, \\ 0 & \text{if } 0 \leq r \leq r(x) \text{ and } h_b(x, r) \leq 0. \end{cases} \tag{5}$$

We remark that

$$h_n(x, r) = h_n(x, \hat{r}(x)) = \hat{r}(x) = h_b(x, \hat{r}(x)). \tag{6}$$

As h_b is monotonically increasing in r while h_n is independent from recommendations, we find

$$r > \hat{r}(x) \Rightarrow h_n(x, r) < h_b(x, r), \tag{7}$$

$$r < \hat{r}(x) \Rightarrow h_b(x, r) < h_n(x, r), \tag{8}$$

and conclude that always

$$h(x, r) \leq \hat{r}(x). \tag{9}$$

[2] The two cases considered here comprise binding and non-binding recommendations. The former indicates that the achieved harvest is exactly constrained by the recommendation, the latter that the harvest is lower than the recommendation, i.e. the industry catches – voluntarily – less than suggested.

[3] There are two additional specific cases that have to be considered (cf. equation (5): $h(x, r) = 0$). If $\hat{r}(x) \leq 0$, it is not profitable to cast for fish, even if there were no deviation costs, and therefore h = 0. If $0 \leq r \leq \hat{r}(x)$, but $h_b(x, r) \leq 0$, the recommendation is so tight that it prevents commercial fishing activities.

Equality is only possible if non-binding recommendations are made ($r \geq \hat{r}(x)$). Otherwise the result of the negotiation process is below the harvest, which would be economically optimal in the case of absent deviation costs (cf. figure 2). Since additionally

$$D_x h_n = D_x \hat{r} = \frac{up}{\beta_1 \beta_2} > 0, \tag{10}$$

the total harvest h is increasing (not strictly) with an increased abundance of fish (supposing the recommendations are unchanged).

3. Viability constraints for sustainability

To answer the question whether a fishery described by this model can be managed in a sustainable way or not, it is necessary to specify this objective in more detail. Generally, sustainability can be characterized by ecological, economic, and social dimensions. Here we concentrate on the first two and facilitate their formalization in the framework of viability theory [14]. Viability constraints characterize an acceptable sub-region of the phase space. A time evolution of a system is called viable (or sustainable) if it remains in this region indefinitely. If a development process is controlled, in the examined case by the harvest recommendation r, we want to analyse whether a control strategy keeps it viable or not.

The choice of viability constraints cannot be purely justified by empirical considerations, because it involves value-laden normative settings (e.g. on what is at least acceptable or what do we want). The viability concept allows evaluation of different normative settings with respect to their consistency and consequences, for instance, whether a given management framework admit controls which satisfy the constraints. For our examination of marine fisheries two reasonable viability constraints are defined and investigated. We deduce conditions under which a control rule for r exists, respecting both constraints at the same time:

1. Ensure that the biomass of a stock resides always above a minimal level $\underline{x} > 0$, i.e.
$$\forall t : x(t) \geq \underline{x}.$$
2. Require that a minimum total harvest $\underline{h} > 0$ can always be realized or exceeded, i.e.
$$\forall t : h(t) \geq \underline{h}.$$
This harvest covers fixed costs in the fishery, guarantees a minimum level of employment, or sustains food safety.

In the following, we refer to the first criterion as "ecological" and to the second one as "economic" viability. The viability problem is introduced more formally as follows.

Let $F(x)$ denote the set of all derivatives $\dot{x}$ which are admissible in x, e.g., $F(x) := \{R(x) - h(x, r) \mid r \geq 0$ and $h(x, r) \geq \underline{h}\}$ for all changes of fish stocks resulting from an economically viable harvest recommendation r. An interval $I = [\underline{x}, \infty]$ is called a viability domain of F if

$$\forall x \geq \underline{x} : F(x) \neq \varnothing \text{ and } F(\underline{x}) \cap [0, \infty] \neq \varnothing. \tag{11}$$

The viability theorem [14, p. 91] states that if I is a viability domain of F, then for every initial value $x_0 \in I$ there exists a control path $r(\cdot)$, such that the solution of the initial value problem

$$\dot{x}(t) = R(x(t)) - h(x(t), r(t)) \in F(x),$$
$$x(0) = x_0,$$

remains in I, i.e., $\forall t \geq 0$: $x(t) \in I$ (more technical premises of this theorem can be found in [14]).

In the following we determine criteria for I being a viability domain, depending on given values of $\underline{x}$ and $\underline{h}$. For such values a 'wise' harvest recommendation can keep the fishery within economic and ecological sustainable limits. If the harvest recommendation r is binding then $\dot{x} \geq 0$, if $R(x) \geq h_b(x, r)$ (catch matches recruitment). The solution of this inequality yields

$$r \leq \frac{R(x)(wx + \beta_1\beta_2) + v}{wx} - \frac{up}{w} =: \bar{r}(x), \tag{12}$$

i.e. a maximal recommendation which results in a negotiation equilibrium for the total harvest which is low enough to ensure an increasing fish stock. This, however, depends on the state of the resource, the market, and other economic parameters. Relation (12) does not necessarily have a positive right-hand side. Since $r \geq 0$, it is impossible to stabilize the fish stock in such a case. The maximal recommendation does not necessarily increase with the fish stock. Differentiating with respect to x yields

$$D_x \bar{r} = \frac{wx^2 D_x R(x) + \beta_1\beta_2(x D_x R(x) - R(x)) - v}{wx^2}, \tag{13}$$

where the expression $xD_xR(x) - R(x)$ may become negative.

In the case of non-binding recommendations (catch is lower than recommendation) $r \geq \hat{r}(x)$, we need $h_n(x, r) = \hat{r}(x) \leq R(x)$ for an increasing resource. This condition does not depend on the concrete value of r.

Due to relation (11) all of the above conditions only have to hold at $x = \underline{x}$, and we can determine the maximal harvest recommendation if $R(\underline{x})$ is known. Again, it may happen that, e.g. due to high prices, this condition cannot be fulfilled. It depends on a non-trivial relation of economic and ecological parameters, whether the quota negotiation process can yield a viable result. To satisfy the economic viability constraint, r has to be chosen for every time such that $h(x, r) \geq \underline{h}$. For $r \leq \hat{r}(x)$ we solve $h_b(x, r) \geq \underline{h}$ for r, yielding

$$r \geq \frac{\underline{h}(wx + \beta_1\beta_2) + v}{wx} - \frac{up}{w} =: \underline{r}(x). \tag{14}$$

Contrary to the former case we obtain a lower limit for the harvest recommendation. While the similarity of the right hand sides of equations (12) and (14) is obvious, the partial derivative with respect to x simplifies to

$$D_x\underline{r} = -\frac{\underline{h}\,\beta_1\beta_2 + v}{wx^2} < 0, \tag{15}$$

i.e. for larger fish stocks, lower catch recommendations guarantee economic viability. However, for non-binding recommendations, the condition $\hat{r}(x) \geq \underline{h}$ has to hold for every $x \in I$.

Combining both viability constraints, we must distinguish whether there is the possibility to choose r at $x = \underline{x}$ such that it respects equations (12) and (14) (in the case of binding recommendations), i.e. $\underline{r}(\underline{x}) \leq r \leq \overline{r}(\underline{x})$, which is equivalent to $\underline{h} \leq R(\underline{x})$. Summarizing all possible cases yields (cf. Appendix A.1 for the proof):

The interval $I = [\underline{x}, \infty]$ is a viability domain, if and only if

$$\begin{array}{ll} \text{(i)} & \hat{r}\,(\underline{x}) \geq \underline{r}(\underline{x}), \quad \text{and} \\ \text{(ii)} & \underline{h} \leq R(\underline{x}), \quad \text{and} \\ \text{(iii)} & \underline{r}(\underline{x}) \geq 0 \quad \text{or} \quad \overline{r}(\underline{x}) \geq 0. \end{array} \tag{16}$$

Although for the proof (A.1) an awkward set of cases has to be considered, these conditions are easy to interpret. The compatibility of both viability criteria only depends on the relation between the recruitment function, the aspiration level for harvest and the efficiency of the firms. If the recruitment at the minimal viable stock level $\underline{x}$ lies below the required harvest, there exists an obvious contradiction between economic and ecological targets (condition 16ii). In this situation, stock approaches $\underline{x}$, the fisheries council has to decide whether to sacrifice conservational or harvest objectives. According to (16i) it is profitable to fish at least $\underline{h}$, even if no deviation costs apply. Otherwise no harvest suggestion guarantees an adequate yield, because the harvest is always below or equal to $\hat{r}(x)$. Condition (16iii) can be met, if the recommendations can reduce the harvest below $R(\underline{x})$ in case the stock approaches $\underline{x}$. Otherwise a recommendation $r < 0$ would be needed in order to achieve a sufficient harvest reduction $h(x, r) < R(x)$. However, in our examinations this makes no sense.

4. Assessment of recommendation strategies

As long as the system stays in the viability domain it is *possible* to keep it viable if an appropriate strategy is selected. However, this does not ensure that *every* control strategy is successful. In addition, in a critical state in which the viability constraints are not satisfied, it is not clear whether a selected strategy leads to ill-management or forces a fishery back to sustainable limits. Consistently, we examine and assess the viability of different recommendation strategies in this section. Formally, such a strategy assigns a value for r to a given system state, i.e. a closed-loop control according to the following schemes.

- *Ichthyocentric control*: The harvest recommendation is purely based on an estimate of the stock recruitment.
- *Conservative control*: The harvest recommendation is based on economic viability in the sense that the minimum harvest $\underline{h}$ is always realized.
- *Qualitative control*: In this case, due to uncertainties, recommendations are only based on qualitative economic and ecological observations.

4.1. Ichthyocentric control

The first control strategy is called “ichthyocentric,” in order to make clear that the scientific organization considers only the state of a fish stock for their harvest suggestions, but not the socio-economic conditions. It is assumed that the harvest recommendation r equals the estimated recruitment of the targeted species and that the scientific institution is able to estimate correctly the recruitment function, i.e.

$$r = R(x).$$

This is a challenging task, since an exact estimation of the stock biomass is bound to fail, due to unavoidable measurement deficits. However, let us assume that the estimator is roughly correct. The examination of the ichthyocentric control strategy shows that even in this ideal case economic viability is not always guaranteed. If $r = R(x) \leq \underline{r}(x)$ the recommendations are too low to sustain a harvest rate $\underline{h}$ (in particular, if the fishery stays in a viability domain, cf. Prop. A.2 in the Appendix). The situation is even more dramatic if one focuses on ecological viability. If recommendations r are binding our results show that the catch exceeds r. As a consequence, recommending $R(x)$ leads to a catch above recruitment, which implies an always decreasing fish stock ($h(x, R(x)) \leq R(x)$, if and only if $r = R(x) \geq \hat{r}(x)$, cf. Prop. A.3).

Ichthyocentric control is only sustainable if recruitment is always large enough to allow a minimal harvest and if recommendations are not binding at $x = \underline{x}$. The latter means that the realized catch $\hat{r}$ must be significantly lower than the scientific recommendation, a situation which normally does not occur in industrial fisheries. But it might be observable in low capitalized fisheries, e.g. if the competitors only use small boats. Otherwise, the stock will necessarily decrease below $\underline{x}$. If this is already the case, the chance for a regeneration of stocks is rather bad until $\hat{r}(x) < R(x)$ is approached. On this level the firms voluntarily catch less than recruitment. We can summarize that even in the case of a perfect stock assessment, the ichthyocentric strategy exposes the fishery to a risky development path.

4.2. Conservative control

The conservative control strategy aims to ensure that the economic viability criterion is satisfied, but nothing more: the scientific institution always approves

$$r = \underline{r}(x).$$

To evaluate this strategy the phase space structure of the model must be discussed in more detail (figure 3). We define the fish stock level a by the intersection $\underline{r}(x) = \hat{r}(x)$. It is unique since $\hat{r}(x)$ is linearly increasing, while $\underline{r}(x)$ is a monotonically decreasing function (equation (15)). If $[\underline{x}, \infty]$ is a viability domain and $\hat{r}(\underline{x}) \geq \underline{r}(\underline{x}) \geq 0$ (equation (16)) holds, it follows that $a < \underline{x}$ and $\hat{r}(a) = \underline{r}(a) > 0$. We further define the fish stock levels $b < c$ as the solutions of $\overline{r}(x) = \underline{r}(x)$. Although $\overline{r}(x)$ is (in general) not monotonic, this equality only holds if $\underline{h} = R(x)$ (cf. equations (12) and (14)). Since the recruitment function R is of Schaefer type, only a maximum of two solutions can occur. If $[\underline{x}, \infty]$ is a viability domain, with the consequence that $R(x) \geq h$ holds (equation (16)), these two intersections satisfy $b < \underline{x} < c$ (the only exception is the marginal case $R(\underline{x}) = \underline{h}$). We have, in principle, to distinguish the cases $a < b$ and $b < a$ (cf. figure 3A,B). We further observe that $\lim_{x \to 0} \overline{r}(x) = +\infty$, indicating an additional intersection between $\hat{r}$ and $\overline{r}$ below b. For the conservative control scheme the system always evolves along the graph of the bold straight and dotted line (cf. figure 3).

If the fishery stays within the viability domain, we always have $r = \underline{r}(x) \leq \hat{r}(x)$ (Prop. A.1) and $h_b(x, \underline{r}(x)) = \underline{h} > 0$ holds. Consequently, it follows from equation (5) that $h(x, \underline{r}(x)) = h_b(x, \underline{r}(x)) \geq \underline{h}$, i.e. conservative control guarantees economic viability in the viability domain. Also, due to the fact that within a viability domain $h(\underline{x}, \underline{r}(\underline{x})) = \underline{h} \leq R(\underline{x})$ is valid, the ecological viability constraint is met. Therefore, it can be deduced that conservative control is – in general – a viable strategy. Nevertheless, the following two aspects have to be considered. (i) This strategy only guarantees a minimal catch level, although a larger harvest might be viable, too (for $x \in [\underline{x}, c]$). (ii) Taking into account the deficits in exact stock estimation, it may happen that the state of the stock is already below $\underline{x}$ indicating that no viable control exists anymore, but this fact is unrecognized by the resource users. However, it is of specific interest whether a stock will recover to a viable level or not if the conservative control strategy is still exercised in such a situation. Both cases are possible, in some cases the stock can recover, but also worse scenarios can occur, e.g. if $\underline{r}(x) \leq \hat{r}(x)$ (as in the viability domain), but $R(x) < \underline{h} \Leftrightarrow \overline{r}(x) < \underline{r}(x)$ (cf. figure 3A, dotted line), i.e. recruitment is below minimal harvest and the stock further decreases. Another situation is given if $\overline{r}(x) < \hat{r}(x) < \underline{r}(x)$ (cf. figure 3B, dotted line), where $h(x, \underline{r}(x)) = \hat{r}(x) = h_b(x, \hat{r}(x)) > h_b(x, \overline{r}(x)) = R(x)$.

We conclude that conservative control can satisfy economic and ecological viability criteria, but only for non-critical situations (i.e. in the viability domain). In contrast to the ichthyocentric control scheme, it has the advantage that only qualitative information is needed to exercise this type of management, i.e. the scientific institution only has to supervise whether the realized catch of the fishery is above or below $\underline{h}$. In the former case, catch recommendations should be reduced, while in the latter they should be increased. This perspective considers the problems arising from uncertainty in fisheries management more seriously. However, in a crisis (i.e. being outside the viability domain) where the aspiration level for harvest is

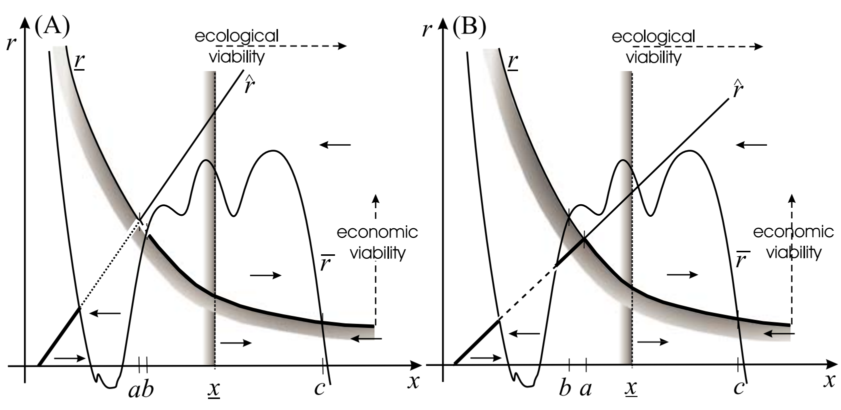

Figure 3. Phase portraits for the conservative control strategy: (A) $a < b$ left, (B) $b < a$. Below $\underline{r}$ a viable harvest cannot be obtained. *Solid arrows* denote the direction of x, being positive below $\overline{r}$ and negative above. Note that it is possible for both cases that $\overline{r}$ has no zero (then the separated areas below $\underline{r}$ are joined) or multiple zeros. In addition, if $a < b$ it might be possible that $\overline{r}$ becomes larger than $\hat{r}$ (cf. (A)), then the area above $\overline{r}$ decomposes into multiple sections which is not shown here, because it does not change the general statements. The *bold* and *dotted lines* correspond to recommending $\underline{r}$, resulting in an increasing (*straight*) or decreasing stock (*dotted*). Note that for $x < a$, recommending $r = \underline{r}(x)$ results in the same catch as recommending $r = \hat{r}(x)$.

Table 1
Qualitative control as discussed in detail in the text.

Rule no.	Qualitative observation	Reaction
(0)	$r > \hat{r}(x)$	Decrease r
(1)	x increases and $h > \underline{h}$	Increase r
(2)	x increases and $h < \underline{h}$	Increase r
(3′)	x decreases and $h > \underline{h}$ and mature	Decrease r
(4′)	x decreases and $h < \underline{h}$ and mature	Moratorium: $h = 0$
(3″)	x decreases and $h > \underline{h}$ and emerging	Decrease r until $h = \underline{h}$
(4″)	x decreases and $h < \underline{h}$ and emerging	Increase r until $h = \underline{h}$

The numbers of rules corresponds to areas in the phase portrait (cf. figure 4). Note that the coat indicates the history of a fishery (cf. text). In the phase plots they are indistinguishable.

too high or the abundance of the targeted species is rather small for a viable control, we cannot be assured that the resource recovers by applying this management strategy. But even in the viable case, profits in the fishery are still limited to a minimum.

4.3. Qualitative control

The third alternative extends the qualitative view discussed above in order to increase profits and limit risks in critical situations, i.e outside the viability domain. It is based only on qualitative observations, which means that the exact numerical values of x, R, $\underline{r}$ and $\overline{r}$ are not known, but that it can be determined correctly, whether x is decreasing or increasing in time, whether the realized catches exceed $\underline{h}$ or not, and whether recommendations are binding or not. The applied control rule provides only qualitative advice, i.e. whether r has to be increased or decreased. The proposed qualitative control strategies are summarized in table 1. To discuss this control scheme in detail, we refer to phase space portraits again (figure 4). The underlying idea is to combine qualitative observations regarding a fishery with phase plane analysis. This knowledge makes it feasible to decide in which region of the phase plane a fishery is currently situated. If sufficient knowledge is available we additionally use information on the history of a fishery in order to decide this question. This makes it feasible to classify it either as emerging, which means that a stock was not exploited considerably before, or we otherwise nominate it as mature. If a region is determined in this way, an appropriate control rule can be selected.

Whenever the system stays within the viability domain only the rules (0, partly), (1) and (3) come into play which warrants that the fishery will remain in the viability domain. In contrast, if a fishery leaves the viability domain, the rules (0), (2), (3), and (4) are able to steer the industry back to sustainable limits.

In case of an emerging fishery, we start with a high x (moving from the right to the left in figure 4). In region (3) it could be reasonable to increase r in order to harvest as much as possible. However, there would be a significant risk to move close to region (0), possibly without recognizing qualitatively that the stock decreases below $\underline{x}$. Such a situation can be avoided if the scientific institution strictly follows the conservative control scheme in an emerging fishery until region (1) is reached for the first time. Thenceforward we call a fishery mature and catch recommendations can be increased to improve the profits. Once the fish stock begins to decrease again, we know that we have approached region (3) and r must reduced to force the fishery back to (1) in order to stay within the viability domain. Contrary to the emerging fishery, it is not needed

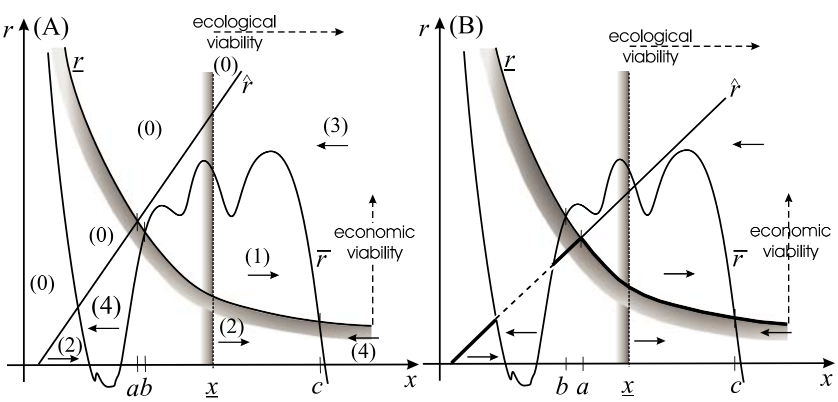

Figure 4. Phase portraits for the qualitative control strategy: (A) $a < b$, (B) $b < a$. The numbered areas correspond to situations which can be distinguished qualitatively and are discussed in detail in the text.

to decrease r until $h = \underline{h}$, because the fish stock begins to increase before (region 1).

Now suppose that we are outside the viability domain. This may be a consequence of, for example, an ill-adapted management scheme which was applied before the co-management came into play. If the fishery stays in region (2) the scientific institution shall increase r to obtain at least $\underline{h}$ as yield. If decreasing stocks and low catches are observed in a mature fishery (region 4) by considering the precautionary principle, we must assume that $x < \underline{x}$. In such a case only a moratorium ($h \equiv 0$) can steer the fishery back to sustainability. If $\overline{r}(x)$ has zeros and the mature fishery resides below the smallest zero, an increase of r results in entering region (4) (same situation as above). As an additional precondition for a safe development, it is required that recommendations are always binding: once $r > \hat{r}(x)$, i.e. the fisheries harvest less than it was recommended r shall be reduced. This prevents that the stock size decreases below a (cf. figure 3). If $b < a$ this guarantees that x approaches the viability domain.

The qualitative control as presented here allows higher profits than for conservative control, because recommendations are increased above $\underline{r}(x)$ for $\max(a, b) < x < c$, which results in higher harvest rates. It is also more secure, because it forces the system back to the viability domain – even if quantitative observations on the system are not available.

5. Discussion

The previous analysis shows that participatory co-management schemes are not a priori viable, since the outcome strongly depends on the relation between biological, economic and political factors, and, in particular, on the catch recommendations of the scientific institution. In the future, is clear that ill-managed fisheries will radically reduce the self-determining options of the coming generations in the fishing industry. The applied viability concept shows how the dangerous effects related to measurement deficits can be surmounted. In this way, the corresponding uncertainty can be confined to a minimum by a parallel achievement of management options.

In this contribution we have shown this for the three cases of ichtyocentric, conservative, and qualitative control. An extreme case in this context is a recommendation strategy, which is purely based on the observation of fish stocks. This exposes the fishery to a high risk of economic and ecological decline. Such a situation can be substantially improved by designing a more flexible strategy, which only needs qualitative information about the state of the fishery and does not deterministically fix the scientific institution. In addition, it is shown that even for a fishery outside of a viable zone, there exists a good chance that it can be steered into the safe region if a suitable control scheme is applied. A disadvantage of the presented model is that it does not take the costs of change into account, i.e. that rapid changes in harvest recommendations may induce high adaption or political costs. On the other hand, even under uncertainty the qualitative control strategy is at least as good as economically conservative control, and less risky than data-intensive ichthyocentric management.

However, the knowledge regarding relevant processes in specific domains of marine fisheries will remain less over the next few decades. Referring to the variety of deficits in environmental management discussed here, the situation in marine capture fisheries more explicitly shows that we need additional techniques to enhance our knowledge. This holds, of course, if we deal with higher-dimensional systems. Here, qualitative simulation offers the possibility of revealing further insights into the phase space structure under uncertainty [33]. It takes assumptions about the monotonicity of the right-hand sides of the ODE and generates all temporal sequences of trends and thresholds which are consistent with the assumptions. The result of such a simulation is a directed graph, where each node represents a region of the phase space (e.g., the regions (1) to (4) in figure 4), and each edge indicates a possible trajectory crossing the boundary between the associated regions (for recent examples in fisheries, cf. [34–36]). By investigating the subgraph induced by the nodes which represent regions adjacent to the boundary of a viability domain, we can find out where the system is on the safe side, where it necessarily degrades, and where the result depends on the control strategy.

6. Conclusions

The situation in industrial fisheries is still facing serious challenges in both an ecological and economic sense. Management objectives are rarely achieved in practice and the debate about adequate management strategies is still ongoing. Since a unique solution is not expected, there still exists the need for some kind of integrated assessment.

In this paper we presented a new approach in the development and assessment of co-management regimes. It is based upon the experience that for sustainable fishery management steering strategies should take diverse uncertainties into account. This is addressed by extracting some robust system properties, even from weak information, and by giving an overview of the capabilities of viability theory in sustainability research. It is shown in this paper that the viability of a fishery strongly depends on the catch recommendations of a scientific institution participating in the co-management framework. The applied methodology makes it feasible to develop a qualitative control strategy which requires only little information about the state of the fishery and is less risky than data-rich management schemes. Of course, this variety of outcomes is not a general objection against co-management. For the future we will use enhanced models, including capital and investment dynamics of the fishing firms. We think that such a strategy not only introduces additional inertia and modified rules for the negotiation process, but also more flexible steering instruments (e.g. effort control). Summarizing, we think that such an analytical concept paves the road toward detailed insights into what happens in marine capture fisheries. We expect similar valuable clues for more complex models, leading towards an integrated assessment of fisheries including ecological, economic, and social issues.

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Appendix

Propositions and proofs

PROPOSITION A.1. The interval $I = [\underline{x}, \infty]$ is a viability domain, if and only if

(i) $\hat{r}(\underline{x}) \geq \underline{r}(\underline{x})$, and

(ii) $\underline{h} \leq R(\underline{x})$, and

(iii) $\underline{r}(\underline{x}) \geq 0$ or $\overline{r}(\underline{x}) \geq 0$.

Proof A.1. We start with some technical remarks: If $r \geq \underline{r}$ then $h_b(x, r) \geq h_b(x, \underline{r}(x))$, since $D_r h_b < 0$. The latter is equivalent to $\underline{h} > 0$ which can be shown by basic calculations, i.e.

$$h_b(x, r) > 0. \tag{17}$$

In particular, it follows from condition (A.1i) and equation (6) that

$$\hat{r}(x) = h_b(x, \hat{r}(x)) > 0. \tag{18}$$

1. It is shown that I is a viability domain, if the conditions (A.1i–iii) are valid. As a consequence of the monotonicity of $\hat{r}(x)$ and $\underline{r}(x)$ (equations (10) and (15)) it follows from condition (i) and from $x \geq \underline{x}$ that also $\hat{r}(\underline{x}) \geq \underline{r}(\underline{x})$.We have to show that $\forall x > \underline{x} \exists r \geq 0 : h(x,\ r) \geq \underline{h}$ and that $\exists r \geq 0 : h(\underline{x},\ r) \geq \underline{h}$ and $R(\underline{x}) \geq h(\underline{x}, r)$. We claim that $r = \max(0, \underline{r}(x))$ respects these properties.
   If $\underline{r}(\underline{x}) \geq 0$ (condition A.1iii), $r = \underline{r}(x)$. Then $h(x,\ r) = h_b(x,\ r)$, due to equation (5), $r \leq \hat{r}(x)$, and equation (17). By elementary calculations we obtain $h_b(x, \underline{r}(x)) = \underline{h}$. In particular, for $x = \underline{r}$, we have $h_b(x, \underline{r}(x)) = \underline{h} \leq R(\underline{x})$, because of condition (A.1ii).
   If $\underline{r}(\underline{x}) < 0$, by condition (iii), $\overline{r}(\underline{x}) \geq 0$, and $r = 0$. Then $h(x,\ r) = h_b(x,\ 0)$ due to equation (5), $0 < \hat{r}(x)$, and equation (17). Thus, for all $x \geq \underline{x} : h_b(x, 0) \geq h_b(x, \underline{r}(x)) = \underline{h}$. Moreover, $h_b(\underline{x}, 0) \leq R(\underline{x})$, because this is equivalent to $\overline{r}(\underline{x}) \geq 0$.
2. Conversely, conditions (A.1i–iii) are a consequence of I being a viability domain, i.e. $\forall x \geq \underline{x} \exists r \geq 0 : h(x,\ r) \geq \underline{h} > 0$ and if $x = \underline{x}$ additionally $h(\underline{x}, r) \leq R(\underline{x})$.
   It is $h_b(\underline{x}, \underline{r}(\underline{x})) = \underline{h} \leq h(x, r) \leq \hat{r}(\underline{x}))$. The first inequality is valid by assumption, the second due to equation (9). Considering equation (6) the last term is equivalent to $h_b(\underline{x}, \hat{r}(\underline{x}))$. Due to a strict monotonicity of h_b in r condition (A.1i) follows.
   It follows directly from the assumptions that $\underline{h} \leq h(\underline{x}, r) \leq R(\underline{x})$, i.e. condition (ii).
   Now let us suppose that $\underline{r}(\underline{x}) < 0$. Equation (6) and condition (A.1i) obviously show that $\hat{r}(\underline{x}) = h_b(\underline{x}, \hat{r}(\underline{x})) \geq h_b(\underline{x}, r) = \underline{h} > 0$. If $r \leq \hat{r}(\underline{x})$ then $h_b(\underline{x}, 0) \leq h_b(\underline{x}, r) = h(\underline{x}, r) \leq R(\underline{x})$. If $r > \hat{r}(\underline{x})$ then $h_b(\underline{x}, 0) \leq h_b(\underline{x}, \hat{r}(\underline{x})) = h_n(\underline{x}, \hat{r}(\underline{x})) = h_n(\underline{x}, r) \leq R(\underline{x})$. Thus, in any case $h_b(\underline{x}, 0) \leq R(\underline{x})$, which is equivalent to $\overline{r}(\underline{x}) \geq 0$, condition (A.1iii) holds. ■

PROPOSITION A.2. If $x \in I = [\underline{x}, \infty]$, I a viability domain and consequently $\underline{r}(x) \leq \hat{r}(x)$. r is economically viable, if and only if $R(x) \geq \underline{r}(x)$.

Proof A.2. At first we observe that $h_b(x, R(x)) \geq h_b(x, \underline{r}(x)) = \underline{h} > 0$ and $\hat{r}(x) = h_b(x, \hat{r}(x)) \geq h_b(x, \underline{r}(x)) = \underline{h} > 0$. Thus, if $r = R(x) \geq \hat{r}(x)$ it follows (with equations (5), (6) and (2)) that $h(x, R(x)) = h_n(x, R(x)) = \hat{r}(x) = h_b(x, \hat{r}(x)) \geq h_b(x, \underline{r}(x)) = \underline{h}$. Also, if $\underline{r}(x) \leq R(x) \leq \hat{r}(x)$ then $h(x, R(x)) = h_b(x, R(x)) \geq h_b(x, \underline{r}(x)) = \underline{h}$. Contrary, if $R(x) \leq \underline{r}(x)$, then $h(x,\ R(x))$ equals $0 < \underline{h}$ or $h_b(x, R(x)) \leq h_b(x, \underline{r}(x)) = \underline{h}$. ■

PROPOSITION A.3. $h(x,R(x)) \leq R(x)$, if and only if $r = R(x) \geq \hat{r}(x)$.

Proof A.3. If $R(x) \geq \hat{r}(x)$, then $h(x,\ R(x)) = h_n(x,\ R(x)) = \hat{r}(x) \leq R(x)$. Otherwise, if $R(x) \geq \hat{r}(x)$ we use the fact that $\hat{r}(x) > r \Leftrightarrow h_b(x, r) > r$ (true by elementary calculations), to see that $h_b(x,\ R(x)) > R(x) \geq 0$, and we have $h(x,\ R(x)) = h_b(x,\ R(x)) > R(x)$ (by equation (5)). ■

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