Formal viability analysis of participatory fisheries management

Authors:
Klaus Eisenack, eisenack@pik-potsdam.de
Potsdam-Instiute for Climate Impact Research, and
Jürgen Kropp, Potsdam-Institute for Climate Impact Research.

The pressure on marine renewable resources has rapidly increased over the past decades, leading to a variety of institutional arrangements. In many cases they have not improved the current situation, mainly due to problems of institutional fit and intrinsic uncertainties about the state of resource stocks. In this paper, different participatory management schemes are assessed by using concepts from formal viability theory and a simple bio-economic dynamic model. It is shown that participatory management may lead to serious problems if a purely ecosystem-based strategy is employed. The analysis suggests that less risky strategies are possible even if only limited biological and economic data are available.

Introduction

Marine fish stocks are under extreme pressure worldwide (e.g. FAO 2004, Myers and Worm 2003). Two divergent but closely related developments are observable (Munro 1999, Pauly et al. 2002). On the one hand increasing surveillance efforts, limited entries, or marine protected areas are established for mitigating over-fishing, 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 (Mace 1996, Banks 1999, Gréboval and Munro 1999). This is, in particular, remarkable since there has been an awareness of these problems for decades and most fisheries are subject to management measures.

A well-known reason is the free rider problem. Without any regulations it is likely that 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, Hardin 1968). However, to overcome this problem, various institutional arrangements are in place, such that there are practically no unmanaged fisheries (Charles 2001). To explain their deficits, higher order prisoner dilemmas about sharing monitoring and sanctioning costs are discussed (Ostrom 1990). In many cases 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 (Agnew 2000, Hollup 2000, Robbins 2000, Jensen and Vestergaard 2002). One solution to avoid these shortcomings is offered by co-management schemes, which include fishing firms in the decision-making process (Jentoft et al. 1998, Noble 2000, Charles 2001, Potter 2002). It is assumed that economic objectives will complement conservational goals of governmental organizations. The aim of this strategy is 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. A plausible conjecture is that under co-management fishermen will show higher compliance with the resulting regulations (cf. Pinkerton 1989, Mahon et al. 2003).

Avoiding overexploitation of marine resources is additionally complicated by inherent uncertainties, which are related to the partial opaqueness on both the ecological and the economic systems (Whitmarsh et al. 2000, Jennings et al. 2001). Scientific fish stock estimates are often not as reliable as required. Hence, when a fishery reaches a state of crisis, scientific organizations come under pressure in the public debate, i.e. for putting too much stress on conservation objectives and neglecting economic sustainability. It is sometimes mentioned that policy advice based on such data is inappropriate management regimes consider only biological measures as steering targets. Such a strategy has been coined as „ichthyocentrism“, indicating that scientific advice puts too much emphasis on the resource (the various fish stocks, in particular their biomass) compared with efforts to examine the behaviour of the resource users, their economic settings and aims (Lane and Stephenson 2000, Davis and Gartside 2001). This paper addresses the following issues using a formal approach:

- Participatory management schemes are increasingly introduced in order to mitigate the consequences of fishery mismanagement.
- 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.

We base the analysis on a formal model to make our basic assumptions explicit and to draw on the possibility to make systematic deductions from the model. It includes fish stock dynamics as well as economic and political decision-making. The latter makes game-theoretic assumptions on actor behaviour and maps a typical institutional arrangement determining economic, political and ecological interaction. The catch recommendations of a scientific organization which participates in the co-management process are analyzed as strategic lever.

The model is assessed using viability theory, which was developed by Aubin (1991), in order to assess different management schemes in. Recent studies have shown that this methodology is valuable for determining completely unacceptable outcomes and defining judicious measures for mitigation (e.g. Petschel-Held et al. 1999, Moldenhauer et al. 1999, Bene e al. 2001, Aubin and Saint-Pierre 2006). This approach does not strive for optimal co-evolution of fishing industry and marine resources, but rather for desirable corridors. These corridors are constrained by measures representing our knowledge of what should at least be avoided in order to achieve sustainability or to prevent catastrophic developments. Such an analytical strategy provides knowledge for decision-making, although constraints are normative and an outcome of public debate. In addition, it shifts attention from the whole set of options to a constrained set of options leaving space for adjustments.

Uncertainties are addressed by clearly indicating which parts of the model are known to which actors. Even importantly, the model makes no claims about quantitative relationships. The deductions we present are only based on general structural and qualitative model features. This method, extensively developed in artificial intelligence (cf. Kuipers 1994, Forbus 1984), is in particular used to design an advanced management strategy.

In the next section, the model is introduced. It is generic in the sense that different co-management strategies can be coupled to it. Then, different viability constraints are imposed and the conditions under which they can be fulfilled, independently from a concrete strategy, are generally derived. This is used to test whether three alternative co-management strategies comply with these requirements. A discussion of the results and a summary concludes the paper.

The dynamic model

The ecological fish stock dynamics are basically described by a state variable, denoted by *STOCK*. It represents the biomass of a fish stock, which continuously evolves over time. We assume that this evolution is mainly influenced by two factors: it increases due to natural growth of biomass („recruitment“) and is reduced by harvest in the fishery. In bio-economic models, growth is typically assumed to be of Schaefer type (Schaefer 1954). Due to the uncertainties discussed above, we generalize this by assuming only the following: (i) There is a biomass level where recruitment is maximal (typically referred to as maximum sustainable yield, *MSY*). (ii) Increasing biomass leads to increasing recruitment if it is below *MSY*, but to a decreasing recruitment above. (iii) If the fish stock is diminished or reached its carrying capacity, there is no growth anymore. All deductions presented below (and the formal computations made by Eisenack et al. 2006) are only based on these properties and make no additional premises about recruitment. For example, the *MSY* level and the change rates of recruitment are not known quantitatively.

The assumptions that determine harvest rates are more complex since they depend on the way we model the management framework and actors' decision-making. The rest of this section is devoted to this issue. We assume the following institutional setting which captures basic structural features of real-world co-management schemes (Charles 2001, Potter 2002, Iglesias-Malvido et al. 2002, Charles 1997). The central arena is a fishery council where the representatives of groups of associated fishing firms, processing firms, scientific organizations and politics negotiate about fishery regulations. For simplicity we assume that the council meets once per year and has to propose a level of total allowable catch (*TAC*) and an allocation of catch quotas between the participating fishery groups for the next year. 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. We denote the firms with an index *i*, and the associated quota by *qi*, such that the total allowable catch is expressed as sum of all *qi*.

We portray the decision process within the fishery council as a bargaining situation where every fishing firm *i* strives for obtaining an optimal quota *qi*. It is furthermore assumed that a scientific organization participates in the fishery council by recommending a level of total allowable catch (denoted by *REC*) in the beginning of the negotiations. At this stage it is left open how this recommendation is made – this depends on the scientific management strategy, and different alternatives will be analysed below. While the scientific organization tries to push their recommendation, each group of the fishing industry tries both (i) to get a share of the *TAC* that promises maximal profits and (ii) to increase *TAC* above *REC* if it is necessary for that target. When these groups agree on an allocation, the result is transformed into practice by the management authority. These premises lay the foundation for a rational choice explanation of actors' behaviour in the fishery council. Therefore, the model applies a game theoretic approach.

It is necessary to specify the actor perspective to make the bargaining situation concrete and to draw conclusions about the fishery councils' decision of *TAC* and quota allocation. We assume that every fishery group tries to maximize profits in a myopic way. This is a limitation compared to intertemporal rational behaviour, but the assumption is realistic if the influence of single fishing firms on the resource is neglectable (Banks 1999, Kropp et al. 2004), or if they push their representatives in the fishery council for higher quotas. This is valid if due to the institutional framework, the burden of long-term responsibility is shifted to the fisheries council or the scientific organization (allowing fishing firms to reduce subjective uncertainties).

A profit function describes a groups profit for one period depending on (i) its harvesting quota *qi*, (ii) market prices, (iii) its physical capital and technical efficiency, and (iv) the amount of available fish. The further deductions require that every fishery group knows its own profit function, but for our analysis only the following features have to be known (ceteris paribus).

1. Higher market prices increase profits due to better revenues.
2. A higher quota leads to better income (since more fish is harvested and sold), but at the same time harvesting costs increase with the amount of caught fish. We assume that overall profit increase for higher quota up to a level above which revenues are offset by costs.
3. Profits increase with physical capital and more efficient technological equipment because harvesting costs are reduced.
4. Profits are higher if much fish is available, but if fish stocks diminish, the costs increase excessively. It is cheaper to catch a given quota if biomass density is higher since less effort is needed, while it is costly to catch „the last fish".

The optimal quota a fishing group aspires differs among the groups due to their capitalization and technical efficiency (e.g. there can be artisanal and industrial fishers). In the bargaining situation in the fishery council, an additional type of costs appears due to negotiations against other fishing groups. Moreover, if catch recommendations are tight, they have to invest more in pushing for higher *TAC*. In the formal model, this is represented by introducing so called deviation costs that reduce profits if the *TAC* exceeds the scientific recommendations.

Negotation power is captured by a theoretical coefficient which expresses the ability to push own positions in the fishery council at low deviation costs. This power coefficient may considerably differ between groups. These costs are linked to the legitimation of bargaining positions challenging the scientific advice and to 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. The assumption of myopic behaviour entails that actors only account for short-term deviation costs and do not take future effects, e.g. on fish stocks, into account. Deviation costs of a group have the following properties (ceteris paribus):

1. They depend on the *TAC* (which results from the negotiations), on the initial scientific recommendation *REC*, and on the negotiation power.
2. If *TAC* is below the recommendation (which is likely in the case where the scientific organization sees a high abundance of fish while the fishery is not efficient enough to realize high catch levels), deviation costs vanish.
3. The more *TAC* is above the recommendation, the higher the deviation costs.
4. The higher the power coefficient, the lower the costs.

Again, we make no quantitative assumptions. For example, the increase of costs for *TAC* above recommendations may be linear but also non-linear. It should be noted that the deviation costs not only depend on the individual quota *qi*, but also on the allocation to the other groups, opening the arena for strategic interaction. It can be argued that the scientific organization may loose reputation if the factual catch is above its initial recommendation. This is indirectly represented in the model via the power coefficient. Introducing a further state variable would obscure the basic argument here.

Negotiations are modelled as a Nash game which assigns an individual quota *qi* to each group *i* that maximizes its profits (reduced by deviation costs) for given prices, fish stock and the quotas of the other participants. The introduction of deviation costs implements trade-offs between the groups directly such that more complex negotation models can be avoided (e.g. Rubinstein 1982, Demougin and Helm 2006). The Nash equilibrium of the negotiation process is given by a quota allocation and the resulting *TAC* is the sum of all quotas. A formal analysis provides some interesting properties of the negotation result (see Eisenack et al. 2006 for mathematical proofs). Basically, two cases are distinguished: If *REC* is above *TAC* we speak of non-binding recommendations, while we call the converse case binding recommendations.

In the non-binding case, catch recommendation are so high that it is not profitable for fishing firms to exceed it. Then, *TAC* is simply equal to the sum of individually optimal catches, such that there is no proper interaction in the fishery council. It can be shown that the sum of catches can be described by a function *TAC** which depends on *STOCK* and increases with available fish. The rate of increase depends on the efficiency parameters. Power coefficients do not matter. Obviously, *TAC** can be used at the same time to discriminate between both cases: if recommendations are higher than *TAC**, they are non-binding. Note, that the exact dependency of *TAC** on other variables cannot be deduced quantitatively since we made no quantitative assumptions. However, we can conclude that for low fish stocks recommendations are more likely to be binding; and if they are still non-binding, less fish is caught than for more abundant stocks. Obviously, *TAC* is never above *TAC** for the binding as well as the non-binding case. It can also be shown that there is a fish stock level below which catches are no longer profitable at all.

For the binding case, strategic relations come into play. The negotiated *TAC* depends positively on fish abundance, in principle as in the non-binding case, but the strength of this effect additionally depends on the power coefficients. Moreover, *TAC* depends on the recommended catch level. Intuitions are formally confirmed by calculating that releasing tight recommendations leads to more catch (ceteris paribus). The strength of this effect depends on power coefficients, harvesting costs and fish stocks. It is high for large fish stocks and an overall strong negotiation power. The influence of high harvesting costs on the effect can be positive or negative, depending on the concrete situation.

By assuming that the *TAC* is actually caught by the fishing firms it can be shown that in the non-binding case there is always caught less then *REC*, while in the binding case catches are always above *REC*. The latter will be crucial in a later argument. It can also be generally concluded that harvest rises with high fish stocks, and is unaffected or negatively effected by catch recommendations – independently whether the binding or non-binding case applies.

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 (see Aubin 1991 for a detailed introduction). *Viability constraints* characterize a set of acceptable states of a system (e.g. desirable levels of biomass, harvest or quota allocations in our case). A time evolution of the system is called *viable* if it remains in this set indefinitely, in other words if it is acceptable forever. If a development process is controlled, in the examined case by the harvest recommendation, we want to analyse whether a strategy or mechanism that determines the recommendations keeps the system viable or not. A subset of acceptable states where at least one evolutions starting from is viable (if an appropriate control is applied) is called a *viability domain*. It characterizes a class of system configurations for which a mechanism can be chosen that sustains acceptable conditions.

The choice of viability constraints cannot be purely justified by empirical considerations, because it involves normative settings. The viability concept allows for their evaluation with respect to consistency and their consequences. For our examination of marine fisheries two reasonable viability constraints are defined and investigated. We deduce conditions under which a mechanism for choosing catch recommendations exists, respecting both constraints at the same time:

1. Ensure that the biomass of a stock resides always above a prescribed minimal level *STOCKmin*. This may be required due to conservational objectives or to keep the ecosystem stable against perturbations.
2. Require that a minimum aspiration level for total harvest *TACmin* can always be realized or exceeded. This harvest may be justified to cover fixed costs in the fishery, to guarantee a minimum level of employment, or to sustain food safety.

One important result of viability theory (the *viability theorem*, Aubin 1991, p. 91) states that a viability domain can be characterized by merely investigating its boundary. A given set of states is a viability domain if it is always possible to choose a control on its boundary that prevents the system from leaving the set of states. In our case the set of all biomass levels above a given threshold (those that fulfill the ecological criterion) is a viability domain, if the harvest strategy can be chosen such that the fish stock regenerates at the threshold *STOCKmin* (the boundary), keeping it viable.

In the following we determine criteria for which a fish stock respecting the ecological criterion is a viability domain supposed the economic criterion holds at the same time. For such stocks a „wise“ harvest recommendation can keep the fishery within sustainable limits. We first identify the general conditions under which a catch recommendation leads to a regenerating fish stock. If the harvest recommendations are binding (i.e. they are below *TAC** as introduced above), the *TAC* depends positively on *STOCK* and the recommendation. The fish stock increases when this *TAC* is below its natural growth rate, which only depends on *STOCK* (see last section). There is thus a maximal recommendation level *RECmax* that prevents the fish stock from declining. This level itself depends on *STOCK*, but detailed computations cannot show a simple relation since we made only non-quantitative model assumptions. There are situations where a higher fish stock leads to increasing *RECmax*, but the converse can also happen. In particular, the latter is the case if *STOCK* exceeds a certain level that is already below the fish stock where the *MSY* were possible. This is explained by natural growth rates that are too low to compensate the increasing negotiation result. For even higher *STOCK*, this amounts to the extreme situtation where no catch at all can be recommended. It can also be shown that *RECmax* rises excessively if fish stocks are extremely low, since fishing firms voluntarily catch less due to rising costs. However, this will lead to non-binding recommendations at some stage. Then, the *TAC* no longer depends on the strategy of the scientific organization. The fish stock only regenerates if the economic conditions are such that natural growth is below *TAC**. Due to the viability theorem (see above), the maximal recommendations only have to hold at the boundary of the ecological constraint *STOCKmin*, such that the extreme situations of high fish stock above *MSY* and of very low fish stock do not matter in most fisheries.

This is different for the economic constraint. In the case of binding recommendations, the level that is sufficient to obtain the prescribed *TAC* has to be determined. Since *TAC* increases with recommendations, this always requires a minimal recommendation *RECmin*. A detailed analysis shows that the minimal recommendation has a simpler structure than the maximal one. Intuitively, it rises with a stricter *TACmin*. On the other hand it decreases with *STOCK*. As was shown in the last section, more abundant fish results in a higher negotiation result (which lies above recommendations). Therefore, tighter recommendations than *TACmin* are sufficient to achive an economic viable catch. This alllows for a simplification: Although recommendations always have to be above *TACmin*, it is sufficient to show this relation holds at *STOCKmin*. If a certain recommendation level is high enough at this state, it is also above *RECmin* for higher fish stocks since it decreases with *STOCK*. The same is true for the binding case, where *TAC** has to be above the catch requirement. Since this optimal catch increases with *STOCK*, it is sufficient to show that this condition is met at *STOCKmin*.

Combining both viability constraints, a recommendation mechanism only works if *REC* can be chosen between *RECmin* and *RECmax* at *STOCKmin* (i.e. the minimal requirement must be below the maximal requirement). Otherwise, both constraints would be contradictory. Then, it is necessary to modify the constraints to enable a sustainable recommendation mechanism. However, the situation is more complicated since different cases of non-binding recommendations and of minimal requirements that become computationally negative (which is not an option in the analysed institutional framwork) have to be considered. Summarizing all possible cases yields the following result (see Eisenack et al. 2006 for the proof):

The states that meet both the ecological and the economic constraint are a viability domain if and only if at the minimum biomass level STOCKmin

1. *the optimal catch* TAC* *is above the minimal recommendation* RECmin*, and*
2. *the natural growth is higher than minimum harvest* TACmin*, and*
3. *the minimal recommendation* RECmin *or the maximal recommendation* RECmax *is non-negative.*

In this case there exists a recommendation mechanism that sustains both economic and ecological viability forever.

These conditions are easy to interpret. The compatibility of both viability criteria depends on the relation between the natural growth, the required harvest level *TACmin*, and the efficiency of the firms. If growth at the minimal viable stock level *STOCKmin* lies below the required harvest *TACmin*, there exists an obvious contradiction between economic and ecological targets (condition 2). In this situation the fishery council has to decide whether to sacrifice conservational or harvest objectives. According to condition (1) it must be profitable to fish at least *TACmin*, even if no deviation costs apply. Otherwise no harvest suggestion guarantees an adequate yield, because the harvest is always below or equal to *TAC**. In other words, it must be possible to achieve *TACmin* with binding recommendations. Condition (3) is met, if the recommendations can reduce the harvest below natural growth if the fish stock approaches *STOCKmin*. Otherwise it would be necessary to make a negative recommendation to achieve a sufficient harvest reduction, which makes no sense in our examinations.

Assessment of recommendation strategies

We can now apply the model and the theoretical viability analysis to assess different recommendation strategies. This allows for discussing the consequences of a purely resource-based strategy within a co-management framework (which is one basic motivation of this paper), and compare it to some alternatives. Although, as long as the system stays in the viability domain, it is *possible* to select a viable strategy, it is not guaranteed that *every* mechanism is successful. In addition, in a critical state in which the viability constraints are not satisfied it is not clear whether a selected mechanism leads to a decline or forces a fishery back to sustainable limits. We examine the following approaches:

- Ichthyocentric strategy: The harvest recommendation is purely based on an estimate of natural growth.
- Conservative strategy: The harvest recommendation is based on economic viability in the sense that the minimum harvest is always realized.
- Qualitative strategy: In this case, due to uncertainties, recommendations are only based on qualitative economic and ecological observations.

Ichthyocentric strategy

The first control strategy is called „ichthyocentric“ to indicate that the scientific organization considers only knowledge about the fish stock for their harvest recommendation. We assume that the harvest recommendation *REC* equals the current estimated natural growth of the fish stock. This is a typical procedure for example in North America and Europe (Charles 2001, Lane and Stephenson 2000, EU 2003). We further make the premise that the scientific institution is able to estimate this growth correctly, which is counterfactual since despite decades of experience, success of quantitative stock assessment is still limited by unavoidable measurement deficits (Charles 2001, Jennings et al. 2001). However, we make this premise since we show below that the ichthyocentric strategy basically cannot guarantee viability even in this ideal case. Thus, if estimation errors come into play, the situation cannot be expected to be better. We also idealistically assume that the viability constraints admit a viability domain (i.e. conditions 1 - 3 hold) and that the system is initially in this viability domain.

Since economic viability can be guaranteed with binding recommendations, the ichthyocentric strategy is not economically viable if natural growth (the recommendation) is lower than *TACmin*. The situation is even more dramatic if one focuses on ecological viability. If recommendations are binding our results show that the catch alway exceeds the catch recommendations. As the latter are equal to natural growth for the ichthyocentric strategy, it is always caught more fish than is recruited, which implies that the fish stock decreases. Ichthyocentric control is only sustainable if (i) recommendations are not binding at *STOCKmin* and if (ii) fish stock recruitment is always large enough to allow for *TACmin*. This means that the realized catch must be significantly lower than the scientific recommendation, a situation that normally does not occur in industrial fisheries. As we are initially in a viability domain, economic viability is met with binding recommendations. Thus, the stock will necessarily decrease until ecological viability is violated. Once this has happened, the fish stock cannot regenerate by the same reasons. We summarize that even in the case of a perfect stock assessment, the ichthyocentric strategy exposes the fishery to a risky development path.

Conservative strategy

The conservative strategy aims to ensure that the economic viability criterion is satisfied, but nothing more: the scientific institution always recommends *RECmin*. It can be straigtforwardly assessed based on the viability results obtained so far (see Eisenack 2006 for a mathematical deduction).

As long as the system is in a viability domain, such recommendations are binding (condition 1), implying that *TACmin* is caught (by definition of *RECmin*), making the conservative strategy economically viable. It is also ecologically viable since at *STOCKmin* natural growth is above *TACmin* (condition 2).

What happens if the system is outside a viability domain, e.g. because the aspired *TACmin* is chosen to high? If only the economic constraint is violated, the *TAC* is still below natural growth, allowing for a recovery. The situation is less favourable if the environmental constraint is no longer met: there is no chance of a recovery above *STOCKmin*, even although *TACmin* may still be possible for some time. But decreasing stocks will lead inevitably to a situation with non-binding recommendations, where fishing firms catch voluntarily less than *TACmin*.

We conclude that the conservative strategy satisfies economic and ecological viability criteria (if the fishery starts from a viability domain). It also outperform the ichthyocentric strategy since only qualitative information is needed to exercise this type of management, i.e. the scientific organization only has to supervise whether the realized catch of the fishery is above or below *TACmin*. 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 too high or the abundance of the targeted species is rather small for a viable control, it cannot be assured that the resource recovers by applying this management strategy.

Qualitative strategy

The third alternative extends the qualitative view discussed above in order to increase profits and to limit risks. It is based only on qualitative observations, which means that exact numerical values for fish stocks and a quantitative relationship between *STOCK* and recruitment are not known, but that it can be determined correctly whether the fish stock is decreasing or increasing in time, whether the realized catches exceed *TACmin* or not, and whether recommendations are binding or not. We will also allow for distinguishing between an emerging fishery that was not considerably exploited before and a mature fishery. By symmety, the control rule we propose provides only qualitative advice, i.e. whether catch recommendations have to be increased or decreased. Also the speed of this change is indicated qualitatively. We will demonstrate that even under such restrictive settings efficient co-management is possible.

The qualitative control strategy (see table 1) depends on four dichotomies (catch level low: below *TACmin /* high: *above TACmin*; emerging/mature; increasing/decreasing fish stock; binding/non-binding recommendations), such that 16 situations can be distinguished and supplied with individual strategies. To reduce complexity, we introduce the rule (Z) which has the consequence that recommendations are always binding, except from very short episodes. This is not only a technical matter, since for binding recommendations the reactions of the fishery groups in the fishery council provides more information to the scientific organization. Two further situations can be excluded since an emerging fishery always reduces the fish stock because regeneration rates are low if the system is close to carrying capacity. We formally define the fishery to be mature after the first time rule (C) is applied. Some qualitative observations correspond to non-viable situations. We nevertheless provide rules for them to assess whether is it possible to cope with such crises with the qualitative strategy. In rule (E) we propose a moratorium where recommendations are set to zero.

The challenge in designing such a strategy is to take uncertainties seriously. For example, some rules are valid with *STOCK* above *STOCKmin* as well as below (in particular, rules C and D). We assume that these two situations cannot be distinguished by the scientific organization, such that they have to use a rule that is wise in both cases.

Rule	***Qualitative observation***	***Reaction***	***Speed***
(A)	emerging, low catches, decreasing stock	increase REC	fast, until *TACmin* is caught
(B)	emerging, high catches, decreasing stock	decrease REC	fast, until *TACmin* is caught
(C)	mature, high catches, increasing stock	increase REC	slow, until stock begins to decrease
(D)	mature, high catches, decreasing stock	decrease REC	fast, until stock begins to increase, but not such that catch is below *TACmin*
(E)	mature, low catches, decreasing stock	moratorium	fast
(F)	mature, low catches, increasing stock	increase REC	slow
(Z)	non-binding recommendations	decrease REC	fast, until recommendation become binding

Table 1: Qualitative control strategy comprinsing of seven rules. See text for detailed explanation.

Such a strategy can be assessed by means of a so called state-transition-graph. It provides a comprehensive overview of the qualitative system states that may be observed. Each state is shortly described and subsumes a broad variety to system states in the quantitative sense, which nevertheless share the qualitative properties. Arrows are drawn between the states to indicate their temporal sequence (transitions). Due to the indeterminate nature of the system and due to the uncertainties, some states have multiple successors in time. This means that there is more than one possibility and that it cannot be predicted which one becomes true (see Eisenack 2006 for a detailed introduction of this concept within the present context). A simplified state-transition graph of the qualitative strategy is shown in Fig. 1. In the following we justify its basic structure (for a detailed deduction see Eisenack et al. 2006, Eisenack 2006).

States with non-binding recommendations are already left out due to rule (Z), which applies in all situations, independently whether the fishery is emerging, viable or in crisis. It was already shown that an emerging fishery has a decreasing fish stock, such that states (1) and (2) cover all possible configurations. Rules (A) and (B) mimic the conservative strategy for an emerging fishery. Adjusting *REC* such that actual catch is close to *TACmin*

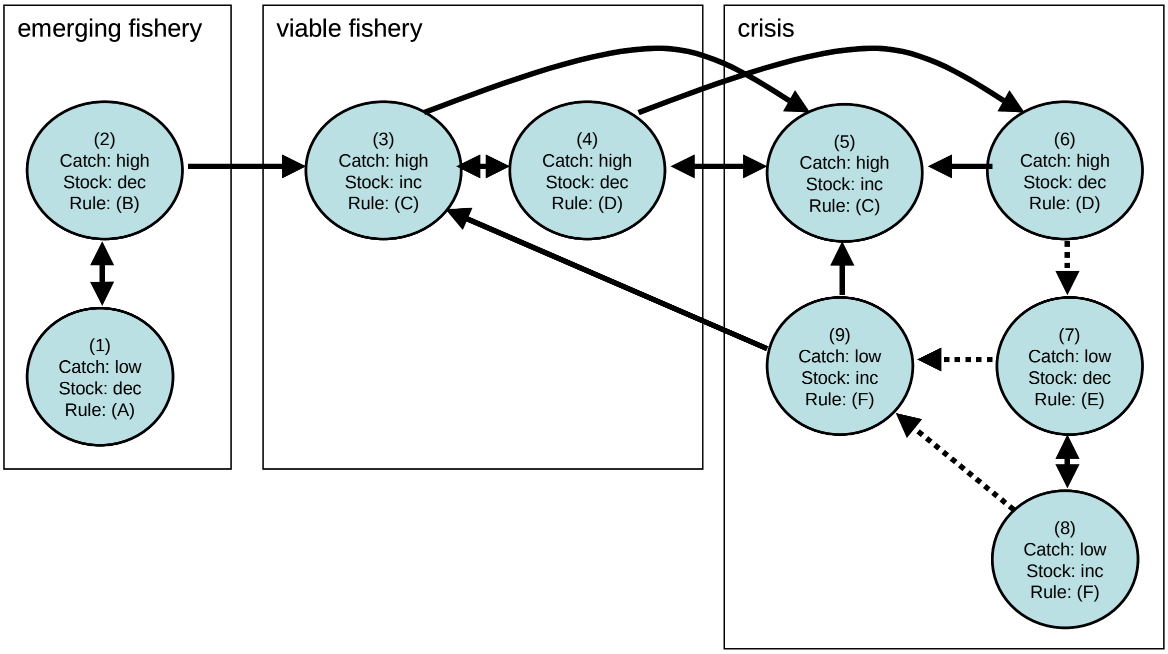

Figure 1: Simplified state-transition-graph for the qualitative strategy. Numbers of states are used for reference in the text. The rules correspond to Tab. 1. „high" means catches above *TACmin*, while „low" below *TACmin*; „inc" refers to an increasing fish stock, „dec" to a decreasing one. Dotted transitions are less likely to occur (see text for further explanations).

(increase of *REC* from below, and decrease from above; recall that *TAC* increases with *REC*) results in viable results with limited business opportunities. The situation becomes more profitable when the fishery is mature. Postponing this is necessary because the scientific organization needs to know when the fishery becomes mature. If recommendations are strongly increased it is likely that the resource is reduced below *STOCKmin* very fast without the option to take notice of that. In state (3), when stocks begin to increase again, the conservative strategy was exercised until recruitment (which initially rises) equals catches. It can be concluded that the fish stock is still above the level where *MSY* is possible. In this viable phase, *REC* is slowly adjusted to keep catches as close to recruitment as possible. If *STOCK* decreases, catches are obviously above recruitment such that recommendations should be reduced; if *STOCK* increases again, the opposite is true. Recall again that this is possible since catches are positively related to recommendations if the latter are binding (which is guaranteed by rule Z). The adjustment leads to a chattering system between states (3) and (4). Since recommendations are higher than for the conservative strategy (and the system is in viability domain), catches are above *TACmin* and profits are higher. The viable fishery is therefore close to the original intention of ichthyocentric control, namely that exactly recruitment is caught. However, the qualitative strategy is more robust since it does not rely on a quantitative forecast of recruitment and on the assumption that recommendations are not modified in the fisheries council.

When catches are above *TACmin* it also has to be clarified whether the fish stock remains above *STOCKmin*. In state (4), application of rule (D) leads to decreasing catches, but it depends on the speed of reduction whether state (6) is reached next, or state (5), where the stock is already recovering. It can be excluded by a detailed analysis that catches cannot fall below *TACmin* first (which would lead to the successors 7 or 9). Therefore, with the qualitative strategy there is the risk of violating the ecological constraint unnoticed. Since the viable states (3) and (4) cannot be distinguished qualitatively from the non-viable states (5) and (6), rules (C) and (D) apply in both cases. However, in state (5) the crisis is automatically resolved since the stock recovers. In state (6) the reduction of recommendations leads to state (5). Also state (7) is a successor of state (6), but it is less likely due to fast reductions of *REC* above the *TACmin* level. We can thus conclude that although the qualitative strategy cannot be guaranteed to be viable, the only possible violation is automatically corrected.

The analysis of states (7-9) relates to a crisis situation which is not brought about by the qualitative strategy, but may be the consequence of a sudden disruption or a previous management regime. In state (7) the situation is worst: ecological and economic constraints are violated and stocks are further reduced. Here only a moratorium can save the fish stock. However, a recovery is likely to lead to state (8) where the stock is still below *STOCKmin*. There is no real solution in state (8), since it cannot be distinguished from state (9), such that the same rule (F) has to be applied in both cases. This is designed to provide the option to become viable again via state (3) or the self-recovering state (5). A transition from (8) or (7) to (9) is only possible for particular fisheries where *RECmax* is never negative for stocks below *STOCKmin*. Otherwise, fish stocks will continue to decrease even under a moratorium. Note that this negativity property of the fishery is not known to the scientific organization in the current strategy.

We sum up that the qualitative strategy presented here allows higher profits than the conservative strategy because recommendations are increased above *RECmin*. It is also more secure because it forces the system back to viable conditions for the case where the ecological constraint is temporarily violated. Finally, it is more robust to uncertainties since only quantitative observations of the system are necessary.

Discussion and conclusions

The situation of marine overexploitation is still facing serious challenges in both in ecological and economic terms, such that it can be classified as a syndrome or archetype of global change (Kropp et al. 2006, Jaeger et al. 2007). 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 sustainable fisheries management 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.

The analysis shows that participatory 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 scientific organizations. This result is not a general objection against co-management, but stresses that participation itself is not a blueprint solution. Participatory institutions do not resolve uncertainties and need to be tailored for the resource they are meant to govern. The actors involved have to take the responsibility for choosing the appropriate strategies in complex settings. This argument is underlined by our results, where the applied methodology makes it feasible to develop a qualitative strategy that requires only little information about the state of the fishery and is less risky than data-rich management. The viability concept and the qualitative strategy shows new options how dangerous effects related to measurement deficits and a purely resource-based strategy can be surmounted.

In this contribution we have assessed the three cases of an ichthyocentric, conservative, and qualitative strategy. An extreme case is a recommendation strategy purely based on the observation of fish stocks. It exposes the fishery to a high risk of economic and ecological decline. This situation can be substantially improved by designing a more flexible strategy, which only needs qualitative information about the state of the fishery. In addition, it is shown that even for a fishery that is currently not viable there exists a good chance that it can be steered into the safe region if the qualitative strategy is applied. A disadvantage of the presented model is that it does not take capital dynamics and the costs of change into account, i.e. that rapid changes in harvest recommendations may induce high adaptation or political costs. The latter introduces additional inertia and modified rules for the negotiation process, but also more flexible steering instruments (e.g. effort control). On the other hand, even under uncertainty the qualitative strategy is at least as good as economically conservative control, and less risky than data-intensive ichthyocentric management.

Taking into account that the knowledge about relevant processes in marine fisheries will remain uncertain to some degree, that fishery systems can be far more complex than portrayed here, that various institutional arrangements with different scale and scope determine the outcome of fisheries management, and that urgency for solving these challenges is increasing with diminishing fish stocks and increasing world population, the situation in marine capture fisheries explicitly shows that we need novel techniques to enhance our knowledge. In this paper we have demonstrated the use of concepts rooted in mathematics and computer science to close the gap between bio-economic modelling and institutional analysis. Such formal methods are not intended to replace qualitative analyses, but to complement them. While non-quantitative methods are strong in interpretative work, investigating case particularities and structuring entangled problems (e.g. Ragin 1987), formal techniques have power in making assumptions and definitions explicit and systematically exploring their consequence by deductive reasoning (e.g. Snidal 2004). There are various formal methods beyond statistics, and a broad set of mathematical and computational methods that deal with uncertainties, non-quantitative data or exploration instead of prediction (e.g. qualitative case study analysis (Ragin 1987), field anomaly relaxation (Rhyne 1995), cellular automata (e.g. Tobler 1979), fuzzy sets (Zadeh 1965), neural networks (e.g. Zell 1994) and others). In this contribution, qualitative differential equations (Kuipers 1994) played an inspiring role (cf. Eisenack et al. 2006). We think that improved analytical and formal concepts pave the road towards 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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