Fishery systems and linkages: from clockworks to soft watches

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The complex systemic nature of fisheries has been recognized for many decades, but attempts to include this reality in day-to-day management have been slow, patchy, and of limited effectiveness. The topic is reviewed again here, with a focus on new directions. After a brief introduction, an historical review is provided of the evolution of fisheries assessment and modelling, highlighting the growing complexity resulting from changing societal demands. The "complexity syndrome" is described in terms of scope, boundaries, scales, components, and linkages, and is demonstrated as reducing understanding, predictability, and controllability, attributable to the effects of delays, teleconnections, scale dependence, and self-organizational capacity. Key issues relate to systemic aspects of fisheries governance and the research needed to support it. Special reference is made to the changes needed to adapt to the newly emerging relationships between science, policy-making, and society within complex fishery systems, and between those systems and their environment. A range of concepts and approaches, such as Integrated Assessment, are elaborated as epistemological and operational frameworks to support the transition process. The conclusion addresses the evolution of the global fishery system and briefly reviews the challenges faced by science, governance, and society.

Keywords: complexity, fisheries, fishery governance, fishery research, systems, uncertainty.

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Introduction

Boulding (1956) referred to simple, predictable, mechanistic systems as "clockworks". In contrast, complex, imperfectly predictable, dissipative structures, such as fisheries, could be referred to as "soft watches", an allegory presented by Salvador Dali in his famous 1931 painting "The Persistence of Memory" to indicate that things may not be as rigid as usually assumed.

A fishery system is a plexus of subsystems. It is also part of broader natural and human systems and is affected by the global environment, economy, and society within which it exists. Fishery systems have evolved in an unpredictable manner, changing natural productivity and species composition, fishing technologies and strategies, markets, and products. Fish stocks and fishery economies have sometimes collapsed despite dedicated attention. As arenas for economic and social development, they remain difficult to understand, forecast, control, and optimize.

Much has been written during the past three decades about the systemic nature of fisheries (Rothschild, 1971; Allen and McGlade, 1986; Charles, 1995) and its implications for science and management, but the integration of available scientific understanding into operational management has been slow and patchy.

We review the complexity of fishery systems and linkages and focus on the implications for marine fishery research and governance, leaving aside the far-reaching consequences for the various subsectors of industry and fisher communities. After giving a brief historical background on the evolution of societal trends and scientific responses, we summarize the structure of fishery system representations (boundaries, components, scales, linkages) and describe some of the resulting fundamental questions. We conclude by providing a succinct summary of the challenges faced by fishery research, governance, and broader society.

Historical background

Societal demands have shaped the evolution of fishery science and of fishery system representations. During the past two decades, many international agreements and conventions have formulated such demands, e.g. the UN Convention on the Law of the Sea (UNCLOS, 1982), the Brundtland Report (Our Common Future, 1987), the UN Conference on Environment and Development (UNCED, 1992), the Code of Conduct for Responsible Fisheries (FAO, 1995), the Millennium Summit (WSSD, 2000), and the World Summit on Sustainable Development (WSSD, 2002). They reflected societal concerns about unsustainability, broadening and aligning societal objectives, and balancing the requirements for poverty alleviation, food security, and sustainable livelihoods with those of conservation and environmental health. Societal objectives shifted from a focus on sustainable development of the fishery sector to a focus on the need to ensure a sustainable contribution of that sector to the economy and society. This new reality has broadened the number of components and constraints to be considered in fishery research and management.

Following the "Occam's razor" principle, scientists initially sought to be parsimonious in their response by reducing the scope and complexity of their representations of the fishery system, given the data, understanding, and computing capacity available to address the questions raised. For instance, this caused little attention to be paid to, *inter alia*, heterogeneities in fleets, biological and technological interactions, environmental or economic externalities, social behaviour, cross-sectoral effects, and the effects of natural or business oscillations (*sensu* Kondratiev; Marchetti, 1987, 1996).

During the 20th century, scientific representations of fishery systems developed while research and management co-evolved, building on the disparate disciplines related to natural resource management. Following various reinforcing streams, this led to increasing scope, detail, realism, and interdisciplinarity (Figure 1). In a parallel and largely independent process, social research on fisheries has proceeded, clarifying, for example, the functioning and dynamics of fishing communities, as well as the interactions between labour and capital ownership. Although not yet seen as part of fishery systems analysis, social research has contributed conceptual models of the human component. At a global level, however, most of the above extensions either remained in the scientific domain or had limited application in development planning and management, particularly at the regional level, where progress towards the integration of social and economic dimensions or towards cross-sectoral integration is not readily apparent.

Fishery system representations

A system representation (or model) requires decisions about its external and internal boundaries, the number and type of components, its scales, and the relevant linkages among components and with the external environment. Boundaries, scales, components, and linkages interact to determine the level of detail (or aggregation). The degree of complexity to be included in a model depends on the questions raised, the data and resources available, and a balancing of the risks involved in specifying a model of suitable but not excessive realism.

Boundaries are basic to any fishery system analysis and, indeed, figure in the FAO definition of the Ecosystem Approach to Fisheries (EAF). They are essentially human artefacts, necessary to reduce complexity to manageable levels and dependent on the purpose and focus of the model as well as on available information. In drawing boundaries, a trade-off must be negotiated between holism and tractability, because boundaries serve to define the scope of the system, in terms of both geographical and functional extension. External boundaries separate the core of the system from its external environment, from which environmental, climatic, political, economic, social, and ethical influences arise. Internal boundaries identify and delimit the various components of a system, so determine the degree of detail or aggregation. When the purpose of the model is to assist in governance, it is important to match the boundaries of the fishery and jurisdictional subsystems. This is a major dilemma, because this must be balanced by the desirability, within an ecosystem approach, of managing on the basis of sensible ecosystem boundaries.

Hierarchies of scales characterize fishery systems, defining the grain and extent of their representation. The grain refers to the minimum time and space interval, the degree of complication or detail, the number of components identified, etc. The extent refers to the time horizon and space extension and is relevant when drawing external boundaries. Natural scales of relevance span from the individual fish or school to the metapopulation, ecosystem, or bioregion. Social and institutional scales span from the individual fisher and community to regional and global organizations. Time scales span from days to decades. Mismatch of scales between the problem to be solved and the jurisdiction available is a recurrent problem in management. For example, solving local conflicts through a central management authority is often impracticable. The lack of connection between enterprise management, fisheries management, and development planning is also a major cause of management failure. In a complex system, components exchange matter, energy, and

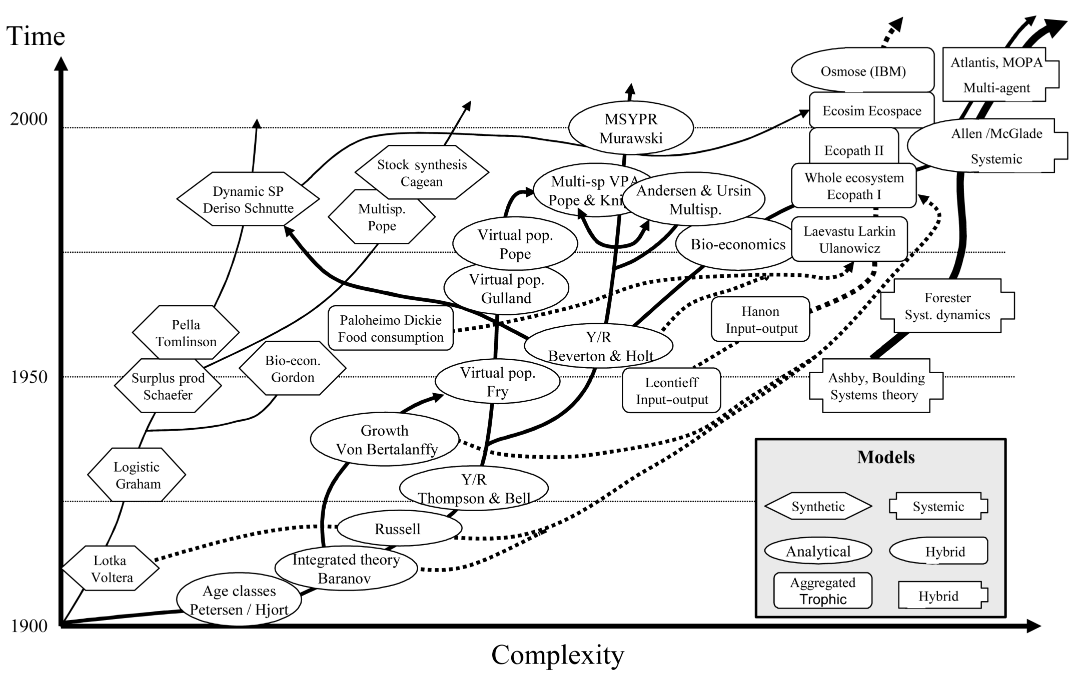

Figure 1. Evolution of fisheries modelling, 1900 – 2005.

information across scales. Microscale events in individual fisheries may generate meso- or macroscale effects, e.g. at the sectoral or national level, and vice versa. Realistic representation will usually require the use of multiple nested scales. In practice, the optimal resolution depends on whether the question raised is of a local or global nature and related to operational or strategic planning. An important consideration is that laws and principles relevant at a given scale might not be predictable solely from those observed at lower or higher scales (e.g. systems may not be fractal).

The system components identified in representations were few and highly aggregated in the early days of fishery science (e.g. a fleet and a stock in a production model). Subsequently, more biological and economic components were added to deal better with aspects of resource supply and economic efficiency. Later, ecological and social components were added as new issues emerged relative to environmental and biodiversity impacts, poverty alleviation, food security, and social welfare.

The articulation of the system components can be conceived of as a series of concentric rings. The core of the system would include the resource complex with its target stocks, the various fleets, the fishers, the post-harvest and trade subsectors, and the management authority. The intermediate ring contains elements with a greater apparent "distance" from the core, but still with significant influence. This could include broader ecosystem components, including the habitats and environment of the natural resources, as well as the climate, the fishery research community, fishing communities, the public and private administrative bodies, government, development banks, and a host of economic sectors with direct impact on fisheries. On the outer ring, one might place the broader academic world, in which scientific paradigms evolve and where fishery scientists are trained, consumers with needs to satisfy, the public at large, with its perceptions, ethical and other values, and voting power, and the non-governmental organizations and foundations active in the environmental and industry arenas. Allocation of all these components to particular rings in the above framework is partly arbitrary, and one could certainly argue for shifting any given component. Moreover, external drivers, even originating outside the outer ring, may influence the system in various ways.

In selecting the most relevant components for a system representation, a central issue is the balance between ecological and human aspects. An ecological model generally details the trophic chain components and linkages, compressing the fishery into a single component. A typical fishing industry model, however, would show the opposite, detailing the various components of the fishing-to-consumption chain while summarizing the resource production process. Finally, a fishing community model would highlight different aspects again. Shifting across disciplines, representing the various components in fisheries and their interactions, can be complex.

In developing simplified representations, scientists should remember the richness of the fishery system, the unbalanced nature of conventional disciplinary modelling, and the dubious validity of scientific advice elaborated on the basis of incomplete, unbalanced, and oversimplified system descriptions.

Linkages reflect the interactions among the system components, and between them and the external environment. Such linkages are responsible for the transfer of matter, energy, information, money, institutional controls, social relations, and signals from global drivers. Linkages determine the system dynamics and their evolution. Human beings are key elements, responsible for the dynamic links among the biological, technological, economic, and social elements of such systems. Global drivers, such as demography, markets, economics, environmental changes, and energy demand, provide particularly important linkages for a sector that trades 50% of its output on international markets. International agreements and instruments have also been important factors of change for fisheries, and the role of non-fishery instruments should not be underestimated. Failure to describe and understand linkages adequately can cause severe misperceptions and policy failure. From a modelling perspective, a key problem is the elucidation of the most relevant and critical functional linkages. The basic role of the media, for example, in linking science and decision-making, and in transforming societal issues into voter perceptions, is one of the facets that are often recognized, but not explicitly dealt with.

The complexity syndrome

Valuable insights into fishery system behaviour, which arise, for example, from General Systems Theory (Boulding, 1956; Ashby, 1962; von Bertalanffy, 1967; Forrester, 1973), have developed over time. Certainly, the implications of broadening from a solely mechanistic "Newtonian–Darwinian" vision of nature, to a systemic, evolutionary, or "Prigoginian" perspective (the latter referring to the seminal work on dissipative structures by Prigogine and Stengers, 1979) had been foreseen in the 1950s (von Bertalanffy, 1967). However, compared with engineering systems, fisheries are typically inherently more variable, functionally more diverse, more hierarchically organized, and potentially capable of self-organization and multiple states. They may be more "soft watches" than "clockworks". This raises conceptual and operational issues related to both the depiction and the governance of the system, to be examined next.

The scientific challenge is in balancing the trade-off between realism and simplicity. Models of greater complexity are needed to address emerging key questions. However, increasing the realism of fishery models has consequences in addition to the likely increase in the cost of using them. First, there is a loss of universality because models tailored for a particular fishery may not be useful beyond the specific circumstances for which they were elaborated. Second, scientific uncertainty increases if, as is often the case, information requirements increase faster than knowledge. Obviously, natural processes and their variability remain unchanged, but the adoption of broader representations reveals new uncertainties. In addition, disciplinary perspectives differ between, on the one hand, quantitative, analytical, and computer-based approaches typical in the natural sciences, and on the other, the largely conceptual, qualitative, people-based approaches that are more common in the social sciences. Some progress has been made in linking these, as with the extension of bio-economic approaches through the inclusion of models incorporating human behavioural response (e.g. Charles, 1989). More recently, multi-agent and individual-based models (Le Fur, 1996; McDonald *et al.*, 2006) reflect new approaches to integrating social data.

The governance challenge is to recognize the fallacy of controllability (Charles, 1997, 2001), steering away from hard scientific forecasts of uncertain robustness and accuracy and rigid objectives, towards developing educated institutional foresight, evolving expectation, and adaptive capacity (Prigogine and Stengers, 1979; Allen and McGlade, 1986; Holling, 1994). Several issues arise in this process. The non-linearity of the relationships, the absence of long-term equilibria, and the risk of irreversibility all imply the necessity to develop a precautionary and truly adaptive approach, balancing the traditional attention paid to structures and mechanisms with equal attention paid to evolutions, crises, and instabilities. Delays may be expected because observed effects may have their roots in the distant past and responses to current actions may not be seen until some time in the future. Effects observed in locations remote from where the action took place may point to teleconnections. Cause–effect relationships may develop across scales, and relationships between factors may be different at different scales (scale-dependent perspectives), obscuring the causal factors involved. In addition, many things change simultaneously, through internal natural and social dynamics, pressure of external drivers, and decisions made in different parts of the system. As a consequence, fisheries governance should expect and be prepared to deal with manifestations of self-organization and evolution in both the natural and human subsystems, as well as with occasional surprises. Finally, because of all this, policies either may have little effect relative to their objectives or may generate unexpected and possibly undesirable responses, leading to ineffective or suboptimal results. In the end, some kind of uncertainty principle might have to be accepted that vaguely reminds one of the Indeterminacy Principle (Heisenberg, 1927) in quantum mechanics, which states that it is not possible to determine simultaneously the position and the momentum of a particle.

Questions and challenges

Systemic aspects of fishery governance

For decades, warnings have been issued that narrow and fragmentary approaches to fisheries would lead to poor management decisions and performance (Graham, 1935; Grant, 1986). The long list of the causes of management failure (Garcia and Grainger, 1997; Caddy and Cochrane, 2001; Sutinen and Soboil, 2003) indicates that these are most likely of systemic origin. Examined from that angle, the problems stem from an oversimplistic management paradigm that evolved too slowly to resolve emerging difficulties: institutional arrangements with chronically insufficient capacity to deliver the expected management functions (Féral, 2002) and a disconnection between long-term strategic planning and short-term tactical measures. One of the consequences is a mismatch between the dynamics and complexity of fisheries systems on one hand, and the constrained nature of the management subsystem on the other. Another is the significant difference between the predicted and the observed developments of fishery systems.

Management faces some fundamental choices and questions. Moving from a sectoral to an integrated approach implies balancing alternatives such as: small- and large-scale fisheries; domestic and export markets; short- and long-term development; well-being of present and future generations; restoration of wild stocks and the development of aquaculture; centralization and devolution. How much is society prepared to pay for improving current performance? How predictable are the environmental and human subsystems? As all facets of the fishery sector can be optimized simultaneously, what should be the priorities? Which regulations will work best (and how should "best" be defined)? What levels of impact, risk, and failure rate is society ready to accept? Which mix of species is wanted now and in the future? How can governance performance be assessed, ex-*ante* and ex-*post*? Can failures be objectively analysed and responsibility assigned?

Although the matters dealt with so far are relevant mainly at local to regional scales of governance within conventional management time frames, models addressing larger spatial and temporal scales could serve to initiate and inspire conceptual developments at a global level. For example, a global bio-economic model has been elaborated to illustrate the problems of overcapacity and subsidies that have been high on the global agenda (FAO, 1993; Garcia and Newton, 1997). This work drew attention also to the threatening vicious circle created by extensive trade in fish from developing to developed countries and the simultaneous reverse trade in excess capacity. This problem seems more serious then ever.

Supplementing a detailed analysis by Garcia (1992), the long-term evolution of world fisheries might be described using the cross-loop "figure of eight" model (Gunderson *et al.*, 1995; Gunderson and Holling, 2002). During the early phase (1900–1945), fisheries in the North Atlantic developed from small-scale to industrial scale, with an interruption during World War II. The initial development phase (1945–1960) saw a rapid increase in technology development and consolidation of the industrial sectors across the North Atlantic and Pacific. The expansion phase (1960–1985) led to exploitation of the remaining fishing grounds in the South Atlantic, South Pacific, Indian, and Antarctic Oceans by coastal states, as well as by long-distance fleets. Fishery research and management bureaucracies developed rapidly with strong support from UNDP and FAO in the developing world, and UNCLOS, and the concept of MSY enshrined in it, were institutionalized. The global fisheries crisis (1985–1995) had been building up since the early 1900s, contributing *inter alia* to the establishment of the International Council for the Exploration of the Sea and, through the 1946 London Conference on Overfishing, to the establishment of the International Convention for the Northwest Atlantic Fisheries (ICNAF, in 1949; Halliday and Pinhorn, 1996). This crisis emerged as a truly global problem in the wake of UNCED and a few spectacular fisheries collapses. New international instruments were adopted, and the debate about the sustainability of fisheries and oceans ecosystems development entered the UN General Assembly, now with aspects of biodiversity conservation also being considered. A reform process has been under way since 1995, and an evaluation will be made by 2015 within the WSSD context.

Next steps in governance

The many prescriptions for creating an environment conducive to sustainable fisheries, including improved governance arrangements, typically advocate a more "human" and participatory orientation of policies, adoption of a precautionary approach in assessment and management, and institutional strengthening. Although not all these prescriptions may have been formulated initially with specific reference to the systemic nature of fisheries, most have some link to this broader perspective. These include: adoption of the EAF; identifying relevant scales and acting simultaneously on them; use of feedback responses (e.g. incentives); reducing the impact of surprise by developing adaptive capacity; using the co-evolutionary properties of people and ecosystems; including variability and uncertainty as a systematic component of all decisions; maintaining and enhancing diversity as a source of adaptation; recognizing history and culture; establishing baselines and analysing trajectories and refocusing governmental action on strategic issues.

Systemic aspects of fishery research

The scientific needs are similar to those underlying an ecosystem approach or sustainable development (Garcia, 1989; Charles, 1995; Catanzano and Rey, 1997; Garcia and Grainger, 1997; Garcia *et al.*, 2003). The desired research approach aims at solving social and large-scale environmental issues, simultaneously considering human and ecological well-being. It will build on approaches developed for what has been called sustainability science (Holling, 1994), Mode-2 research (Nowotny *et al.*, 2001), post-normal science (Funtowicz and Ravetz, 1995), Participatory Integrated Assessment (Rotmans and Van Asselt, 2001; Toth, 2003), and Participatory Action Research (Lewin, 1948; Chambers, 1994). It is strongly interdisciplinary, better integrating the human subsystem (Charles, 2001, 2005). It deals explicitly with uncertainty and assists in fine-tuning management through monitoring and recurrent analyses. It validates traditional knowledge, integrating it with scientific knowledge, and serves the stakeholders as much as it does the governments.

With respect to methodologies, the research can build on the application of management and social sciences to natural resources. It needs to develop and use nested and multiscale models, combining qualitative and quantitative approaches (Berkes, 2002). It also needs to adapt general non-equilibrium models, such as multi-agent models, in an interdisciplinary assessment framework. It should elaborate integrated indicator frameworks (Charles, 1994, 2001; Garcia, 1994, 1996) and undertake systematic policy analysis and performance assessments (Moxness, 2003), incorporating both historical and scenario analyses.

Communication strategies within institutionally based science, in particular, need to be improved radically in all directions: between scientists, fishers, and stakeholders; between administrations, managers, and policy-makers; among disciplines; and even in judicial situations when necessary (Garcia, 2005).

Integration of research and decision-making

As noted above, the systemic nature of fisheries requires integration across relevant disciplines. It also requires integration of science with policy (for decision-making), of analytical processes with negotiations, and of factual knowledge with societal values and people's perceptions. These various aspects of integration are not entirely new in a fisheries context, but integration of the human side of the fishery system is still deficient.

An effective interaction process between science and policy-making, aiming at producing a scientifically defensible but also socially robust knowledge base, requires a dual decision-making process consisting of (i) a component involving mainly scientists to resolve as much as possible scientific uncertainties or divergences carrying political weight (and societal cost), and (ii) a component involving mainly policy-makers and stakeholders, but including scientists, as appropriate, to decide on the best course of action. Note that the whole integrated process can be ineffective in a context of scientific disagreement, disparate social and political values, or in an adversarial (judicial) context. Participation by scientists and experts in the negotiating process leading to decisions (e.g. in Advisory Committees) might be needed, if only to clarify concepts. Conversely, the participation of stakeholders in the scientific process might be facilitated, provided that strict boundaries are defined around that scientific process to preserve the independence and objectivity necessary for the political acceptability of the advice. Finally, commitment of all actors to moderate their views towards an acceptable societal position will be essential to avoid situations in which free-riders or uncompromising stakeholders may stall the process (Jasanoff, 1994).

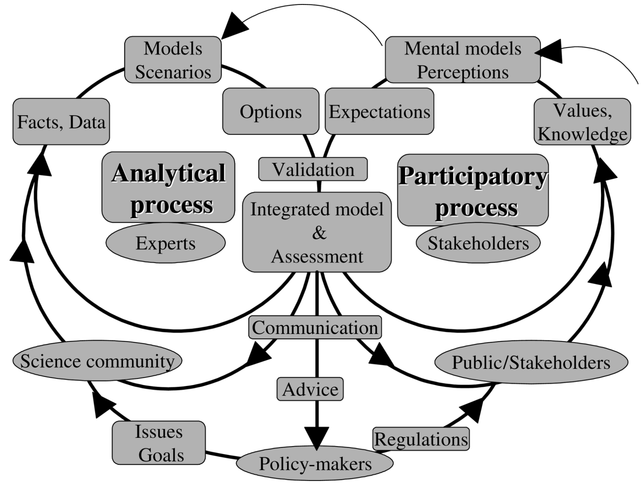

Figure 2. Integrated assessment process. Inspired by and redrawn from Pahl-Wostl (2002).

Figure 2 illustrates an Integrated Assessment Process that could be applied to fisheries. The process explicitly combines a science-based analytical process with a negotiation-based participatory process within which qualitative social analyses and stakeholder involvement can take place. Links between the two processes allow for exchanging information at various levels, in manners compatible with respective roles and rules.

The participatory process that is needed to involve stakeholders and society more closely in the science/decision process is the interface between society and science, as well as between the reality of a fishery system and its representation in a model. The interface may be seen as an osmotic membrane through which issues are crystallized and made intelligible to science and through which scientific conclusions are elaborated and tested (Checkland, 1981). The consensual outcomes of the process would typically include: (i) the representation of the system (the model) or its likely alternatives, if any; (ii) an assessment of the present situation and its dynamics with its related uncertainties; (iii) scientific advice selected from among a number of options elaborated in response to specific strategic or operational questions, analysing the implications of the residual uncertainties; (iv) elements for communication with the public and society contributing to transparency; (v) new regulations, as required; and (vi) revised goals, etc., as appropriate.

Such an overall participatory process is not new to the fisheries arena (Le Fur, 1996; Butterworth and Punt, 1999; Sainsbury *et al.*, 2000; McDonald *et al.*, 2006), but it often needs strengthening, notably in terms of (i) the active participation of social scientists and integration of social sciences into fishery science along with (ii) greater institutionalization of the full process as an integral part of management "good practice".

Conclusions

The fishery system is only a minor element of the global socio-ecological system. It is affected by, and also contributes to, the global "syndrome" characterized by overexploitation of natural resources, environmental degradation, accumulation of waste, biodiversity loss, increasing mobility, increasing energy consumption, and amplification of worldwide disparities, among other environmental and human concerns. Understandably, this reality increases the pressure for better management of fisheries and greater protection of resources and their habitats. Indeed, sustainability of fisheries and other resource systems is surely one of the major goals for science, governance, and society, and this, in turn, creates a clear set of challenges.

The scientific challenge in developing coherence across the ecological, economic, social (and societal), and institutional planes of the multidimensional system is to provide decision support systems based on a full range of disciplines. This requires, *inter alia*: the use of all relevant knowledge (notably through methods of participatory research and incorporation of validated traditional and/or local knowledge); explicit recognition of uncertainties together with suitable approaches to account for them; approaches that deal simultaneously with long- and short-term scales; improved communication with stakeholders and the public; and the development of interdisciplinary integrated assessment processes.

As science deals more closely with heavily value-laden societal issues and risk, a broader part of society wants to have a say in its processes, to set priorities, and to shape its course. This development may seem to some scientists an anathema, but with scientists being called upon and accepting to deal with questions that are not satisfactorily answerable by science, it seems natural that there should be stronger interactions with society, its perceptions, values, and ethics. Keeping independence and objectivity in that process, while maintaining a level of humility, will be a challenge in coming decades.

There is, perhaps, a further challenge to consider. As the systemic complexity of fisheries is increasingly embraced, the following question arises (Hilborn and Gunderson, 1996): to what extent is this embrace of system complexity truly necessary? It will be important to determine, at least on a case-by-case basis, how much of a systems approach is needed, considering benefits and costs. When does the weight of evidence indicate the "added value" of systemic approaches in terms of understanding, forecasting, and managing a system? At what point does the cost of taking on more complexity exceed the costs of not doing so? And what are the scales and boundaries within which a more tractable "partial equilibrium" analysis might be an effective option? These considerations are worthy of further attention. The challenge is to try to capture the essential dynamics with minimum increase of complexity. The more comprehensive representations are necessary for ecosystemic and cross-sectoral analyses of a strategic nature in support of development, investment, or management strategies, e.g. to develop ranges of scenarios related to long-term climatic or socio-economic changes and to identify potential "surprises". Comprehensive representations are also useful as simulation platforms to test the reliability of less-demanding representations, to use, for example, in data-poor situations. Simpler representations, with fewer components and a more limited time–space range will remain useful for operational management, dealing with short-term effects (e.g. at a stock level and in the context of an adaptive management framework).

The governance challenge is in developing—at local, regional, and global levels—the enabling environments necessary to guide and control the users' activities, based on imperfect information. Actions required to deal with systemic complexity include: decentralization and devolution of management responsibilities; empowering of stakeholders; development of environmental and other national norms against which to frame and assess decentralized governance; coordination with other sectoral administrations for integrated area-based management; and generation of sufficient research capacity to deal with the added requirements and nesting of tactical (stock-based) management strategies into strategic (ecosystem-based) plans. There may be no clear-cut optimal strategy, or even mixture of strategies, for seeking sustainability, but rather a network of pathways to choose from, within an ever-changing landscape. Governance will need to be truly adaptive, rationally considering new measures if failures are detected.

The societal challenge within this context lies in clarifying overall objectives and acceptable levels of impact, as well as in defining equitable allocations of resources and costs among all potential users and beneficiaries of aquatic systems. The challenge lies also in raising citizen awareness of societal stakes in fishery systems and the need for an effective, rational, and integrated response. As a prerequisite to improving governance, more attention will need to be paid to understanding the motivations of the range of players.

A full recognition of the complex nature of fishery systems must lead to the recognition that fisheries issues, like other large-scale environmental and societal issues, are not merely ecological or scientific, but also social, economic, institutional, and political, requiring strong processes that necessarily involve societal values and issues of social justice and equity. Science, policy-makers and managers, industry, and other stakeholders are called upon to collaborate on an uncomfortable yet unavoidable, and indeed worthwhile, journey, navigating across wide, uneven, and foggy environmental, economic, and social landscapes, equipped only with a "soft watch". This is a journey in which time is relative, the direction taken only indicative, and where the only certainty may be just more uncertainty.

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References

Allen, P. M., and McGlade, J. M. 1986. Dynamics of discovery and exploitation. The case of the Scotian shelf groundfish fisheries. Canadian Journal of Fisheries and Aquatic Sciences, 43: 1187–1200.

Ashby, R. W. 1962. Principles of the self-organizing system. *In* Principles of Self-Organization. Transaction of the University of Illinois Symposium, pp. 255–278. Ed. by H. Von Foerster, and W. Zopf. Pergamon Press, London.

Berkes, F. 2002. Cross-scale institutional linkages: perspectives from the bottom up. *In* The Drama of the C, 293–321. Ed. by E. Ostrom, T. Dietz, N. Dolsak, P.C. Stern, S. Stonich, and E.U. Weber. National Academy Press, Washington, DC.

Boulding, K. 1956. General system theory: the skeleton of science. Management Science, 2(3): 197–208.

Butterworth, D. S., and Punt, A. E. 1999. Experiences in the evaluation and implementation of management procedures. ICES Journal of Marine Science, 56: 985–998.

Caddy, J. F., and Cochrane, K. L. 2001. A review of fisheries management past and present and some future perspectives for the third millennium. Ocean and Coastal Management, 44: 653–682.

Catanzano, J., and Rey, H. 1997. La recherche halieutique entre science et action: réflexions sur fond de crise. Nature, Science et Société, 5(2): 19–30.

Chambers, R. 1994. The origins and practice of participatory rural appraisal. World Development, 22: 953–969.

Charles, A. T. 1989. Bio-socio-economic fishery models: labour dynamics and multiobjective management. Canadian Journal of Fisheries and Aquatic Sciences, 46: 1313–1322.

Charles, A. T. 1994. Towards sustainability: the fishery experience. Ecological Economics, 11: 201–211.

Charles, A. T. 1995. Fishery science: the study of fishery systems. Aquatic Living Resources, 8: 233–239.

Charles, A. T. 1997. The path to sustainable fisheries. *In* Peace in the Oceans. Ocean Governance and the Agenda for Peace, 201–213. Ed. by E. Mann Borgese The Proceedings of Pacem in Maribus XXIII, Costa Rica, 3–7 December 1995. UNESCO, Paris.

Charles, A. T. 2001. Sustainable Fishery Systems. Blackwell Science, Oxford. Fish and Aquatic Resources Series. 300 pp.

Charles, A. T. 2005. Toward sustainable and resilient fisheries: a fishery-system approach to overcoming the factors of unsustainability. *In* Overcoming Factors of Unsustainability and Overexploitation in Fisheries: Selected Papers on Issues and Approaches, pp. 221–233. Ed. by J. Swan, and D. Greboval. International Workshop on the Implementation of the International Fisheries Instruments and Factors of Unsustainability and Overexploitation in Fisheries. Siem Reap, Cambodia, 13–16 September 2004. FAO Fisheries Report, 782.

Checkland, P. 1981. Systems Thinking, Systems Practice. Wiley, Chichester.

FAO. 1993. Marine Fisheries and the Law of the Sea: A Decade of Change. Special chapter (revised) of The State of Food and Agriculture. FAO, Rome. 66 pp.

FAO. 1995. Code of Conduct for Responsible Fisheries. FAO, Rome. 41 pp.

Féral, F. 2002. La contribution du droit et de l'analyse institutionnelle aux politiques publiques des pêches maritimes. Le cas des pêcheries de Méditerranée occidentale. Oceanis, 28: 89–113.

Forrester, J. W. 1973. World Dynamics, 2nd edn. Pegasus Communications, Waltham, MA. 144 pp.

Funtowicz, S. O., and Ravetz, J. 1995. Risk management, uncertainty and post-normal science. *In* Sustainable Fish Farming, 261–270. Ed. by H. Reinertsen, and H. Haaland. Proceedings of the First International Symposium on Sustainable Fish Farming, Oslo, 28–31 August 1994. A. A. Balkema, Rotterdam.

Garcia, S. M. 1989. La recherche halieutique et l'aménagement: grandeur et servitude d'une symbiose. *In* L'homme et les Systèmes Halieutiques et Acquacoles Marins, pp. 711–744. Ed. by J. P. Troadec. Masson et Cie, Paris.

Garcia, S. M. 1992. Ocean fisheries management. The FAO Programme. *In* Ocean Management in Global Change, pp. 381–418. Ed. by P. Fabbri. Elsevier Applied Science, Amsterdam.

Garcia, S. M. 1994. The precautionary principle: its implications in capture fisheries management. Ocean and Coastal Management, 22: 99–125.

Garcia, S. M. 1996. The precautionary approach to fisheries and its implications for fishery research, technology and management: an updated review. *In* Precautionary Approach to Fisheries. 2. Scientific Papers, pp. 1–75. FAO Fisheries Technical Paper, 350/2.

Garcia, S. M. 2005. Fishery science and decision making: dire straights to sustainability. Bulletin of Marine Science, 76: 171–196.

Garcia, S. M., and Grainger, R. 1997. Fisheries management and sustainability: a new perspective of an old problem? *In* Developing and Sustaining World Fisheries Resources. The State of Science and Management, pp. 631–654. Ed. by D. A. Hancock, D. C. Smith, A. Grant, and J. P. Beumer. Proceedings of the Second World Fisheries Congress. CSIRO, Australia.

Garcia, S. M., and Newton, C. 1997. Current situation, trends and prospects in world capture fisheries. *In* Global Trends: Fisheries Management, 3–27. Ed. by E. I. Pikitch, D. D. Huppert, and M. P. Sissenwine. American Fisheries Society Symposium, 20.

Garcia, S. M., Zerbi, A., Aliaume, C., Do Chi, T., and Lasserre, G. 2003. The ecosystem approach to fisheries. Issues, terminology, principles, institutional foundations, implementation and outlook. FAO Fisheries Technical Paper, 443. 71 pp.

Graham, M. 1935. Modern theory of exploiting a fishery, and application to North Sea trawling. Journal du Conseil International pour l'Exploration de la Mer, 10: 264–274.

Grant, W. E. 1986. Systems Analysis and Simulation in Wildlife and Fisheries Sciences. Wiley, New York.

Gunderson, L. H., and Holling, C. S. 2002. Panarchy. Understanding transformations in human and natural systems. *In* Planning for Resilience: Scenarios, Surprises, and Branch Points, pp. 361–394. Ed. by G. C. Gallopin. Island Press, Washington, DC.

Gunderson, L. H., Holling, C. S., and Light, S. S. (Eds.) 1995. Barriers and Bridges to the Renewal of Ecosystems. Columbia University Press. 535 pp.

Halliday, R. G., and Pinhorn, A. T. 1996. North Atlantic fishery management systems. A comparison of management methods and resources trends. Journal of Northwest Atlantic Fishery Science, 20: 3–135.

Heisenberg, W. 1927. Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik. Zeitung für Physik, 43: 172–198.

Hilborn, R., and Gunderson, L. H. 1996. Chaos and paradigms for fisheries management. Marine Policy, 20: 87–89

Holling, C. S. 1994. New science and new investments for a sustainable biosphere. *In* Investing in Natural Capital. The Ecological Economics Approach to Sustainability, pp. 57–73. Ed. by A. Jansson, M. Hammer, C. Folke, and R. Costanza. Island Press, Washington, DC.

Jasanoff, S. 1994. The Fifth Branch: Science Advisers as Policymakers. Harvard University Press.

Le Fur, J. 1996. Simulation de la dynamique d'une exploitation à l'aide de modèles multi-agents: le cas de la pêche artisanale au Sénégal. Lettre du Programme Environnement, Vie et Sociétés, 15: 16–20.

Lewin, K. 1948. Resolving social conflicts. *In* Selected Papers on Group Dynamics. Ed. by G. W. Lewin. Harper and Row, New York.

McDonald, A. D., Fulton, E., Little, L. R., Gray, R., Sainsbury, K. J., and Lyne, V. D. 2006. Multiple-use management strategy evaluation for coastal marine ecosystems using in vitro. *In* Complex Science for a Complex World: Exploring Human Ecosystems with Agents. Ed. by P. Perez, and D. Batten. Australian National University Press, Canberra.

Marchetti, C. 1987. The Kondratiev cycle. Predicting for the next 25 years. R + D for the 21st Century. An analysis of trends affecting strategies for industrial innovation. The Research and Development Society Jubilee Exhibitions and Proceedings of Symposium, November 1987, pp. 80–111. The Research and Development Society, and Cranfield Press, London.

Marchetti, C. 1996. Pervasive long waves: is human society cyclotymic? Prepared for the Conference "Offensiv zu Arbeitsplätzen: Weltmarkte 2010", Cologne, 14–15 September 1996. 31 pp.

Moxness, E. 2003. Policy sensitivity analysis: simple versus complex models. Working Papers in System Dynamics. WPSD 3/03. 19 pp.

Nowotny, W., Scott, P., and Gibbons, M. 2001. Re-thinking Science. Knowledge and the Public in an Age of Uncertainty. Polity Press, London. 278 pp.

Pahl-Wostl, C. 2002. Agent based simulation in integrated assessment and resources management, 2nd edn. *In* Integrated Assessment and Decision Support. Proceedings of the 1st Biennial Meeting of the International Environmental Modelling and Software Society, Lugano, Switzerland, Volume 2, 239–244. Ed. by A. E. Rizzoli, and A. J. Jakeman. SEA.

Prigogine, I., and Stengers, I. 1979. La Nouvelle Alliance. Métamorphose de la Science. Gallimard. 302 pp.

Rothschild, B. J. 1971. Systems analysis and fishery management. Proceedings of the Indo-Pacific Fisheries Council, 14(2): 13–23.

Rotmans, J., and Van Asselt, M. B. A. 2001. Uncertainty in integrated assessment modelling: a labyrinthic path. Integrated Assessment, 2: 43–55.

Sainsbury, K. J., Punt, A. E., and Smith, A. D. M. 2000. Design of operational management strategies for achieving fishery ecosystem objectives. ICES Journal of Marine Science, 57: 731–741.

Sutinen, J. G., and Soboil, M. 2003. The performance of fisheries management systems and the ecosystem challenge. *In* Responsible Fisheries in the Marine Ecosystem, pp. 291–309. Ed. by M. Sinclair, and G. Valdimarsson. FAO, Rome, and CABI Publishing, Wallingford, UK.

Toth, F. L. 2003. State of the art and future challenges for integrated environmental assessment. Integrated Assessment, 4: 250–264.

von Bertalanffy, L. 1967. General theory of systems: application to psychology. Social Science Information, 6: 125–136.

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