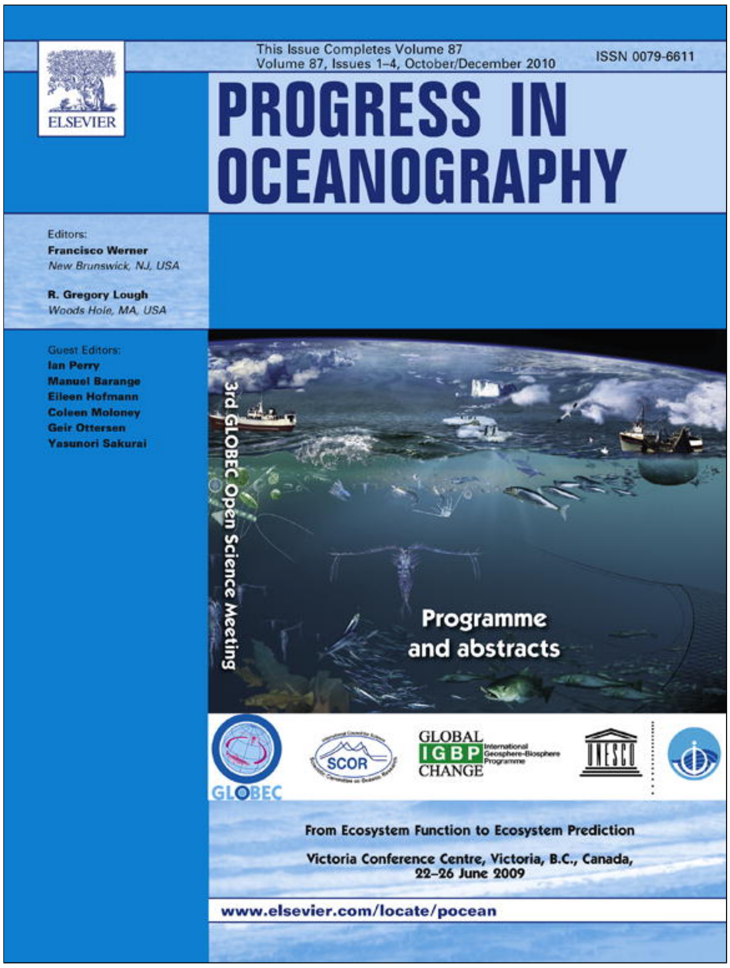
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Climate change, uncertainty, and resilient fisheries: Institutional responses through integrative science

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ABSTRACT

This paper explores the importance of a focus on the fundamental goals of resilience and adaptive capacity in the governance of uncertain fishery systems, particularly in the context of climate change. Climate change interacts strongly with fishery systems, and adds to the inherent uncertainty in those complex, interlinked systems. The reality of these uncertainties and linkages leads to a recognition of the need for robust and adaptive management approaches in order to enhance system resilience. To this end, the paper proposes a focus on stronger moves to 'integrative science' methods and processes – to support suitable institutional responses, a broader planning perspective, and development of suitable resilience-building strategies. The paper explores how synergies between institutional change and integrative science can facilitate the development of more effective fisheries policy approaches. Specifically, integrative science can provide a vehicle (1) to examine policy options with respect to their robustness to uncertainty, particularly to climate-related regime shifts and (2) to allow better assessments of behavioral responses of fish, humans and institutions. The argument is made that understanding these aspects of fishery systems and fishery governance is valuable even in the absence of climate-induced processes of change, but that attention to climate change both reinforces the need for, and facilitates the move toward, implementation of integrative science for improved fishery governance.

1. Introduction

This paper focuses on three key themes dominating discourse in fisheries today: the evolution of fishery governance, the prevalence of uncertainty, and the goal of resilience. Furthermore, we explore how these themes interrelate with the reality of climate change, which is bound to play an increasing role. Each of these themes poses massive challenges. For example, many volumes have been written about new directions emerging in the management and governance of fishery systems. These directions are made all the more challenging by the wide range of uncertainties found in the biophysical, socioeconomic and governance-related aspects of the fishery. Similarly, resilience – the capability of a system to maintain key systemic properties in the face of 'shocks', rather than to shift into undesirable states (Holling, 1973; FAO, 1996; Ludwig et al., 1997; Folke et al., 2004) – is increasingly recognized as a fundamental goal of fisheries management. This necessarily shifts governance thinking away from one-size-fits-all 'solutions', which may be relevant in a hypothetical deterministic and completely

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controllable situation, but which lack the breadth to work in an uncertain real-world (Mahon et al., 2008).

Climate change is likely to complicate the picture. In many cases, it will worsen the already difficult task of maintaining the biological health, as well as the social and economic value, of marine fish stocks and their supporting ecosystems. It will do so by potentially introducing increased uncertainty throughout the entire complex system of biophysical and socioeconomic processes that determine the fate of a fishery. This uncertainty pertains to each element of the sequence of alterations in states or processes, impacts, and feedbacks that link physical changes to biological changes to changes in fishing patterns, and socioeconomic impacts, which responses, in turn, feed back to impacts on the biophysical system, and so on, iteratively. There also is uncertainty about the direct human impacts of policy imperatives to reduce fossil fuel use in industrial fishing fleets (see Tyedmers et al., 2005). This therefore reinforces the need to live with and make decisions under higher levels of uncertainty in both the short-term and long-term, and to focus on resilience in management and policy design (Adger et al., 2005).

Marine ecosystems provide a variety of goods and services, including fisheries, recreation, shipping, biodiversity and habitat protection. The marine environment is also used as a disposal site for waste and pollution. Threats to fisheries arise from human population increase, changes in land use, damming, straightening of water courses, flood control, pollution and also overfishing and climate change (McGoodwin, 1990; Sindermann, 1996; Pauly et al., 2000; Essington et al., 2006; Halpern et al., 2008; Allsopp et al., 2009). To be effective, a governance system must provide means of resolving many conflicts of interest and produce adaptive, robust solutions. It is clear that we can no longer treat fisheries separately from other marine management. An integrated approach is needed to understand the interplay among these elements and how the system may evolve in a changing climate.

We argue here that to tackle these big fishery challenges – governance, resilience, uncertainty, and climate change impacts – there is a need for suitable institutional responses, and that these in turn are facilitated by appropriate combinations of knowledge and research, what is referred to in this paper as 'integrative science'. It is only through the application of such integrative science that we can hope to efficiently coordinate the assessment, monitoring and management of fisheries with the other goods and services derived from marine systems. We further argue that by focusing on the linkages between integrative science, institutional change, and effective use of the knowledge base in the policy process, one can identify mechanisms to stimulate the application of integrative science for more resilient management of marine systems.

We use the term 'integrative science' in this paper to describe a 'thing' and a 'process'. The 'thing' is a broad combination of natural and human science, along with other forms of knowledge such as traditional ecological knowledge (TEK) and local knowledge (LK), that is applied to the study of systems, notably social-ecological systems (Berkes et al., 2003; Haggan et al., 2007; Ommer and Team, 2007). The term "social-ecological systems" was proposed by Berkes and Folke (1998) to identify highly connected and interactive systems with biophysical and human (including economic, cultural and socio-political) components. The 'process' is how institutionally we get to this combination of knowledge, e.g., in the steps involved in bringing together suitable teams to engage on key research challenges or knowledge needs. This involves the whole production spectrum from data collection and analysis, to information gathering, knowledge production and communication across space and time (FAO, 2009). Integrative science is systems-oriented and produces a shared understanding (a 'shared conceptual map') of the nature, structure and dynamics of the problem at hand. It can transcend disciplines in asking about the fishery system 'what are the tipping points?', 'what are the most sensitive variables?', 'what are the variables that tell us we are into uncharted territory?', 'what are the predictability limits of these tipping points and the sensitive variables?'.

We note that there have been many other calls for increased application of integrative science for fisheries management (e.g., Charles, 1995; Degnbol et al., 2006). In particular, Degnbol et al. (2006) persuasively argue that many academic experts who provide advice to fishery managers suffer from a type of 'tunnel-vision' arising from their disciplinary training. Their limited perspectives lead them to advocate a narrow set of standard 'fixes' for fishery problems. These solutions have frequently come with undesired side-effects that could have been avoided had the analysis taken a broader interdisciplinary approach.

The prospect of climate change both heightens the dangers of discipline-bound tunnel vision and the value of developing mechanisms to dismantle the tunnels to facilitate true integrative science. But the existence of integrative science is not enough to ensure that marine system management will actually be based on the resulting knowledge base (Bundy et al., 2008). Other key elements include the means by which that information is incorporated in the policy process and the governance system that defines who makes which decisions and how those decisions are made.

This paper begins with a discussion of the potential contribution of integrative science to understanding the interactions of climate change with fishery systems, and the nature of the inherent uncertainty in fisheries. We then examine the role of fishery governance institutions, together with major elements of the fishery policy process in providing a facilitative environment for the application of integrative science. This leads into a discussion of resilience and adaptive capacity as fundamental goals in uncertain fishery systems, and the value of moving toward robust and adaptive management in order to enhance resilience. The final major section of the paper discusses ways to develop and apply integrative science methods and processes that support suitable institutional responses (and a broader planning perspective) oriented to achieve both near-term and long-term fishery objectives. This involves the development of appropriate resilience-building strategies, ones that are important to fishery system well-being in any circumstances, and particularly in the presence of climate change.

2. Climate change, uncertainty and fishery systems: an integrative science approach

Impacts of climate change on fishery systems operate over a variety of pathways (Barange et al., 2010a). This section focuses on the flow of impacts from physical changes (e.g., in terms of ocean temperatures) to biological/stock changes and onto fishing and consequent human impacts, as well as the impacts of fishing on the vulnerability of fish stocks to physical changes – with feedbacks on human communities. Other pathways may include impacts on harvesters and fishing communities of policies to restrict environmentally damaging fishing practices, or reduce fossil fuel use. Indeed, it has been suggested that one way to conserve fish resources would be to significantly increase oil prices (Sumaila et al., 2008). Such changes comprise ecological, economic, and social processes that are evolving and interacting on multiple temporal and spatial scales (Gunderson and Holling, 2002). There is a need for a broad systems thinking to incorporate all these pathways, and to develop a sense of what is known, unknown and perhaps unknowable, thereby providing a realistic foundation for an analysis of fishery policy options in the face of climate change.

The potential consequences of climate change for marine fisheries include large-scale redistribution of fish stocks and productive habitats. For example, Cheung et al. (2009) argue that climate change may redistribute global catch potential, with an average of 30–70% increase in high-latitude regions and a drop of up to 40% in the tropics. In addition, many observers worry that climate change will bring substantial declines in the overall value of the harvest. One estimate suggests that climate change will cause global fishery losses of up to $10 billion USD in revenue by 2050 (World Bank, 2009). In the US, Cooley and Doney (2009) studied the impact of ocean acidification on coral reef habitats and benthic commercial shellfisheries, and estimated large impacts on ecosystem goods and services as well as socioeconomic ramifications in the loss of revenue and employment.

It has long been recognized that climatic processes play key roles in the functioning of marine biological systems (e.g. Bakun, 1996; Yáñez et al., 2001). These roles span a wide range of temporal and spatial scales. The term "climate variability" is generally used for the shorter time scales and climate change for the longer scales. The ocean climate variables that affect fisheries include shifting currents and temperature changes that alter feeding patterns, growth and migratory behavior of the various fish species targeted by human harvesters.

Natural systems have a certain inherent resilience to such climatic variations (Gallucci, 1973; Holling, 1986), but their capacity to cope with disturbance can be degraded by harvesting, pollution and other stressors – and resilience also can be enhanced by management actions (Carpenter et al., 2001). Adaptive capacity in ecological systems is related to genetic diversity, biological diversity, and habitat heterogeneity (Holling, 1996; Carpenter et al., 2001). In social systems, the existence of institutions and networks that learn and store knowledge and experience, create flexibility in problem solving and balance power among interest groups play an important role in adaptive capacity (Scheffer et al., 2001; Berkes et al., 2003). Systems with high adaptive capacity are able to reconfigure themselves without significant declines in crucial functions. A consequence of a loss of resilience, and therefore of adaptive capacity, is loss of opportunity, constrained options during periods of re-organization and renewal, an inability of the system to do different things and an increased likelihood of emerging from such a period along an undesirable trajectory (Holling, 1986; Gunderson and Holling, 2002).

There is a growing body of scientific research that seeks to understand the pathways and processes through which physical and chemical changes in the marine environment affect the various interacting biological components of the marine ecosystem (Barange et al., 2010a). This work is shedding light on the meaning of ecological resilience in a continually variable marine environment, and the possible biological impacts of anthropogenic climate change (Brander, 2007). Several parts of this body of biophysical research touch directly on fish species that are important to commercial and artisanal fisheries, and insights on the nature of ecological resilience and response to physical change are directly pertinent to the analysis of fishery management options.

One thing that is only now becoming clear is that it is very difficult to separate the impacts of climate from the impacts of harvesting (e.g. Rose, 2004). In fact, simple models of biophysical interactions "…which do not consider the effects of exploitation and cannot resolve key climate –fishing interactions, may not adequately reproduce observed changes in marine systems because of the non-linearities and alterations in system structure that are induced by exploitation." (Perry et al., 2010a, p. 6). In many cases, harvesting pressure can increase the sensitivity of fish stocks to climate variability (Pauly et al., 2000; Perry et al., 2010a). This occurs because harvesting tends to differentially remove large individuals and older spawners from a population, thus reducing the biological diversity, reproductive fitness and average size of the remaining stock. Furthermore, intense harvesting tends to lower the mean trophic level of the fisheries and reduce the turnover time of fish communities, making the entire community more sensitive to climate forcing, basically by simplifying marine foodwebs which increases their vulnerability to stochastic phenomena (Pauly et al., 2000). Climate change also may increase the frequency of extreme events – both climatic (e.g. severe storms) and biological (extremely good or poor recruitment years). Thus, the combined effects of climate change and continued heavy harvesting pressure could destabilize marine ecological communities, increasing the likelihood of stock collapses and sudden transitions to new states, which some resource users may view as less desirable.

It is also increasingly clear that the responses of biological systems to climate changes follow a wide variety of patterns that depend on the life history strategies of individual species, the nature of the climate forcing (Barange and Perry, 2009), interactions with other species through predator–prey relationships (Stenseth et al., 2002), and other factors. Biological systems may "…respond to climate changes with a mix of slow fluctuations, prolonged trends, and step-like changes that may be difficult to predict, and yet that cannot be avoided." (Barange and Perry, 2009, p. 51–52). The difficulty of predicting these abrupt changes is related to the fact that the biological effects of climate variations are typically nonlinear, lagged, and mediated through a sequence of interlinked processes at different trophic levels. This complexity has been a frequent source of surprise – as, for example, when a seemingly subtle shift in the timing or intensity of upwelling leads to an unexpectedly large impact on recruitment for a commercially important fish stock (e.g., Hsieh et al., 2005; Barth et al., 2007). In addition, dramatic changes in species abundance or community structure can occur when a key species is in a fragile state and a climate change pushes the system over a threshold. For example: "The possibility exists for catastrophic changes in marine ecosystems resulting from apparently small perturbations, as has been observed for coral reef and North Pacific marine systems (e.g. Scheffer et al., 2001)." (Perry et al., 2010a, p. 7). Such non-linearities and complex processes are likely to characterize the response of marine biophysical systems to long-term climate change, such that we may see an increase in the likelihood of sudden regime shifts.

Another general observation is that the ongoing effects of climate variability on marine species are often so large that they may confound detection of a separate longer-term climate change "signal" (Rose, 2004; Lehodey et al., 2006; Brander, 2007; Tasker, 2008; Perry et al., 2010a; Overland et al., 2010). This does not mean that long-term anthropogenic climate change can be safely ignored while we concentrate our attention on managing the effects of ongoing climate variability, because some of the processes associated with anthropogenic climate change, such as ocean acidification, will tend to reduce the likelihood that a system, once disturbed, will return to its previous state.

The human side of the integrative science enterprise is equally complex. This has led to increasing calls for attention to the human side of marine social-ecological systems – the drivers, controls and human values associated with harvesting – and for analysis of interactions between the natural and human subsystems (e.g., Garcia and Charles, 2008; Ommer and Team, 2007; Ommer et al., 2009; Ostrom, 2009; Perry et al., 2010b).

It is well known that human pressures on marine biological resources have intensified in recent decades in tandem with growing human populations and ever improving technologies for finding and catching fish. It is also well known that there is tremendous diversity among harvesters, including differences in technology, motivations and identity – for example, as members of a coherent place-based community, as "roving bandits" (Berkes et al., 2006), or as participants in a mobile, but well-regulated industrial fishery (Ostrom, 2007; Chuenpagdee and Jentoft, 2009; Ommer et al., 2009). There are also scale differences, and motivational ones between subsistence/cultural fisheries, those of small-boat fleets, and the large industrial footloose factory freezer fleets (Perry and Ommer, 2003). These differences play a large role in determining impacts of climate variability and change on harvesters and fishery-dependent communities, their adaptations to changing resource availability, and their responses to specific fishery management policies.

The impact of climate change and greenhouse gas policies on fisheries and food security could be substantial for coastal communities and national economies in tropical poor regions especially in Western Africa and Southeast Asia (Allison et al., 2009; Cheung et al., 2009). Significant responses of fishers to transient but large increases in oil prices also can occur in developed regions (Schau et al., 2009). In addition, harvesting is only part of the picture, because other human activities including pollution from mining, industry, forestry, agriculture and coastal urban development, have had major impacts on coastal systems (Ommer and Team, 2007; Halpern et al., 2008). Depending on the particular problem or policy question to be addressed, attention may also need to be directed to these other sources of human impact on marine systems. Indeed, implementing an ecosystem-based approach to fisheries management would require such a larger view.

To best guide fisheries policy in a changing climate, the integrative science should explicitly treat fisheries as complex adaptive social-ecological systems that are difficult to predict, especially far into the future (Mahon et al., 2008). Climate change may increase uncertainty and change its form, thereby exacerbating the challenge of making policy choices today. If this occurs, it would increase the need to be adaptive and nimble in our policymaking. While we would like to be able to track the shifting envelope of possibilities over time, it is difficult to assess the range of eventual consequences in the future.

3. The institutional context for integrative science: fishery governance

Even the best scientific information about the status and dynamics of socio-ecological systems may have little value in the absence of effective institutions for cooperative governance of those systems. For integrative science to be most useful for the management of fisheries and other aspects of marine systems, three key processes require attention: the generation of integrative science; its interplay with governance institutions; and the specific mechanisms for linking the resulting knowledge base to formulation and implementation of management actions. There is an inherent two-way synergy between the creation of integrative science and institutional change. Amassing a diverse integrated knowledge base can help in the design and evaluation of governance arrangements, while an appropriate institutional framework is needed in order to make "integrative science for management" happen more comprehensively.

In common parlance, the terms "governance" and "management" are sometimes used interchangeably (Gray, 2005). However, the academic literature treats "governance" as the higher-order concept – encompassing the institutions (laws, customs, treaties and social relationships) that define rights and responsibilities with respect to a resource as well as the procedures that will be followed to develop and implement policies and management actions that may alter those rights and responsibilities in order to achieve a shared, or social objective (North, 1991; Williamson, 1998; Chuenpagdee and Jentoft, 2009). Policy decisions occur at two levels. They can be directed at the design of the governance system, or more narrowly at developing management measures within the existing system of governance. The broader questions of governance design will have important effects on how quickly and effectively management measures can be adjusted in response to changing conditions, and whose interests are likely to be represented in the development of those measures (Costanza et al., 1998). Integrative science can inform decisions at both levels.

The central problem for fisheries governance is how to design and maintain a system of incentives that constrains competitive harvesting and other destructive human activities, in order to avoid the depletion of fish stocks and the dissipation of potential resource rents and social benefits. The roots of this problem lie in the challenge of determining the balance between current and future generations (how much to catch now versus later, c.f. Sumaila, 2004) and the balance among the competing users (or potential users) of the resource. The difficulty of achieving and maintaining suitable management regimes is especially acute in the case of internationally shared fishery resources (Munro et al., 2004), and there have been cases in which a change in the status or migratory behavior of a shared fish stock disrupted an existing cooperative management regime (Miller et al., 2001).

The evolution of fishery governance and the application of management measures dates back well over a century. Modern management efforts began with an almost exclusive focus on biological considerations, but increasingly, recognition of issues relating to human behavior has come to the fore, i.e. it is the fishery that one is attempting to manage, not the fish. In particular, there is realization that if fishers are not involved in setting the rules of fishing, they will tend not to support those rules, and with fishing taking place out at sea, this non-compliance will create major enforcement problems. Case studies of such enforcement and compliance issues can be found in a wide variety of contexts (Kuperan and Sutinen, 1998; Sutinen and Kuperan, 1999; Ommer and Team, 2007; Hauck, 2008; Vodden, 2009; Munro et al., 2009). In addition, when fishery managers have focused only on biological considerations, the resulting regulations have often proven to be socially and economically damaging (e.g., Crutchfield and Pontecorvo, 1969), provoking reactions that tend to thwart the intended purpose of the regulation (Ommer, 2002; Ommer and Team, 2007 esp. Ch. 3; Hutchings and Myers, 1995).

Current thinking on fishery governance, policy and strategic management demonstrates a global recognition that effective governance of common-pool resources will require attention to both biological and socioeconomic issues. An iterative approach to policy development and analysis, as described in Fig. 1, will likely be critical for achieving increasing prosperity in the face of population growth and ongoing environmental change (Ostrom, 2005, 2009). Policy

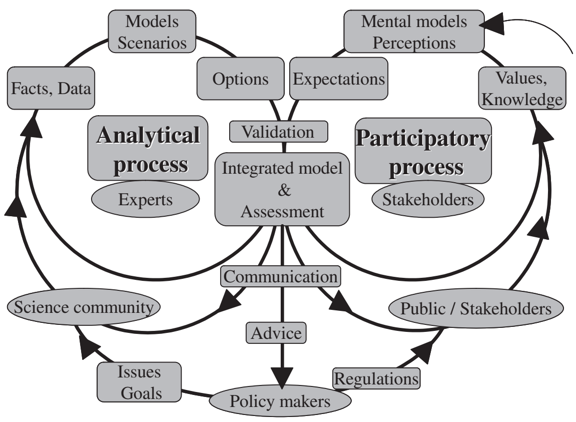

Fig. 1. Integrated assessment and policy-development process, indicating key ingredients, flows, and interactions between the analytical and participatory components of the process. From Garcia and Charles (2008), inspired by and redrawn from Pahl-Wostl (2002).

development in fisheries is a long-term, continuing and multi-tiered "rolling" process in which historical choices have long-term consequences. The drivers of this process include vulnerabilities to large-scale forces such as increasing competition and related stock declines associated with open-access regimes, as well as the relationship of fisheries to a nation's ability to solve other economic problems (e.g., Allison et al., 2009). A holistic long-term conception of the management problem and the place of current policy options in the evolution of the system is required to avoid the "band-aid" approaches to fishery policy that have been too common in the past (Hilborn et al., 2004). Such a perspective is valuable even in the absence of long-term climate change, especially for certain types of decisions – specifically, those that have difficult-to-reverse consequences, like decisions regarding capital investments, or allocation of use rights over fishery access, or voting schemes in a multinational RFMO. Once we realize that some of our current decisions are likely to cast long shadows, it becomes clear that we need to consider all of the factors that can affect the ultimate consequences of our current policy choices including long-term climate change.

The imperative of climate change, and the uncertainties it implies, reminds us of the need to recognize our limitations – both in knowledge and in capability to manage. We consider these aspects in detail below, but with respect to governance, it is important to build in a flexibility that allows for the possibility of change in the future, while also recognizing impediments to change and the incompleteness of the understanding and data available. In particular, just as adaptability and nimbleness are advocated for management, so too should these qualities be reflected in recommendations made for fishery governance.

Related to this is the need for approaches to governance that reflect its inherent complexity, as well as pragmatic realities. Consider, for example, the widely-accepted and advocated approach of stakeholder involvement in fishery decision-making. While this is often summed up in the recommendation to "bring all the stakeholders together", the reality is more complex (see, e.g., Chuenpagdee and Jentoft, 2009). What responses and interactions might we expect when the variety of stakeholders is brought together? What is the power structure in play? How does this process affect compliance, cooperation? These are but some of the questions that arise. Therefore, discussing 'stakeholder involvement' is at least as complex on the human side as discussing 'fish reproduction' on the biological side. The broader implication of this is that assessing governance options requires a nuanced approach based on real and deep understanding - this is where 'systems thinking' is crucial. In addition to stakeholder involvement are all of the impacts, at various scales, of the processes of globalization such as technological advancements, reduction of trade barriers, vertical integration of food companies, and the separation of consumers from those who actually catch the fish (e.g. Kolb and Taylor, 2007).

Second, from a perspective of pragmatism, it is important to go beyond declarations concerning the desirability – in theory – of certain governance arrangements, to assess empirically whether such changes are in fact feasible and worthwhile, and over what time frame. While much of the research and writing on fishery governance seems to focus on generic governance systems, or advocating what 'should be' the governance arrangements, as for the standard 'fixes' discussed by Degnbol et al. (2006), in fact there are always impediments to any change – notably adjustment costs, distributional impacts creating winners and losers, etc. These realities need to be better incorporated in policy prescriptions for fishery governance. Moves towards evidence-based policy development, in which policies are based on demonstrated abilities to achieve the stated goals, should be encouraged, while recognizing that where evidence is lacking, both precaution and further research are warranted.

4. Resilience, robustness and climate change

The fishery governance challenge is not new – and exists independently of the climate change reality – but the latter adds new complexity and urgency to dealing with the former. This is because climate change is not likely to proceed in a smooth predictable fashion, but rather as extreme events, regime shifts and other inconvenient forms of change (Miller and Munro, 2004; CCSP, 2008; deYoung et al., 2008; Barange and Perry, 2009). This heightened and deepened uncertainty calls, then, for a focus on governance approaches that are able to create a resilient fishery system under conditions of high uncertainty – with climate change exacerbating the challenge. This implies a need to re-design governance in ways such that its structure and methods are *robust* and *adaptive* (e.g., Charles, 2001, 2005). Regarding the process of developing and implementing fishery management measures, increased uncertainty heightens the importance of shifting toward approaches that 'live with uncertainty' and that facilitate decisions that are able to move the fishery more safely toward resilience.

The pursuit of robust and adaptive management reflects the reality that fishery management, and indeed natural resource management more generally, have tended to embrace some key underlying misconceptions. First, the *Illusion of Certainty* leads to policy measures (such as the setting of catch quotas) that do not properly take account of uncertainty, leading to decisions that fail to work within the bounds of this uncertainty (Charles, 2005). The expression of management policies without also expressing the known (to say nothing of the unknown) uncertainties contributes to this illusion, for example when catch quotas are expressed as single numbers when in fact a range of values with their associated uncertainties of stock collapse would provide a more accurate presentation. Second, the *Fallacy of Controllability* occurs when policy and management measures are designed without taking into account the limitations within fishery systems that lead to at best partial and imperfect controllability in practice (Charles, 2001, 2005).

A third problem is the *Trap of the Expert* (Gunderson and Holling, 2002), in the sense that so much of our expertise loses the sense of the whole in the effort to understand the parts. The great complexity, diversity and opportunity in complex regional systems emerge from a handful of critical variables and processes that operate over distinctly different scales in space and time. The complex issues connected with the notion of sustainable fisheries are not just ecological problems or economic or social, but a combination of all three. Each approach is built upon a particular world-view or theoretical abstraction that can be correct in the sense of being partially tested and credible representations of one part of reality. The problem is that they are partial. They are too simple and lack an integrative framework that bridges disciplines and scales (Gunderson and Holling, 2002).

Fundamentally, then, the goal is to build robustness into an increasingly uncertain governance system, and to build resilience (and adaptive capacity) into a fishery system that is shifting and changing in a highly uncertain manner. This is a form of 'living with uncertainty' through approaches that are less sensitive to uncertainty, less reliant on high levels of controllability in the system, and more in keeping with a true adaptive approach, one that can respond to change in a manner that fits the circumstances (Charles, 2001).

These approaches seem particularly suitable in the more uncertain world of climate change. Climate models are providing increasing insights into the future, and downscaling of the results to more local areas may help to reduce uncertainties over time. Nevertheless, there are bound to be higher levels, and different forms, of uncertainty to be faced in fisheries, both short-term and longer-term. It is thus important to develop governance approaches that are effective within these constraints. The Precautionary Approach and the Ecosystem Approach can help in this direction, as they imply the need for adjustments not only to fishery management but also to the underlying nature of the governance system (see, e.g., Charles, 2002).

5. Putting integrative science into action

Several elements need to be woven together to achieve a workable holistic approach to policy development. Among the key ingredients are a diverse knowledge base, a mechanism to link that knowledge to the policy process, and a set of suitable institutional responses.

With respect to the first of these, we need to understand: (a) the nature of climate change, (b) the pathways of interaction governing its possible manifestations in complex social-ecological systems, (c) the nature of the associated uncertainties, (d) how to evaluate policy alternatives in the context of such uncertainty, and (e) how to develop robust management strategies. Here, predictive models can be powerful tools for understanding processes and linkages, and for elucidating uncertainties. For example they can be used to generate "best guess probability distributions" for the future evolution of climate, biological responses and fishery activities. They also can be used to demonstrate the inherent limits of predictability. Such information would be valuable for testing the robustness of proposed management actions. A theoretical framework in which to place all of the forces acting on the system is needed to underpin such models. Theoretical formalisms also make it easier to develop the specifications of management options and to conceptualize and incorporate uncertainties. Furthermore, the collection of data for future projections is more directed when a formalism exists. However, a systematic integrative analysis of management options would likely couple qualitative information with the output of formal models. For example, one might start with simple influence diagrams to organize an analysis and represent some processes with different degrees of formalism than others. In Fig. 1, many considerations on the "participatory process" side of the diagram could be usefully represented by qualitative influence diagrams, even if their contributions are difficult to quantify.

The second key ingredient, a mechanism to link knowledge to policy, is really where the "rubber meets the road" in that it speaks to how to coordinate the associated science approaches for incorporating all of this information into policy formation (Ommer, 2006). Here, the development of forums and tools for joint evaluation of the diverse scientific and stakeholder information base will be the key to successful implementation of integrative science. Several recent developments promise to contribute to the development of such processes. For example, there has been attention to the value of developing a varied and extensive 'management portfolio' (Charles, 2001) – a 'toolbox' of management measures that are in themselves robust to uncertainty, and which together provide a risk reduction strategy. An integrative science framework can provide a rigorous and comprehensive approach for contingency planning and scenario analysis. Specifically, one can explore and assess a range of possible futures to identify which pieces of the management portfolio to implement at which points in time, and what should be the triggers leading to the change. In this context, we can envision the future as a shifting envelope of possibilities. Efforts to evaluate the robustness and resilience of a set of policy options would consider scenarios at the boundaries of the envelope, recognizing that climate change increases the uncertainty about where those boundaries lie. A policy analyst would want to consider how the envelope of possible futures might depend on current policy choices and how a precautionary approach might help keep the envelope of possibilities manageable.

Integrative science provides a means to answer questions based inherently on systems, linkages and feedbacks within the social-ecological fishery system. In addition, an integrative science framework allows analysis of two key considerations that are as relevant to human aspects as to biophysical: (1) multiple spatial and organizational scales (e.g., of processes, structures, management bodies) and (2) various time scales and rates of change. These arise in considering shifting spatial distributions (of fish, of fishers, of institutional arrangements) and feedback loops (whether in ecosystems, socioeconomic systems, cultural systems or institutions). The pervasive potential for conflict associated with such shifting opportunities and the distributional effects of possible management regimes also can be better evaluated through the application of the integrative science approach. Scale matching, appropriate use of policy instruments and institutional arrangements will promote effective governance and resilient socio-ecological systems (Wilson, 2005; Ekstrom and Young, 2009).

Methods for analyzing the performance of different portfolio configurations and their robustness in the face of multiple uncertainties include computer simulations of large ensembles of alternative scenarios, such as the "Robust Decision" methods being developed by RAND (Lempert et al., 2003). Such simulation methods can facilitate rapid and cost-effective first-cut glimpses of the potential outcomes of alternative management strategies, allowing identification of a smaller set for more in-depth integrative analysis. In addition, the type of Management Strategy Evaluation (MSE) systems now being used in fisheries management in South Africa and Australia (De Oliveira et al., 2008) could be extended to include the human dimensions.

Finally, a sufficiently broad suite of institutional structures and management options can facilitate the development of management approaches that fit the scale, scope and characteristics of the particular management problem at hand. It is important that this array include mechanisms for balancing inherently competing objectives, and strategies that can be readily modified in response to changing conditions (Charles, 1992; Ostrom, 2007; Worm et al., 2009).

Relevant institutional innovations might include formal requirements to engage a diversity of participants in the management of a resource, and to consider multiple factors in evaluating outcomes for fisheries and related marine ecosystem services. Such rules could make decision-making better informed by providing a greater variety of policy options for consideration and a broader view of potential outcomes. Other alternatives include enhancing the bargaining latitude for stakeholders by recognizing a legitimate role for various sorts of side-payments (Munro et al., 2004). An option suggested by Mahon et al. (2008) in the context of limited predictability and controllability, is for managers to step aside and allow the fishery to self-organize. They note that this approach may be "most immediately useful . . . in small-scale fisheries where complexity is highest and options for control are least feasible". One could add that feasibility would be enhanced by strong social cohesion among harvesters possessing good indigenous understanding of the exploited resource and a long-term interest in its preservation. On the other hand, in the case of intensely competitive commercial harvesting by roving bandit fleets, following such an approach may hold risks of fishery collapse that are considered too high.

Institutional responses to the broadening of the fishery 'game' (e.g., through ecosystem-based management, connections with integrated ocean and coastal management, etc.) include a recognition of the need to broaden the knowledge base correspondingly (Gunderson et al., 1995; Estrella Santos and Nauen, 2008). For example, many national governments and international bodies (such as ICES and FAO) are looking for mechanisms to incorporate human-oriented information alongside natural science information, in order to provide more integrated and useful fishery advice. Moreover, there have been discussions on the flow of information and knowledge-sharing approaches amongst stakeholder groups for policy formulation (Haggan et al., 2007; FAO, 2009). With the right governance structure, a broader knowledge base that incorporates inputs and advice from key stakeholder groups would create a better chance to identify what is or is not a 'workable policy' in practice.

Global climate predictions and projections are now being extended to Earth System predictions and projections to provide skillful seasonal-to-decadal information that serves many of the global governance issues (Keenlyside et al., 2008, http://wcrp.ipsl.jussieu.fr/). The physics to fish models are becoming more realistic and have started to include end-to-end management scenarios (Lehodey et al., 2006). With regional Earth System prediction, dynamic and statistical downscaling techniques can produce natural-human system information at very high resolutions for daily management of resources, human health, etc. (Murtugudde, 2009). Additional ammunition for the integrative science approach includes game theory tools, new methods in computational social sciences, and validated human-natural system information including uncertainty ranges (Barange and Perry, 2009; Lazer et al., 2009). Such tools can inform the development of monitoring systems, regulations, governance structures, and cooperative arrangements (Murtugudde, 2010).

Some examples are beginning to appear of efforts to develop integrative science programs that are directly tied to the ongoing management of coastal and marine resources. For example, Barange et al. (2010b) describe efforts to use ecological risk assessments to implement ecosystem-based management in Australia (Fletcher, 2005) and South Africa (Nel et al., 2007). Ommer and Team (2007) describe the work of the Canadian *Coasts Under Stress* project, involving interdisciplinary research that examined, in an integrated manner, environmental and social change on the east and west coasts of Canada's social-ecological systems. Innovative fisheries ecosystems research in Southeastern Brazil, constructing a knowledge base towards a pragmatic ecosystem approach to fisheries in data-poor situations, is also a pertinent example (Gasalla, 2003, 2004; Gasalla and Diegues, 2010; Gasalla et al., 2010; Pincinato and Gasalla, 2010). Another example involves the use of dynamic downscaling of seasonal to inter-annual climate forecasts and IPCC projections for the Chesapeake Bay region, to provide routine forecasts of atmospheric, watershed and estuary conditions, including seasonal predictions and decadal projections of a wide range of ecological and fishery-related variables. This work is directly engaging resource users and managers in identifying the types of information needed through the Climate Information: Responding to User Needs (CIRUN) program (Murtugudde, 2009). In all of these cases, understanding the system's response in the face of change, through observational analysis, is a key first step towards predictive capability.

European efforts to implement a fully integrated approach as mandated by the EU Marine Strategy Framework Directive have already made progress towards broadening adoption of integrative science for management. The European Marine Strategy Framework Directive, agreed in June 2008, establishes measures to achieve or maintain good environmental status in the marine environment by 2020 at the latest. This includes the application of an ecosystem-based approach to the management of human activities while enabling sustainable use of marine goods and services. The Directive focuses on defining the desirable state of marine ecosystems rather than prescribing what regulations and controls are required to achieve this state. It creates a framework that is responsive and adaptive in terms of monitoring, scientific assessment and governance. The Directive sets out eleven descriptors of good environmental status. These qualitative descriptors are being expanded into operational goals and targets to be measured and monitored. This will generate a substantial requirement for routine observations of the state of the ocean.

6. Conclusion

This paper has focused on the importance of suitable institutional responses, supported by integrative science, as a means to develop governance approaches for enhancing resilience in fishery systems under uncertainty, particularly in the face of climate change. What questions and challenges may arise in the face of climate change? How can a broader planning perspective, supported by integrative science, help to tackle these? As part of this challenge, it is important to be able to analyze policy options with respect to their robustness to uncertainty, and particularly to climate-related regime shifts, and to understand behavioral responses of fish, humans and institutions. To understand the diversity among components of the fishery system, and their dynamics, we need 'deep expertise' from both the biophysical and human sides, to avoid over-simplified views of the world, ones that lead us wide of our goals. With a broad perspective on integrative science, there is potential that climate-induced processes of change may in fact present opportunities as well as obstacles.

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