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Fisheries, food security, climate change, and biodiversity: characteristics of the sector and perspectives on emerging issues

Jake C. Rice[1]* and Serge M. Garcia[2]

[1]Department of Fisheries and Oceans, Ottawa, ON, Canada K1A 0E6
[2]Former Director, FAO Fisheries Management Division, Rome, Italy

*Corresponding Author: tel: +1 613 990 0288; fax: +1 613 991 1378; e-mail: jake.rice@dfo-mpo.gc.ca

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This paper reviews global projections to 2050 for human population growth and food production, both assuming constant climate and taking account of climate-related changes in growing conditions. It also reviews statistics on nutritional protein requirements, as well as how those requirements are met by fish on a regional basis. To meet projected food requirements, the production of fish has to increase by ~50% from current levels. The paper also summarizes the main pressures on marine biodiversity that are expected to result from the impacts of changing climate on marine ecosystems, as well as the management measures and policy actions promoted to address those pressures. It highlights that most of the actions being proposed to address pressures on marine biodiversity are totally incompatible with the actions considered necessary to meet future food security needs, particularly in less developed parts of the world. The paper does not propose a solution to these conflicting pulls on policies for conservation and sustainable use. Rather, it emphasizes that there is a need for the two communities of experts and policy-makers to collaborate in finding a single compatible suite of policies and management measures, to allow coherent action on these crucial and difficult problems.

Keywords: climate change, fisheries, food security, marine biodiversity, policy coherence.

Introduction

In every field where there are economic, social, or cultural uses of biotic resources, or concerns over conservation of nature, the dialogue on climate change, conservation, and sustainable uses is escalating (IPCC, 2007a, b; Valdes *et al.*, 2009). The dialogue is forward looking, in that efforts are made to explore plausible future scenarios, consider uncertainties, and seek strategic policies and tactical measures that will sustain uses and/or conserve biodiversity in a changing world.

This paper will examine a pattern of this escalating dialogue in the context of climate change and fisheries. Specifically, several components of this dialogue are proceeding simultaneously. Interactions among subsets of the themes are being explored, but the first two major lines of discussion are proceeding largely independently of the third. Subsets of the dialogue include:

(i) discussions about climate change and fisheries, exploring questions, such as:
   (a) how climate change interacts with ocean physics and chemistry, and what these interactions imply for fish populations and aquatic ecosystems (Engelhard *et al.*, 2011);
   (b) how climate change might affect fish and invertebrate distribution, abundance, and productivity, and what those interactions imply for fisheries (Fulton, 2011).

(ii) discussions about what climate change implies for efforts to conserve biodiversity, exploring questions, such as:
   (a) questions similar to (i), but about components of biodiversity more generally (Sala *et al.*, 2000; Ottersen *et al.*, 2004);
   (b) what factors affect the vulnerability of biodiversity to impacts of climate change (Folke *et al.*, 2004; Perry *et al.*, 2010)?
   (c) what biodiversity conservation policies and measures are expected to be robust to climate change (CBD, 2009; Stern, 2009)?

(iii) finally, largely outside the oceans and fisheries community, a third related set of questions are being explored:
   (a) what implications does climate change have for global and regional food security (Easterling *et al.*, 2007; FAO, 2008a, b)?
   (b) what are the future human demographic trends and what do they imply for future food security (UN-DESA, 2008, 2009; OECD-FAO, 2009)

None of these investigations and dialogue has fully answered their central questions. However, each is displaying trends in the direction in which the participating experts and members of the governance processes think the answers—for policies and practices resulting in desired outcomes—might lie. For policies and management measures for conservation of biodiversity and sustainability of fisheries to succeed, they have to be coherent (Rice and Ridgeway, 2009; Ridgeway and Rice, 2009). Unfortunately, because the lines of dialogue outlined above are being pursued largely independently, they are going in directions (policies, measures or, simply, desirable outcomes) that are not achievable simultaneously or not even compatible. We believe that a set of policies, management measures, and desirable outcomes that could address all of these challenges in a coherent manner might well exist. However, this set can only emerge from a dialogue sufficiently inclusive of all the issues to be addressed and not from continuing to address different parts of these interlinked challenges in different fora.

The purpose of this paper is to present some of the major findings of each of these discussion streams, explain their interconnectedness, and open a dialogue about adaptation strategies that simultaneously consider food security and biodiversity conservation and climate change (Figure 1). In focusing on the interactions among different major areas of policy development, this paper can only address each issue at a strategic level. Projections are used to illustrate the scale of the trends and patterns involved. Although the information presented all comes from competent and credible sources (usually United Nations agencies), assumptions underlie all the projections. Other plausible assumptions would result in quantitatively different projections and all the source agencies consistently emphasize the uncertainties of such projections. Nonetheless, because the figures are presented only to communicate the scale of the challenges for which coherent, consistent, and achievable outcomes must be found, the robust general patterns are considered sufficient. If we succeed in stimulating a sufficiently broad dialogue about these issues, the process of refining the quantitative basis for coherent policy and management actions will be part of that dialogue

The independent expected trends

Trends in human demographics and food security requirements

Human population is projected to grow to more than 9 billion people by 2050, an increase of more than 30%, with essentially all that growth occurring in the less developed states (UN-DESA, 2009). This growth is expected to be accompanied by a continuation of migration and relocation patterns, such

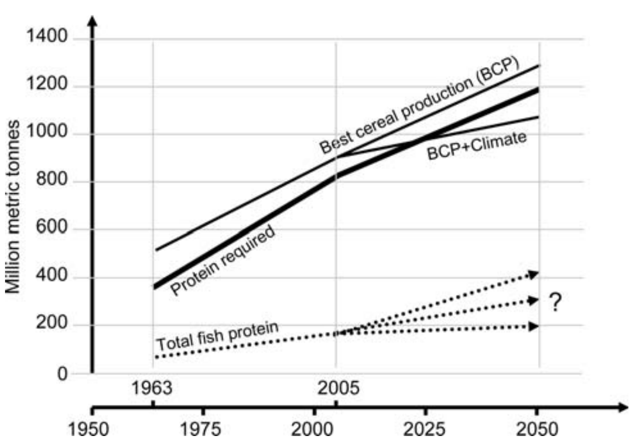

Figure 1. Plot of changes in food requirements and food supply components from 1963 to 2005 on to estimates for 2050. Data from Easterling *et al.* (2007), OECD-FAO (2009), and FAO (2008a).

that by 2050, 70% of the human population will live in urban centres; most will live in mega-cities of more than 20 million inhabitants (UN-DESA, 2009). In addition, currently half the world population lives within 60 km of the ocean, a proportion projected to increase to more than 60% by 2020 (Kennish, 2002; UNEP, 2007). Beyond 2050, trends in all of these projections continue to increase, but become driven by highly uncertain assumptions.

What does this increase represent for food security? The World Health Organization (WHO) has published minimum nutritional requirements for calories and protein (UN-WHO, 2002). The WHO tables disaggregate nutritional requirements by age, weight, and gender, but for a given weight, age and gender have little influence on the level of protein intake per day. If an average weight of 60 kg is assumed, the estimated increase in human population from 2010 to 2050 represents an increase in demand of more than 365 million tonnes of dietary protein. For a population of adults, 60 kg might be a reasonable figure, but the age composition of a human population is always skewed towards younger (and, therefore, smaller) individuals; hence, the average weight of a human in 2050 might be $<$60 kg. However, the need for protein and for many fatty acids, micronutrients, vitamins, and minerals is substantially higher per kilogramme during growth, and the computations quickly become complicated and assumption-dependent. Therefore, 350 million tonnes of dietary protein is probably a reasonable figure to plan for regarding the increase in demand because of human population growth by 2050. Based on the UN-WHO (2002) minimum standards cited above, failure to meet this target and/or an uneven distribution of the food available could result in widespread malnutrition and possibly starvation in some places.

Expected trends in terrestrial food production

In the work leading up to the 2007 IPCC report, likely declines in food production resulting from changes in temperature and rainfall were identified (Cline, 2007; Easterling *et al.*, 2007). The Food and Agriculture Organization (FAO), in partnership with groups like Agro-Biodiversity, subsequently explored in greater depth how well future food requirements could be met (FAO, 2005, 2008a, b, 2009; OECD-FAO, 2009). Bruinsma (2008) presents extrapolations of trends in agricultural practices over the past couple of decades, considering increases in land under cultivation, expansion of irrigation, continuation of the "Green Revolution" in crop productivity, and increased intensification of production (shorter fallow periods, denser mixed plantings, etc.). Projections do not indicate that all the rates of increase experienced from the 1980s to the present will be maintained to 2050. Nonetheless, tonnes per hectare of wheat, rice, and maize (the top three grains grown for human consumption and livestock feed) are all assumed to increase by another 30% between 2007 and 2050 (Bruinsma, 2008; FAO, 2009). As with projections of nutrition requirements, it is easy to make these computations more complicated, particularly given the large differences among countries in current yield rates and crop mixes and the many economic factors that influence decisions about crop production. However, IIASA projected overall crop production increasing from 2143 million tonnes in 2000 to 3402 million tonnes in 2050 (OECD, 2008; OECD-FAO, 2009). This is a slightly faster rate of increase than the increase in human population. All should be well; however, the Millennium Ecosystem Assessment (MA, 2005) concludes that the current rate of development has been unsustainable. Therefore, maintaining increases in crop production portends further degradation of water, forests, soils, and fisheries resources.

Bruinsma (2008) summarized projections assuming current climatic conditions. The picture changes dramatically when the effects of climate change are taken into account (Fischer, 2008). For production supported by rainfall, using output from the Hadley model under the A2 carbon emissions scenario for temperature and rainfall and assuming "best adapted" strains and the growth benefits of a higher CO_2 atmosphere (aside from central Asia), projected wheat production overall and per hectare declines substantially. The effect varies greatly by region, but, large declines in wheat production occur in Central America (−57%), South America (−26%), Africa (−47 to −99% depending on area), and South and Southeast Asia (−43 and −58%). Europe and North American might compensate for changing rainfall patterns through irrigation, but sufficient water is not expected to be available for that option to be adopted in the other wheat (and maize) growing areas (Comprehensive Assessment of Water Management in Agriculture, 2007). Changes in projected rainfall and temperature actually support increases in maize production of between 20 and 30% in Europe, North Africa, and Central and West Asia, and as large as 60% in the Russian Federation (Fischer, 2008; Table 4.2). However, maize has the lowest protein content per unit of weight of any of the "big three" crops. Projected changes in rice production are not available in Fischer (2008). However, both the 2008 Expert Consultation of FAO and Agro-Biodiversity (FAO, 2008a, b) and OECD-FAO (2009) consider the main climate-change threat to rice production to be the increase in the frequency and intensity of severe storms in the rice belt in South and East Asia. No quantitative estimates were made of the expected net trade-off of increases resulting from improvements in crop strains with losses incurred because of weather changes associated with climate change. However, a loss of one rice crop in four to flooding associated with severe storms would be a reasonable planning scenario (FAO, 2008b).

There are many alternative scenarios for climate-change effects on rainfall, effects of higher CO_2 levels on plant growth, and many other assumptions regarding the ability and willingness of farmers to change crops and develop genetic strains to adapt to changing conditions and land use managers to allocate water to irrigation rather than other uses. Changing scenarios and assumptions change quantitative forecasts of grain production, but some robust conclusions can be found in Fischer (2008):

> The results suggest three conclusions: (i) there are a number of regions where climate change poses a significant threat for food production [by 2050]; (ii) the global balance of food production potential for rain-fed cereal production of current cultivated land might slightly improve in the short term [between 2010 and 2020]; effective agronomic adaptation by farmers to a changing climate and the actual strength of the so-called CO_2 fertilization effect on crop yields will be decisive . . . and (iii) beyond 2050, negative impacts of warming dominate and cause a rapid decrease of the crop production potential in most regions and for the global aggregate.

Although crop production might be maintained to 2050 by adapting strains and realizing benefits from higher CO_2, much more than current production levels will be required to meet the increased demands from human population growth. Experts considering challenges of climate change and food security (e.g. http://agrobiodiversityplatform.org/) are giving particular attention to potential increases in climate variability, e.g. more numerous or intense severe storms, or more prolonged periods of seasonal droughts, or periods of extreme high or low temperatures, which could all result in declines in crop production. Conversion of crops to livestock feed or biofuels also would erode the ability to maintain crop production sufficient to satisfy the increase in human consumption (OECD-FAO, 2009). Moreover, if there are not substantial improvements in global food distribution and equity of wealth, even if food production were to be maintained or even kept pace with population growth, the protein deficit becomes greater (MA, 2005). In summary, in discussions among terrestrial food production experts, it has been assumed that oceans, lakes, and rivers could feed an additional 2–4 billion people (mostly in Africa and southern Asia) by 2050 (FAO, 2008a).

Can the caloric and dietary protein needs of future populations be met? Calorie needs are considered predominantly met with grains, fish, and seafood, which are important sources of protein, as well as rich in important micronutrients, minerals, and essential fatty acids. Globally, fish and invertebrates comprise ~5% of dietary protein (FAO, 2009). However, for countries with an essentially cereal-based diet (i.e. low *per capita* consumption of protein from livestock), fish provide important nutritional supplements to diets (Worldfish, 2010). Fish currently are estimated to provide more than 2 billion people with at least 20% of their average *per capita* intake of animal proteins (FAO, 2009) and in many poorer island and coastal states fish provides around half the total animal protein intake (FAO, 2007; Laurenti, 2007; Bell *et al.*, 2009). Taking the world population projections of 2 billion more people primarily in Africa, Asia, and Oceania and using the lower figure of 20% for dietary protein, the requirement is for an additional production of 75 million tonnes of fish from fisheries and aquaculture.

Global fish production has increased ~80 times in volume since 1950, to reach some 144 million tonnes in 2006 (FAO, 2007, 2009). Capture fisheries production was considered unsustainable when catches reached 100 million tonnes in the early 1990s and it appears to have stabilized at ~90 million tonnes over the past decade (FAO, 2008a, 2009). Aquaculture production has increased significantly and now contributes well over one-third of the total fish production. From the 144 million tonnes produced in 2006, ~110 million tonnes was used for food directly and 33 million tonnes indirectly through fishmeal used for aquaculture, cattle, pig, and poultry farming, etc. To meet the increased needs of human population growth, the additional 75 million tonnes represents ~50% increase in protein supply from fish and aquatic invertebrates. We project that if aquatic sources have to compensate for the projected declines in wheat or rice production, which are greatest in areas where livestock is of limited availability now and might decline further under many climate-change scenarios, the necessary increase will be greater than 50% of current production.

Trends in marine biodiversity

Many of the papers in this issue consider specific cases of how recent changes in climate are affecting marine biodiversity. Some of the documented changes in marine populations and communities are very large, such as the reductions in abundance of large predatory fish in most oceans (Myers and Worm, 2005; Heithaus *et al.*, 2008), the comparably large declines of sharks and rays (Baum *et al.*, 2003, 2005), and the widespread mortality of reef structures and loss of associated fish communities (Hughes *et al.*, 2003; Sheppard, 2003; Keller *et al.*, 2009; Roberts *et al.*, 2009). Effects of human impacts can be found in essentially all marine ecosystems, with most areas under pressure from multiple uses (Helpern *et al.*, 2008). Below the global scale, evidence of changes in marine biodiversity are found throughout the world's seas and oceans (Poloczanska *et al.*, 2007; Yatsu *et al.*, 2008; A'mar *et al.*, 2009; Gambaiani *et al.*, 2009; Mueter *et al.*, 2009) and for many components of biodiversity (Lotze and Worm, 2002; Mieszkowska *et al.*, 2005; Learmonth *et al.*, 2006; Ellingsen *et al.*, 2008; Möllmann *et al.*, 2008; Whitehead *et al.*, 2008).

There is substantial debate about the true global extent and magnitude of these changes in biodiversity (Garcia and Grainger, 2005; Hilborn, 2007; Murawski *et al.*, 2007), but there is little disagreement that the biota of the ocean is changing (Garcia and Grainger, 2005: Valdés *et al.*, 2009; Worm *et al.*, 2009). Likewise, there is debate about how to allocate responsibility for these changes among pressures from fishing, coastal eutrophication and nutrient enrichment, habitat damage, climate variation, and change and other factors (Benoît and Swain, 2008; Holt and Punt, 2009; Kotta *et al.*, 2009; Noakes and Beamish, 2009; Rijnsdorp *et al.*, 2009). Resolving these debates is outside the scope of this paper. It is sufficient that an increasing number of thorough studies and reviews of patterns of species distributions and abundance are finding evidence of changes in biodiversity. The changes include both new occurrences and increases in abundance of some species (Stachowicz *et al.*, 2002; Boersma *et al.*, 2007; van Damme and Couperus, 2008; Arvedlund, 2009) and abundance reductions or disappearances of some populations from their traditional ranges (Perry *et al.*, 2005; Dulvy *et al.*, 2008; Sundby and Nakken, 2008; Tasker, 2008; Stram and Evans, 2009). In addition, evidence clearly implicates changing ocean conditions in these biodiversity dynamics (King, 2005; de Young *et al.*, 2008a; ICES, 2008; Knowlton and Jackson, 2008; Garcia and Rosenberg, 2009).

An increasing number of models is being developed and applied to project future patterns of biodiversity under accepted scenarios for future climate conditions and the corresponding projected states of ocean salinity, temperature, and currents. These models predict that climate-related biodiversity changes will increase in range and amount. The projected marine communities will not necessarily be depauperate in species or biomass, but they will be different from present communities and be undergoing rapid change (Beaugrand *et al.*, 2008; Cheung *et al.*, 2008; Hollowed *et al.*, 2009; Planque *et al.*, 2010).

Trends in policy on conservation of marine biodiversity

The marine policy and conservation biology communities are paying close attention to the potential impacts of climate change on marine biodiversity. Notwithstanding all the uncertainties about future trends in marine biodiversity and the relative roles of fishing, climate, and other pressures on those trends, there are clear calls for action. Nearly a decade ago, the World Summit on Sustainable Development (WSSD) called for rebuilding all exploited fish stocks to maximum sustainable yield (MSY) by 2015 and for the creation of networks of marine protected areas (MPAs), including representative areas by 2012 (UNEP, 2002). These were justified in part as key steps for "addressing critical uncertainties for the management of the marine environment and climate change" (WSSD paragraph 30b; UNEP, 2002). More generally, the WSSD acknowledged the growing concern about climate change as a pressure on ocean ecosystem, both through references to the oceans in several subparagraphs of general paragraph 38 and through specifically referencing oceans in paragraph 37(e) calling on States to "Improve techniques and methodologies for assessing the effects of climate change, and encourage the continuing assessment of those adverse effects by the Intergovernmental Panel on Climate Change". After the WSSD, climate change and marine biodiversity received increasingly prominent attention in the Ocean and Coastal Resolutions of the Convention on Biological Diversity (CBD, 2006, 2008), and in the UN *ad hoc* Open-ended Working Group on Biodiversity Beyond National Jurisdiction (http://www.un.org/Depts/los/biodiversityworkinggroup/marine_biodiversity.htm), and by intergovernmental agencies such as FAO (FAO, 2009), UNEP (2007) (http: //www.unep.org/climatechange/UNEPsWork/Science/Impacts ofClimateChange/tabi/2057/language/en-US/Default.aspx), and IOC/UNESCO (http://ioc.unesco.org/iocweb/climateChange.php).

The most recent policy statements that reflect views of states and agencies on climate change, marine biodiversity conservation, and sustainable use are captured in the CBD—Subsidiary Body on Scientific, Technical and Technological Advice resolutions relating to the programmes of work on Marine and Coastal Biodiversity, Protected Areas and on Biodiversity and Climate Change (Table 1).

> Biodiversity is affected by climate change, with negative consequences for human well-being, but biodiversity, through the ecosystem services it supports, also makes an important contribution to both climate-change mitigation and adaptation. Consequently, conserving and sustainably managing biodiversity is critical to addressing climate change (CBD, 2010a, b).

This resolution illustrates the types of concern that were recognized and the types of action considered appropriate to addressing them.

Scientific research is incomplete and at times conflicting publications can be found. Moreover, the abilities of marine populations and communities to adapt to changing conditions, including climate change, are poorly known. With due account of these sources of uncertainty, the general concerns include:

(i) changes in species ranges might destabilize species relationships that help maintain ecosystem processes;

(ii) productivity might be reduced and/or mismatched to phenology of grazers and secondary consumers;

(iii) alien invasive species might become a greater threat and uses of non-native species and strains in aquaculture could aggravate this threat;

(iv) ecosystem resilience to the pressures associated with climate change might be reduced by stresses placed on marine communities by fishing and degradation of coastal environmental quality; and

(v) marine and coastal habitats will be under joint stress from climate-related pressures of sea-level rise, temperature change, and acidification, and from direct anthropogenic

Table 1. Provisions of 2010 CBD (SBSTTA) resolutions and 2020 targets most relevant to conservation of marine biodiversity, food security, and climate change. (Where text has been deleted from a quotation, the deletions are usually guidance on which agencies should be taking the indicated actions.)

Sustainable use of biodiversity (UNEP/SBSTTA/14L.4)
2(g) Where appropriate review, revise, and update national biodiversity strategies to further coordinate at the national level and engage different sectors, (including . . . fisheries . . .) to fully account for the value of biodiversity and ecosystem services in decision-making
2(j) Encourage, among others, the effective market-based instruments that have the potential to support the sustainable use of biodiversity and improve the sustainability of supply chains . . .
Protected areas (UNEP/SBSTTA/14L.5)
1(d) Promote the application of the ecosystem approach that integrates protected areas into the broader land or seascapes for effective conservation of biological diversity and to ensure sustainable use of protected areas.
7(d) Increase awareness of the benefits resulting from the implementation of the programme of work on protected areas to . . . fisheries. Industries, climate change mitigation. . . .
19: Encourages . . . on a regional or subregional basis, to identify and protect ecologically or biologically significant areas in open-ocean waters and deep-sea habitats in need of protection, including by establishing representative e-networks of marine protected areas
20 . . . Urges Parties . . . to increase their efforts, in accordance with national capacities, to improve the design and extent of marine protected area networks to achieve the 2012 target . . .
Marine and coastal biodiversity (UNEP/SBSTTA/14L.8)
12(a) Further efforts on improving the coverage, representativity, and other network properties, as identified in the Annex to decision IX/20 (including areas of high productivity and diversity) of the global system of marine protected areas . . . achieving the commonly agreed 2012 target of establishing marine protected areas . . .
12(b) Making progress on marine and coastal biodiversity conservation and sustainable use in areas beyond national jurisdiction. . . .
12(f) Further efforts on minimizing the impacts of destructive fishing practices, unsustainable fishing, and illegal, unregulated and unreported (IUU) fishing on marine and coastal biodiversity . . . on the need to manage catches and reduce discards, to attain a sustainable exploitation level of marine fisheries resources and contribute to good environmental status in marine waters.
12(g) Further efforts on minimizing the specific, as well as cumulative impacts of human activities on marine and coastal biodiversity . . . and further emphasis on the contribution of environmental impact assessments and strategic environmental assessments to further strengthening sustainable use of living and non-living resources . . .
44: in view of identified information gaps (in knowledge of destructive fishing practices, unsustainable fishing, and IUU fishing] . . . review the extent to which biodiversity concerns are addressed in existing assessments and propose options to address biodiversity concerns and report on progress . . .
Encourages Parties and other Governments to fully and effectively implement paragraphs 112 through 130 of the UNGA resolution 64/72 on responsible fisheries related to preventing the destructive impacts of deep-sea fisheries on marine biodiversity and vulnerable marine ecosystems . . .
Biodiversity and climate change (UNEP/SBSTTA/14L.9)
8(c) Reduce the negative impacts of climate change as far as ecologically feasible, through conservation management strategies that maintain and restore biodiversity
8(d)(i) Reducing non-climate stresses, such as pollution, overexploitation, habitat loss and fragmentation, and alien invasive species.
8(d)(iv) Integrating biodiversity into wider sea- and land-scale management
8(j) . . . implement where appropriate ecosystem-based approaches for adaptation, that may include sustainable management, conservation, and restoration of ecosystems . . .
8(n) Implement ecosystem management activities, including . . . conservation of mangroves, saltmarshes, and seagrass beds
8(t) Enhance the conservation, sustainable use, and restoration of marine and coastal habitats, which are vulnerable to the effects of climate change or which contribute to climate change mitigation, including mangroves, tidal saltmarshes, kelp forests, and seagrass beds . . .
Alien invasive species (UNEP/SBSTTA/14L.16)
2(b) Identified a number of possible ways forward to address certain gaps through the work of other international instruments, in particular. . . . The Committee of Fisheries Investigations (COFI) of FAO . . .
2(c) Called for further work under the Convention on the specific area of invasive alien species introduced as . . . live bait and live food . . .
23: . . . CITES Parties are urged, before the establishment of captive-breeding operations for exotic species, to undertake an assessment of the ecological risks, to safeguard against negative effects on local ecosystems and native species.
29(a): (the workshop) highlighted the essential role of risk assessments to assist in making decisions regarding imports of live alien animal species. . . . such processes should be (i) science based, (ii) appropriate to the specific context, and (iii) include biodiversity and environmental risks associated with the alien species . . .
29(b): (the workshop) noted existing gaps in the international regulatory framework, highlighting that other international agreements, including the WTO SPS Agreement, do not explicitly address the invasiveness of animals as a distinct category. . . .
Outcome-oriented goals and targets . . . for 2020:
Target 6: by 2020 the exploitation rates of fisheries on target species and all bycatch species are all sustainable and the impacts of fisheries on ecosystem and their components are within safe ecological limits.
Target 7: by 2020 all areas under agriculture, aquaculture, and forestry meet standards for sustainability and protection of biodiversity
Target 11: by 2020 at least *x*% of land, freshwater, and sea areas, including areas of particular importance for biodiversity have been protected through representative networks of effectively management marine protected areas and other means, integrated into the wider land- and seascape. (At the COP X in October 2010 the variable percentage “x” in this target was negotiated to be 17% of terrestrial and inland waters areas, and 10% of marine and coastal areas.)
Target 14: by 2020 ecosystems that provide essential services, and contribute to local livelihoods, are identified and safeguarded or are being restored and adequate and equitable access to essential ecosystem services is guaranteed for all . . .

impacts of destructive fishing practices, nutrient enrichment, etc.

In response to these concerns, the marine biodiversity resolutions echo the existing calls for reduction on emissions of greenhouse gases (UNEP, 2007; CBD, 2010c). They also call actions to reduce anthropogenic stresses through actions, such as

(i) ensuring fishing mortality at or below sustainable levels for all targeted stocks and bycatch (CBD Draft 2020 Goal 6);
(ii) establishing networks of no-take marine reserves with appropriate connectivity and including biodiversity hotspots and area of high productivity, with at least 10% of ocean area in appropriately managed MPAs (CBD, 2010b and Draft 2020 Goal 8);
(iii) the exclusive use of native species and strains in aquaculture (CBD, 2010a); and
(iv) designation of special habitats, including coral reefs, mangroves, and estuaries as particularly sensitive ecosystems, with special conservation measures in place (UNEP–WCMC, http://www.unep-wcmc.org/climate/impacts.aspx).

Therefore, the trends in policy frameworks on marine biodiversity conservation are clear. Marine biodiversity is influenced by many anthropogenic pressures. Climate change is only one of those pressures, but it is a pervasive and persistent threat. The resilience of marine ecosystems to pressures from climate change might be being reduced by the aggregate effects of the other pressures. Climate-change impacts can only be reversed on very long timescales (if at all). Therefore, there is even greater need to reduce the impacts of other anthropogenic pressures, to protect the resilience of marine ecosystems and the goods and services derived from marine biodiversity (CBD, 2009).

Finding coherence in food security: marine biodiversity conservation and climate change

Are we headed to a coherent future?

The oceans, coasts, lakes, and rivers must play an important role in addressing global food security needs in the changing planet. To achieve anything like a 50% increase in protein from the sea, a number of options must be considered. There is little reason for optimism that substantially expanding capture fisheries on high trophic levels can be sustained any more successfully in future than in past decades (FAO, 2007, 2009). A number of ecosystem models suggest that if currently depleted populations were allowed to recover to historically observed levels, greater sustainable yields could be taken (Pitcher and Cochrane, 2002; Okey and Wright, 2004). The actual amount of increased yield is highly assumption-dependent regarding stock and ecosystem productivity under changing environmental conditions, the duration of the period of restricted catches while the stocks recover, and the ways the density-dependent feedbacks are expressed in the systems. Some model results also indicate that there are much greater yields available if fishers concentrate the harvest at lower trophic levels (Pope *et al.*, 2006; Genner *et al.*, 2010). Again, estimates of the actual amount of increased yield depend on assumptions of how harvesting is distributed among trophic levels and how density-dependent predator–prey interactions are affected by altering total abundances at each level.

Each strategy comes with costs. Rebuilding stocks to former abundances would have a long transition time at greatly reduced harvest rates. Recent reviews of efforts to recover currently depleted populations in cases where recovery goals have been adopted in fisheries management do not give reason to expect rapid and secure recovery (Hammer *et al.*, 2010). Moreover, many areas most in need of such recovery approaches would be areas poorly positioned to bear the transition costs of long periods of reduced harvest to promote fast rebuilding (FAO, 2007, 2009). A strategy of consciously intensifying the exploitation of lower trophic levels: "fishing *through* the food chain" (Essington *et al.*, 2006) might be of help. If substantial amounts of protein were removed from lower trophic levels, the foraging success of a wide range of dependent predators would be affected (Furness, 2003; Daunt *et al.*, 2008). Increasing evidence of trophic cascades as harvesters reduce different parts of the size composition of a community also suggest such harvesting strategies could alter marine ecosystems substantially, even if sufficient biomass were left for dependent predators (Benoît and Rochet, 2004; Andersen and Pedersen, 2010).

If opportunities for greatly expanded harvests from capture fisheries are limited, artificial production through marine and freshwater fish culture is a possible candidate for the source of the necessary increase in fish for food security. Aquaculture production has increased at a rate of more than 7% annually throughout the past decade and there is no indication that maximum potential is being approached globally or regionally (FAO, 2008a, b). Estimates are available for capacity of production per hectare for freshwater and coastal sources if practices to maximize production are adopted. These estimates depend greatly on many factors with the species and strains in culture and their feeding habits (herbivore, omnivore, piscivore) and environmental conditions (annual temperature regime, flushing rate, and oxygen conditions), with the feeding regime often the dominant factor.

With current strains and intensive technologies, reported production levels vary by well more than an order of magnitude (Naylor *et al.*, 2000; Pillay, 2005; OECD-FAO, 2009). Reported production can be as high as of 100 kg m^{-3} (1000 t ha^{-1} $year^{-1}$) of tilapia, and 10–15 t ha^{-1} $year^{-1}$ of shrimp in freshwater ponds (Anon, 2009a, b) is being achieved in culture and 7.5 kg m^{-3} for mariculture of in coastal pens (Anon, 2009b). Estimates vary greatly with details of practices, strains, and geography. Improved technologies and better selected strains could increase the production per hectare somewhat more, particularly in mariculture for species on lower trophic levels; expanding culture to less optimal conditions might mean these levels of production are not achieved everywhere. Guidelines are being developed for "organic aquaculture", which would lower the environmental impact, but currently realizes production of 450 kg ha^{-1} of salmon. The scale of total aquaculture production will depend primarily on decisions about what species and strains are used in culture and on how much area of what natural productivity is placed in intensive culture (Leschin-Hoar, 2010). If the objective is to meet global food security requirements, herbivorous or low-trophic level species should be preferred (to minimize use of other sources of protein in making fish protein), strains should be selected for high productivity disease resistance, and areas of high productivity and good water quality used (to achieve the largest return for the area devoted to culture facilities). Consistent with this argument, the Outlook section of the 2008 SOFIA Report (FAO, 2009) highlights that in sub-Saharan Africa and parts of Asia where aquaculture, particularly freshwater culture, is being developed for food security rather than high-value trade, most production is based on a small number of species of cyprinids (tilapias) and catfish. Particularly for tilapia, selective breeding for captive production has been intense for more than a decade (World Fish Center, 2004; Brummett and Ponzoni, 2009).

An alternative technology might also contribute to the production of aquatic protein, i.e. artificial enhancement of natural production. Isolated successes have been recorded in enhancing natural production of salmon, through spring fertilization of natal lakes that were nitrogen- or phosphorous-limited (Budy *et al*., 1998; Hyatt *et al*., 2004). Although successes were not universal, fertilization regimes matched with the characteristics of specific lakes were considered to have increased production of salmon smolts nearly 50% (McQueen *et al*., 2007). There is speculation that large-scale enhancement of some parts of the ocean through fertilization of limiting elements, particularly iron, might yield benefits of higher overall ocean productivity, but such proposals have high uncertainty and raise many scientific questions (Buesseler *et al*., 2008). There have been attempts to restock or enhance depleted populations of wild species by augmenting the populations with large numbers of recruits raised in culture facilities. Results have been mixed for salmonids, on which most such experiments have been done (Fraser, 2008), and abalone (DFO, 2003), and sea ranching of Atlantic salmon by Iceland (ICES, 2001). Stock enhancement of some bivalves has produced more consistent benefits (Uki, 2006), but such positive outcomes are to be expected for only a limited number of species (Bell *et al*., 2005, 2008). At best, based on current evidence, enhancement might be a strategy that contributes to accelerating the recovery of lost production from depleted populations (if the causes of depletion have been addressed; Fraser, 2008). Its potential for increasing production above natural current levels is unproven for all but circumstances where there are known nutrient limitations on production.

If the main factors in governing global food production from aquaculture are the selection of species and strains and areas selected for use, there might be significant opportunity to continue the growth in production from culture. However, maximizing production of protein would entail often using non-native (and sometimes hybrid or engineered) species and strains, placing this activity in direct opposition to biodiversity concerns about alien invasive species (CBD, 2010d). It would require widespread locating of freshwater facilities where communities can be engaged in local projects to serve both community and commercial needs, increasing the risk of escapement into wild systems during floods or accidents, with concomitant impacts on biodiversity. It would require locating mariculture facilities in coastal and possibly offshore areas of highest productivity. These are also the areas most sought for protected areas to conserve biodiversity and maintain ecosystem processes.

Is there a way forward?

The literature indicates that options are available to increase production of fish and aquatic invertebrates enough to contribute significantly towards meeting needs for global food security in a world with a changing climate and increasing human population. These options do not come without costs. Almost all the options, if pursued strongly, also go strongly counter to increasing global agreements on conservation of biodiversity (Table 2).

Table 2. Differing directional pulls on policies and activities to address the role of oceans and coasts in addressing global food security and to improve conservation of aquatic biodiversity.

Policy or activity	Food security	Biodiversity conservation
Fisheries harvest rate	Maximum sustainable, allowing for major uncertainties	Low (precautionary)
Fishing on lower trophic levels	At sustainable rates; ensure impacts on dependent predators are sustainable	Minimize to avoid impacts on dependent predators
Fishing in high productivity areas	Fully use at sustainable rates; highest catches at lowest cost and effort	Key areas for inclusion in highly protected MPA networks (EBSA Criterion)
Aquaculture generally	Increase scale and use optimal strains for domesticated growth and integrated facilities	Avoid non-native species and strains, site only where habitat and ecosystem impacts are minimal
Mariculture	Expand in productive coastal areas; use optimal species and strains	Protect productive coastal habitats as priority; use only local strains

The cases for food security and conservation of biodiversity are each strong. Can a way be found that does not put them in conflict? Certainly, there are technological adjustments to fishing and aquaculture practices that reduce their ecological footprints and correspondingly reduce their adverse ecosystem impacts. Wise spatial planning, including zoning, could reduce conflicts. However, the scale of the challenge in feeding the growing human population as climate change threatens to reduce rather than increase many terrestrial food production sources leaves us pessimistic that simple technological adjustments will resolve all the potential conflicts with biodiversity conservation. Hard choices have to be made, which involve risks of declines in biodiversity to be balanced against risks of famines for poor human populations. Science has a role in providing projections of the implications of choices, so that managers can make informed decisions. Science also has a role in identifying areas where policy gaps exist or where policies being pursued by separate agencies might conflict and, using sound science, provide advice on options to fill the gaps or make the outcomes of policies more coherent. These roles require that the science be sound and transparent and that any dialogue on these issues should occur widely and be taken seriously.

In facing these choices, it might help to have a more dynamic idea of conservation related to ecosystem functions and services than on individual species, a change that is coming for several reasons (Worm *et al*., 2006; Higgason and Brown; 2009; Stram and Evans, 2009). It might help to have a more Darwinian view of species and ecosystems as inherently adaptive (again a change that is coming; Pullin *et al*., 2009), as well as management being adaptive. However, such a more fluid concept of what healthy ecosystems and species comprise would challenge current thinking about using historical states of ecosystems and populations as the appropriate reference benchmarks for management (Knowlton and Jackson, 2008), a way of thinking that is becoming more entrenched, rather than more flexible.

The required dialogue will have to bring together policy-makers and science advisors working on human wellbeing, on ecosystem approaches to conservation and sustainable use of aquatic resources, and on climate change. With policy dialogue on these first two issues largely occurring in separate settings (Ridgeway and Rice, 2009), changes even in institutional roles will be needed. The conservation community should expect to be challenged to face the limitations of both "fortress" conservation (top-down decisions, exclusion of humans from networks of selected highly protected areas, violent enforcement) and "small is beautiful" (an effort to return to a pre-industrialization era of small-scale operations, with the view to reduce ecological footprint and improve livelihoods, usually at local scales). Both downscale the possible solutions and move away from global challenges, such as food security, charging implicitly most of the costs to humans, usually with no real analysis of the sometimes very serious socio-economic implications (de Young *et al.*, 2008b). The usage and human-requirements community can expect to be challenged to face the contribution that inequities in purchasing power and consumer preferences among richer and poorer states and communities make to the difficulty of solving basic problems, often without explicit consideration of the short- and long-term costs to the environment. The global trade-related forces redistribute ecosystem costs to those less able to bear them and food security benefits to those already advantaged. This is particularly the case with fisheries production, which is already much more globalized then agriculture and other sectors.

It seems inevitable to us that options that increase food production from aquatic sources involve major changes in freshwater, coastal, and/or offshore ecosystems. There is an urgent need to have a forum where fisheries, food security, and biodiversity conservation change are discussed together. Scientists and policy-makers must confront basic questions:

(i) How do we meet food security needs in a world with a changing climate?

(ii) What role do aquatic ecosystems have in meeting those food security needs?

(iii) What objectives for conservation of aquatic biodiversity are appropriate in a world with a changing climate?

(iv) What does "conservation" means if the past becomes "irrelevant" and the baselines move from behind us to in front of us?

In the end, of course, both sustainable use and sustainable development require healthy ecosystems and viable communities and societies. Scientists will play an important role providing synthetic projections of the implications of proposed options. This should help policy-makers find coherent answers and adopt policies and practices that serve both humanity and sustain ecosystems. The absence of serious consideration of the issues as interrelated outcomes means science will fail to provide the sound and comprehensive advice required to inform policies and practices that are designed to satisfy the demands for food security and conservation of biodiversity.

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