Chapter 3

Predicting the Impacts and Socio-Economic Consequences of Climate Change on Global Marine Ecosystems and Fisheries

The QUEST_Fish Framework

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Abstract

Climate change is accelerating and is already affecting the marine environment. Estimating the effects of climate change on the production of fish resources, and their dependent societies, is complex because of:

1. difficulties of downscaling Global Climate Models (GCM) to scales of biological relevance;
2. uncertainties over future net primary production and its transfer through the food chain;
3. difficulties in separating the multiple stressors affecting fish production; and
4. inadequate methodology to estimate human vulnerabilities to these changes.

QUEST_Fish, a research project led from the UK, is addressing some of these challenges through an innovative, multi-disciplinary approach focused on estimating the added impacts that climate change is likely to cause, and the subsequent additional risks and vulnerabilities of these effects for human societies. The project uses coupled shelf seas biophysical ecosystem models forced by GCM forecasts to predict ecosystem functioning in past,

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present, and future time-slices. For each slice, and for 20 Large Marine Ecosystems, we estimate plankton production and use this to estimate size-based fish production through models based on macro-ecological theory. Ways of assessing vulnerability of fisheries to future climate change are developed, including the market consequences for fish-based global commodities. The results provide a new framework and new insights into the complex interactions between humans and nature.

Keywords: Climate change, marine ecosystems, bio-physical modeling, fish production, macro-ecological theory, vulnerability assessment, economic impacts, marine commodities

Introduction

The fourth IPCC (Intergovernmental Panel on Climate Change) assessment report concluded that over the period 1961–2003 almost 90% of all the heat in the climate system had been taken up by the ocean (Bindoff *et al.*, 2007). The same report noted that there were only 85 known examples on which to base conclusions about the impacts of climate change on marine and freshwater ecosystems: less than 0.3% of the number of examples available for terrestrial ecosystems (Richardson and Poloczanska, 2008). This reflects the inaccessibility of most marine systems, the relatively limited sustained monitoring of the marine environment, and thus the paucity of long-term observations on which to base assessments. As a result, we currently lack an adequate framework with which to assess the impacts of climate change on global marine ecosystem goods and services.

Capture fisheries are one of the largest services provided by marine ecosystems. Over 80t of fresh fish are caught annually (FAO, 2007) in regions subject to very different degrees of exploitation, management, and control (FAO, 2005). Direct consumption of fish and seafood products is on the rise. It currently accounts for ca. 16 kg person^{-1} year^{-1} globally. This rate has doubled in developing countries in the last 30 years and, combined with the doubling in the population size of developing countries over the same period, indicates an very large growth in the demand for fish (Delgado *et al.*, 2003). The value of fish production to the developing world goes beyond its direct impact as food. Net fish exports to developed countries surpass the monetary value of many other traditional developing-country agricultural exports (Delgado *et al.*, 2003; FAO, 2007). Consequently, the future of marine fisheries has significance in terms of global food security but even more significance in terms of the economy and livelihoods of the developing world.

At the same time, it is well known that capture fisheries are in a state of crisis. Total catches reached a plateau in the 1990s, and appear to have since declined (Pauly *et al.*, 2003). Continued growth in the production of both low-value (e.g., grass carps) and high-value (e.g., shrimp and salmon) aquaculture products has, until recently, compensated for the lack of growth in capture fisheries, but concerns have been raised about environmental risks associated with the ongoing intensification and spread of fish production, and about competition between traditional fishers – many of whom live in poverty – and large-scale operations. Additional pressures on capture fisheries come from increasing demand for fishmeal for aquaculture production (Deutsch *et al.*, 2007). On top of these, the ecological impacts of climate change, on what is in a severely stressed global production system, are largely unknown.

Nevertheless, there is enough information to suggest that climate changes will have profound consequences for marine ecosystems and fisheries (Barange and Perry, 2009; Edwards *et al*., 2002; Hall-Spencer *et al*., 2008; Harvell *et al*., 2002; Lehodey *et al*., 2006; Perry *et al*., 2005; Stenseth *et al*., 2005). It is expected that in general terms ocean warming may result in increasing vertical stratification, reduced vertical mixing, and reduced nutrient supply, thereby decreasing overall productivity. Increasing stratification may also alter the balance between pelagic and benthic recycling of material, favoring pelagic pathways at the expense of the benthos (Frank *et al*., 1990). Fish production predictions, however, will not only depend upon changes in net primary production, but also on its transfer to higher trophic levels, about which there is low predictive confidence (Brander, 2007). Observations and models agree that severely contrasting geographical differences resulting from climate change impacts are likely to be observed (Fréon *et al*., 2009). For example, net primary production may increase in some high latitudinal regions because of warming and reduced ice cover, but decrease in low latitude regions because of reduced vertical mixing and replenishment of nutrients (Gregg *et al*., 2003; Sarmiento *et al*., 2004). Low productivity ocean regions are already expanding in size, a trend that is expected to continue in the future (Polovina *et al*., 2008). Changes in species composition (Bopp *et al*., 2005) and seasonality (Hashioka and Yamanaka, 2007; Edwards and Richardson, 2004; Mackas *et al*., 1998) of plankton may cause mismatches between early life stages of fish and their prey. The warming of the oceans is already affecting the distribution of particular species (Hawkins *et al*., 2003; Mackas *et al*., 2007; Sissener and Bjørndal, 2005; Ware and McFarlane, 1995), particularly moving species towards the poles and to greater depths (Dulvy *et al*., 2008; Perry *et al*., 2005). In addition, fishing is believed to affect the sensitivity of fish populations to climate change (Anderson *et al*., 2009; Perry *et al*., 2010).

The above processes involve many unknowns, and depend on the transfer of processes through complex food chains, so predicting climate change impacts and directions for specific species can only be done with low confidence (Brander, 2007). However, predicting net impacts on fish communities (i.e., total biomass or productivity) may be possible because of compensatory dynamics among the members within the various functional groups that make up that community (Jennings and Brander, 2009; Mackas *et al*., 2001). Jennings *et al*. (2008), for example, observed that marine ecosystems have remarkably constant and simple relationships between body size, energy acquisition and transfer, suggesting that basic macro-ecological rules can be brought to bear to assess the role of a changing climate, through food web processes, on global fish production (Brown *et al*., 2004).

Unveiling the impacts of climate change on marine ecosystems tells only part of the story. As marine ecosystems respond to the physical changes brought about by climate change, these responses will in turn affect the human communities that use and depend upon the benefits provided by marine ecosystems. Climate change impacts cannot thus be estimated without incorporating an understanding of the vulnerability to ecosystem change of the marine fisheries and the communities, industries, and nations that rely on them. According to the IPCC, vulnerability to climate change depends upon three key elements: the frequency and magnitude of exposure to external shocks (e.g., climate changes), the degree of sensitivity to those impacts (i.e., how they are experienced), and the adaptive

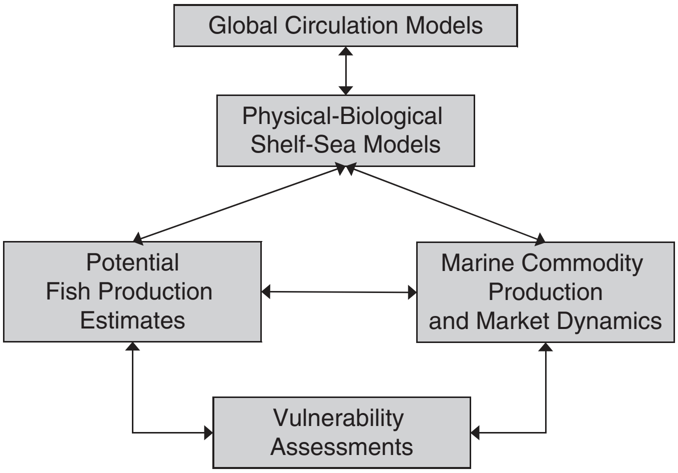

Fig. 3.1 Conceptual diagram of the QUEST_Fish approach to estimate the impacts and consequences of climate change on marine ecosystems and global fish production.

capacity of the group or society experiencing those impacts (i.e., how capable they are of self-recovery). Vulnerability of a system thus involves an external dimension (exposure) and an internal dimension (sensitivity and adaptive capacity) (Füssel and Klein, 2005; Perry *et al*., 2009; Smit and Wandel, 2006).

The continued growth of human populations and fish consumption will place additional demands on heavily exploited ecosystems (Delgado *et al*., 2003). Predicting the impacts of climate change on global marine fisheries would further require an understanding of the social and economic dynamics of fleets, fishing communities, national and global markets, and their capacity to adapt to change. This calls for a two-pronged approach to develop detailed global-scale "physics-to-fish-to-fishers" models, on the one hand, while using indicators in combination with a risk-assessment or vulnerability framework at national level on the other (McClanahan *et al*., 2008; Turner *et al*., 2003; Villa and McLeod, 2002).

The QUEST_Fish approach attempts to frame the problem by developing a set of models and tools interfacing processes from the physics of climate to people, across a diversity of scales (temporal and geographical), disciplines, and modeling principles (Fig. 3.1). We start by using Global Circulation Model (GCMs, otherwise referred to as Global Climate Models) outputs to force a series of high-resolution physical-biological regional models throughout the world. Generic principles that describe the relationships between organisms and their environment at large spatial scales are then used to estimate fish production based on the output of such regional models. Finally, potential fish production changes are used to investigate the impacts of such changes on the production/consumption system of the largest marine-based global commodity: fishmeal and fish oil. In addition, an indicator-based analysis is applied to estimate the relative vulnerabilities of a number of countries to climate change-driven fish production changes. The results provide a framework, applicable to the study of other global resources, to investigate how environmental change will re-shape the interactions between human societies and nature in searching for global sustainability.

Framing the problem

Geographical and temporal framework

Assessing climate change impacts at the global scale requires division of the task along geographical scales that respect the integrity of the ecosystems for which physical, biological, ecological, economic, and social principles need to be extracted. The concept of Large Marine Ecosystems (LME) is particularly suited for this purpose. LMEs are regions of ocean space with unique biogeochemical properties, encompassing coastal areas from river basins and estuaries to the seaward boundaries of continental shelves and the outer margins of the major current systems (Longhurst, 1998). They are relatively large regions characterized by distinct bathymetry, hydrography, productivity, and trophic interactions. LMEs are also the appropriate size to address the problem of fit between institutional arrangements and biophysical systems, taking into account jurisdiction and governance scale, as well as ecological processes. Since the early 1990s, the Global Environmental Facility (GEF) and its implementing agencies (World Bank, UNDP, FAO, UNEP) have used the LME as a framework to study, protect, and restore marine ecosystems (Sherman, 2005). It is thus appropriate to conduct assessments along LMEs, recognizing their unique and homogeneous characteristics, and their link to global management.

Therefore, while the domain of QUEST_Fish is global, the work will be framed at the level of regional LMEs. Because of resources and computational investment, the implementation of QUEST_Fish will initially be limited to a total of 20 LMEs. These were selected on the basis of fish catch volumes as well as diversity of ecosystem types, so that extension of the conclusions to other areas could be done by proxy (Fig. 3.1, Table 3.1). The LMEs selected contribute over 60% of the world's fish catch, thus they are likely to reflect the major trends in global production. They also include over 40 nations, an important component for the assessment of vulnerabilities to climate impacts, as described later on.

QUEST_Fish thus computes ecosystem and fish production estimates, and socio-economic consequences of these impacts, for the 20 LMEs listed in Table 3.1. Four fixed

Table 3.1 Primary production, area and fish catch for the 20 LMEs considered in the QUEST_Fish project, contributing >60% of the world fish catches. Data from www.seaaroundus.org

LMEs	$mgC.m^{-2}.d^{-1}$	$10^3.km^2$	2003 Catch	% catch
East China Sea/Yellow Sea	1,058	1,212	8,193,703	13.28
Humbolt	737	2,544	7,882,524	12.77
Bay Bengal	568	3,660	4,005,393	6.49
South China Sea/Sulu Celebes/Indonesian Sea	619	3,269	3,400,611	5.51
North Sea/Central Biscay Shelf	908	1,449	3,270,453	5.30
East BS/West BS	609	3,349	2,660,944	4.31
NW Africa	1,280	1,121	1,963,028	3.18
Norwegian Shelf	498	1,116	1,767,790	2.86
Benguela	1,158	1,456	1,415,244	2.29
Iceland Shelf/East Greenland	509	634	1,320,155	2.14
California	501	2,208	692,277	1.12
NE US/Scotian shelf/Newfoundland Labrador	916	1,199	614,389	0.99

temporal scenarios are considered: pre-industrial (1850), present (2005), and future (2050 and 2100), allowing for the quantification of climate impacts relative to past and present situations. For each time slice a total of 10–15 years of data will be extracted, to make sure that we capture both the interannual climate variability as well as the longer-term anthropogenic climate change signals. For the future runs, up to two IPCC emission scenarios (and associated socio-economic storylines) will be considered (SRES, Nakicenovic and Swart, 2000). These scenarios were set up to encapsulate different developments that might influence the emission of greenhouse gases. While it is impossible to predict future emissions, SRES scenarios provide "alternative futures" to analyse the effects of future emissions and to develop mitigation and adaptation measures. The scenarios considered in QUEST_Fish provide two contrasting world views. The first one is the A1B scenario, characterized by rapid economic growth, a peak in population growth by 2050, a spread of new and efficient technologies, and a balance of energy demands across all sources. Like the rest of the A1 family, this scenario is for a more integrated world, based on economic development and convergence of income (Leggett *et al.*, 1992; Nakicenovic and Swart, 2000). The second scenario has not been agreed upon, but will respond to a low emissions framework, possibly following the B1 SRES model. The central elements of the B1 future are a high level of environmental and social consciousness combined with a globally coherent approach to a more sustainable development. In the B1 storyline, governments, businesses, the media, and the public pay increased attention to the environmental and social aspects of development. Technological change plays an important role, but the storyline does not include any climate policies (Nakicenovic and Swart, 2000). Recent developments, however, suggest that it may be possible to use a modification from the B1 model, associated with aggressive mitigation policies of CO_2 emissions to an equivalent atmospheric concentration of 450 ppm (Bouwman *et al.*, 2006). Either model provides a more environmental alternative to the A1B model.

The role of GCMs and RCMs

Our understanding of the global climate and of the role of human activities in driving changes in the climate has developed rapidly in recent years, particularly in respect to land use change (Hegerl *et al.*, 2007). The understanding has been greatly enhanced by the use of general circulation models (GCMs) of the atmosphere and ocean. Comparisons between observations and model results have demonstrated that GCMs have the power to simulate many aspects of the real climate. GCMs are constructed using the equations governing the large-scale circulation and thermodynamics of the atmosphere and oceans. In order to make the computational problem manageable they split the world into a series of interconnected atmospheric and oceanic horizontal grid cells, and solve the equations numerically for each cell. Current models typically have a horizontal resolution of 100–300 km^2 with 20–40 vertical levels in the ocean and a similar number in the atmosphere. Those smaller-scale processes that can impact on the larger scale (such as formation of clouds) are usually represented by simplified relationships known as parameterizations, derived from observations or limited area models with much higher resolution and complexity.

These same ocean-atmosphere GCMs can be forced with estimates of future greenhouse gas emissions to project future climate conditions several decades or even a hundred years into the future. However, they cannot yet directly simulate detailed impacts in relatively local shelf seas because they do not resolve small spatial scales (<100 km) in the ocean. Key features that determine ocean productivity, such as upwelling, eddy formation, and the wind and tidal mixing of shelf seas are poorly represented by such models. In QUEST_Fish the problem of spatial scale is overcome by using the GCM to provide boundary conditions for a more detailed local model of the atmosphere (simulating 25 km scales), which in turn provides the surface fluxes for the shelf ocean models. In QUEST_Fish, the GCMs are used to drive shelf-seas hydrodynamic models (POLCOMS, Holt and James, 2001) as described in the next section.

Developing physical-biological models for the shelf seas

Shelf and coastal seas play an important but largely unquantified role in the Earth System. Their significance is due to their exceptionally high biological productivity and close interaction with human activity. Coastal seas comprise only 18% of the Earth's surface, yet support half the world's fish and marine mammal biodiversity and provide more than half of global primary production, global denitrification, and carbonate deposition and most of the global fisheries catch (Longhurst *et al*., 1995; Sloan *et al*., 2007; Walsh *et al*., 1988; 1991). The processes mediating this re-supply include heterotrophic nutrient recycling (by zooplankton and bacteria in pelagic and benthic ecosystems), coastal upwelling, cross-frontal transport, and land-derived inputs.

Investigation of the causes and effects of climate change (recent, future, historical, and paleontological) currently involves the use of GCMs, which increasingly include biological and biogeochemical processes in addition to the physics (Friedlingstein *et al*., 2001). However, such models invariably give a very poor representation of the land-ocean interface and the shelf seas. There are three reasons for this, related to resolution and process representation. First, for typical Ocean General Circulation Models (OGCM) grid scales of 1° (~100 km), the topography of continental shelves is not resolved. Second, the dominant scale affecting shelf processes is determined by the barotropic Rossby radius, which for water depths of ~80 m at mid-latitudes is ~200 km. This can barely be captured by ~100 km Ocean GCMs. In addition to resolution, many processes important in coastal and shelf seas are generally not well represented in global models. Examples include tides, sea bed processes (e.g., benthic ecosystems and fluxes of nutrients back to the water column), or the optical properties of coastal seas. And finally, while the equations of motion for the deep ocean and shelf seas are the same, the approach to solving them for the deep ocean differs widely. In the case of OGCMs, long gravity waves are often prevented altogether (by a rigid lid approximation) or damped using a filtering method. In coastal seas, however, these waves are often the dominant signal, since they represent the astronomical tide and wind-generated, coastally-trapped waves. The representation of the flow over the sea bed and turbulent mixing at multiple boundary layers are also often not well represented in OGCMs, which tend to have very limited vertical resolution in shallow water. Other issues include the representation of benthic and microbial processes in ecosystem models and optical properties of the water column. In the open ocean, optical properties are generally determined solely by phytoplankton pigments (known as Case I waters), whereas in coastal seas colored dissolved organic material (CDOM) and suspended particulate material (SPM) both make a substantial contribution to the inherent optical properties of the water (Case II water). These properties in turn determine the depth to which solar heating penetrates and the light climate in which phytoplankton grow. This can have a substantial effect on near-coastal primary production.

The most practical option to address these issues, given current modeling technology and computer resources, is the grid nesting approach, which we follow here. Nesting is standard practice in downscaling from an ocean basin scale domain to a particular coastal region of interest. In the context of QUEST_Fish the aim of this work is to estimate primary (phytoplankton) and secondary (zooplankton) production in key coastal-ocean fisheries around the world under climate change scenarios, using key domains from the Global Coastal Ocean Modelling system (GCOMS; Holt *et al*., 2009). The GCOM system provides a flexible framework within which to set up any number of regional models of the continental shelf over the globe (Plate 1 in the color plate section shows an example of the selected regions/LMEs), taking lateral boundary conditions from a global OGCM to drive the POLCOMS-ERSEM (Proudman Oceanographic Laboratory Coastal Ocean Modelling System–European Seas Regional Ecosystem Model) modeling system (Allen *et al*., 2007; Blackford *et al*., 2004; Plate 2 in the color plate section). The framework enables multiple regional model configurations to be generated from user defined domain boundaries.

The POLCOMS system (Holt and James, 2001) is a three-dimensional hydrodynamic model, with a sophisticated representation of vertical mixing provided by the General Ocean Turbulence Model (Umlauf and Burchard, 2005). The European Regional Seas Ecosystem Model (ERSEM, Baretta *et al*., 1995) was developed to simulate nutrient cycling and ecosystem response in European shelf seas. It is a generic model which incorporates eight plankton functional types (PFT: picoplankton, autotrophic flagellates, diatoms, dinoflagellates, heterotrophic bacteria, heterotrophic nanoflagellates, microzooplankton. and mesozooplankton; see Plate 2 in the color plate section), which describes the cycling of carbon, nitrogen, phosphorus, and silicate through the pelagic ecosystem and includes dynamic C:N and C:P ratios for each PFT. We use a generic parameter set, which was devised by fitting to data at six diverse stations (well mixed and a stratified, oligotrophic, upwelling, etc., Blackford *et al*., 2004), allowing us to use the same ecosystem model in all regions.

The model configuration is arranged on a regular latitude-longitude grid of 1/10° horizontal resolution and with 42 levels in the vertical. The domains (LMEs) used are defined in Table 3.1 and illustrated in Plate 1 in the color plate section. The bathymetry is interpolated from the GEBCO 1-arcminute dataset[1] onto the model grid (some minimal smoothing is required where there are extreme changes in water depth), and the coastal mask is defined by the World Vector Coastline. Within each rectangular domain an automatic procedure is used to define the coastal region. The shelf and slope regions are included and coupling to the OGCM occurs in deep water. The locations of the open boundary and boundary condition data are automatically extracted from global datasets.

Surface fluxes are calculated within POLCOMS using a bulk formula approach (COARE 3.0, Fairall *et al*., 2003). Fluvial discharge into coastal grid cells is estimated from river gauge data held by the Global Runoff Data Centre[2] (GRDC). The location of the discharge is determined using the Simulated Topological Network (STN-30p; Vörösmarty *et al*., 2000). The barotropic tidal boundary conditions for the GCOMS domains are obtained from the global inverse tidal model TPXO6.2,[3] eight tidal constituents are used here (K2, S2, M2, N2, μ2, K1, P1, O1, and Q1).

The surface and oceanic boundary conditions provide the vectors by which large-scale climatic conditions impact on the shelf seas. For this work we consider two classes of simulations:

1. re-analysis forced simulations (i.e., atmospheric model runs constrained by observations through data assimilation) provide the reference simulations; and
2. simulations forced by coupled ocean-atmosphere models (OAGCMs) allow us investigate climate change impacts.

For this work, we adopt a time-slice approach whereby the model is initialized from the OAGCM at a recent past and several future stages, and then run forward for several years. The difference between the model statistics at each time-slice then provides the climate change signal. The need to distinguish between the long-term drift and inter-annual variability leads us to a 15-year time slice.

For the re-analysis forced simulations, we use ERA-40 atmospheric model output and ORCA025 ocean boundary conditions. For the climate forced simulations we choose two of the AR4 models: HadCM3 (as a well established UK climate model) and IPSL-CM4 (since this has a common ocean model to the re-analysis forcing).

Initial and boundary conditions for the ecological state variables are taken from the World Ocean Atlas nutrient climatology,[4] which provides nitrate, phosphate, and silicate data. To initialize the model, the inorganic nutrient values are taken to be indicative of the total concentration of the corresponding element present in the water column, and are distributed among the state variables. Organic carbon concentrations within each plankton group are then derived from the corresponding nitrogen and phosphorous concentrations using the Redfield ratio. Boundary conditions for inorganic nutrient variables are advected into the model domain using an up-wind scheme on inflow conditions. The remaining ERSEM variables are subject to a zero-gradient boundary.

The computational effort for these simulations as a whole is substantial: all the time-slices for all the domains adds up to about 1.5M CPU hours. However, the system can be flexibly deployed across a range of computer resources, such as the 11,000 core HECTOR system available to UK researchers (www.hector.ac.uk). With efficient use of these massively parallel computers, the largest domain takes ~30 days to complete a total 100 years simulation (using 512 processors).

Through this modeling structure we will simulate the production of the planktonic communities under past, present, and future climate conditions, aiming to establish the sensitivity of the primary and secondary production to changes in heat flux, stratification, ocean-shelf exchange, and wind forcing and, where information is available, river run-off and nutrient loading. As noted in the Introduction, IPCC scenarios will provide past, present, and future oceanic and atmospheric climatic forcing and re-analyses simulations will provide accurate present-day conditions for use as a benchmark. This will provide the background physical and lower trophic level conditions, upon which the rest of QUEST_Fish will be built.

As a test run, Plate 3 in the color plate section shows a comparison of simulated and observed (SeaWifs satellite data) annual primary production from the Humboldt LME off

Peru and Chile. Visual comparison suggests that the model reproduces upwelling driven production in the region, but may underestimate it. Also shown are P values for differences between primary production from a pre-industrial climate simulation, and primary production from a simulation under the SRES A1B emissions scenario over the period 2085–2094. This initial test shows significant changes in net primary production over much of the domain.

Estimating potential fish production

The next stage in the QUEST_Fish process is to predict how changes in temperature and primary production influence fisheries production. As well as being accurate, ideal predictions of potential fish production should be regionally explicit and species based, because most assessment and management units, and many of the social and economic responses to changes in fisheries production, are region and species dependent. However, longstanding experience with single species models has demonstrated that predictions of population distribution and abundance on decadal time-scales are too inaccurate to support management needs. Thus predictions of total fishery production that are based on predictions for multiple populations may also be inaccurate, especially when interactions between populations change as they redistribute and change in abundance. Walther *et al*. (2002) have also suggested that “the complexity of ecological interactions renders it difficult to extrapolate from studies of individuals and populations to the community or ecosystem level.” An alternative approach is to ask how the aggregate properties of communities or ecosystems might be influenced by climate change and to consider whether there are levels of cross-species aggregation at which climate effects become more predictable. Such an approach would parallel and inform work that focuses on the responses of populations (Cheung *et al*., 2008). Despite offering greater potential to give accurate predictions of total fish production, the disadvantage of a community approach is that it focuses on aggregate fish production rather than the potential value of the catch. Predictions will therefore be more valuable in countries where fisheries yields primarily meet subsistence needs and/or are converted to fishmeal.

Three methods for predicting aggregate fish production from temperature and primary production are being used in the QUEST_Fish project. These vary in complexity and parameter demands and the time and spatial scales at which they can be applied. The first draws on the tradition of linking primary production and fish catches by statistical methods. The second uses macro-ecological theory to predict the steady-state properties of marine food webs. The third approach uses dynamic size-based models that capture the effects of short-term variability in primary production and temperature and allow catches to be predicted given assumed rates of fishing mortality.

There have been many statistical explorations of links between primary production and fish production, using direct correlations or methods that account for differences in the trophic levels or categories of fish production. At large spatial scales primary production is broadly correlated with fish yields (Iverson, 1990), and positive relationships between primary production (or annual mean chlorophyll a concentration used as a proxy for primary production) and long-term average fishery catches have since been

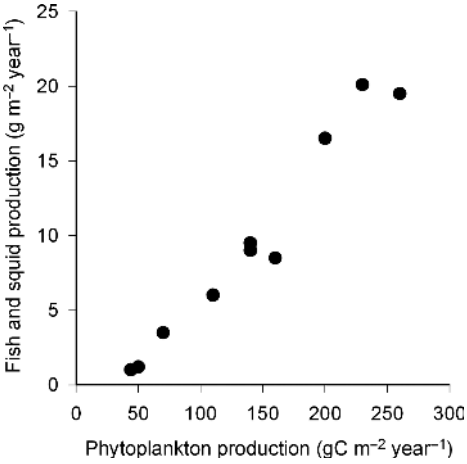

Fig. 3.2 Relationship between annual phytoplankton production and the production of carnivorous fishes in open ocean and coastal ecosystems. After Iverson (1990). Copyright (1990) by the American Society of Limnology and Oceanography, Inc.

described for 9 fisheries areas in the mid-latitude region of Northwest Atlantic (Frank *et al*., 2006), 11 fisheries areas in the Northeast Pacific (Ware and Thomson, 2005), and 14 European eco-regions (Chassot *et al*., 2007) (Fig. 3.2). Information on primary production also improved the fit of a statistical model to predict maximum catches from 1,000 exploited fish and invertebrates (Cheung *et al*., 2008). Technically, the strength of correlations will depend on comparable rates of exploitation in different areas or fisheries, though at large scales the fisheries in many of the systems are fully or over-exploited. Other examples of these correlations and the factors that influence them are provided by Dulvy *et al*. (2009).

The significance of relationships between primary production and fish catches can be increased by accounting for the trophic level of the catch, since potential catches will be lower at higher trophic levels when energy transfer through the food web is inefficient (Ware, 2000). In QUEST_Fish, statistical models that link primary production and fish production, after accounting for trophic level and temperature, will be developed and applied to predict potential future catches from estimated primary production. The strength of these models is that they are well supported by data and that the relationships have been shown to hold among ecosystems and through time. The weakness is that predictive power at local scales may be relatively low and there is uncertainty about the extent to which the trophic composition of the present catch would be sustained through time.

The second method for predicting future fish production from projected primary production and temperature relies on macro-ecological theory (Jennings *et al*., 2008). The method assumes that the fundamental size-based processes that determine the use and transfer of energy in communities respond to changes in temperature and primary production in consistent and predictable ways, based on empirical observation of these processes in contemporary marine ecosystems ranging from the poles to the tropics.

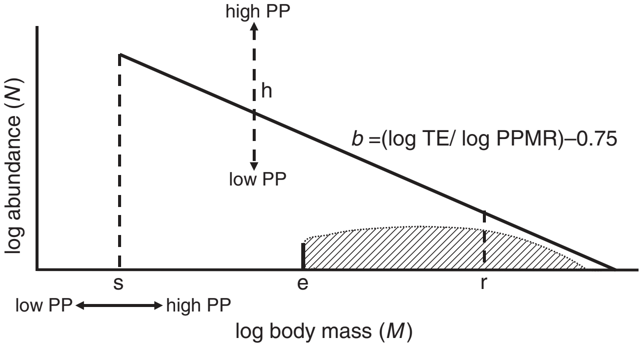

Fig. 3.3 Conceptual illustration of the process used to predict the slope and intercept of the size spectrum and the contribution of fish to the total biomass predicted by the spectrum. The height (h) of the size spectrum and the smallest size class (s) in the spectrum are functions of primary production (PP, which affects phytoplankton biomass and size composition). Fish are assumed to be part of total community of animals larger than the size of their eggs (e) and their biomass in all size classes is predicted in relation to an assumed biomass in a given size class (r). The slope of the spectrum is predicted from transfer efficiency (TE) and the predator-prey mass ratio (PPMR).

For a given temperature and rate of primary production, size-based methods allow biomass and production of consumer communities to be calculated from estimates of the primary production available to support them, accounting for the factors that affect the rate and efficiency of energy processing. These factors are:

1. temperature, which affects rates of metabolism and hence growth and mortality;
2. the ratio of predator to prey body mass, which determines the number of steps in a food chain; and
3. trophic transfer efficiency, which measures how much energy is lost at each step.

The method predicts the intercept and slope of the size spectrum, the relationship between numbers of individuals by body mass class vs. body mass, from the abundance and body mass distribution of primary producers, the ratio of predator mass to prey mass and trophic transfer efficiency (Fig. 3.3). Well established power laws (Brown *et al*., 2004) that link production and biomass at body size can be used to translate between the currencies of biomass and production, and integration of the biomass or production spectrum between defined body mass classes gives total biomass or production (Boudreau and Dickie, 1992). Methods of predicting size spectrum slopes from the ratio of predator mass to prey mass and trophic transfer efficiency are well supported by theory (Andersen *et al*., 2008; Borgmann, 1987). The predator-prey mass ratio can be used to define the number of trophic steps to any body mass class and hence the trophic level body mass relationship. Body mass and abundance at the intercept of the size-spectrum can be fixed from knowledge of the relationship between size distributions of primary producers and primary production (Agawin *et al*., 2000). While temperature and production do not affect predator-prey mass ratios, transfer efficiency, or the slope of the spectrum, temperature does influence rates such as production. To account for temperature effects, a temperature term based on the Arrhenius form can be added to the relevant scaling relationships.

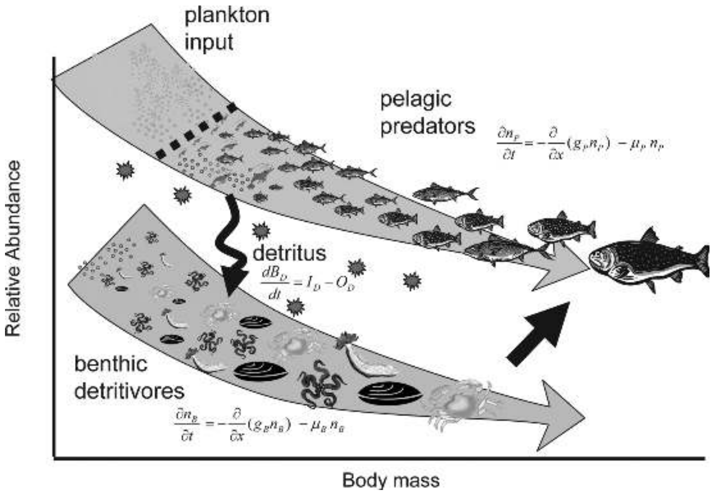

Fig. 3.4 Conceptual illustration of two size structured communities with trophic interactions resulting in growth and mortality. The pelagic community consists of predators feeding on increasingly larger prey, as they themselves grow larger. Animals in the benthic zone share and compete for the same food: sinking detrital particles that are comprised of phyto-detritus, feces, and dead animals. Reproduced from Blanchard *et al*. (2008), with permission of Blackwell Publishing Ltd.

The first and second methods of describing fish production are discrete and static, and do not explicitly account for the continuous time-dependent processes of growth and mortality that arise from fluctuations in primary production, predation, and human exploitation. For this reason, fish production will also be predicted using a dynamic size-based method. This third method will also allow us to investigate how different rates of fishing might modify responses to climate change, to simulate seasonal variation in potential production, and to look at effects on production of predator (predominantly pelagic fish and squid) and detritivore (predominantly benthic invertebrate) communities. The model builds on the work of Silvert and Platt (1978, 1980), who defined partial differential equations for size spectra with growth and mortality as continuous functions of size and time, and accounted for food-dependent growth by relating the growth at one size to mortality at another using a predator-prey size ratio. Subsequent developments have assumed that a probability density function rather than a fixed value defines realized prey size (Benoît and Rochet, 2004; Camacho and Solé, 2001).

The third method captures the dynamics of interacting predator and detritivore communities (Fig. 3.4), and the model predictions of size-spectrum slopes in detritivore and predator communities have been validated with data (Blanchard *et al*., 2008). The model will be extended to incorporate temperature effects on feeding rates of predators. Model inputs from the POLCOMS-ERSEM models are a size spectrum of primary producers and temperature. The model can accept inputs on a daily time step to capture the effects of short-term variation in temperature and production. Model outputs are biomass and production of predators and detritivores, by body mass and through time, for specified rates of fishing mortality.

Estimating socio-economic consequences

Methodology for national vulnerability assessment

Vulnerability assessments are conducted to address different goals: to identify specific targets for mitigation, to provide recommendations on adaptation measures for specific regions and sectors, and to prioritize resource allocation for research and for adaptation at the national and international level (Füssel and Klein, 2005). Few studies have looked at vulnerability to climate change from a fishery sector perspective. Assessments of the potential impact of climate change on fisheries have tended to emphasize predicted changes in resource production and distribution (Brander, 2007; Cheung *et al*., 2008; Perry *et al*., 2005) and make only broad inferences about consequent socio-economic vulnerabilities. Only one study to date has assessed the vulnerability of national economies to potential climate change impacts on their capture fisheries (Allison *et al*., 2009). Using a conceptual framework based on the IPCC definition of vulnerability (Fig. 3.5), the authors captured present-day vulnerability of national economies using an indicator-based approach.

While this analysis provides a valuable means of identifying the countries where potential impacts of climate change on fisheries are of greatest social and economic significance, it has a number of limitations. First, the indicator of exposure only incorporates one driver – climate change (only reflecting changes in ambient temperatures). Second, the assessment provides a static picture of vulnerability, because it focuses on "current vulnerability" to future climate change (current socio-economic conditions are used to define a countries' capacity to adapt to future climate change). Third, it takes no account of historical processes of increasing vulnerability. The QUEST_Fish vulnerability assessment in contrast seeks to understand multiple pathways of climate change impacts on fisheries systems through the development and use of scenarios. In so doing, the vulnerability assessment takes into account non-climatic drivers of change and acknowledges that global environmental change

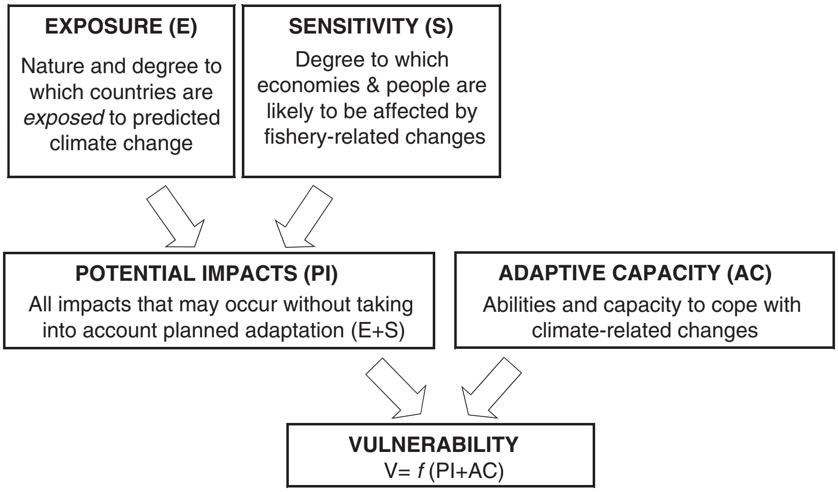

Fig. 3.5 Conceptual model for vulnerability assessment of national economies to potential climate change impacts.

Table 3.2 Construction of composite vulnerability index (adapted from Gall, 2007; OECD and European Commission, 2008).

1. **Framework and initial data collection**
    - Conceptual underpinning
    - Relevance, coverage, accessibility, quality, and completeness of data
2. **Exploration of data and normalization**
    - Statistical exploration (e.g., multivariate analysis) to assess the suitability of the dataset and provide an understanding of the implications of the methodological choices
    - Harmonize units of data selected
3. **Weighting and aggregation**
    - Understand the different dimensions of vulnerability
    - Expert elicitation process, identify relevance, and importance of indicators for current vulnerability (e.g., Analytic Hierarchy Process, conjoint analysis)
4. **Robustness and sensitivity**
    - Assess weighting schemes, country rankings, and indicators definition
    - Uncertainty and sensitivity analysis (e.g., inclusion-exclusion of sub indicators, several weighting schemes, expert selection)
5. **Validation, visualization and dissemination**
    - Compare index output with other vulnerability indices to identify analytical overlap and explanatory trajectories
    - Maps (GIS)
    - Reports, peer-reviewed articles

unfolds over different scales. Assessing how vulnerability to global climate change might itself change requires a dynamic assessment framework that accounts for changes in all elements of vulnerability over time (Füssel, 2007). Scenarios are useful tools to estimate future socio-economic conditions, accounting for the dynamic nature of vulnerability and the multiple external drivers a system is or will be exposed to (Belliveau *et al*., 2006). Scenarios can be defined as plausible descriptions of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces (Nakicenovic and Swart, 2000). It must be noted that while they are a useful tool for exploring uncertainties that may shape the future of fishery systems, they are not predictions or forecasts (Nakicenovic and Swart, 2000; Biggs *et al*., 2007).

In QUEST_Fish we build on the work of Allison *et al*. (2009) by coupling an indicator-based approach with a conceptual framework based on the IPCC definition of vulnerability (Fig. 3.5, Table 3.2). At both the national and global scales we thus investigate exposure, sensitivity, and adaptive capacity in the context of multiple stressors. The vulnerability assessments will be linked across the geographical scales through a nomenclature based on the work of Zurek and Henrichs (2007) for the Millennium Ecosystem Assessment (MA). "Soft" links will be created between scales through a parallel development process (i.e., using the common conceptual framework).

For the global-scale assessment, after the creation of a small expert panel, the scope and boundaries of the scenario building exercise will be clearly defined. In a second step, the past and current status of the fisheries systems will be assessed to identify major trends and driving forces, select proxy values to represent important elements of socio-economic conditions and non-climatic driver(s) of change currently and for 2050, and generate qualitative storyline(s) of the future (Fig. 3.6). These simple qualitative storylines describe

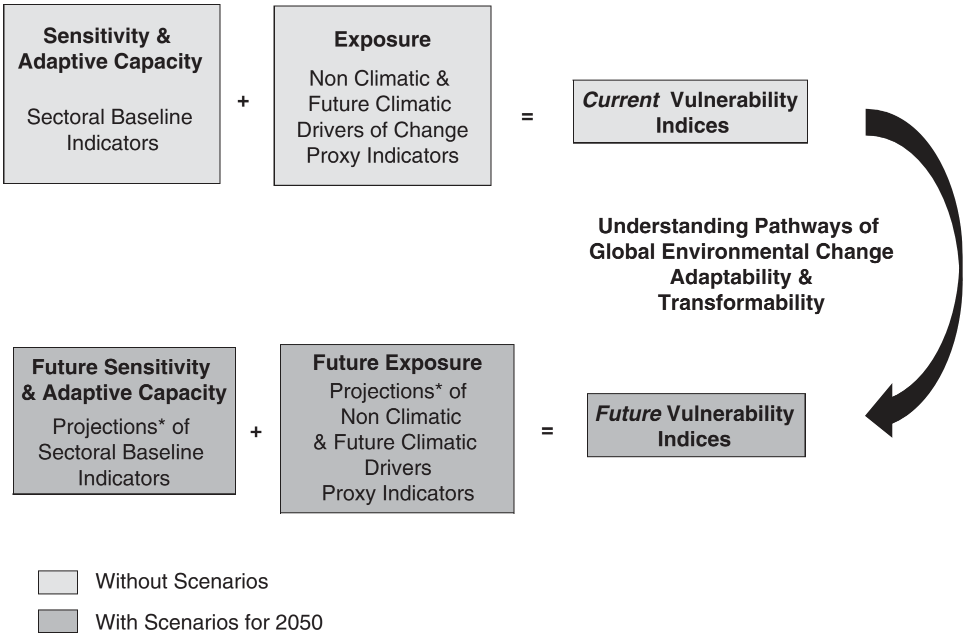

Fig. 3.6 QUEST_Fish conceptual framework for the vulnerability assessments of national economies to the effect of climate change and other drivers on fisheries systems. *Projections can be based on a quantitative (e.g. % of change) or qualitative (e.g. direction of change) approach.

pathways of change in fisheries systems without taking into account climate change (referred to as the "climate ceteris paribus" scenario(s) in Fig. 3.7) and will also form the basis of the future scenarios that will incorporate projections from the QUEST_Fish physical-biological models. Thus four fishery systems scenarios (possible futures A, B, C, and D) are created, each incorporating one IPCC scenario of climate change (storylines A from IPCC), producing a set of four scenarios by combining the fisheries and climate scenario.

The future scenarios will be coherent to the storylines attached to the two IPCC scenarios described in the section on Framing the problem. Coherent scenarios follow the same logic or rationale, while comparable scenarios are independent but address the same issue (Zurek and Henrichs, 2007). Throughout the scenario-building process a larger group of identified international experts in the field of climate change research and fisheries social-ecological systems will be involved in the identification and weighting of key drivers as well as in the review and validation process (Fig. 3.7). Final activities in the scenario building process will include a pilot testing exercise in which QUEST_Fish and associated scientists will analyse a set of policy options using the scenarios developed. Techniques such as "wind-tunneling" and "backcasting" will be used to understand the implications of the future scenarios for current policies as well as the pathways leading to these alternative futures. "Backcasting" involves working backwards from a vision of the distant future (in this case in 15-year time-slices) to the present to identify the pathways to these alternative futures.[5] "Wind tunneling" in contrast considers the logic and plausibility of the internal structure against a set of policy options. These techniques have been widely used in sectoral scenario-building processes in the UK.[6] They involve working backwards from a vision of

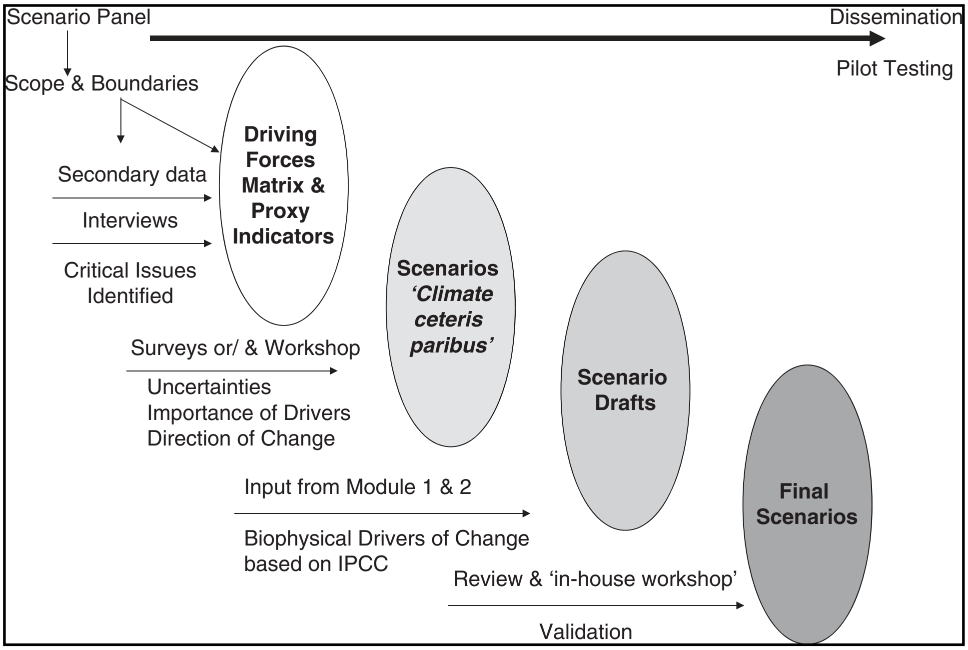

Fig. 3.7 QUEST_Fish scenario development. The main difference in the scenario building process across scales is the level of involvement of experts and secondary stakeholders. All scenarios are for 2050.

the distant future to the present, asking in increments what steps 10, 20 years in advance can lead to these alternative futures (backcasting), and looking at the logic and plausibility of the internal structure against a set of policy options (wind-tunneling[7]).

Also at the global scale, the second aspect of the vulnerability assessment is the identification of relevant indicators for each component of the vulnerability index through a combination of secondary data and expert elicitation (Table 3.2). Expert judgement and computational methods such as multivariate analysis (e.g., multiple components and factor analysis) will be used to weight and aggregate the individual indictors of exposure, sensitivity, and adaptive capacity into a composite vulnerability index. The biophysical models developed in Module 1 and 2 will provide the basis for the exposure component and will be complemented by non-climatic driver(s) of change identified in the scenario-building exercise such as trade (changes in tariffs, protectionism, changes in consumption preferences) or utilization (changes in demand for fish as food or animal feed). One key challenge will be to develop sensitivity and adaptive capacity indicators that are not only development-driven (e.g., relying on Human Development Index trends) but possess specific elements relating to the vulnerability of the fishing sector (e.g., level of diversification of the fleet, types of property rights, flexibility in utilization of fish products).

The national scale level vulnerability assessment will be applied in two case studies: the Humboldt Current Large Marine Ecosystem (HCLME), with a country focus on Peru, and the South China Sea (SCS) LME, with a country focus on Vietnam. The HCLME is the most productive large marine ecosystem in the world, providing about 15% of the world's fisheries catch (FAO, 1998). Peru is the largest producer of fishmeal and fish oil worldwide, with the overall production absorbed by aquaculture, one of the fastest growing animal food producing sectors dominated by China and the Asian Pacific region. The price and availability of fishmeal and fish oils from Peru play an important role in the global trade of fisheries products and are dependent on a highly fluctuating environment, because Peruvian fisheries are strongly influenced by El Niño Southern Oscillation (ENSO) effects on the distribution and abundance of pelagic resources. Localized changes in the productivity of Peruvian marine waters induced by climate change and increased climate variability, management decisions, and global drivers such as market changes are thus critical to the fishery and the aquaculture sectors globally.

The South China Sea LME is a diverse marine ecosystem incorporating eight countries, including Vietnam, which is the third producer of aquaculture in terms of volume in 2004 (FAO, 2007). In addition, fish is an important part of the diet, representing around 40% of animal protein intake (Briones *et al*., 2004). With an important national demand for fish as food and feed, and a key role in the global aquaculture sector, changes in the fisheries systems of Vietnam in the context of climate change will have significant implications for local livelihoods and global markets.

The two case studies represent a key producer of fishmeal and fish oil, and important consumers of aquaculture feeds, respectively. The scenarios and indicators developed will inform and contextualize the results of the bio-economic models developed in QUEST_Fish to assess the impact of climate change on the global trade in fishmeal and fish oil. National stakeholders as well as international experts will be included in the scenario and indicator development processes of both case studies.

While links between food systems and the environment are well documented, few interdisciplinary studies have investigated the vulnerability of fishery production systems to climate change and other drivers of change. The QUEST_Fish vulnerability assessment presented here seeks to understand the pathways of climate change impacts on fisheries systems through the development of scenarios. In addition, the proposed vulnerability assessment accounts for non-climatic drivers of change and acknowledges that global environmental change unfolds over different scales. The outputs are expected to provide decision support system tools for decision-makers at multiple scales (national through regional and international), enhancing their ability to adapt and transform while promoting the sustainable use of fisheries resources. The project results will be used to increase awareness regarding the opportunities and negative impacts that climate change brings, promoting planned adaptation, thereby reducing vulnerability to climate change.

Methodology for global assessment of a marine-based commodity: fishmeal

The complexity of fisheries and the factors that drive them limit our ability to parameterize simulation models, which can be useful tools to inform wider scenario-building. Such models can, however, be constructed for sub-sectors of the fishery where the main structural features of the system are simpler, and where the main drivers of change are relatively easy to discern. The most suitable and important fishery systems whose dynamics can be simulated in this way are those associated with marine-based, global commodities: fishmeal and fish oil. These products are the result of reducing around 20% of the

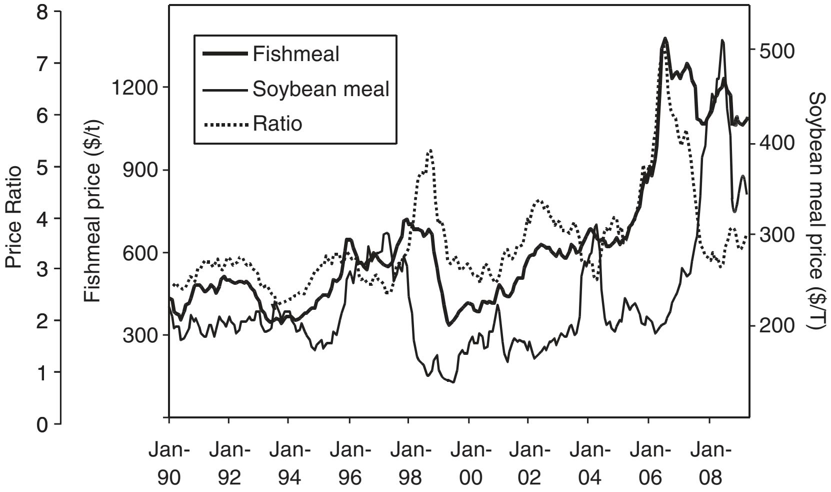

Fig. 3.8 Price dynamics for fishmeal and soybean meal in international markets from January 1990, and price ratio between both commodities.

world's marine fish catch (mostly small pelagic fisheries, i.e., anchovy, sardine, herring, etc.) to a high protein powder and oil compounds. They are used extensively as aquaculture feeds, but also in other animal husbandry industries and as health supplements for human consumption. As global commodities, fishmeal and oil are traded freely in the international market.

Unprecedented increases in fishmeal demand and price have been observed in recent years (Fig. 3.8). The causes are complex, but are particularly linked to two factors: i) concerns over climate impacts, particularly El Niño events, on global fishmeal production (Hansen *et al*., 2006); and ii) aquaculture development driving up demand. The impacts of climate on fishmeal producing species are well established (Checkley *et al*., 2009). Humboldt anchovy (*Engraulis ringens*) in particular, contributes almost 50% of the world fishmeal production, and is negatively affected by El Niño events (Chavez *et al*., 2003), which have been predicted to increase in intensity in a warmed world (Hansen *et al*., 2006). The impacts of regional fluctuations in fishmeal are felt globally, allowing us to estimate the vulnerabilities of this climate-driven trade at different scales. Currently aquaculture absorbs almost 70% and 90% of the total fishmeal and fish oil production, respectively (Tacon and Metian, 2008), raising concerns over whether aquaculture can contribute to satisfying the increasing global demand for fish while depending so heavily on capture fisheries (Asche and Tveterås, 2004; Delgado *et al*., 2003; Deutsch *et al*., 2007; Kristofersson and Anderson, 2006; Naylor *et al*., 2000; Tacon and Metian, 2008).

In QUEST_Fish we aim to investigate the global and regional capacity for fishmeal and oil production under a number of climate and emission scenarios, as well as feedbacks with international markets. We do this through a bio-economic model, which couples the ecological and the economic dynamics of these global resources into a multi-species, multi-producer, and multi-market model (Mullon *et al*., 2009). The result is a network in the framework of network economics (Nagurney, 1993) with a bi-layered structure with a set of production systems from fish to fishmeal and fish oil, on the side of supply, and a set of

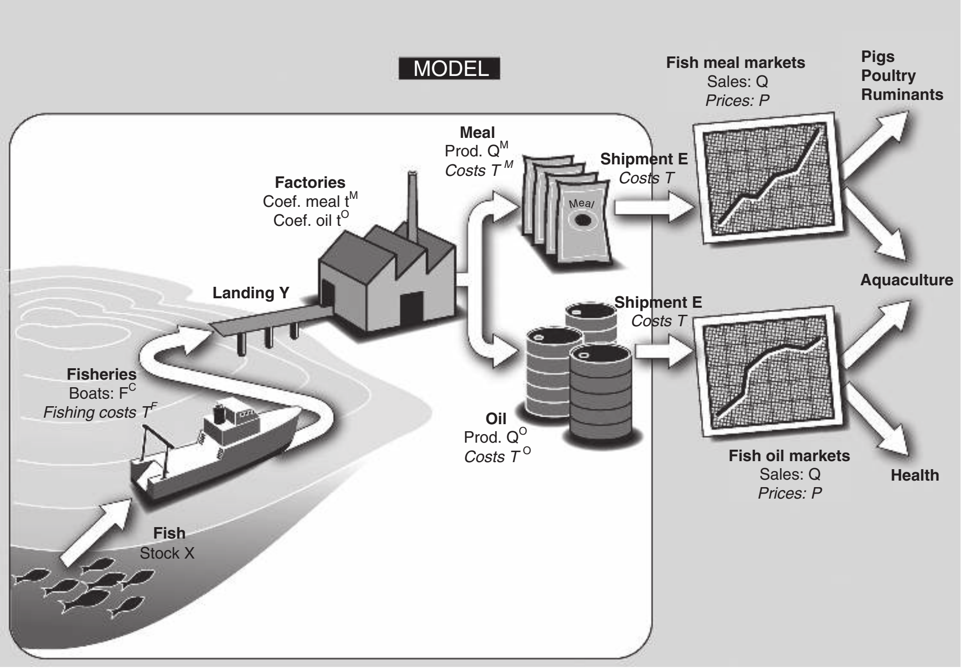

Fig. 3.9 Supply and markets for the global fishmeal trade. Reproduced from Mullon *et al*., 2009, with permission of Blackwell Publishing Ltd.

fish product markets, and the economic exchanges between them, on the demand side (Fig. 3.9). Modeling principles lie in simultaneously identifying:

1. the economic equilibrium between production systems selling on fish products markets; and
2. deterministic evolution rules for production systems and fish products markets.

The basis of the model is that fishmeal/oil producers exploit their regional resource with the objective of maximizing their profits. Production systems are characterized by the available stock biomass, yield and fishing and transforming industries. Stocks evolve following surplus production dynamics, depending on a set of biological parameters (intrinsic growth rate, carrying capacity, and the catch, Schaefer, 1954), which can be parameterized based on ecosystem and fish model outputs described in previous sections. In the model, entities are national production systems and markets, including dedicated fleet and associated transformation factories. Peru, Chile, Japan, Thailand, China, USA, Denmark, Iceland, Norway, Morocco, and South Africa are the main production systems, representing more than 70% of the world production of small pelagic fish. The main fishmeal markets considered are China, Japan, Taiwan, UK, Germany, Chile, Norway, Denmark, Russia, and Indonesia, while fish oil markets considered are Norway, Denmark, Chile, Japan, and USA, representing more than 80% of the world fish product consumption.

The model evaluates the paths between production systems and markets. The quantity of the commodity placed in a market will be the sum of its imports from the production systems and the model allows for simulated expansion, i.e. increasing the price of the same amount of commodity traded. Within each market, commodity prices are estimated by means of a simple linear supply-price relationship based on recent records for each time step, allowing for potential changes in commodities demand. Landings are reduced into fishmeal or oil at observed transformation rates. Income is estimated from the sale of the commodity at a price in each of the markets. Each production system trades a fraction of the commodity to each market. Investments can change fishing capacity as a result of income and production costs, capital, and amortization costs.

The model applies to any common resource where single production systems share their access to globalized markets. Producers interact through a market externality (Oakerson, 1992); each producer's quantity placed on a shared market will affect the price of the product for the other producers. Consequently, each producer's trade, production, and exploitation will be the result of a profit maximization strategy designed to take into account other producers' and markets' behavior, as well as individual fishing, transforming, and shipping costs. The network is solved in terms of a Nash solution for non-cooperative games (Nash, 1951), i.e., producers will determine their production strategy (fishing and shipping) taking into account other producers' access to markets and individual regulation and technical limitations. Producers place their product on the available markets, depending on the prices they will get as a result of the market demand.

Sensitivity analyses of specific input parameters in the model have been conducted to evaluate the robustness of the overall system to such changes and show that local responses of production systems and markets cannot be considered in isolation from the set of interactions at global level (Mullon *et al*., 2009). Initial runs of this model have also been conducted to interpret the dynamics of the fishmeal price in recent years, based on two alternative 10-year simulation scenarios, based on random climate variability on the climate side, and either a stable fishmeal market (no expansion or contraction) or an expansion of the fishmeal market (increased demand at a rate similar to the global aquaculture expansion) on the economic side. Preliminary results indicate that the sustainability of the fishmeal system, and the fisheries underpinning this system, in the face of climate variability and change, depends more on how society responds to climate impacts than on the magnitude of the climate alterations *per se* (Merino *et al*., 2010). This highlights an important principle behind QUEST_Fish activities: the impacts of climate change on renewable natural resources provide only half of the story, the other half being the response of human societies to these impacts.

QUEST_Fish modeling of future scenarios for the use of marine-based products will consider the potential for substitution as a key element to allow the continued growth in aquaculture production. The substitution of fishmeal is governed by several factors (e.g., growth, palatability, product quality, etc.) but ultimately "new feeds" will need to be both technically and economically efficient if they are to be adopted commercially. Substitution in carnivorous aquaculture (e.g., salmon) is nowadays limited (Drakeford and Pascoe, 2008), but the increasing price of fishmeal represents an incentive to innovate on direct replacements (Kristofersson and Anderson, 2006).

Opportunities and boundaries of the QUEST_Fish approach

The main objective of QUEST_Fish is to provide a framework to assess climate change impacts on the potential production for global fisheries resources in the future and to estimate the added vulnerability of these effects on national and regional economies, and on specific elements of the fishery system. One of the motivations to develop this framework was to respond to concerns that current approaches to modeling social-ecological system response to environmental change often produce a highly selective or reductive consideration of the system. For the ecological system, the prevalent use of single species traits, simple ecological interactions, and/or steady states, leads to concern about how accurately these approaches will capture future responses to environmental change in real biological systems (Savage *et al*., 2007). In the marine fisheries context, the social system has usually been left out of the analysis altogether (Allison *et al*., 2005), and where it is incorporated, once again, it is usually either considered on the basis of poorly resolved global and national data (Allison *et al*., 2009) or case studies using climate variability as a proxy for future climate change (Hamilton *et al*., 2000; McGoodwin, 2007).

The QUEST_Fish approach is unique in its focus on assessing the relative change between pre-industrial, present, and future scenarios, based on climate change effects, and in its quasi-global nature. The focus on "relative change" is important as it shifts the emphasis from the changes estimated using the same framework and models to the accuracy of particular regional model outputs for particular time periods. QUEST_Fish is structured along three modeling interfaces: from climate to primary production processes, from primary production to potential fisheries production, and from potential fisheries production to the consequences for human society. Each one of these interfaces has specific characteristics that define the uses and limitations of the results.

The "climate to primary production" interface is defined by high geographical (1/10°) and temporal (daily) resolution regional shelf seas models. This high resolution is required to capture the main processes responsible for fish production, and its coupling with GCMs ensure that the additional impact of climate change is adequately estimated. While these regional models are not coupled, they are nested, ensuring that the boundary conditions are permeable with respect to the outputs of neighboring regions. The validity of the approach is, however, limited by two factors:

1. ecosystem processes are parameterized according to present conditions, and thus stationarity in these parameters is assumed; and
2. future runs depend on socio-economic emission scenarios and associated storylines, and thus should be considered as probable outcomes given the assumptions considered in those storylines rather than actual predictions.

The "primary production to fisheries" interface limits its remit to potential production for global fisheries resources, and in two of the three approaches followed (see section 4 on Estimating potential fish production) this potential is considered in the absence of exploitation. This approach was preferred over more complex ones, given the uncertainties regarding management and exploitation patterns in the future. However, the "dynamic size spectrum" method can make use of specified rates of fishing mortality, thus it would be possible to attach specific management scenarios to the socio-economic storylines considered. Apart from this consideration, QUEST_Fish is particularly focused on the bottom-up impacts of climate change, understood as impacts that translate from the climate through the marine food web from its primary producers to fish. As for the first interface of QUEST_Fish, this interface suffers from the fact that the predictive power at local scales may be relatively low, although this shortcoming is balanced by the value of having a quasi-global prediction. The use of size-based estimators and reliance on robust macro-ecological considerations is intended to by-pass the difficulty of extrapolating complex ecological interactions at the ecosystem level based on studies of individuals and populations (Walther *et al*., 2002). The strength of our approach is that predictions of potential fish production would be regionally explicit, but a shortcoming is that they will not be species based. Many of the trade and national income-generation related responses to changes in fisheries production will be species-dependent (in terms of access, management, trade, and value), but experience with single species models has demonstrated that predictions on decadal time-scales are too inaccurate to support management needs. However, size-based multispecies fisheries, which tend to be the mainstay of the majority of the subsistence and artisanal fisheries practiced by the lower-income coastal fishers, may well be best represented by size-based model outputs. This approach requires innovative and flexible ways of estimating the social consequences of the fish production estimates.

The third and last interface of QUEST_Fish involves "from fish production to societies". This is undertaken following two approaches. The first is the development of a detailed global "physics-to-fish-to-fishers" model for one particular set of global fish-based commodities (fishmeal and fish oil) and the second is a pragmatic approach that uses indicators in combination with a vulnerability framework. The former has a number of additional interests in the context of climate change: its dynamics depend not only on climate-driven production changes, but also on the responses of commodity markets to these changes, and their interaction with markets for other food commodities (e.g., soy). Such structure provides opportunities to explore the two-way connectivity between climate change and economic development (O'Brien and Leichenko, 2000). The second consists of a vulnerability assessment framework developed to identify countries highly exposed to hazards related to climate change, where livelihoods and economic growth depend on climate-sensitive industries, such as agriculture, fisheries, forestry, and tourism, and where limited resources, infrastructure, and societal capacity constrain adaptation. The work builds on existing vulnerability assessments (Allison *et al*., 2009) but improves substantively on their parameterization and scope by using a much more direct measure of exposure to climate-induced changes (including climate-driven size-based fish abundance changes), incorporation of other risks to which the fishery sector and the national economies it contributes to is exposed (including possible scenarios for changes in trade and fishery governance, or competing uses for coastal waters that affect fisheries), and improved measures of adaptive capacity that are based on an understanding of how the fishery sector (fleets, processing lines, value chains, governance arrangements) in different national contexts is able to adapt to change.

In summary, QUEST_Fish provides a framework capable of investigating the complex relationship between natural resources and human societies in the context of climate change. This framework allows investigations at different spatial scales, by using specific nested modeling interfaces, and can provide essential information for the development of policy options at international, regional, and national levels that can help minimize negative impacts of climate change, improve on mitigation and prevention, and maintain and build adaptive capacity to climate change (cf. FAO, 2008). While specifically focused on fish and fisheries, this framework is applicable to other natural resources subject to similar multi-scale, multi-driver impacts.

Endnotes

1. http://www.bodc.ac.uk/projects/international/gebco/
2. http://grdc.bafg.de/
3. http://www.esr.org/polar_tide_models/Model_TPXO62.html
4. http://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html
5. Backcasting must not be confused with hindcasting. Hindcasting involves using historical evidence to understand past events and trace human responses in order to help forecasting and to assess probable reaction to future problems; it is widely used to test the validity of models. Backcasting involves an imaginary moving backwards in time, step-by-step to understand mechanisms that lead to a future scenario (Barrow, 2005: 28).
6. http://horizonscanning.defra.gov.uk
7. Kees van der Heijden – at the Graduate Business School of Strathclyde University, Glasgow – coined the phrase, referring to trying out a new aeroplane wing in a wind tunnel before letting it take off in the sky (see http://horizonscanning.defra.gov.uk).

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