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Climate variability and change scenarios for a marine commodity: Modelling small pelagic fish, fisheries and fishmeal in a globalized market

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A B S T R A C T

The world's small pelagic fish populations, their fisheries, fishmeal and fish oil production industries and markets are part of a globalised production and consumption system. The potential for climate variability and change to alter the balance in this system is explored by means of bioeconomic models at two different temporal scales, with the objective of investigating the interactive nature of environmental and human-induced changes on this globalised system. Short-term (interannual) environmental impacts on fishmeal production are considered by including an annual variable production rate on individual small pelagic fish stocks over a 10-year simulation period. These impacts on the resources are perceived by the fishmeal markets, where they are confronted by two aquaculture expansion hypotheses. Long-term (2080) environmental impacts on the same stocks are estimated using long-term primary production predictions as proxies for the species' carrying capacities, rather than using variable production rates, and are confronted on the market side by two alternative fishmeal management scenarios consistent with IPCC-type storylines. The two scenarios, World Markets and Global Commons, are parameterized through classic equilibrium solutions for a global surplus production bioeconomic model, namely maximum sustainable yield and open access, respectively. The fisheries explicitly modelled in this paper represent 70% of total fishmeal production, thus encapsulating the expected dynamics of the global production and consumption system. Both short and long-term simulations suggest that the sustainability of the small pelagic resources, in the face of climate variability and change, depends more on how society responds to climate impacts than on the magnitude of climate alterations *per se*.

1. Introduction

Capture fisheries production has stabilized at approximately 95 Mt year^{-1} over the last decade, while aquaculture production has increased from 13 Mt in 1990 to nearly 50 Mt in 2006 (FAO, 2007). This increase has been particularly achieved through the culture of low-value freshwater fish in East Asia (Delgado et al., 2003). While the role of aquaculture in satisfying the global demand for fish is well recognized, there are also some concerns over the potential negative consequences of aquaculture growth for marine fish stocks (Deutsch et al., 2007; Kristofersson and Anderson, 2006; Naylor et al., 2000).

Aquaculture and other animal food production systems depend on fishmeal as food and primary source of protein, lipids, minerals, and vitamins (De Silva and Turchini, 2008; Jackson, 2008). Approximately 30 Mt year^{-1} of anchovies, sardines, mackerels and other small pelagic species are reduced into ca. 6 Mt year^{-1} of fishmeal, almost half of it from Humboldt anchovy (*Engraulis ringens*), captured in Peru and Chile. Denmark and Norway supply ca. 12% of global fishmeal mainly from North Sea sandeel (*Ammodytes marinus*), while China, the world's top fishmeal consumer, produces ca. 6% of the world's production from Japanese anchovy (*Engraulis japonicus*), chub mackerel (*Scomber japonicus*) and sardine (*Sardinops sagax*).

Because small pelagic fish species are short lived and fast growing they are highly dependent on interannual, environmentally-driven recruitment fluctuations (Barange et al., 2009; Lehodey et al., 2006), and are thus significantly affected by climatic events. For example, short-term (El Niño, ENSO) climate variability patterns cause significant reductions in Humboldt anchovy production (Chavez et al., 2003). The potential for climate change to impose additional pressures on this and other stocks is under consideration, especially through potential increases in ENSO variability (Gergis and Fowler, 2008; Hansen et al., 2006; Meehl et al., 2007; Merryfield, 2006; Trenberth et al., 2007). North Sea sandeel also appear to be negatively correlated with climate variability patterns such as the North Atlantic

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Oscillation (NAO) winter index, apparently because warmer sea surface temperatures negatively affect their recruitment (Lewy et al., 2004). Continued warming of the North Sea and a consistent positive NAO index are predicted over the 21st century (Taylor, 2005), indicating that sandeel populations may be negatively affected (Lewy et al., 2004). Japanese anchovy and sardine regime shifts across the North-Pacific have been suggested to be driven by temperature regimes too (Takasuka et al., 2008).

On a longer scale, climate change is expected to affect marine resources through alterations in ecosystem primary production (Barange and Perry, 2009; Behrenfeld et al., 2006; Polovina et al., 2008; Sarmiento et al., 2004). A linear relationship between primary production and fish yield, both at the species (Perry and Schweigert, 2008) and multispecies level (Ware and Thomson, 2005) suggests that primary production could be used as a proxy to estimate climate change-related impacts on ecosystems carrying capacity. Carrying capacity is the asymptotic population biomass supported by an ecosystem under the limitations of food, shelter, predation, exploitation, etc. (Kashiwai, 1995). In marine ecosystems, environmental effects have been modelled as additive or multiplicative effects in carrying capacity and therefore, in fish stocks' productivity (Mueter and Megrey, 2006; Perry and Schweigert, 2008).

Global aquaculture production can be broadly divided between the culture of herbivorous and carnivorous species. The latter include salmonids, mostly Atlantic salmon (*Salmo salar*) and Rainbow trout (*Oncorhynchus mykiss*), particularly from Chile and Norway (4% of total production and 8% of total value), as well as shrimp (*Penadeus monodon*) mainly from Thailand and recently from China (3.4% of total production but 8% of total value in 2008). Shrimp farming in Asia is actually increasing at a rate higher than that of total aquaculture (Deutsch et al., 2007; Lebel et al., 2002). Herbivorous farming is mainly contributed by different *Cyprinidae* (Folke et al., 2004) species, and represents 55% of global aquaculture production, the majority produced in China. Recent patterns in aquaculture production are shown in Table 1 (FAO, 2008), demonstrating that carnivorous aquaculture, which is highly dependent on fishmeal, has grown at a higher rate than herbivorous farming. Although fishmeal was not traditionally used in herbivorous aquaculture, its addition is gaining interest due to improved growth rates and thus profits (Deutsch et al., 2007).

As a global commodity, fishmeal price is the result of global supply and demand equilibria. During the 1980s and 1990s the price was reasonably stable except for small fluctuations resulting from El Niño-modulated production changes in Humboldt anchovy. In the last few years the price has increased significantly, not necessarily responding to supply dynamics. The increasing use of fishmeal in aquaculture (63% of total fishmeal production in 2007) (Jackson, 2008) suggests that further aquaculture growth may drive the demand side, unless it comes hand in hand with technological developments that reduce its reliance on fishmeal (Kristofersson and Anderson, 2006).

In this paper we model the combined role of future climate and market perturbations on the global fishmeal production and consumption system. First, a ten year bioeconomic simulation investigates the consequences of short-term climate-induced variability on fish and fishmeal systems under static and expanding market hypotheses. Second, a long-term simulation investigates the impacts of changes in primary production in response to global warming, on fish and fishmeal production, under two different management scenarios for marine ecosystems, labelled as Global Commons and World Markets (Pinnegar et al., 2006). Both short-term and long-term models are initialized using actual data (1997–2004) for three main regional production systems: import and export data from the International Fishmeal and Fish Oil Organization (IFFO) are used to estimate the size of the three regional fish stocks considered, fleets and associated transforming industries. The global market is calibrated under the condition that at the present time fish stocks are exploited at their maximum sustainable capacity and that differences in fishmeal production reflect differences in available fish stocks, fleets and technology. This approach allows us to investigate the impact of multiple-scale regional climate-induced alterations on production systems whose products are traded in global commodity markets. The link between climate variability and change, capture fisheries and aquaculture dynamics, and societies' demand for natural resources is proposed as a paradigmatic case study on the limits of ecosystem services under global environmental change.

Table 1
Total aquaculture production (current expansion rate is 6.5% year^{-1}); salmon and trout productions in Chile and Norway (expanding at 8.2% year^{-1}); shrimp and prawn productions in China and Thailand (expanding at 19.2% year^{-1}) and Chinese herbivorous species culture (growing at 5.2% year^{-1})(FAO, 2008).

Year	Aquaculture production (Mt)	Salmon and trout productions in Chile and Norway (Mt)	Shrimp and prawn productions in China and Thailand (Mt)	Herbivorous spp production in China
1997	28.52	0.61	0.33	12.01
1998	30.37	0.67	0.40	12.81
1999	33.24	0.70	0.45	13.73
2000	35.34	0.83	0.53	14.49
2001	37.79	1.01	0.58	15.17
2002	40.23	1.03	0.65	16.11
2003	42.34	1.07	1.12	15.93
2004	45.54	1.20	1.30	16.89
2005	48.05	1.24	1.43	17.91
2006	51.21	1.35	1.74	19.06

2. Material and methods

2.1. A simplified global production and consumption system

A simplified fishmeal system linking distant fish stocks and production systems through a globalized market was designed based on records from IFFO databases (Fig. 1, Table 2). Small pelagic fish populations, fisheries and associated fishmeal industries from three regional systems are considered on the fishmeal supply side: (i) Humboldt Current: Peru and Chile produced an average of 1.8 and 0.82 Mt of fishmeal per year between 2002 to 2006 from Humboldt anchovy (*E. ringens*) and Chilean sardine (*S. sagax*). Peru supplies world fishmeal markets with its entire national production while Chile directs part of its production (25%) to national salmon and trout aquaculture. Their exports are consumed mainly in China, Thailand and Norway to feed their salmon, trout, freshwater and crustacean cultures; (ii) Scandinavian countries: producing approximately 0.76 Mt (15% of total production), mostly from North Sea sandeel and fished by Denmark and Norway. Denmark exports almost its entire production, while Norway supplies local salmon and trout farming industries with 60% of its national production; (iii) China and Thailand: the former is the top fishmeal consumer, importing 18% of the total fishmeal traded and consuming all its production, to feed cultured freshwater and crustacean industries. Thailand uses local fishmeal production but has recently started importing fishmeal from Peru (Deutsch et al., 2007) for shrimp farming. These three regional systems encompass a total of 4.17 Mt or ~70% of the global production and consumption of fishmeal (Mullon et al., 2009), and thus capture adequately the main global patterns (FAO, 2008).

2.2. Modelling structure

2.2.1. The short-term model

A global small pelagic fisheries and fishmeal and oil markets model is used to characterize a global bioeconomic network (Mullon et al.,