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Modelling the sequential geographical exploitation and potential collapse of marine fisheries through economic globalization, climate change and management alternatives

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SUMMARY: Global marine fisheries production has reached a maximum and may even be declining. Underlying this trend is a well-understood sequence of development, overexploitation, depletion and in some instances collapse of individual fish stocks, a pattern that can sequentially link geographically distant populations. Ineffective governance, economic considerations and climate impacts are often responsible for this sequence, although the relative contribution of each factor is contentious. In this paper we use a global bioeconomic model to explore the synergistic effects of climate variability, economic pressures and management measures in causing or avoiding this sequence. The model shows how a combination of climate-induced variability in the underlying fish population production, particular patterns of demand for fish products and inadequate management is capable of driving the world's fisheries into development, overexploitation, collapse and recovery phases consistent with observations. Furthermore, it demonstrates how a sequential pattern of overexploitation can emerge as an endogenous property of the interaction between regional environmental fluctuations and a globalized trade system. This situation is avoidable through adaptive management measures that ensure the sustainability of regional production systems in the face of increasing global environmental change and markets. It is concluded that global management measures are needed to ensure that global food supply from marine products is optimized while protecting long-term ecosystem services across the world's oceans.

Keywords: fisheries modelling, sequential exploitation, economic globalization, climate change, fisheries management.

RESUMEN: MODELIZACIÓN DE LA EXPLOTACIÓN SUCESIVA Y POSIBLE COLAPSO DE LAS PESQUERÍAS MARINAS POR MEDIO DE LA GLOBALIZACIÓN ECONÓMICA, CAMBIO CLIMÁTICO Y ALTERNATIVAS DE GESTIÓN. – La producción pesquera mundial ha superado su máximo potencial y parece estar en declive. Esta tendencia es el resultado de una sucesión de desarrollo, sobreexplotación, agotamiento, y en algunos casos, colapso de los stocks pesqueros individuales. Este proceso conecta recursos distantes a nivel geográfico. Esta secuencia es a menudo atribuida al efecto combinado de una gestión deficiente, consideraciones económicas y efectos ambientales pero la influencia de cada uno de estos factores suele ser difícil de determinar. En el presente trabajo hemos utilizado un modelo bioeconómico global para explorar los efectos conjuntos de la variabilidad climática, presiones económicas y medidas de gestión para producir o evitar esta secuencia. El modelo muestra como una combinación de variabilidad de origen climático en los stocks, el aumento de la demanda de productos marinos y una gestión deficiente es capaz de dirigir las pesquerías mundiales a través de un proceso de desarrollo, sobreexplotación, colapso y recuperación similar a los patrones observados. Además, mostramos cómo el patrón secuencial de sobreexplotación puede emerger como una propiedad endógena de la interacción entre fluctuaciones regionales y un mercado globalizado. Esta situación es evitable con una gestión adaptativa de los recursos que asegure la sostenibilidad de los sistemas de producción regionales en un contexto de cambio y mercados globales. Se concluye con que una gestión global de los recursos es necesaria para garantizar la óptima producción de productos de origen marino y la conservación de los ecosistemas.

Palabras clave: modelización de pesquerías, explotación secuencial, globalización económica, cambio climático, gestión de pesquerías.

INTRODUCTION

The world's fisheries have reached and possibly exceeded their maximum sustainable production potential. Despite increasing fishing effort and technological capacity, global catches have stagnated over the last 2 decades, and may decline if the current rates of exploitation are not reduced (Watson and Pauly, 2001; Pauly *et al*., 2002; Zeller and Pauly, 2005; FAO, 2007; World Bank, 2008). Historical data also indicate that while production in developed countries has declined in the last 35 years, it has increased in developing countries over the same period (Delgado *et al*., 2003).

Several authors have recently argued that the development, growth, overexploitation and collapse that have characterized many natural resources since the 1950s follow a sequential geographical pattern (Orensanz *et al*., 1998; Kirby, 2004; Watson *et al*., 2004; Berkes *et al*., 2006; FAO, 2007; World Bank, 2008; Sethi *et al*., 2010). Berkes *et al*. (2006) summarized that these sequential patterns can deplete stocks faster than regulatory agencies are able to respond to, a process that could only be put right through global institutions with broad authority and conservation incentives. Sequential overexploitation patterns can be explained by a combination of 3 major processes: increasing demand in a globalized market, climate effects and ineffective management. Additionally, overcapacity of the fishing fleets and improved technology have contributed to the unsustainable harvest of fish stocks.

The increasing global demand for marine products caused by both population growth and higher rates of per capita consumption (Delgado *et al*., 2003), combined with constant or reduced catches (FAO, 2007), has increased the value of marine commodities, provided new market opportunities, and thus encouraged further fishing pressure (Delgado *et al*., 2003; Pinnegar *et al*., 2006; Sumaila *et al*., 2007). Geographically distant production systems can pick up global demand thanks to the opportunities provided by economic globalization (O'Brien and Leichenko, 2000; Merino *et al*., 2010a). Thus, global forces can impose additional pressures on resources initially exploited for local consumption.

In addition, climate has emerged as an important issue for fisheries by affecting processes at the bottom of the food web (Brander, 2007; Barange and Perry, 2009; Cheung *et al*., 2009). Climate-driven inter-annual, decadal and inter-decadal fluctuations in regional fish stocks resonate in international commodity markets where prices react to supply variability (Chavez *et al*., 2003; Arnason, 2006; Behrenfeld *et al.,* 2006; Merino *et al.,* 2010a, b).

Finally, inefficient management can amplify the effects of climate-driven fluctuations (Anderson *et al.,* 2008) and is considered responsible for the economic inefficiency, and poor stewardship of global fisheries (World Bank, 2008). While adaptive management systems (Hoggarth *et al*., 2006; FAO, 2007) are being developed to avoid the overexploitation of fish stocks, and are advocated to ensure the recovery of those already overexploited (Worm *et al*., 2009), effective adaptive management is still an exception to the global norm (Mora *et al*., 2009).

Here we build a global network model to demonstrate how economic globalization, climate impacts, and inefficient fisheries management systems interact to drive geographically distant fisheries through the process of sequential development, growth, overexploitation and collapse. The simulated global system is characterized by 10 theoretical, geographically distant and identical regional fisheries production systems which converge in a globalized market and are subject to environmental fluctuations. Each fishery is represented by its own characteristic fishing production system with the goal of maximizing its short term economic return (Lleonart and Merino, 2010). Competent authorities set maximum allowed catches based on maximum sustainable yield management principles (Schaefer, 1954; Seijo *et al*., 1998). Two ways of achieving this objective are contrasted: the first does not consider environmentally driven fluctuations effects on fish stocks, while the second does with a perfect knowledge of the system. In the first, managers underestimate the potential negative environmental effects and aim to maintain high sustainable catch rates. In the second, fleets and authorities adaptively respond to fluctuations to reach maximum sustainable yield (MSY) targets. The price for the resultant fish products in the international market is the result of the global production, the so-called "market externality" (Oakerson, 1992; Merino *et al*., 2007), thus driven by both global demand and supply of the marine commodity. Alternative management principles are implemented in the simulations to investigate the ability of efficient adaptive systems to avert or slow down the sequential principles of geographical overexploitation.

The work aims to understand the synergies between global market and climate drivers in amplifying fluctuations in the production and exploitation patterns of marine commodities, how these synergies can trigger sequential overexploitation and collapse patterns, and how adaptive management can be used to sustain the underlying resources. The main novelty of this modelling work is that fisheries are described as a global issue in which the fate of distant resources is interconnected.

MATERIALS AND METHODS

The bioeconomic network model used is inspired by patterns of global fisheries production systems. The network is composed of 2 layers. The first layer includes N production systems composed of their fish stocks and fishing fleets. Each of the $i = 1, 2 \ldots N$ fish stocks are characterized by a logistic growth and a harvest rate (Schaefer 1954). The harvest rate is driven by fleet activity dynamics, considered here to follow a short-term economic maximization strategy (Lleonart and Merino, 2010). Fleets and human capital involved in fisheries operations are not fixed, but producers are only able to modulate their fishing effort to a certain extent (Clark *et al.*, 2005). The model imposes that producers can vary their yearly fishing effort to be between 70 and 130% of the previous year. The simulation model assumes that managers' knowledge of the system is complete in relation to the periodic state of their regional fish stocks and their cost of fishing, and delayed in relation to the market price they will get for their product. Producers will modulate their fishing effort so that they will maximize their economic profits at each time interval. To do so, they will account for the expected revenues from selling their product and their fishing cost, which in this model are limited to a proportionality function to the distance between the stock and the globalized market (production and consumption). The equations that describe production system dynamics are as follows:

Biomass dynamics are driven by logistic growth and harvest of each of the i stocks (Eq. 1), where r is the intrinsic growth rate, K is the carrying capacity parameter or pristine biomass, defined as that reached by the fish stock in the absence of fishing, B is the stock biomass and Y is the catch:

$$\partial B_i / \partial t = r\, B_{i,t}\,(1 - B_{i,t} / K_i) - Y_{i,t} \qquad (1)$$

We approximate the discrete time interval solution and introduce a normally distributed climate variability factor in the stocks biological production (Eq. 2), where the mean of the normal distribution is μ and the standard deviation σ:

$$B_{i,t+1} = B_{i,t} + r B_{i,t}(1 - B_{i,t}/K_i)\,N(\mu = 1, \sigma = 0.25) - Y_{i,t} \qquad (2)$$

Yield (Y) is the product of the fishing mortality (F) and the available stock biomass. Fishing mortality is composed of the catchability coefficient (q), or fishing mortality produced by a unit of fishing effort, and fishing effort itself (E) (Eq. 3). The producers' yearly effort strategy aims to maximize their profits (π) in that fishing period. To do so, revenues and cost of fishing will be calculated, based on the price (p) of fish at international markets and the cost (c) per unit of effort. As can be deduced, the cost of a harvest unit will depend upon the fish stock level, i.e. scarce resources are more expensive to exploit than abundant ones.

$$Y_{i,t} = F_i\, B_{i,t} = q_i E_{i,t}\, B_{i,t} \qquad (3)$$

$$\pi_{i,t} = p_t\, Y_{i,t} - c_i E_{i,t} \qquad (4)$$

Note that the price-to-cost ratio will be a key variable for analyzing fisheries development. The fishing effort that producers will choose will be that which maximizes their profits with the following malleability limitation: the following condition will be satisfied if a 30% variation on the previous year's effort is allowed:

$$\pi\,(E_{i,t}) \geq \pi\,(E^*_{i,t}) \text{ for any}$$
$$E^*_{i,t} = [0.7E_{i,t-1}, ..., E_{i,t-1}, ..., 1.3E_{i,t-1}] \qquad (5)$$

Regional producers' strategies will be limited by management policies too. Producers' catch will be modulated by 2 alternative measures. Initially, yield is limited through management by the estimated MSY. For the Schaefer model assumed here, MSY is defined as $r_i/2q_i$ (Seijo *et al.*, 1998), which would prevent stock biomass from falling below 50% K_i=B_{MSY} in a stable environment. As a consequence, this management system does not consider the potential negative effects of environmental fluctuations on fish stocks. Another way of seeing it is that managers tend to underestimate the probability of a negative environmental event occurring and thus assume a mostly optimistic view of the uncertainty about fish stocks' response to fishing and climate. Furthermore, it mimics the aim of fishing at high rates at any time. Alternatively, adaptive management is imposed on to yearly catch limits so that fish stocks will reach their B_{MSY} levels the following year. This management system assumes that the periodic knowledge on the state of the exploited stock is complete, and no uncertainty is thus considered. As we will discuss in the last section of the manuscript, none of the above management scenarios fully reflects the real decision-making process in fisheries management but they are useful for understanding global fisheries trends.

Catch limits (Y^+) imposed by adaptive management are estimated by:

$$Y^+_t = B_{i,t} - (K_i / 2) + r_i\, B_{i,t}\,(1 - B_{i,t} / K_i) \qquad (6)$$

If exploiters' effort decisions involve fishing beyond their limits, their effort is automatically driven to levels that will produce the permitted maximum catch.

The second layer of the network is the globalized market. Trade occurs when market equilibrium conditions are reached (Nagurney, 1993; Mullon *et al.*, 2009), which means that the price consumers are willing to pay for the marine commodity meets the price producers ask to produce the demanded quantity of commodity. For a constant supply, if the quantity of product demanded increases, its price will increase and, for a constant demand, the price will increase if the quantity supplied declines. We formulate this equilibrium with a linear price:

$$p_t = \alpha_t - \beta \sum_{i=1}^{I} Y_i \qquad (7)$$

where α is the maximum price that consumers would pay for the last unit of the marine commodity and β is the price flexibility which reflects how the price will react to fluctuations in the supply for a given level of demand, driven by the dynamics of α. Demand has been imposed to grow exponentially in time following:

$$\alpha_{t+1} = \alpha_t + \gamma^t \qquad (8)$$

where γ^t is the time-dependent annual increase in demand. Equation 7 allows the market externality to be modelled (Oakerson, 1992). The price that producers expect to obtain for their product depends not only on their production but on the production of other producers too. Moreover, a decline in the supply of a distant production system will increase the economic opportunity for other producers.

The above equations allow us to investigate through simulation how market and climate dynamics interact and amplify their individual signals. It also allows recommendations to be made on the basis of the 2 alternative management scenarios considered. The simulation seeks to understand how global fisheries have been driven through 6 different phases of development (pre-development, growth, full exploitation, overexploitation and recovery or collapse) in recent decades, when strong socioeconomic changes have impacted fisheries simultaneously with multi-scaled temporal environmental fluctuations (Delgado *et al.*, 2003; FAO, 2007; Barange and Perry, 2009).

In order to make the model tractable, the numerical parameterization of the network is based on some simplifying assumptions. First, the 10 stocks considered are identical in biological terms, i.e. their intrinsic growth rates and carrying capacities are the same. Moreover, the fishing fleets' technical capacities are also identical, so they all have the same catchability coefficient. Differences among fish stocks are uniquely related to their distance from the global market (Fig. 1), which determines fishing cost. The parameters used in the numerical simulations are shown in Table 1.

RESULTS

The bioeconomic network model is used to explain the different phases that interconnected fisheries go through. In the first simulation (Fig. 2) the only economic driver reflects historical increases in demand for marine commodities, but without fluctuating resources. Fishing starts because there is a market demanding marine commodities. In the following years, under this simplistic simulation global demand does not perturb the price-to-cost ratio of each production system. As the cost of fishing is proportional to the stock's distance from a single global market, if the price of the marine commodity increases at a constant rate, single exploiters start fishing when a certain price-to-cost ratio is reached (Fig. 2). Note that the same pattern would have been obtained if instead of increasing price for marine commodities we had modelled a constantly decreasing fishing cost. The price–to-cost ratio expansion drives each fishery through pre-development, growth and full exploitation phases. In the model fisheries are regulated through equilibrium MSY limits. As a certain human and technical capital, activity or fishing effort is reached, the producer's strategies will be limited so that the estimated MSY is not exceeded and the fishing effort remains at levels that maximize ecosystem productivity. Under the MSY regulation and after a certain critical price-to-cost ratio is reached,

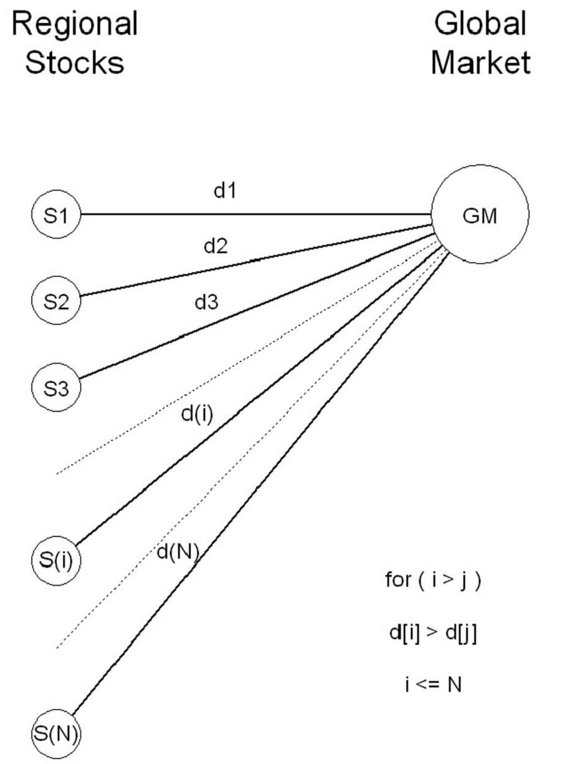

FIG. 1. – Model framework. The *N* regional fish stocks (S_i) have identical productivity, and the only significant difference among them is their distance from the globalized market. This distance is translated into larger fishing cost for resources located furthest away from the market.

TABLE 1. – Model parameter values. While they are scaled to real examples, they do not fit to any particular fishery. Biological parameters are *r* (intrinsic growth rate), *K* (carrying capacity), *q* (catchability coefficient). Environmental fluctuations are normally distributed (μ = mean and σ = standard deviation). Economic parameters are *c* (cost of fishing), α_0 (maximum price of the marine commodity at t = 0), β (flexibility of price to changes in supply) and γ (yearly increase in demand for marine commodity).

	r	K	q	c	μ	σ
Production Systems	1	10^6	5×10^{-4}	i=1: 1 i=2: 600 2<i<10: 250 + c_{i-1}	1	0, 0.25

	α_0	β	γ
Global market	1	0, 5×10^{-5}	0.01

the global fisheries production is maximized because all the individual fisheries remain at full exploitation or MSY levels.

In the second simulation (Fig. 3) we introduce fluctuations in market conditions. Price dynamics are now not just driven by a constant demand but, at certain levels, the increase in fisheries production slows down the price-to-cost ratio, so fleet activity fluctuates according to demand, and so does yield. Thus, price dynamics are the cause of the observed variability. However, after the critical price-to-cost ratio has been exceeded, demand drives the fisheries

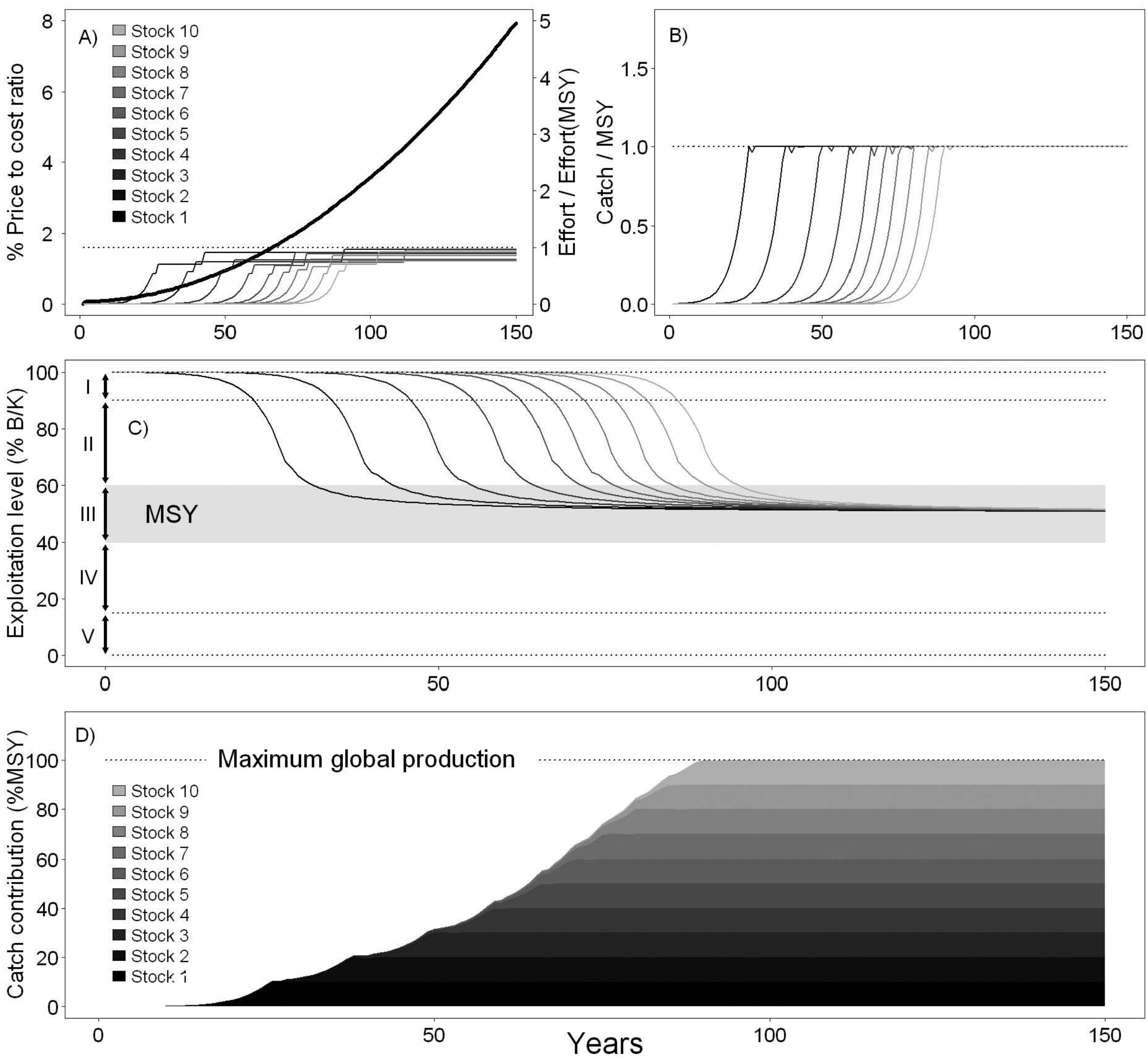

Fig. 2. – Dynamics of the global fisheries over a 150-year simulation, driven solely by an increase in the demand for marine commodities, and managed according to MSY criteria. A) Price of the marine commodity as a function of its production cost (thick line), representing the change in demand (averaged for the 10 fisheries). The fishing effort applied by regional fisheries in their fish stocks in relation to the effort that would produce maximum sustainable catches is shown in thinner grey shades. Dotted line represents the effort that would produce maximum sustainable catches. B) Regional fisheries catch in relation to their MSY values over 150 years. MSY is indicated by a dotted line. C) Available biomass in the regional stocks, in relation to their pristine levels, and indication of the exploitation phases for each stock (I, Pre-development; II, Growth; III, Full exploitation; IV, Overexploitation; V, Collapse; VI, Recovery). Grey region indicates MSY obtained when the available biomass is nearly 50% of the carrying capacity. Note that the MSY regulation under conditions of biological equilibrium prevents stocks from reaching overexploitation. D) Global fisheries production in 150 years, in relation to their potential maximum, which is achieved when the 10 fisheries are fully exploited. The maximum global production is thus related to the maximum potential productivity of marine ecosystems in stable conditions.

exploitation phases. After this critical price-to-cost ratio is exceeded, global fisheries follow the same patterns as those observed in Figure 2. Stocks never fall below $B_{MSY}=(K/2)$ and world fisheries reach their maximum production capacity before the 100th year of the simulations and remain at the full exploitation phase thereafter. In both simulations shown until this point, the ecosystem's potential is optimized as all 10 stocks are fully exploited.

The third simulation investigates how climate perturbations can destabilize the global network when occurring simultaneously with demand expansion. A first look at Figure 4 suggests instability and collapse of global fisheries. The initial years of the simulation show a similar pattern to that in Figure 3. However, following the sequential exploitation of stocks until phase III, they seem to become vulnerable to climate fluctuations. Approximately at a time when the price-to-cost

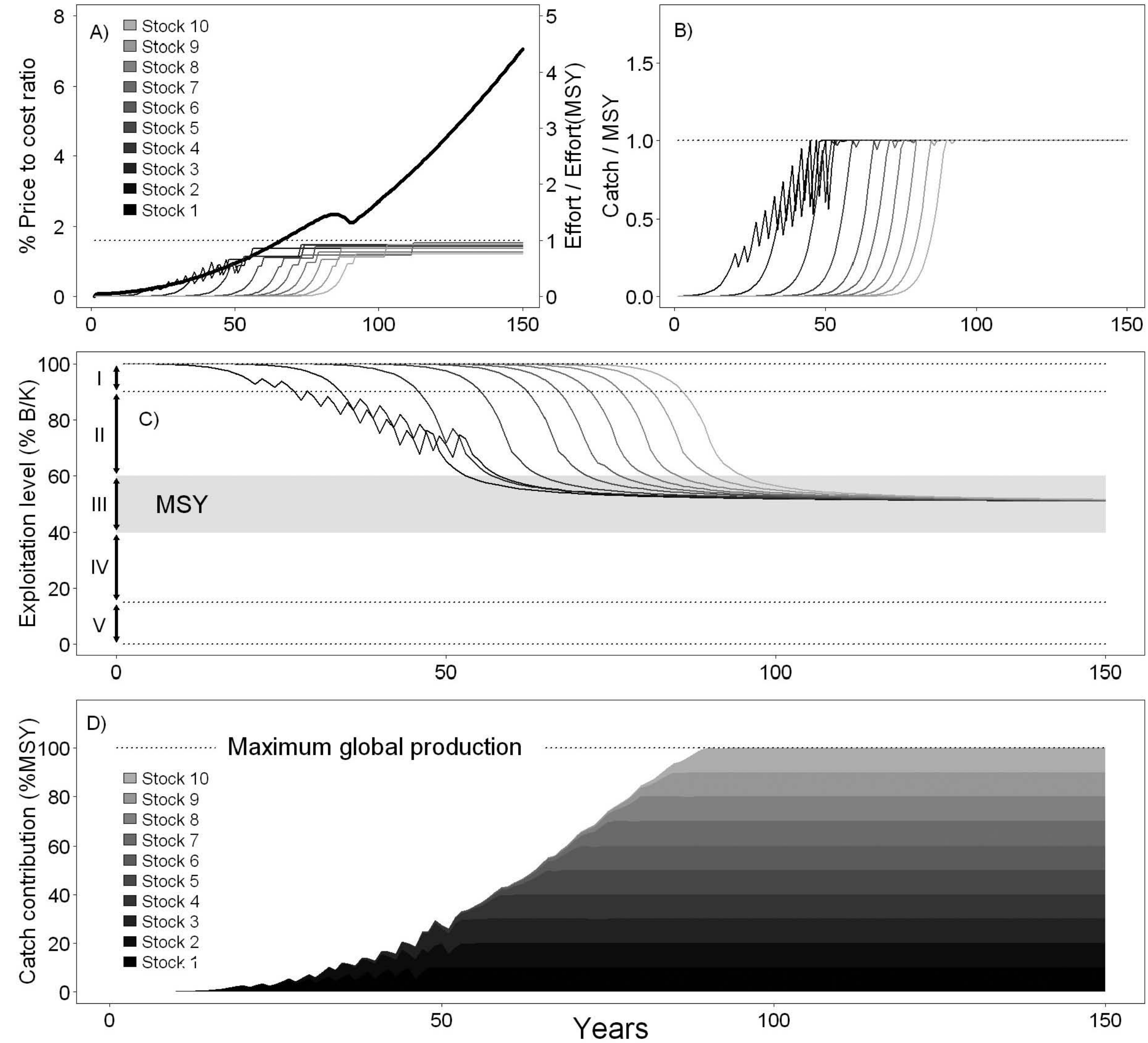

FIG. 3. – Dynamics of the global fisheries over a 150-year simulation, driven by an increase in the demand for marine commodities and market equilibrium, and managed according to MSY criteria. A) Price of the marine commodity as a function of its production cost (thick line), representing the change in demand (averaged for the 10 fisheries). The fishing effort applied by regional fisheries in their fish stocks in relation to the effort that would produce maximum sustainable catches is shown in thinner grey shades. Dotted line represents the effort that would produce maximum sustainable catches. B) Regional fisheries catch in relation to their MSY values over 150 years. MSY is indicated by a dotted line. C) Available biomass in the regional stocks, in relation to their pristine levels, and indication of the exploitation phases for each stock (I, Pre-development; II, Growth; III, Full exploitation; IV, Overexploitation; V, Collapse; VI, Recovery). Grey region indicates maximum sustainable yield obtained when the available biomass is nearly 50% of the carrying capacity. Note that the MSY regulation under conditions of biological equilibrium prevents stocks from reaching overexploitation. D) Global fisheries production in 150 years, in relation to their potential maximum, which is achieved when the 10 fisheries are fully exploited. The maximum global production is thus related to the maximum potential productivity of marine ecosystems in stable conditions.

ratio doubles, the system is dominated by demand, resulting in a sequential development and growth of the global fisheries. It is at the time when stocks reach their full exploitation phase that negative or unfavourable climatic perturbations make single stocks fall below B_{MSY} levels. As this occurs when the price and cost ratio is beyond a critical level, producers are economically motivated to reach their assigned catch limits. They do so by investing in fishing effort, which increases to 5 times the level that would be consistent with ecosystem productivity or E_{MSY} (dotted line in Figure 4A). The catch limits are set again by MSY equilibrium estimations and they are fulfilled by removing a larger fraction of the available biomass, below B_{MSY} due to the unfavourable climatic perturbations. When this happens, i.e. when a negative climatic perturbation impacts a fully exploited stock in synergy with certain demand values, a single stock is driven into the overex-

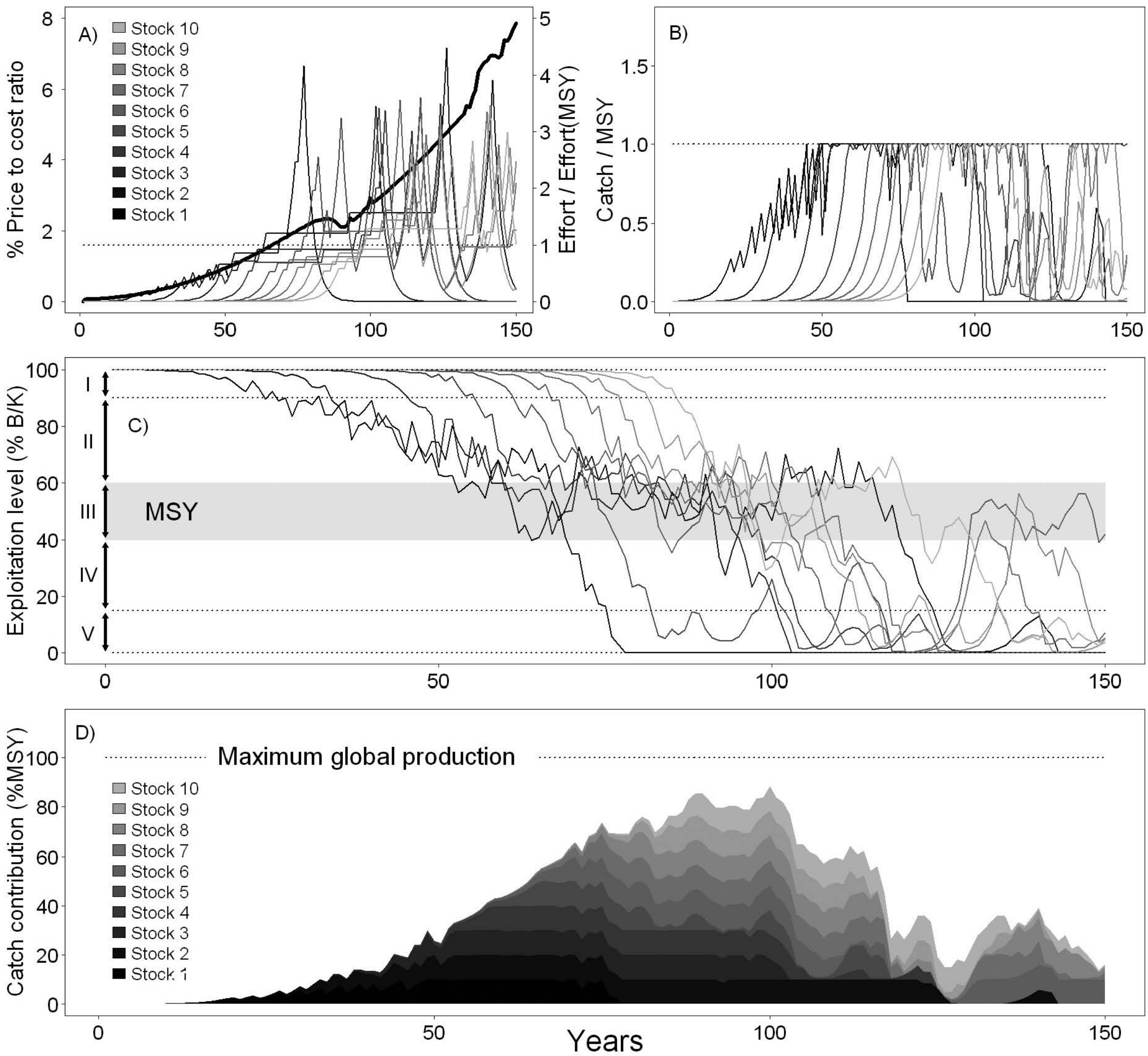

FIG. 4. – Dynamics of the global fisheries over a 150-year simulation, driven by an increase in the demand for marine commodities, market equilibrium and environmental (production) fluctuations, and managed according to MSY criteria. A) Price of the marine commodity as a function of its production cost (thick line), representing the change in demand (averaged for the 10 fisheries). The fishing effort applied by regional fisheries in their fish stocks in relation to the effort that would produce maximum sustainable catches is shown in thinner grey shades. Dotted line represents the effort that would produce maximum sustainable catches. B) Regional fisheries catch in relation to their MSY values over 150 years. MSY is indicated by a dotted line. C) Available biomass in the regional stocks, in relation to their pristine levels, and indication of the exploitation phases for each stock (I, Pre-development; II, Growth; III, Full exploitation; IV, Overexploitation; V, Collapse; VI, Recovery). Grey region indicates maximum sustainable yield obtained when the available biomass is nearly 50% of the carrying capacity. D) Global fisheries production in 150 years in relation to their potential maximum, which is achieved when the 10 fisheries are fully exploited. The maximum global production is thus related to the maximum potential productivity of marine ecosystems in stable conditions.

ploitation phase. Recovering a stock from overexploitation and avoiding collapse would imply fishing less than the estimated MSY but once an overexploitation phase has been entered and there is enough economic incentive to fulfil MSY catch limits, the stocks will be driven to collapse. When this happens, even the high price of the product is not enough to make fleet activity profitable and effort is subsequently reduced. Stocks are then allowed to enter a recovery phase until the exploitation becomes profitable again, when the process starts again. In this case, regional shifts in ecosystems could be triggered not only because of climatic factors (Chavez *et al*., 2003) but also because of fishing activity (Anderson *et al*., 2008). Figure 4D shows that the sequential overexploitation and collapse of the closest fisheries (those with the lowest transport cost) occurs before the development and growth of the farthest ones. The development of the more distant resources might disguise the negative effects of overexploitation and collapse of the depleted stocks and give the

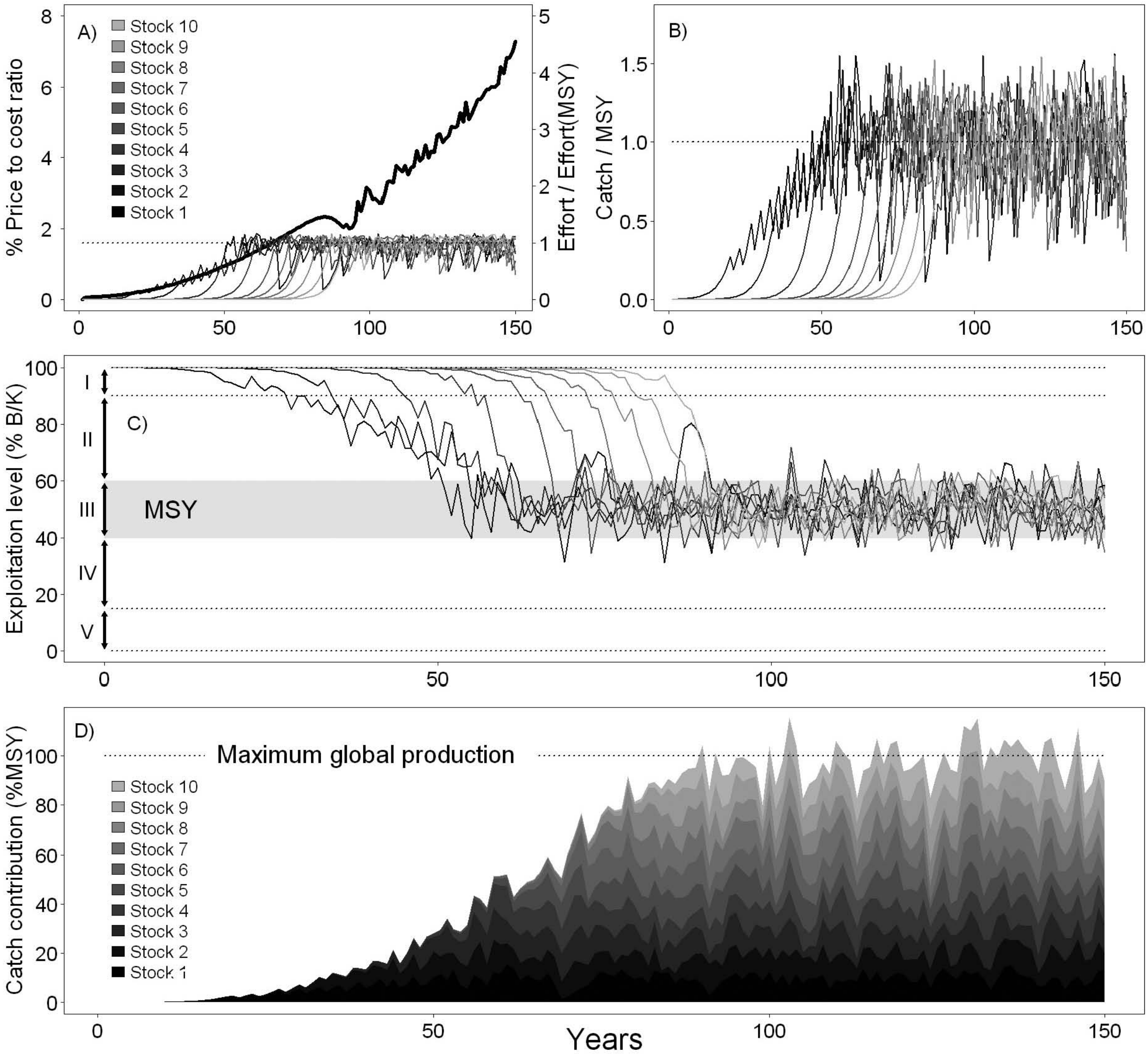

FIG. 5. – Dynamics of the global fisheries over a 150-year simulation, driven by an increase in the demand for marine commodities, market equilibrium and environmental (production) fluctuations, and managed adaptatively to drive stocks to B_{MSY} levels. A) Price of the marine commodity as a function of its production cost (thick line), representing the change in demand (averaged for the 10 fisheries). The fishing effort applied by regional fisheries in their fish stocks in relation to the effort that would produce maximum sustainable catches is shown in thinner grey shades. Dotted line represents the effort that would produce maximum sustainable catches. B) Regional fisheries catch in relation to their MSY values over 150 years. MSY is indicated by a dotted line. C) Available biomass in the regional stocks, in relation to their pristine levels, and indication of the exploitation phases for each stock (I, Pre-development; II, Growth; III, Full exploitation; IV, Overexploitation; V, Collapse; VI, Recovery). Grey region indicates maximum sustainable yield obtained when the available biomass is nearly 50% of the carrying capacity. D) Global fisheries production in 150 years in relation to their potential maximum, which is achieved when the 10 fisheries are fully exploited. The maximum global production is thus related to the maximum potential productivity of marine ecosystems in stable conditions.

impression that a constant high catch is sustainable. Any negative trend in global supplies is thus smoothed by the development of new fisheries and a relatively apparent stable global production is maintained over 2 decades (years 75-95 in the simulation), before the sequential collapse becomes obvious at a global scale. It must be noted that each fishery's collapse imposes an additional pressure on other stocks through the market equilibrium condition. When the global supply declines due to the collapse of a fishery, a well-established globalized economic system allows consumer demand to shift between production systems. As a consequence, the economic incentive to fish is accelerated in the last years for those distant producers (Fig. 4A, solid line). Note that MSY catch limits have never been exceeded in this simulation, and that the sequence of overexploitation and collapse does not necessarily follow the same sequence of full development. What triggers the collapse is the negative climatic signal, which is set through a normal distribution when it happened at the same time as high demand levels. Similar simulations run with several iterations would reorder the sequence of collapse and then, as the sequence of fisheries entering their full exploitation phase follows a geographical pattern, those who remain longer at MSY levels will be those that collapse first.

In the final scenario (Fig. 5), an adaptive regulation system is able to cope with synergies between markets and natural fluctuations in fish stock abundance. Every year, after the state of the resources is monitored, fishing quotas are set so that stocks will be driven to B_{MSY} levels. The development and growth phases are very similar to previous figures. In contrast, once the critical price-to-cost has been reached and the global fisheries have entered the full exploitation phase, regulators will impose a decrease in yearly catches if they are negatively affected by a climatic fluctuation. Thus, stocks will recover to B_{MSY} levels. If the environmental signal is positive, adaptive management will allow a yield larger than MSY. Once the critical price-to-cost ratio has been exceeded, the marine commodities price will be driven both by the constantly expanding demand and by climate-induced supply variability. At this full exploitation level, fleet fishing effort will remain at E_{MSY} levels, set accordingly to the periodic climate-induced biomass variability and without further economic considerations. After the world's fisheries have reached their maximum capacity in the simulation, the global supply fluctuates around their maximum potential. The probability of exceeding the average maximum potential is determined by the mean of the normally distributed environmental function in the model. Note that a very strong assumption is considered here, i.e. that the knowledge of the system is perfect.

DISCUSSION

Our simulations suggest that the synergies between global markets and regional climate can potentially trigger a sequential overexploitation and collapse of the resources. However, from a theoretical point of view, this situation may be managed to secure global sustainability.

In recent decades technological developments have increased fisheries catches and allowed the exploitation of remote marine ecosystems. Our first 2 simulations consider that every fish population has the potential to produce a harvestable surplus and that the harvest that could be removed is determined by the MSY which can be estimated (Lackey, 2005). Management targets following this assumption are estimated to be potentially stable, e.g. where the sustainable yield and/or economic revenue are maximized (Gordon, 1954; Lleonart and Merino, 2010). For both, fisheries development is triggered by economic profits (Sethi *et al.,* 2010) and regulated following ecosystems' capacity to replace the removed biomass. In our second simulation, the initial development phase of a fishery is characterized by a market interaction between producers and consumers, producing fluctuations in the system. However, once the demand is sufficiently high it encourages the full development of the fishery. When a critical price-to-cost ratio is reached, producers tend towards MSY conditions and not MEY (maximum economic yield) conditions, even though the fishery is driven by economic incentives, which may seem contradictory to equilibrium solutions in classic bioeconomic models (Gordon, 1954). This happens due to 2 particularities of our model: First, MSY and MEY targets assume constant market and environment conditions. In our first 2 simulations (Figs. 2 and 3), the environment is considered to be stable, which validates the MSY capacities, but not the market, considered to be subject to a constant increase in demand and a market equilibrium. MSY and MEY tend to converge as the price-to-cost ratio increases (Gordon, 1954; Lleonart and Merino, 2010), which may be caused by price increases in concert with growing demand or cost reductions arising from technology, subsidies or other economic incentives (Clark *et al*., 2005). Second, in the model exploiters maximize not their sustainable economic yield but their short term economic return and, as demonstrated in Lleonart and Merino (2010), exploiters tend to exceed the MSY point. Maximizing short-term economic profit has been identified as another cause for the unsustainable exploitation of fisheries (Pauly *et al*., 2003; Clark *et al*., 2005; Lleonart and Merino, 2010).

Despite being commonly perceived as national or regional, fisheries have gone through similar sequential exploitation phases, which confirm that regional fisheries are not isolated systems (Pauly *et al*., 2003; Watson *et al*., 2004; Berkes *et al*., 2006). In the network model proposed here, marine resources are not geographically isolated but part of a common resource in a globalized economic market (Oakerson, 1992). The consequence of globalization, as demonstrated through simulation, is the sequential exploitation, overexploitation and collapse of the world's fisheries. The synergies between climate change and economic globalization have been pointed out as being responsible for the sequential overexploitation of marine resources observed since the mid-20th century (O'Brien and Leichenko, 2000; Berkes *et al*., 2006). In our network, the demand for marine products provides an incentive for the development of fisheries in a sequential pattern, with the closest production systems being exploited first, and thereafter, when the demand is high enough farther ones are exploited too. In reality, the early development phases of global fisheries ended in the Northern Atlantic soon after second world war and in the rest of the world between 1960 and 1990 (Christensen *et al*., 2003; Garcia, 2009; Sethi *et al*., 2010).

Climate change and environmental oscillations can produce fluctuations in fisheries production at inter-annual, decadal and inter-decadal scales (Chavez *et al*., 2003; Barange and Perry, 2009). Fishing can amplify environmentally driven fluctuations, cause fish distribution changes, alterations to fish age structure (Hsieh *et al*., 2006; Anderson *et al*., 2008; Hsieh *et al*., 2009) and alterations to ecosystems (Pauly *et al*., 1998; Essington *et al*., 2006). Periods of variable price, driven by climate-induced fluctuations in small pelagic fisheries supply, or by increases in fishmeal demand due to aquaculture expansion, have been observed in recent decades (Chavez *et al*., 2003; Merino *et al*., 2010b). In our model climate perturbations are introduced by a random yearly fluctuation. Stock variability is considerably larger when stocks are fully exploited (phase II). There are alternative explanations to why fishing magnifies fluctuations in fish abundance (Anderson *et al*., 2008) and our model mimics this phenomena using a perturbation term that multiplies the stock's surplus production or a logistic term, which is maximum when the stocks are close to their MSY levels. In contrast, our model considers that as stocks tend to carrying capacity or extinction, the variability tends to disappear. Another issue with the adopted assumption of randomness in variability is that the probability of a positive effect of the environment on the recruitment or other process is equal to that of negative ones. In practice, good environmental effects are more exceptional than bad ones, which seem to be more frequent for example for the Peruvian anchoveta recruitment in the Pacific (Chavez *et al*., 2003). Introducing this effect in our modelling framework would probably accelerate the collapse of fish stocks.

The synergies between environmental and market drivers are managed in 2 alternative ways in our model. In Figure 4, the synergies are managed through a quota system based on the regionally estimated MSY. This management system seeks stable and maximum catches. Our model assumes that the knowledge of the system is complete, except for the environmental variability, and that exploiters' compliance is complete, which is far from being accurate (Mora *et al*., 2009). With this management system fisheries sequentially become overexploited and collapse. As discussed, these developments can create the illusion of global production being stable. FAO and other international databases report stagnated global catches of 95 Mt annually although several important stocks have been depleted during the last 3 decades (Pauly *et al*., 2003). Similar compensations of declining and developing resources have been observed not only in real fisheries (Berkes *et al*., 2006; Scales *et al*., 2006) but also in some non-renewable resources (Curtis, 2009). While the global collapse emerges here as a result of a theoretical simulation, it has been predicted using real fisheries data (Worm *et al*., 2006), although those predictions were later rebutted by the same authors (Worm *et al*., 2009).

An additional consequence of the simulations under a stable MSY target management scheme is overinvestment. In order to fulfil their assigned quotas, exploiters have economic incentives to invest in fishing effort, which in certain phases, for a high enough price-to-cost ratio, multiplies the estimated fishing capacity of developed fisheries by a factor of 5 in our simulation. Our results illustrate how world's fisheries have been overcapitalized following economic opportunities. Overcapitalization is one of the causes of the state of world fisheries and an important issue for future international policies (Pauly *et al*., 2003; FAO, 2007; World Bank, 2008; EU, 2009).

Our simulations were run under the assumption of a constantly increasing demand for marine commodities (Delgado *et al*., 2003). In contrast, some authors demonstrate that prices of fish fell in the period 1950-2002 (Sumaila *et al*., 2007). However, the price-to-cost ratio has increased due to other reasons, such as the development of fishing technology and subsidies. The development of new fisheries has been mediated by the establishment of new markets and their associated trade opportunities. Although our way to model the increasing demand by a price function may be debatable, the effective price-to-cost ratio that explains profits and fisheries dynamics is accurate (Sethi *et al.,* 2010). Another important factor that could modulate demand is substitution. Eventually, if a valid substitute is found for a marine commodity, as happens with the replacement of fishmeal by soymeal, the demand for a marine commodity will presumably be reduced. The effect of substitution in fishmeal has been analyzed in empirical studies (Kristofersson and Andersson, 2004) and with theoretical models (Merino *et al.,* 2010a; Briones, 2006) and could be incorporated in the model used here in the future.

All our simulations were run under the condition of constant catchability. However, technological development and the increasing demand for marine products has encouraged fishing fleets to exploit increasingly remote resources (Pauly *et al*., 2002). While a technological development parameter was initially added to the model, it was eventually removed for the sake of simplicity, as it did not introduce significant changes in the results. However, increasing the price-to-cost ratio accounts for the effects of technological development, as it aims to reduce the cost of fishing in a similar way as it aims to increase fishing capacity.

Our simulations are run with theoretical parameters. However, non-dimensional variables are shown in our figures. More accurate parameters would produce variations in the contribution of single stocks to global fisheries production and accelerate or decelerate their time in each exploitation phase. Moreover, only 10 fish stocks are considered to represent world's fisheries, which is a major simplification. Increasing the number of stocks simulated would make our analysis a bit fuzzier and would not provide a relevant clarification to our discussion.

The management based on a stable MSY criterion (Figs. 2, 3 and 4) implies ignoring the natural variability affecting fish stocks even without fishing (Hilborn and Walters, 1992) and proved inefficient (Pauly *et al.,* 2002). Adaptive management has recently been promoted as one of the factors that sustain the recovery of endangered fish stocks (Worm *et al*., 2009). In our model, we have introduced an adaptive management scheme that sets quotas periodically using yearly fish stock assessments. In the simulation shown in Fig. 5, adaptive management measures were effective in avoiding the risk of collapse of fully exploited stocks, even when they were negatively affected by environmental conditions. In contrast, when a favourable climatic cycle occurs, catch is allowed to exceed the estimated MSY, so the extra ecosystem productivity was optimized. Fully developed fisheries would fluctuate largely driven by climate and additional fishing effects. Fishing effort would fluctuate accordingly, similarly to what in practice happens when abundance cycles modulate fleet activity and production in annual, inter-annual and inter-decadal scales following well-known environmental events in upwelling and cascading regions (Chavez *et al*., 2003; Company *et al*., 2008; Maynou, 2008). In this simulation, global fisheries fluctuate within the limits of the ecosystem's maximum production potential. Adaptive management, under the assumption of full knowledge of the system's dynamics and compete compliance, would lead to the optimum use of marine ecosystems.

In practice, the majority of managed fisheries aim to apply adaptive management, but their knowledge of the system is not perfect as we considered in our simulations. Current management aims at harvesting at a rate likely to lead to MSY, resulting in lower catches when biomass is low for any reason, including natural or human. Inefficient management causes collapses due to a combination of reasons, including poor knowledge of stock status, undermining the potential negative effects of uncertain environmental drivers, and the aim of maintaining high catches (Larkin, 1977). Another cause of collapse is the delayed response to scientific assessments, as happened in the Bay of Biscay anchovy recently (De Oliveira *et al.,* 2005). In contrast, some fisheries show a significant reactivity to signals of a potential environmental impact on fish stocks, as happens with the anchoveta fishery off Peru, where the national fishery is completely closed 2 days after El Niño signals have been detected (Arias-Screiber *et al.,* 2010). As stated in the introduction, we designed a simplistic, highly inefficient management scenario that was compared to a perfect adaptive management one. None can be assigned to reality but our results suggest the need to increase our knowledge in order to provide better periodic stock assessments, to reduce the uncertainty of climate impacts on fish stocks, and to adapt flexible fishing industries to dynamic ecosystem opportunities. Furthermore, our results indicate that economic globalization allows our fisheries to be understood as a common issue, which should therefore be managed following international agreements.

In conclusion, this work suggests that the combination of global rising demand for marine products and regional climate-induced variability requires a global and adaptive perspective. It will help to optimize and protect the services obtained from marine ecosystems. This work also suggests the need for further research aimed at reducing uncertainty about climate impacts on fisheries in order to assess the courses of action to enhance the sustainable use of marine resources. Adaptive management, in addition to the ecosystem and precautionary approaches, can improve the global ecosystem's performance (Cury *et al*., 2008; Worm *et al*., 2009).

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