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The dynamics of collapse in world fisheries

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Abstract

The fear of a rapid depletion of world fish stocks because of over-exploitation is increasing. Analysis of 1519 main series of the FAO world fisheries catch database over the last 50 years reveals that 366 fisheries' collapses occurred, that is nearly one fishery of four. The robustness of this result is tested by performing several complementary analyses using different conservative options. The number of collapses has been stable through time since 1950s indicating no improvement in the overall fisheries management. Three typical patterns emerge from the analysis of catch series during the period preceding the collapses: smooth collapse (33%), i.e. a long regular decline, erratic collapse (45%), i.e. a fall after several ups and downs, and a plateau-shaped collapse (21%), i.e. a sudden fall after a relatively long and stable persistence of high level of catches. Using a simple mathematical model, we relate the plateau-shaped collapses (which are, by nature, the most difficult to predict) to surreptitiously increasing exploitation and a depensatory mechanism at low population levels. Thus, a stable level of catch over several years is shown to conceal the risk of a sudden collapse. This jeopardizes the common assumption that considers the stability of catch as a goal for fisheries sustainability.

Keywords catch, depensation, fishing efficiency, fishing effort, overexploitation, production models, stock assessment

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Introduction

Serial depletions of marine fish stocks because of over-exploitation are endangering the future of marine fisheries and this issue is largely debated within the scientific community (e.g. Pauly *et al.* 2002; Baum *et al.* 2003; Myers and Worm 2003). Such depletions may also lead to species extinction (e.g. Casey and Myers 1998; Dulvy *et al.* 2003) and to ecosystem regime shifts (Jackson *et al.* 2001). In this context, a precautionary approach to fisheries management requires a better understanding of the dynamics of past collapses and the detection of early warning signs.

In an attempt to evaluate the current state of the world fisheries, FAO has collected a quasi-exhaustive data set of catches since the 1950s, and classified the 200 major fisheries resources into four phases of development (undeveloped, developing, mature or senescent) along with the observed patterns of catch (Garcia and Grainger 1997). According to this classification, undeveloped fisheries (0% in 1994) are characterized by a period of stable catches followed by a period of increase, while developing fisheries (25%) are those showing an increasing trend in the time series of catches. Mature fisheries (50%) are characterized by stable catches over the entire period. Senescent fisheries (25%) are those whose time series display a decreasing trend, or stability followed by a marked decline. This simple analysis matches a more sophisticated one performed on available FAO data at the end of 1999 on 441 'stock' items, for which there was some information on the state of the stocks based on stock assessment methods (Garcia and de Leiva Moreno 2003). The stock items were classified as under-exploited (4%), moderately exploited (21%), fully exploited (47%), overexploited (18%), depleted (9%) or recovering (1%), depending on how far they were – in terms of biomass and fishing pressure – from the levels corresponding to full exploitation.

These analyses provide a global view on the state of the world fisheries, but do not intent to explicit their dynamics. They develop an empirical approach based on the analysis of the patterns of exploited stock without detailing the processes that are involved in collapses. Here we propose to focus on past collapses, aiming to make explicit their dynamics.

Fisheries collapses have, most of the time, been related to stocks depletions (Pauly *et al.* 2002; Baum *et al.* 2003; Myers and Worm 2003) although other factors can also play a major role: some of these events are the result of the closure of a fishery for administrative or economic reasons. Let us make it clear that collapses of single species or genus catches by a national fishery were thus considered in the core of this study. The rationale of this choice was to make use of the elementary data in the FAO database, that is the catch per country per area, without having to make use of debatable aggregation; we have performed complementary analysis to check the validity of this choice.

Few fisheries collapses are the result of purely economic or administrative reasons. Not all of them are associated with the downfall of the stock. But when they are, they become a paradox in the framework of the conventional theory of fisheries (Beverton and Holt 1957; Ricker 1975): these theories are based on an equilibrium principle, which ensures that, if effort is constant and not too high, there is a stabilization of stock and catch at a given level. This allows the evaluation of maximum sustainable yields and the corresponding effort, and thereby hypothetically ensures that if fishing effort is maintained at, or below, a reasonable value, collapses should never occur. Nevertheless, they do occur. Therefore, when considering a past fishery collapse associated to a stock fall down, one may conclude either that conventional theory was insufficient, or that fishing effort was not effectively controlled.

Notwithstanding many recent improvements of conventional theories, the second explanation is emphasized here: the lack of control or appreciation of the effective fishing effort (i.e. proportional to the fishing mortality) as the principal cause of past collapses. We analysed the FAO data set in order to quantify and characterize the fisheries collapses, and then identified typical patterns of collapses. Using a modelling approach, we related these patterns to biological and exploitation characteristics of the fisheries concerned. We mainly related sudden crashes to the concomitance of the existence of a depensatory mechanism in the stock-recruitment relationship and a slow increase in fishing effort.

Material and methods

Material

We analysed the FAO data set of world fisheries catches during the period 1950–2000 (accessible on the FAO–Fish Stat. Website: http://www.fao.org/fi/statist/FISOFT/FISHPLUS.asp) by focusing on the dynamics of past fishery collapses. In order to decrease the risk of finding spurious collapses, we excluded irrelevant data such as those from ex-USSR countries, Yugoslavia, Czechoslovakia, South Africa, Namibia because they display abrupt decrease in catches that are only due to political changes but that could mimic fishery collapse. Also excluded were: distorted series from China (Watson and Pauly 2001); series corresponding to distant fleets subject to fishing rights agreements from 1973 (Boely and Fréon 1979). We also except aggregated series with no identified fish genus; series with any missing data during the last 20 years; series of fisheries for which average catches during the observation period were below 500 tonnes per year. This resulted in a data set of 1519 series of catches, most of them from the 1950s.

The robustness of our approach was tested in two ways: first, the original data were aggregated in different ways; second, the value of the threshold of the minimum total catches over the observation period was varied. In order to test the effect of shortcoming related to the use of national fisheries as proxy to stocks, we repeated the previous analysis on three geographical entities: (i) at a smaller resolution, we aggregated the catch data by subarea used in the Atlantic by different regional commission except for Western Central and Southwest Atlantic (data from 1960 to 2001 available on the FishStat website), regardless of the fishing country; (ii) at a higher resolution, we aggregated the world catch by FAO area, regardless of the fishing country (period 1950–2002); (iii) at even a higher resolution and for tunas only, we used the basin-scale aggregated data commonly used by the different tuna commissions for the period 1950–2002 (A. Fonteneau, IRD, personal communication; we double-checked that this data set was in agreement with FAO data).

Data analysis

The collapse of a fishery has been defined as a sustained period of very low catch values occurring after a period of high catch values (Cooke 1984). The utilized definition of a collapsing fishery is the following: if $X_{\max}$ is the maximum value of a series of catches, and $D_{\max}$ is the year this maximum has been reached, then a collapse is considered to have occurred at year $D_c > D_{\max}$ if catches were less than $X_{\max}/10$ for four consecutive years beginning at D_c.

For all corresponding collapse events, the dynamics of the series of catches during the 11 years before the year of collapse D_c (normalized in order to have the same range of values) have been analysed using *K*-means (Bishop 1995) clustering trials with different numbers of clusters. The mean-series corresponding to these clusters have then been analysed in order to characterize their dynamics in terms of variability, i.e. trend and resilience.

From the results of the *K*-means clustering, we propose a set of simple logical rules, which allow the association of a typical pattern with any collapsing catch series of single species or genus. Finally, these results were cross-tabulated by super-groups of species (International Standard Statistical Classification of Aquatic Animals and Plants or ISSCAAP group) and by period of collapse providing a retrospective description of the collapsing processes for world fisheries.

Models

The differences between typical dynamics of collapses of fisheries have been explained with simple mathematical models of a fishery under increasing exploitation. These are classical models, all encompassing a renewal function $R(x)$ of the stock x and a yield function $Y(x,e)$, depending on effort e and stock x. The renewal function represents the difference between recruitment (of young fish to the stock) and natural mortality. We have considered discrete models $x(t+1) = x(t) + R(x(t)) - Y(x(t),e(t))$ as well as continuous models: $\mathrm{d}x(t)/\mathrm{d}t = R(x(t)) - Y(x(t),e(t))$. The equilibrium analysis of such systems (the level of stock for which renewal compensates yield) is usually of interest, and leads to the optimization of the corresponding yield. In a previous modelling approach of the effects of increasing fishing pressure, Evans (1981) assumed that the yield (fishing quotas) was increasing, and studied the evolution of the resulting equilibrium stock. We have considered that fishing quotas do not usually increase while stock decreases and, in order to take into account the effects of the modernization of the fleet and a concealed increase in fishing capacity, it was more realistic to assume that the yield rate was increasing. We assumed that the yield rate is regularly and indefinitely increasing, that is: $y = v \times t$ (v represents how fast the yield rate is increasing). If we consider, as it is done conventionally, that yield is the product of the stock biomass x, the catchability coefficient q and nominal fishing effort e: $y = qex$, a regularly increasing effective fishing effort is the result either of an increase in effort e or in catchability q. Resulting models are $x(t + 1) = x(t) + R(x(t)) - vx(t)t$ in discrete time models and $dx(t)/dt = R(x(t)) - vx(t)t$ in continuous time models. Of course, the yield rate tends towards infinity and the system is ultimately forced to collapse.

Avoiding any equilibrium argument, we studied the trajectories of the differential equation instead of the dependency of the equilibrium stock to fishing effort. The dynamic behaviour of the model has been explored with systematic simulations using a mathematical solver (Mathematica). Emphasis has been put on how collapses occur.

Results

Data analysis

Among the 1519 series of the selected data sets, 366 (24%) met the above criteria of collapse definition.

Typical resulting patterns of *K*-Means analysis appear in Fig. 1. This allowed identification of three typical patterns of collapse: a smooth collapse characterized by a long regular decline (giving several clusters, according to the slope of the decline of the series), an erratic collapse, i.e. a fall after several ups and downs, or as a plateau-shaped collapse, i.e. a sudden fall after a relatively long and stable persistence of high level catches (giving several clusters according to the length of the plateau). These results are explicit (Fig. 2) and robust, i.e. independent of the number of clusters (from six to 20) and of the method that is used for choosing initial clusters (Fig. 1).

The following logical rules have been set to define, in a general way, these three types of collapses:

1. 'Plateau-shaped' collapse – when catches were greater than $X_{max}/4$ in years $D_c - 3, D_c - 4, \ldots, D_c - 8$.
2. 'Smooth' collapse – when correlation between the series of catches in years $D_c - 10, D_c - 9, \ldots D_c - 1, D_c$ and series $(0,1,\ldots, 10)$ was less than -0.7.
3. 'Erratic' collapse in any other case.

The number of collapses does not show a clear trend, only a slight increase (Fig. 3), suggesting that fishery management is not improving with time. The larger proportion of fisheries collapses (Table 1) occurred in the demersal species group (cods-hakes–haddocks: 31% and salmons–trouts–smelts 33% but with few observations) and less in the pelagic groups (herrings–sardines–anchovies: 23%, other

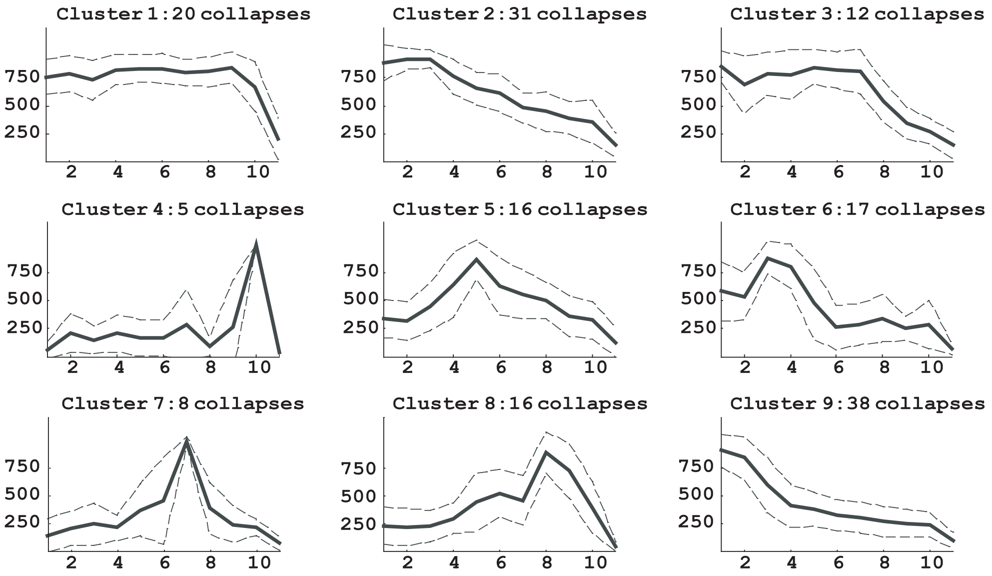

Figure 1 Results of a *K*-means analysis with nine clusters. Mean ± standard deviation are plotted for the resulting cluster. One considers that collapses of cluster 1 are plateau shaped, that those of clusters 2, 3, 5 and 9 are smooth collapses, and that those of other clusters are either erratic or ambiguous.

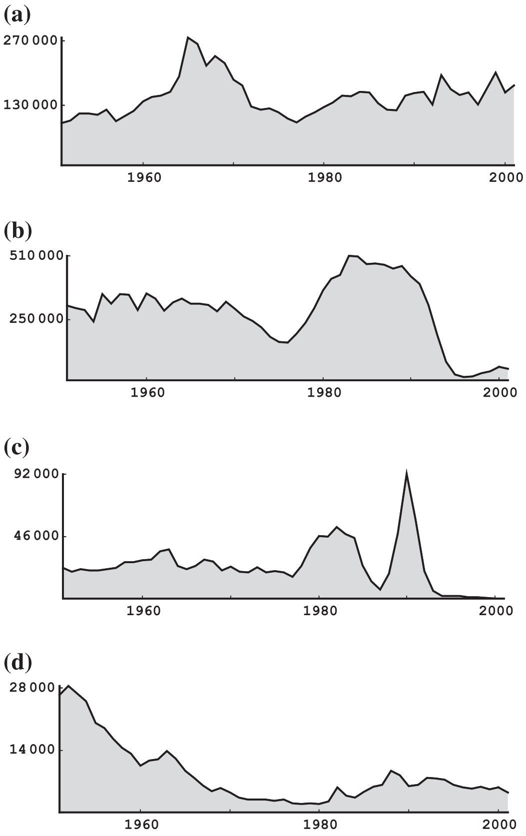

Figure 2 Typical observed patterns of catch time series: (a) no collapse: Atlantic herring in Sweden, (b) plateau-shaped collapse: Atlantic cod in Canada, (c) erratic collapse: Atlantic cod in Greenland, (d) smooth collapse: European hake in the UK.

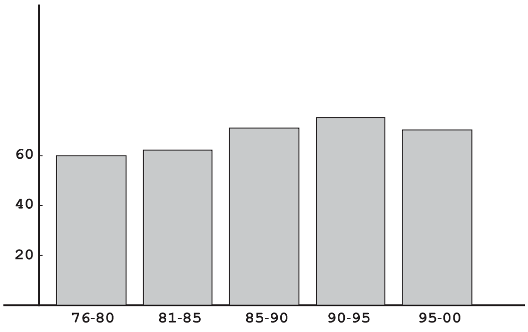

Figure 3 Total number of world fisheries collapse between 1975 and 2000.

pelagic: 16%). This suggests that, despite their high instability, small pelagic fisheries are less prone to collapse than demersal fisheries and supports recent findings stating not only that clupeoids stocks are more resilient than others to collapse (Beverton 1990) but also that vulnerability to species extinction is not dependent on biological attributes (Dulvy *et al.* 2003).

Among the 366 collapses, 167 (45%) were erratic collapses, 78 (21%) plateau-shaped collapses and 121 (33%) smooth collapses (Table 1). There is no strong relationship between the type of collapse and the ISSCAAP groups, except for the relative predominance of plateau collapses in the herrings–sardines–anchovies group (36%) that contrasts with a low occurrence of erratic collapses (23%), higher numbers of erratic collapses in miscellaneous pelagic fishes (53%) that contrasts with a low proportion of plateau collapse for this group (12%) and, finally, the low proportion of plateau collapses in the groups of salmons–trouts–smelts and sharks–rays–chimaeras but there are not enough observations within these two groups to draw firm conclusions on that respect.

Small fisheries are characterized by a highest occurrence of erratic collapses, while plateau-shaped collapses and smooth collapses are predominant in fisheries larger than average (Table 2) that target, in most cases, a single species of fish as indicated by a detailed analysis of the results (not presented here).

Robustness

The proportions of collapses in the Atlantic data set of small subareas and in the data set of world catch by FAO area are comparable with what we initially observed on data aggregated by country and FAO area (Table 3), whereas there was no collapse at all observed in the tuna data set aggregated at the basin scale. An increase of the threshold value results in a slight decrease of the proportion of collapses and a change in the relative importance of the types of collapses: a decrease in erratic collapses and a slight increase in plateau and smooth collapses (results not shown) as expected from Table 2. In conclusion, even a conservative analysis of the data suggests that about one fishery of four collapsed during the last five decades.

Models

The differences between smooth and plateau-shaped collapses have been explained with a continuous-time model: $\mathrm{d}x(t)/\mathrm{d}t = R(x(t)) - vx(t)t$. It appears

	Stocks	Collapses	Plateau	Erratic	Smooth
Cods, hakes, haddocks	179	57 (31)	11 (19)	28 (49)	18 (31)
Flounders, halibuts, soles	91	18 (19)	4 (22)	8 (44)	6 (33)
Herrings, sardines, anchovies	161	38 (23)	14 (36)	9 (23)	15 (39)
Miscellaneous coastal fishes	267	51 (19)	13 (25)	20 (39)	18 (35)
Miscellaneous demersal fishes	133	35 (26)	8 (22)	16 (45)	11 (31)
Miscellaneous pelagic fishes	234	39 (16)	5 (12)	21 (53)	13 (33)
Salmons, trouts, smelts	30	10 (33)	0 (0)	5 (50)	5 (50)
Sharks, rays, chimaeras	30	6 (20)	2 (33)	2 (33)	2 (33)
Tunas, bonitos, billfishes	394	112 (28)	21 (18)	58 (51)	33 (29)
All species groups	1519	366 (24)	78 (21)	167 (45)	121 (33)

Percentage values are given in parenthesis.

Table 1 Number of fisheries according to the type of dynamics and the FAO super group of exploited species (ISSCAAP group). Percentages of collapses are related to the number of stocks, percentages of plateau-shaped collapses, erratic collapses and smooth collapses are related to the number of collapses.

Table 2 Mean and standard deviation of averaged catches of the fisheries in the different categories of collapses (tonnes, per year, during the 1950–2000 period).

	Mean	SD
No collapse	18 047	63 566
Plateau	53 261	185 587
Erratic	6 393	22 687
Smooth	48 155	389 175

very clearly, when simulating this model with a large number of renewal functions of all kinds (Logistic, Ricker, Beverton-Holt), that using renewal functions deduced from conventional stock/recruitment functions (such as the logistic: $R(x) = r \times (1 - x/K)$, Ricker's: $R(x) = r \times \exp(-kx)$ or Beverton and Holt's: $R(x) = ax/(b + x)$) results in a smooth collapse (Fig. 4a). To obtain a crash after a fishery reaches a plateau, it is necessary for the renewal function to be negative for stock sizes lower than a given threshold (Fig. 4b): a minimal stock size is necessary to ensure its renewal, i.e. a depensatory mechanism operates. This illustrates a hypothesis regarding the causes of collapses, which is now classical (Liermann and Hilborn 2001; Walters and Kitchell 2001), even if controversial (De Roos and Persson 2002). The involved mechanism is as follows: as the effort increases, the stock starts to diminish until it reaches the level at which the depensatory mechanism comes into play. Continued increase of effort, coupled with ecological dynamics, then contribute to the decrease of biomass, up to the point where collapse occurs (Fig. 4b), often very abruptly. Moreover, with further modelling experiments, it appears that there is a plateau effect when v, the rate of increase in yield, is smaller than a given threshold and that the length of the plateau depends on v according to a power-law (a log–log relationship).

Since the seminal paper of May (1976), irregular solutions (such as those of erratic collapses) to dynamical systems, in contrast with regular solutions (such as those of smooth collapses and plateau-shaped collapses), can be interpreted within the framework of the chaos theory. This implies using a discrete-time dynamical model, with a high level of periodic renewal ($r > 3$) and a density-dependent renewal function. We have plotted

Aggregation level	Stocks or fisheries	Collapse	Plateau	Erratic	Smooth
Sub-areas from regional commissions (Atlantic only)	689	156 (22)	30 (19)	90 (57)	36 (23)
FAO areas (World)	790	182 (23)	33 (18)	108 (59)	41 (22)
FAO countries/areas (World)*	1519	366 (24)	78 (21)	167 (45)	1213 (33)

Percentage values are given in parenthesis.
*For FAO countries/areas data refer Table 1.

Table 3 Sensitivity of the analysis according to the aggregation mode of data (see text for details).

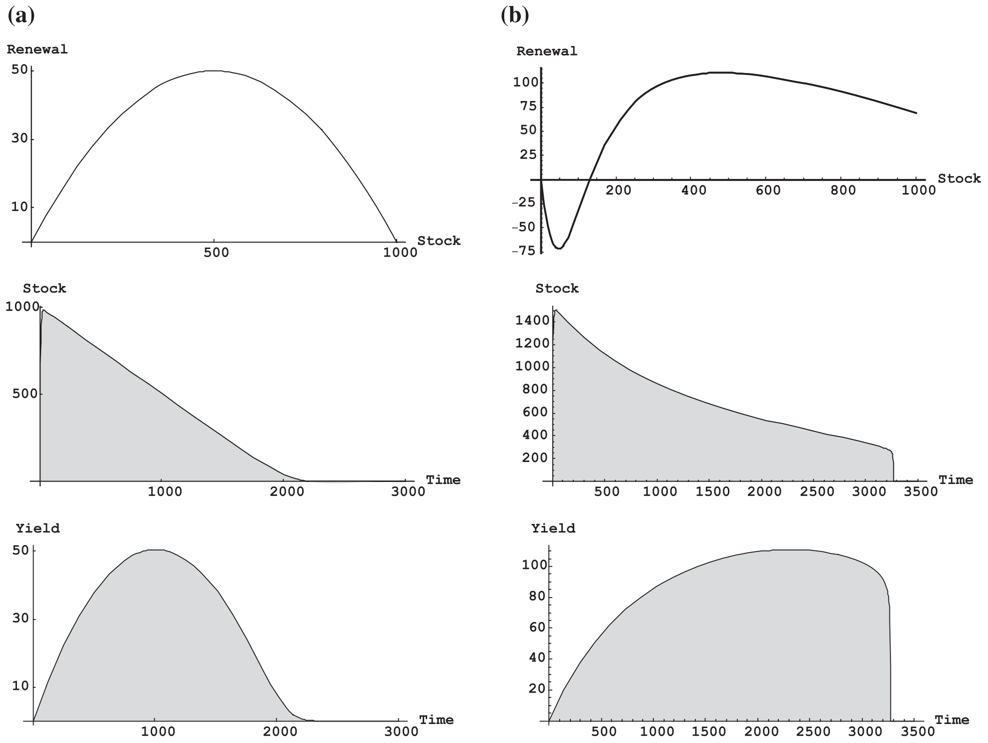

Figure 4 Dynamics of fish stock (the renewal function, change in stock size and yield) under a scenario of increasing exploitation when (a) the renewal function is logistic and (b) when the renewal function includes depensation at low population levels.

(Fig. 5) the trajectories of the series issued from the model: $x(t+1) = x(t) + rR(x(t)) - vx(t)t$, using, successively, a logistic renewal function and a depensatory renewal function for several values of parameter r (periodic renewal) and v (increase of fishing effort). It may be considered that this model represents, quite fairly, the observed dynamics of the erratic collapses from the FAO data set. It appears, when using discrete-time models, that a slowly increasing exploitation results in smoothing of the trajectories (Fig. 5): when exploitation is high, it confines the stock at low levels, in which the density-dependent effect is positive, and the decline of the stock is then quite smooth. Even if this effect is more pronounced with a compensatory renewal function, the simplest explanation of erratic collapses lies in their highly variable dynamics (usually associated with favouring factors such as periodicity, short lifespan, high fecundity), and we may conclude that a highly density-dependent stock-recruitment relationship and a slowly increasing effort create an erratic collapse, that second condition is sufficient, but not necessary.

Discussion

Nearly one of four fisheries collapsed during the period 1950–2000. There was no apparent sign of improvement in preventing collapses during this period, despite increasing awareness of such risk and supposed improvements in stock assessment methods by direct and indirect methods. We examined how this result depends on the definition of series (level of aggregation and minimal threshold value) and show how robust is this result, despite uncertainties on the quality of the data that are used. Smaller fisheries and smaller stocks appear to be more sensitive to collapse than larger ones (Tables 2 and 3). Differences between results obtained at different levels of aggregation (e.g. too coarse resolution) reopen the debate of the identification of relevant stock management units as subsets of the whole population (Cury and Anneville 1998; Fréon and Misund 1999; Gaughan *et al.* 2002). Our results confirm that different segments of an exploited population can collapse whereas the stock as a whole looks healthy. Nonetheless, the

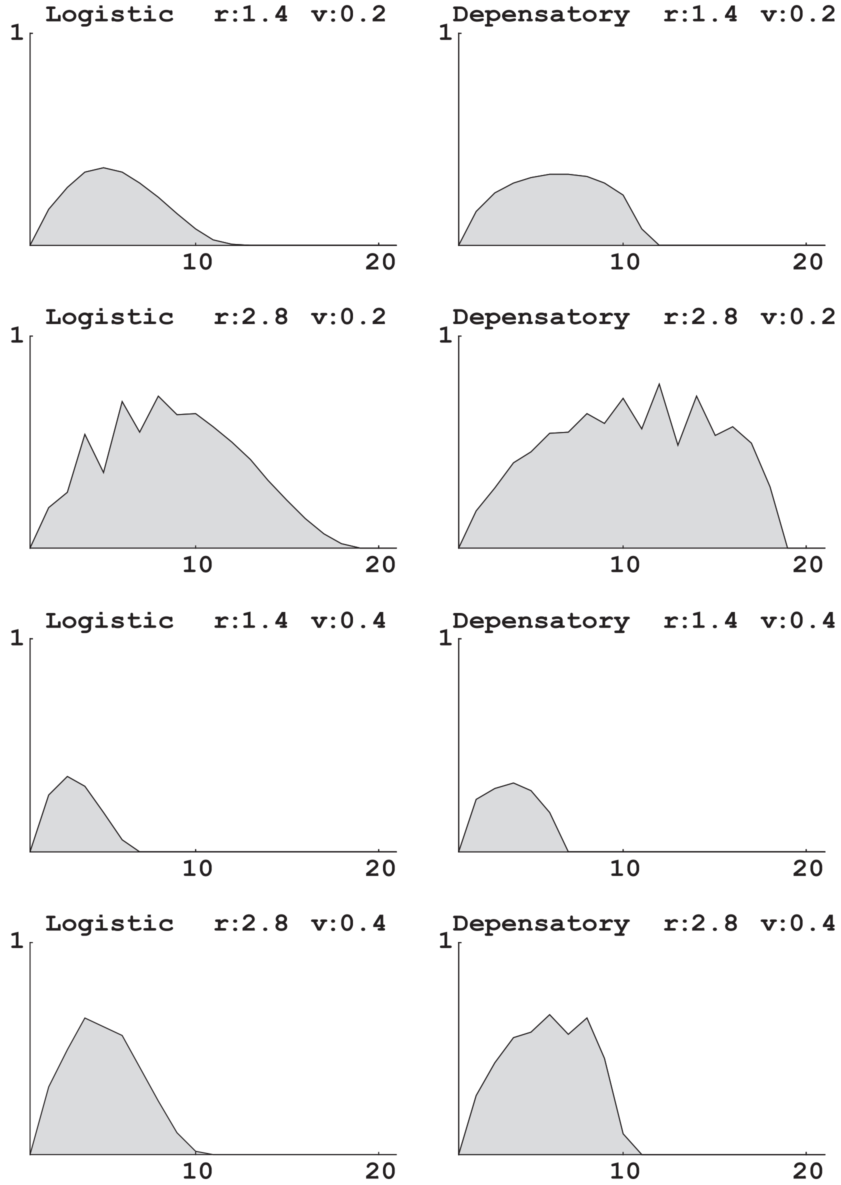

Figure 5 Dynamics of fish stock under a scenario of increasing exploitation using a discrete-time model: $x(t + 1) = x(t) + rR(x(t)) - vtx(t)$. Renewal function is logistic: $R(x) = x(1 - x)$ on the left panel, and depensatory: $R(x) = (-10x + 120x^2 - 110x^3)/(1 + 225x^2)$ on the right panel. In all part figures r is the parameter of periodic renewal and v quantifies the increase of fishing effort multiplied by catchability.

collapse of some components of the stock has strong economical consequences and it can decrease intraspecific genetic diversity and total productivity (review in Fréon *et al.* 2005).

Analysing the trajectory of catches during the decade preceding the collapses led to the identification of three typical patterns: smooth, erratic and plateau-shaped collapses. From a theoretical point of view, plateau-shaped collapses are puzzling whether or not they seem to reflect interdecadal pseudo-periodic variability which remains largely unexplained, for small pelagic species particularly (Klyashtorin 1998). Differences between smooth collapses and plateau-shaped collapses have been related to a main feature of the population dynamics of species, i.e. the existence of a depensatory mechanism at low population levels. Several depensatory mechanisms, such as reduced probability of fertilization, impaired group dynamics, predator saturation and conditioning of the environment, are invoked to explain the lack of resilience of fish populations (Liermann and Hilborn 2001) and these play a major role in the dynamics of collapses (Post *et al.* 2002; Dulvy *et al.* 2003). Going further, our modelling approach demonstrates that, under a scenario of a surreptitiously and slowly increasing fishing effort, a fishery may experience a sudden collapse if depensatory mechanisms act at low levels of biomass. These two conditions (increasing effort and depensatory mechanisms) must be met for the plateau-shaped collapse to occur. Observing persistence at the level of catches can give the false impression that the fisheries have reached equilibrium and that effort has stabilized, when in fact the fishery is about to collapse. This leads one to accept stable catches, even under a scenario of declining biomass, as potentially sustainable. By doing so, one favours a gradual resource degradation that goes unnoticed in the long-term, or at least that is thought to be acceptable for fisheries sustainability, a mechanism known as the shifting baseline syndrome (Pauly 1995).

The likelihood of a hidden increase in fishing efficiency should be first kept in mind when analysing the dynamics of any fishery. Indeed, fishers have incessantly improved their efficiency to ensure the stability of their catch and revenues, despite decreasing fish abundance. Modernization of fishing gears and vessels, use of sophisticated detection and positioning techniques, better knowledge of the spatial and temporal pattern of fish distribution, increased cooperation within the fleets, dissemination of artificial floating objects to attract fish, among other factors, have all contributed to this trend (Hilborn and Walters 1992; Fréon and Misund 1999; van Oostenbrugge *et al.* 2002). In most cases, the increase in fishing efficiency remains poorly quantified and is not properly accounted for in most fisheries models, despite the fact that overfishing is recognized as the major contributor to observed collapses (Garcia and Grainger 1997; Hall 1999; Pauly *et al.* 2002). Furthermore, it is not simply the level of fishing effort that is critical to avoiding stock collapse, but also how that fishing effort is distributed in time and space. Too often the catchability associated with fishing effort has increased significantly, despite a stabilization of total effort, because of fishers' ability to target local concentrations (Hilborn and Walters 1992; Fréon and Misund 1999) or substocks.

Patterns of declining yield have been used by FAO as one of the criteria to assess the present state of the world fisheries (Garcia and Grainger 1997). Using trend in catch constitutes a conceptually simple and meaningful indicator to characterize fisheries status and to communicate to stakeholders. Nonetheless, to use catch trend as an indicator to define sustainability and to characterize the 'health' of fish stocks might be dangerous and controversial, particularly when it is the only indicator of sustainability used to evaluate the state of the world fisheries (Lomborg 2002). Catch analysis could hide the role played by a lack of control or appreciation of the effective fishing effort as the principal cause of past collapses.

Fishing down the food web (Pauly *et al.* 1998), as well as plateau-shaped collapses, together contribute to a false impression of sustainability in fisheries. The current underestimation of an always increasing fishing efficiency, associated with the lack of fish stock resilience and with depensatory mechanisms are likely to promote a global collapse of many more fisheries, not always with detectable warning in time series of catches. Properly quantifying effective fishing effort and depensatory threshold effects at low stock levels should constitute one important step, the other being to restore depleted stocks, if we really decide to bring fisheries, and ecosystems on which they depend, back to viability.

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