FISH and FISHERIES

Using global catch data for inferences on the world's marine fisheries

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Abstract

Detailed stock assessments, including the estimation of the absolute biomass of the 'stocks' exploited by fisheries, are often viewed as the gold standard for indicators of their status. However, such stock assessments are not available for the overwhelming majority of exploited stocks and fisheries globally. This requires the development, testing and dissemination of other, less data-demanding indicators for use throughout the world, for example, for comparing the status of fisheries between different maritime countries or large marine ecosystems. Stock status plots, initially developed by staff of the United Nations Food and Agriculture Organization to assess global fisheries, are reviewed here, and their most recent incarnation, which accounts for stock rebuilding, is found to provide a robust overview of fisheries and of the major trends besetting them.

Keywords Fisheries, indicators, inventory and monitoring, marine, population dynamics, stock status

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Introduction

The last 60 years have seen remarkable changes in the nature of fisheries. These include rapid geographical (Swartz *et al.* 2010b) and bathymetric (Morato *et al.* 2006) expansion, along with the deployment of technology of ever-increasing sophistication (Pauly *et al.* 2002), resulting in greater efficiency (Pauly and Palomares 2010) of more powerful fishing fleets (Anticamara *et al.* 2011). Because of these changes, the world catch has been stagnating, then slowly declining since the late 1980s (Watson and Pauly 2001; FAO 2010), which has been widely interpreted as being the result of widespread overfishing leading to sequential depletion of exploited stocks (Garcia 1992; Hutchings 2000; Jackson *et al.* 2001; Froese *et al.* 2009). This near consensus, however, has been challenged by a few authors asserting that the partial stock rebuilding scenarios that have recently occurred in the United States and a few other developed countries may be representative of a global trend, and that globally stocks can be managed and rebuilt if countries take the initiative (Hilborn 2010; Daan *et al.* 2011). We agree that stocks can be rebuilt, and there have been some successes in fisheries management in recent decades (Castilla *et al.* 2007; Gelcich *et al.* 2008; Gallardo *et al.* 2011), but caution against the tendency to make global inferences based mainly on the health of assessed stocks.

There are a number of reasons why this debate occurs, the most important being that it is difficult to measure the exploitation status of the vast majority of the world's stocks. The economically most important resources in developed countries are evaluated with stock assessment techniques, which depend critically on the ability to measure or estimate the abundance or biomass (both current and unexploited) of the stock. While these techniques have been touted as the best, or even only legitimate methods available for measuring stock status, many reviews have found the efficacy and reliability of stock assessment techniques debatable (Parsons 1996; Walters and Pearse 1996; Rose 1997; Ulltang 2003; Conn *et al.* 2010). Crucially, all of these techniques require reliable estimates of stock biomass, which can be extremely hard to obtain even in the best of circumstances, as evidenced by the collapse of Canada's well-studied Northern cod (*Gadus morhua*, Gadidae, Walters and Maguire 1996; Myers *et al.* 1997).

Another caveat is that these stock assessment techniques, and the biomass estimates upon which they depend, are available for only a small fraction of the world's exploited stocks. For example in Europe, one of the most developed regions of the world, the International Council for the Exploration of the Sea (ICES) fully assesses only approximately 54 of 190 fished stocks. Importantly, stock assessments have been made only for a tiny minority of stocks in countries of the developing world, which despite hosting a wealth of biodiversity, and being the source of much of the seafood consumed in the developed world (Swartz *et al.* 2010a), are also data poor and generally lack scientific, and especially stock assessment expertise. Thus, it is not possible to obtain a view of stock status in developing countries based solely on stock assessments and species-specific biomass estimation such as performed in more developed countries. Consequently, in view of the enormous contributions of developing countries to world fisheries catches, it is also not possible to draw credible inferences for the world as a whole as was presented in the study by Worm *et al.* (2009) from stock assessments mostly carried out in developed countries.

An alternative exists, however, and that is to use indicators that, while potentially less precise than stock assessments, can give a fair representation of stock status in all countries. These indicators need to be based on data which are widely available and which, like the Body-Mass Index for epidemiological studies of obesity (Deurenberg *et al.* 1991; Gallagher *et al.* 2000), allow for assessments and comparisons between countries (Pitcher *et al.* 2009; Alder *et al.* 2010). One set of such indicators are the graphs, here called 'stock status plots' (SSPs), which have their origin in the need for staff of the United Nations Food and Agriculture Organization (FAO) to assess the global status of fisheries (Grainger and Garcia 1996) — the same goal as we have.

History of the stock status plots

'The usual evolution of a fishery with time can be described by the following phases: (i) predevelopment, (ii) growth, (iii) full exploitation, (iv) overexploitation, eventually (v) collapse, and hopefully (vi) recovery.'' This matter-of-fact statement reflecting the idea that a time series of landings could be used to characterize a fishery's development was made in a 1984 FAO report, assembled to examine the changes in abundance and species composition of neritic fish resources (Csirke and Sharp 1984). Diagrams reflecting the stages of development of a fishery under intense fishing effort (Fig. 1a) and moderate fishing effort where the stock fluctuates because of environmental conditions (Fig. 1b) were presented by Csirke and Sharp (1984), which illustrated the relationship between abundance, fishing effort and total catch in each developmental phase. Under high fishing pressure, abundance decreases as effort increases and catches increase, which are designated as the development, growth and exploitation phases. The abundance and catch trends are decoupled until the high fishing effort pushes the resource into decline. At this point, abundance, fishing effort and total catch follow similar trajectories through the collapse and recovery phases. In the second case, where a fishery is under moderate fishing effort, there is a tighter coupling of the abundance and catch trends and catches tend to be maintained under full exploitation for a longer period unless there are adverse environmental conditions that push the stock into collapse. Interestingly, Csirke and Sharp (1984) found that a large-scale change in an exploited resource will typically result in a corresponding change in fishery dynamics. For example, when abundance increases, catch rates, total catches and fishing effort should also increase. However, when the stock abundance decreases, catch will usually decrease as well, and fishing effort will decrease more slowly, and may even increase owing to a desire to maintain high catches. Csirke and Sharp's figure (our Fig. 1a) was subsequently reprinted in the textbook by Hilborn and Walters (1992) as an example of the exploitation phases of a fishery.

Grainger and Garcia (1996) provided a global metric for evaluating the status of the world's fisheries resources by building on Csirke and Sharp's definitions of the development phases of marine

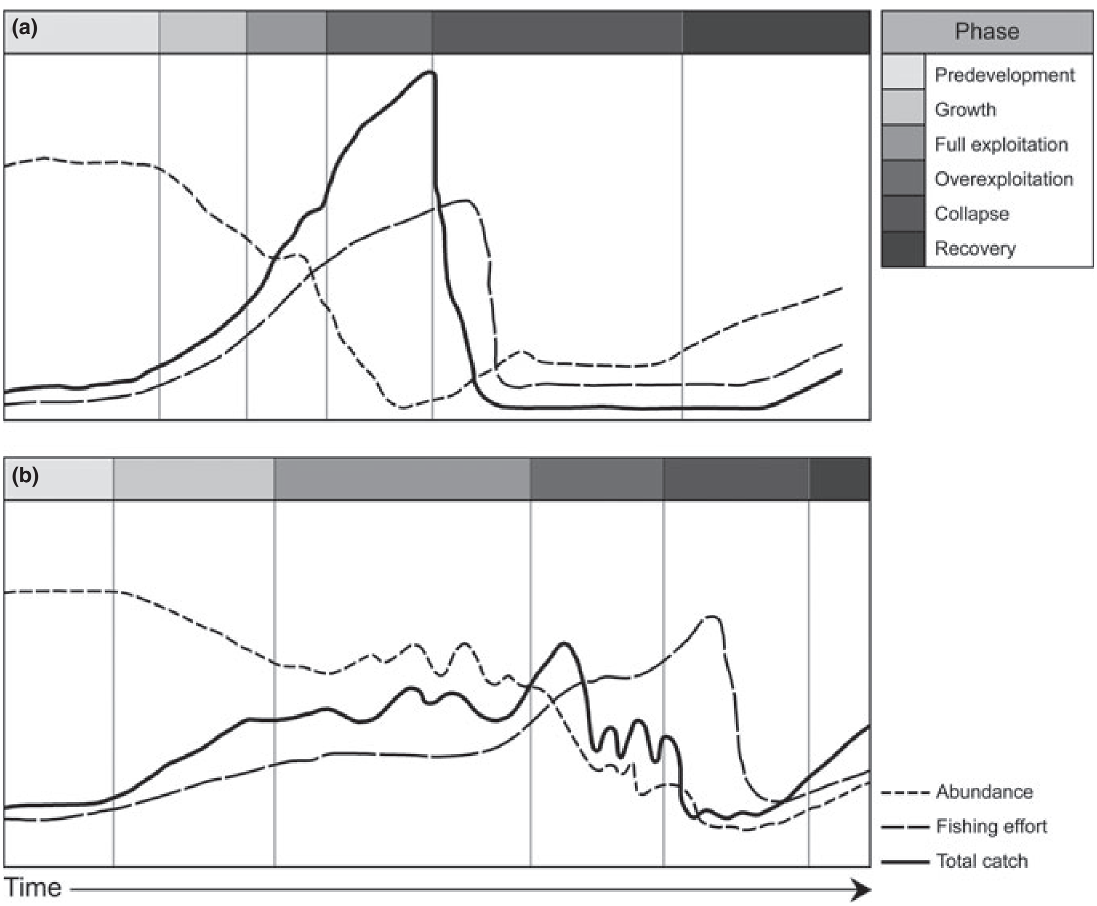

Figure 1 Patterns and phases in the development of (a) a general fishery and (b) a fishery susceptible to environmental fluctuations (redrawn from Csirke and Sharp 1984).

fisheries. Their analysis of the trend of global marine fisheries landings was based on the top 200 species–area combinations, or 'stocks', which at the time accounted for 77% of globally reported fish landings. The data were standardized by rescaling the time series of catch to a mean of zero and a standard deviation of one, which were then fitted with polynomial curves, whose slopes were binned into three major categories, which were 'increasing' with a slope >0.05, 'little change' where the slope was between +0.05 and −0.05 and 'decreasing' where the slope was <−0.05. These groupings corresponded to three inferred status categories, that is, increasing = 'developing fisheries,' little change = 'mature fisheries' and decreasing = 'senescent fisheries.' Another minor category characterized by little change associated with low catches = 'undeveloped fisheries' was then added, and plots of development phases were constructed for the percentage of stocks of each status in each year (Fig. 2).

Based on this, Grainger and Garcia (1996) suggested that increases in global catches were not likely and that, rather, increased exploitation rates would result in lower catches. They also warned that trends in total landings might provide a false sense of security when the development phase is not taken into account.

Subsequently, Froese and Kesner-Reyes (2002), in their analysis of time series of catch data from ICES and FAO, simplified the approach of Grainger and Garcia (1996) by replacing the fitting of polynomials and the estimation and binning of their slopes by defining a relationship between the status of a fishery and the ratio of their catches to the maximum catch taken from a time series (Table 1). The status of the fisheries was labelled as 'undeveloped', 'developing', 'fully exploited', 'overfished' and 'collapsed'. They then applied this method to over 900 stocks and used it to illustrate the transition of a fishery from undeveloped through fully exploited to collapsed (Fig. 3). In addition to allowing far more stocks to be included in analyses (Froese and Pauly 2003), Froese and Kesner-Reyes (2002) noted that their new plots confirmed the following two trends:

1. A tendency for the transition from one stage to another to occur faster in recent times. We will return later to this theme.
2. A tendency for the boundary between 'overfished' and 'collapsed' on this graph to steadily decline (see Fig. 4).

The approach of Grainger and Garcia (1996) has also been applied to regional fisheries with Garibaldi and Grainger (2004): Eastern Central Atlantic, and Baisre (2000): Cuba, being examples that illustrate the use of the approach.

Garcia *et al.* (2005) made an important modification to the FAO assessment of the state of world fisheries resources using catch data from 1950 to 1994 by adding a 'recovering' category, which had not been considered in the earlier studies. This category defined recovery as catches that showed a new phase of increase after a period of senescence,

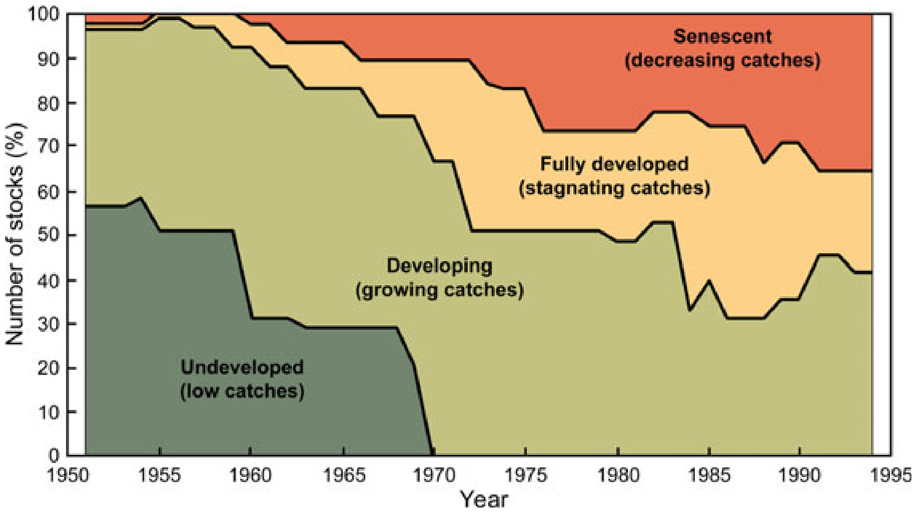

Figure 2 Evolution of the state of marine fishery resources from 1950 to 1994, based on the analysis of catch trends in 200 major stocks (redrawn from Grainger and Garcia 1996).

Table 1 Algorithm designed by Froese and Kesner-Reyes (2002) to categorize the status of a fisheries resource based on their catch time series.

Status of fishery	Criterion applied
Undeveloped	Year < year of maximum catch AND catch < 10% of maximum catch
Developing	Year < year of maximum catch AND catch is 10–50% of maximum catch
Fully exploited	Catch >50% of maximum catch
Overfished	Year > year of maximum catch AND catch is 10–50% of maximum catch
Collapsed	Year > year of maximum catch AND catch < 10% of maximum catch

and was, originally, explicitly included in the 'developing' category as it was believed that rebuilding was not a common event until the late 1990s. In the present study, we expand upon this concept to better define fisheries 'recovery'.

Recently, Pauly *et al.* (2008) created SSPs for a United Nations Environment Programme (UNEP) compendium on Large Marine Ecosystems (LMEs, Sherman and Hempel 2008) based on definitions slightly modified from those of Froese and Kesner-Reyes (2002) and using landings data from the *Sea Around Us* project (http://www.seaaroundus.org, accessed 20 January 2012). One of the modifications was the combination of the previous categories 'undeveloped' and 'developing' into a single category labelled as 'developing', to reduce the effects of graphs featuring by definition the fraction of 'undeveloped' stocks as zero in the last year covered by the analysis. It should be noted that Pauly *et al.* (2008) defined stocks as time series of species, genus or family for which (i) the first and last reported landings are at least 10 years apart; (ii) there are at

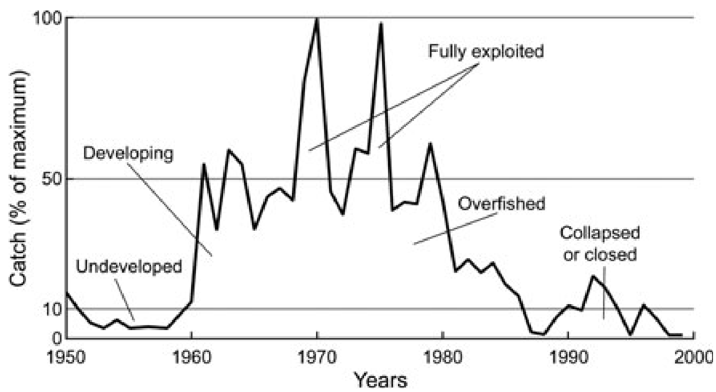

Figure 3 Typical transition stage of a fishery (here: Basking shark *Cetorhinus maximus*), from undeveloped to collapsed or closed. See Table 1 for definitions (Froese and Kesner-Reyes 2002).

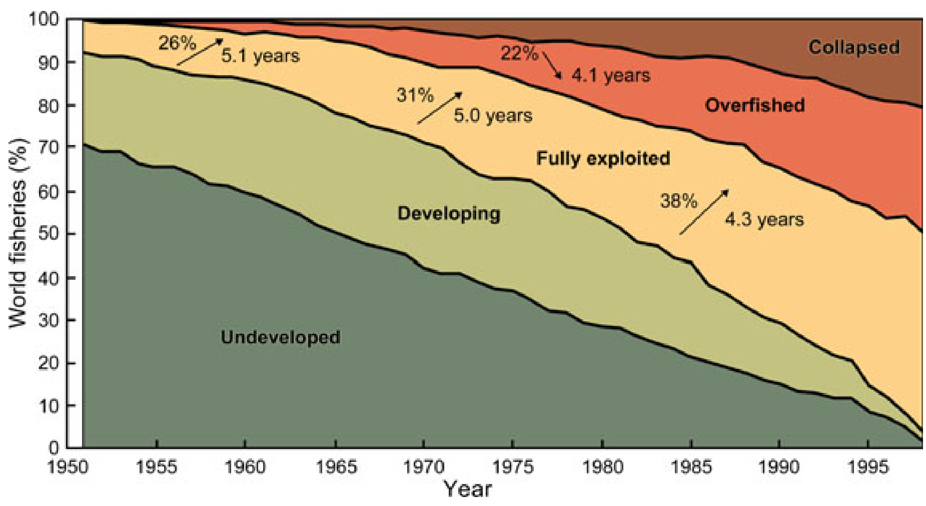

Figure 4 Trends in world fisheries as reflected in FAO landings statistics 1950–1999 (adapted from Froese and Kesner-Reyes 2002). Note that the boundary line between 'overfished' and 'collapsed' is steadily progressing downward.

least 5 years of consecutive landings; and (iii) the landings in a particular area such as a country's exclusive economic zone (EEZ) or LME is at least 1000 tonnes. Thus, higher taxonomic groupings and pooled groups were excluded.

Furthermore, two types of SSPs were created for each LME by Pauly *et al.* (2008), standard SSPs based on the numbers of stocks by status and SSPs based on the percentage of the bulk catch by stock status over time, called 'stock-catch status plots' (SCSPs). This made it possible to contrast fishing impacts on 'biodiversity' as measured by the percentage of stocks each year in each development category as opposed to impacts brought about by changes in 'biomass' expressed by the weight of the catch in each development category. Thus, the 'number of stocks by status' graph illustrates the percentage number of stocks that are considered overfished or collapsed, while the 'catch by stock status' graph demonstrates that, more often than not, a larger percentage of the catch tonnage originates from a declining number of stocks, as more stocks become overfished or collapsed. For the latter graph, the catch trends are smoothed to avoid random fluctuations in the catch data. There is no need for smoothing of the 'numbers of stocks by status graph' as year-to-year fluctuations are generally smaller. Jointly, these two forms of SSPs point to an increase in stocks that seem compromised, and tend to confirm that biodiversity as measured by the percentage of different stocks is affected by fishing more strongly than is bulk catch measured by the biomass of a stock expressed as a percentage of catch tonnage (but see Discussion).

In the following, we (i) address some objections to the use of SSPs based on questionable simulations; (ii) propose two modifications of SSPs that correct for two negative features, one of them quite important; (iii) assess whether, and to what extent, shifts in stock status, based on the newly formulated SSPs, have accelerated over time; and (iv) present scenarios wherein the SSPs may not be doing the job they were designed, thus invalidating their use as a tool to infer global trends in stock status.

Challenges, improvements and using SSPs

Simulations that appear to invalidate SSPs

Branch *et al.* (2011) hypothesize that, by definition, the SSP algorithm will always produce increasing trends of collapsed stocks. They test this hypothesis by generating random autocorrelated time series fluctuating around a mean, which tend to feature, over time, peak catches slightly exceeding previous peak catches, and therefore generating proportions of 'collapsed' and 'over-exploited' stocks that always increase over time. They applied the stock status algorithm of Froese and Kesner-Reyes (2002) to these random time series and concluded that their results invalidated the use of catch-based methods to infer trends on the status of stocks.

However, the logic of the argument made by Froese and Kesner-Reyes (2002) implies that the distinct peak occurring in real time series of catch is attributable to overshooting maximum sustainable yield (MSY). Following the basic conventional wisdom of production modelling, they define biomass in years before C_{max} to be above biomass at MSY (B_{msy}) and below B_{msy} thereafter. Consequently, 'over-exploited' and 'collapsed' stocks tend to occur after a fishery is fully developed (after C_{max}), whereas they tend to be 'undeveloped' and 'developing' before C_{max} (Figs 1 and 3). Implicit in the catch-based analysis is the assumption that fishing mortality (F) is increasing over time. This assumption, essentially the driving force in the catch-based analysis, is missing from the simulation of Branch *et al.* (2011). Therefore, the original, unmodified algorithm of Froese and Kesner-Reyes (2002) cannot be applied to log-normal random data as done by Branch *et al.* (2011) because quite simply, fisheries development follows a complex curve (Fig. 1) with random fluctuations around that curve, rather than a stable mean with random fluctuations. Therefore, the simulated data do not model reality. Here, we present a simple modification to the SSP algorithm, which accounts for the artificial nature of the random time series, while maintaining the implicit assumption underlying the algorithm of Froese and Kesner-Reyes (2002). We simply constrain the algorithm such that the year of a first 'high catch' marks the start of a fully developed fishery, which is consistent with the implicit assumption in the study by Froese and Kesner-Reyes (2002). For log-normal random data, this year of first high catch can be defined as catch larger than one standard deviation above the random simulated time-series mean.

The results of the simulated time series as presented in the study by Branch *et al.* (2011) resulted in increases in the 'over-exploited' and 'collapsed' categories. However, when we used the properly constrained algorithm, there was a clear effect on the simulated random data (Fig. 5). The similarity with the analysis of the actual catch data disappeared, as most simulated time series reached the 'fully developed' status in fewer than 30 years. More importantly, the trend lines became flat thereafter (compare with Fig. 4 in Branch *et al.* 2011), suggesting that random data, properly constrained, do not generate increasing collapses. In essence, the trend reported by Branch *et al.* (2011) and forming the core of their argument does not bear any relation with reality. What it does do is illustrate that, under the modelling conditions used, the percentage of overfished and collapsed stocks increases mechanically. Thus, the claim by Branch *et al.* (2011) that trends in global catch data are artefacts of the catch-based algorithm does not hold, at least when the logic of the method is respected.

Two real issues: developing and rebuilding stocks

What we consider a more serious criticism than the above are two other issues, which are that most SSPs published to date fail to account for either the potential stock development in later years or the possibility of stock recovery (Branch 2008). These are valid concerns, which require addressing. We deal with subsequent stock development by modifying our definitions. Firstly, the undeveloped category has been integrated into the developing category (Pauly *et al.* 2008). Secondly, we now count stocks that have a peak in catch in the final year of the time series as 'developing', following similar modifications presented in the study by Garcia (2009, 2011). The effect of these modifications may be seen in Fig. 6. This results, in the last year of a time series, in the percentage of stocks in the 'developing' category not being zero by default, and allows the possibility that there may be stocks that have not yet reached a peak catch.

Previous versions of SSPs did not take into account stocks that had recovered (Branch 2008). The North Sea stock of Atlantic herring (*Clupea harengus*, Clupaeidae) provides an excellent example of this (Fig. 7a). Here, catches reached their maximum in 1966, which was followed by the collapse of this stock with associated catches declining to a minimum in 1979. Thereafter, catches gradually increased through the 1980s and early 1990s as a result of management rebuilding actions and remained above 50% of the maximum catch through 2008 (Zimmerman 2002). Thus, the low catches imposed by management actions would have been wrongly interpreted as overfished or collapsed using the criteria of Froese and Kesner-Reyes (2002) and Pauly *et al.* (2008). Garcia *et al.* (2005) defined a 'recovery' phase for 200 catch time series representing 66% of marine capture fishery production. Unlike the algorithm used here to define fisheries development phases for global catch trends, their analysis was designed for a subset of global catches using an analysis of slope to 'slice' the catch profiles into development phases. In this same vein, we propose here an additional category, 'rebuilding', which occurs when the stock drops to 'collapsed' status

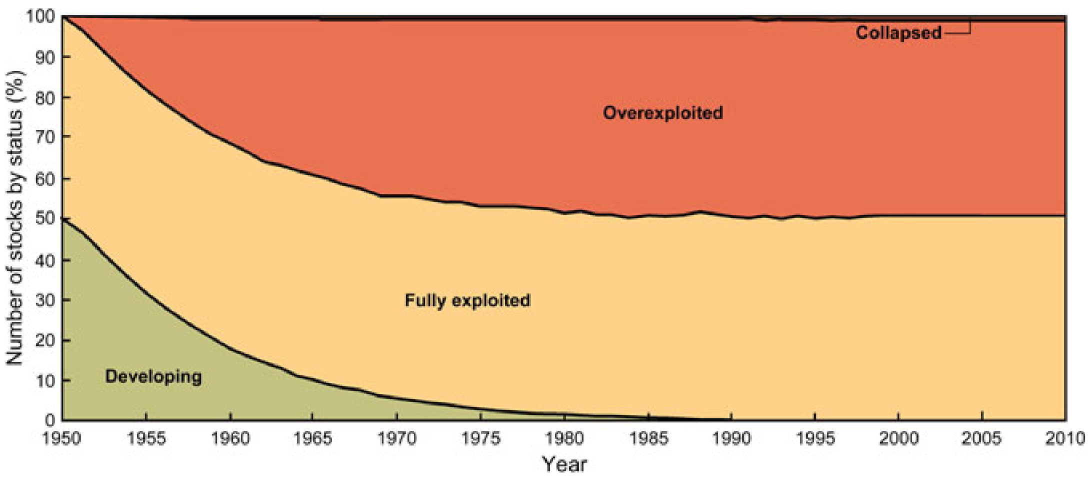

Figure 5 Stock status plot of 20 000 time series of log-normal random catch data using a constrained algorithm modified from Froese and Kesner-Reyes (2002). Note that the rate of collapse is not accelerating (see text).

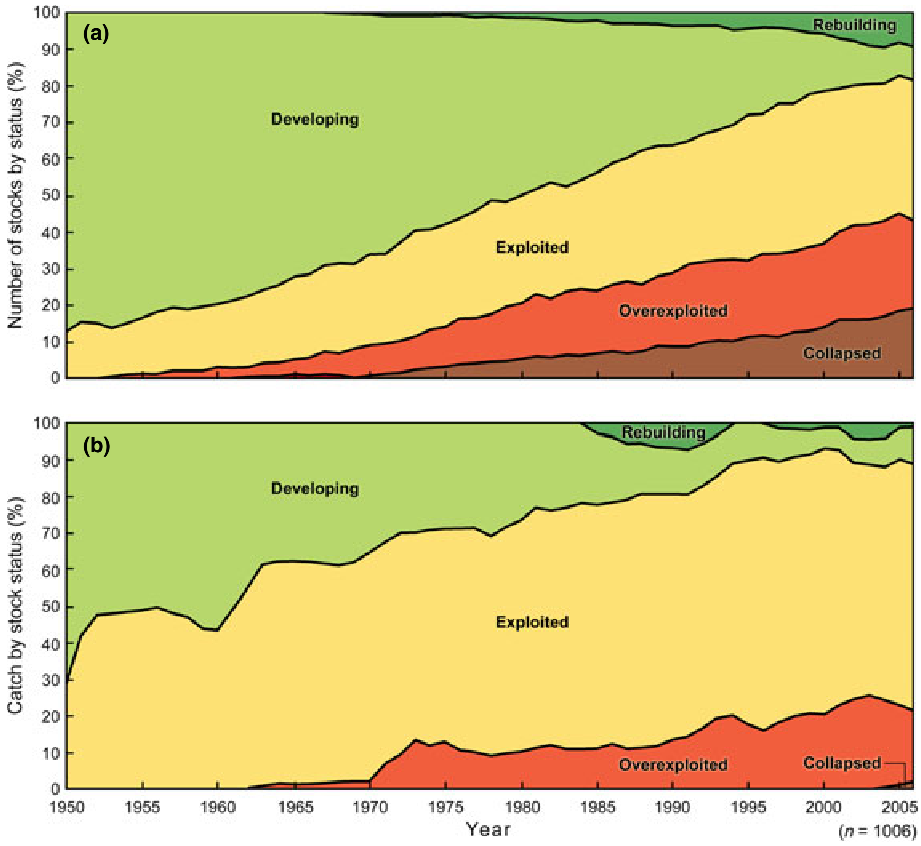

Figure 6 Example of a stock status plot (SSP), here for global catches, as defined by the *Sea Around Us* Project, showing (a) the *number of stocks by status* graph (in percentage), which illustrates the typically increasing number of stocks that are considered overfished or collapsed, and (b) the *catch by stock status* graph, or stock-catch status plot (SCSP). While there may be a reduction in biodiversity in terms of numbers of stocks, the bulk weight of the catch tends to remain in the 'exploited' category, and hence, the SCSP presents a more optimistic picture of fisheries. Note the newly defined 'rebuilding' category in the upper right corner of the graphs (see text).

and then recovers. To facilitate this, a 'post-maximum minimum' is defined as the minimum landing occurring after the maximum landing. Because 'rebuilding' is a form of stock (re-) development, it is displayed with the 'developing' category in the SSPs and thus appropriately illustrates the amount of improvement in the status of stocks within a given area (Fig. 6a,b). It should be noted, however, that some fisheries management regimes do not aim for full recovery but rather keep stocks in a permanently growth-overfished state, just avoiding recruitment over-fishing (Froese and Proelß 2010). The 'rebuilding' categorization thus hinges on the hope that such policies will be phased out in future and full recovery will eventually be allowed. The new algorithm definitions accounting for Fig. 6 are presented in Table 2.

Using SSPs: acceleration of shifts in global stock status

Building on Froese and Kesner-Reyes (2002), we analyse temporal trends in the number of stocks by stock status over time. Garcia and Newton (1997) noted that the transition time for a developing stock to become overfished had declined from around 10 years in the 1950s to about 2–3 years in the mid-1990s. Under this hypothesis that, over time, stocks are changing more quickly to a more exploited status, Froese and Kesner-Reyes (2002) found that the percentage of 'fully exploited' stocks (now called 'exploited', Table 2) that reached 'over-exploited' status in <10 years was about 26% in the 1950s, but increased to 38% in the 1980s (Fig. 8). When they focused on the north-east Atlantic (FAO area 27), from 1974 to 1988, 46% of the stocks moved to the 'over-exploited' status within 10 years,

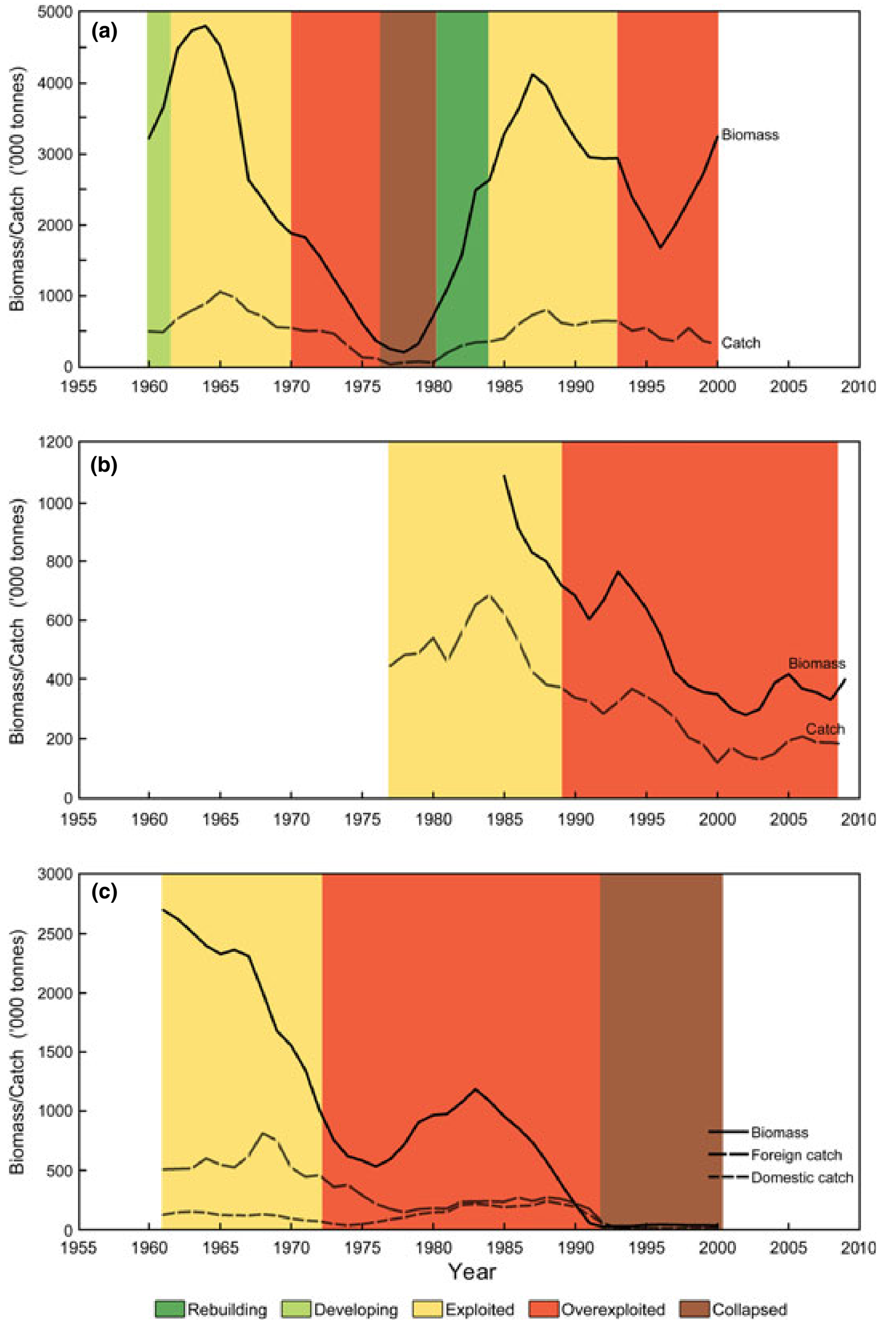

Figure 7 Biomass and catch trends for (a) North Sea herring, (b) Gulf of Alaska pollock and (c) Newfoundland cod, illustrating the ability of the stock status plots (SSP) to capture changes in biomass. These examples illustrate rebuilding (a), the effect of management on a fishery (b) and the exclusion of foreign fleets from an exclusive economic zone (EEZ) (c). The colours correspond to different status categories as defined by our SSP algorithm. Pale green is 'developing', yellow is 'exploited', red is 'over-exploited', brown is 'collapsed', and dark green is 'rebuilding'.

with an average stock-status transition time of 3.9 years (SE ± 0.37).

We evaluate this hypothesis of accelerating transition times using the improved stock status algorithm presented here (Table 2) by computing the length of time a stock remains in a particular category relative to the start year of each time series, that is, a 'run'. The average run time for all stock time series

Table 2 Refined algorithm for catch-based stock status plots as presented here, and used to categorize the status of fisheries resources based on their catch time series. The newly incorporated 'rebuilding' category requires the definition of a 'post-maximum minimum' (post-max. min.): the minimum catch after the maximum catch.

Status of fishery	Criterion applied
Rebuilding	Year of catch > year of post-max. min. catch AND the post-max. min. catch < 10% of maximum catch AND catch is 10–50% of maximum catch
Developing	Year of catch < year of maximum catch AND catch is ≤50% of maximum catch OR year of maximum catch = final year of catch
Exploited	Catch > 50% of maximum catch
Over-exploited	Year of catch > year of maximum catch AND catch is 10–50% of maximum catch
Collapsed	Year of catch > year of maximum catch AND catch < 10% of maximum catch

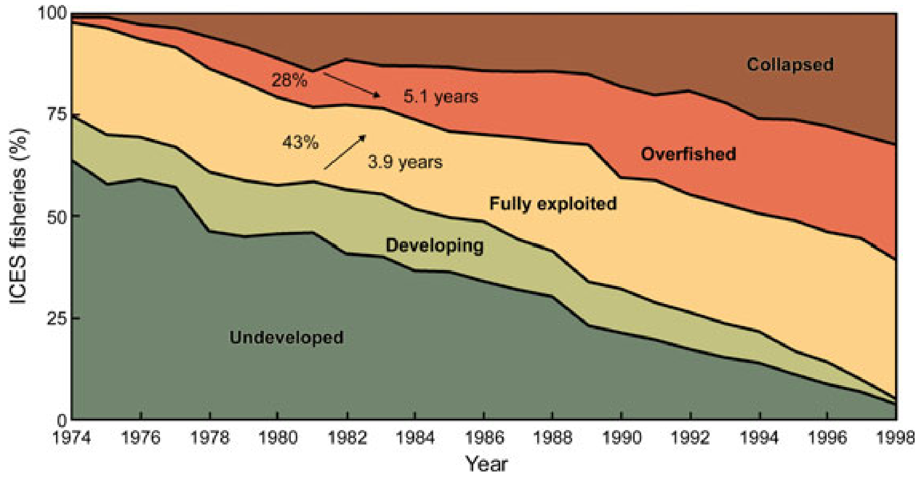

Figure 8 Trends in the status of fisheries in the north-east Atlantic derived from International Council for the Exploration of the Sea (ICES) catch data for 1973–1999. Forty-three per cent of the species items were overfished within <10 years, with an average transition time of 3.9 years (SE ± 0.37). Only 28% of species items that had collapsed during this period recovered in <10 years, with an average duration of 5.1 years (adapted from Froese and Kesner-Reyes 2002).

beginning in the same year is calculated and used to produce a trend of average run time for each status category. We also compute the percentage of stocks in each year that remained in the 'developing', 'exploited' (i.e. formerly 'fully exploited') and 'over-exploited' categories for <10 years, and the average number of years within this subset that a stock remained in each status group.

From 1950 through the 1990s, the percentage of stocks that remain in a specific category for <10 years increases (Table 3). In the case of the 'developing' category, the increase is substantial (from 2.8 to 84.8%), while in the case of 'exploited' and 'over-exploited' categories, the percentages approximately double. This suggests that there have been accelerations in transition times or, alternatively, decreases in the time a stock remains within a given category. Also, the transition time in years has declined between the 1950s and 1990s for all categories (Table 3), and the relationship between the average number of years in the 'exploited' or 'over-exploited' categories and the start year of the time series reveals a decreasing trend over time (Fig. 9a,b), supporting the findings of Garcia and Newton (1997) and Froese and Kesner-Reyes (2002).

Expected SSP performance under various scenarios

Finally, we evaluate situations where trends in catch are related to corresponding changes in biomass, which results in a correct interpretation by the SSPs. This is in contrast to situations where they are likely to fail as a result of poor correlation

Table 3 Percentage of stocks and average number of years in the '<10 years' group.

Decade	Developing %	Developing years	Exploited %	Exploited years	Over-exploited %	Over-exploited years
1950s	2.8	5.8 (5.2–6.4)	46.4	4.9 (4.8–5.1)	23.3	4.5 (4.3–4.7)
1960s	16.2	4.3 (3.7–4.8)	48.2	4.1 (3.8–4.4)	24.4	4.7 (4.2–5.3)
1970s	10.1	5.4 (4.5–6.3)	61.4	4.7 (4.4–5.0)	17.6	4.0 (3.5–4.5)
1980s	46.4	4.7 (3.1–6.3)	53.6	4.9 (3.7–6.2)	50.0	4.0 (3.0–5.0)
1990s	84.8	4.6 (4.0–6.1)	87.9	3.4 (2.7–4.2)	51.5	2.6 (2.0–3.2)

95% Confidence intervals are in parentheses.

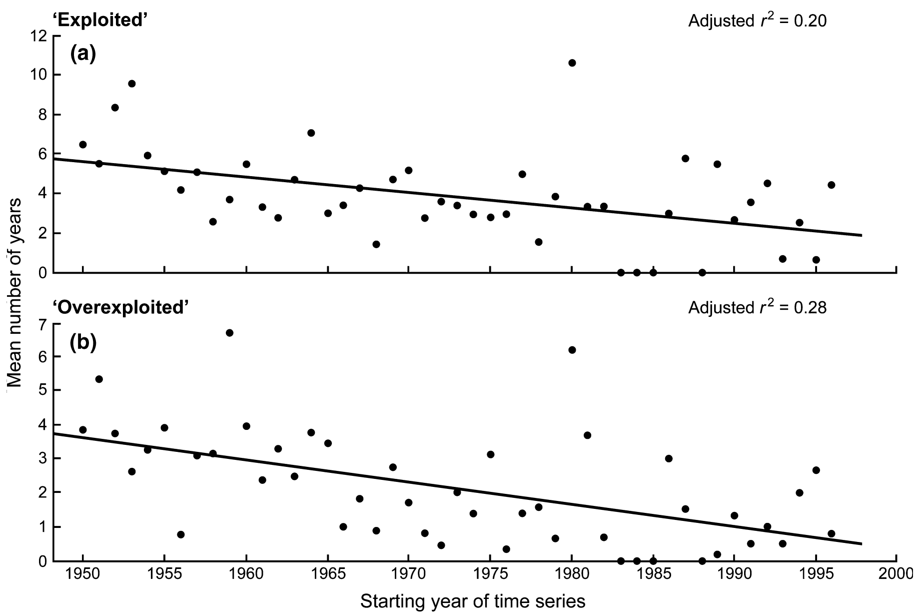

Figure 9 Average time spent by stocks in the (a) 'exploited' and (b) 'over-exploited' status categories.

between catch-based status and biomass. We present six scenarios and evaluate them for their potential effects on SSPs: (i) open-access fisheries and regulated fisheries; (ii) marine protected area implementation; (iii) increased cost of fishing; (iv) loss of access of a fleet to EEZ waters; (v) changes in the price of fish; and (vi) catch of non-target species declines because of restrictions on target species (Table 4).

Open-access and regulated fisheries

'Open-access' conditions are widespread in global fisheries and are characterized by poor controls on effort and capacity (Churchill and Low 1988). When these situations are combined with a lack of management, fish biomass may be driven down by overfishing (de Alessi 2007). In these situations, SSPs, which categorize the fluctuation of catch relative to the peak catch, should reflect fluctuations in the underlying biomass relatively well. In other words, without effective management and under open-access conditions, market forces will cause catches to initially increase as fishing pressure increases and more entrants access the resource while profitability is high (see Fig. 1a). Biomass will decrease as soon as fishing pressure is applied. Catches will eventually also decrease, although they may lag behind in the case of concentrated fishing pressure on a range-contracting species (e.g. Atlantic cod; Rose and Kulka 1999; Hendrickson and Vazquez 2005; Wilberg *et al.* 2010). This will be reflected in the SSP as over-exploitation and possibly collapse. However, it is important to point out that

Table 4 Scenarios for differences in catch and biomass trends.

Scenario	Catch trend (proposed)	Biomass trend (proposed)	Effect on SSP	Examples	Sources
Open-access fishery	Declines	Declines	Trend is captured	Pacific halibut; Northern anchovy	Skud (1976); Opsomer and Conrad (1994)
Regulated fishery	Declines owing to management action (e.g. reduced TAC)	Declines (reason for the management action)	Trend captured	Gulf of Alaska Pollock; North Atlantic swordfish	Dorn *et al.* (2008); ICCAT (2009)
MPA	Becomes zero	Increases	Effects on very small scale: area of no-take MPAs is negligible	Less than 1% of the global oceans are protected	Cullis-Suzuki and Pauly (2010)
Increased cost of fishing	Declines: fishers alter fishing patterns	Sustained or increasing owing to reduced pressure (unless recruitment overfishing occurring)	Falsely reflected as decline in SSPs, but fuel subsidies counter this problem	Fishery in Newlyn (no fuel subsidies and no significant decline in landings)	Abernethy *et al.* (2010)
Foreign fleet loses permission to fish in EEZ waters	Declines	Sustained or increasing owing to reduced pressure	Falsely reflected as decline in biomass, but poor monitoring and enforcement in developing countries	Namibia restricted foreign access; SSP will be inaccurate; however, domestic catches partially compensate for decrease in foreign fishing	Willemse and Pauly (2004); Lynam *et al.* (2006); Utne-Palm *et al.* (2010)
Value of fished species declines	Declines (if there is not a steady demand for the species)	Remains high or increases	Falsely reflected as a decline in SSPs	Used to challenge catch-based metrics, but no real example ever presented	Mackinson *et al.* (1997); Orr *et al.* (2004)
By-catch species (reported)	Declines owing to a fishery closure for a target species	Does not decline or could increase	May be falsely reflected as a decline in SSPs	Dolphinfish	Kleisner (2008); Kleisner and Pauly (2011)
By-catch species (not reported)	Declines owing to heavy fishing on target species	Declines	Not captured by SSPs as not in reported data	–	–

EEZ, exclusive economic zone; MPA, marine protected areas; SSP, stock status plots.

there are other factors that can cause catches to decline. For example, if stock biomass declines because of climate shifts, catches will also eventually decline and this scenario will also be interpreted as overfishing and collapse in the SSP (e.g. Peruvian anchoveta, *Engraulis ringens*, Engraulidae, Bakun and Weeks 2008; Arias-Screiber *et al.* 2010; Merino *et al.* 2011).

A good number of fisheries in coastal regions (mainly in developed countries) progressed to tighter regulations to either prevent collapse or in response to a significant decline in landings, usually attributable to heavy exploitation. The Gulf of Alaska (GOA) pollock (*Theragra chalcogramma*, Gadidae) provides an example of such management action (Dorn *et al.* 2008; Fig. 7b). Prior to the 1970s, it was primarily foreign vessels that were fishing for pollock, under open-access conditions. In 1976, the United States declared a 200-mile EEZ, but landings of pollock continued to increase under fishing pressure from both US and foreign vessels. By 1988, foreign vessels had been virtually eliminated from the US EEZ waters, but this did not stop the decline of the biomass of pollock, which had begun in 1985. Landings also began to decline after 1986, prompting a moratorium on pollock fishing in international waters in 1994. Because of management regulation, stocks within the GOA have stabilized, although both catch and biomass levels are well below mid-1980s levels. If management exists in such cases, it will react to a decline in stocks by attempting to reduce catch (Duffy 2009), and thus SSPs will track these patterns, as a decline in biomass results in tighter restrictions on harvest which are expressed as reduced catches. However, it should be noted that if management is effective, biomass could increase, while catches may not. This would be an instance of stock rebuilding that the SSP would fail to detect. However, political pressure to increase the catch quotas would likely increase at some point resulting in the validation of the SSP.

Marine protected areas

There has been a push to increasingly protect areas of the world's oceans using marine protected areas (here defined as no-take MPAs). Current protection targets aim to conserve at least 10% of the marine environment, and to this end, the number of MPAs has increased in the past decade at a rate of about 5% annually (Wood *et al.* 2008). However, the total area protected globally is just over 2 million km^2, or about 1% of the world ocean (Cullis-Suzuki and Pauly 2010), while the percentage of no-take MPAs is even smaller (Wood *et al.* 2008). Despite the small area protected overall, MPAs are considered to be a potentially important management tool to help mitigate and prevent future losses in marine biodiversity (Agardy 1994; Pauly *et al.* 2002; Roberts *et al.* 2005). In theory, no-take marine reserves can be used as a tool for reducing or preventing overfishing and for rebuilding stocks that have been overfished. Some studies have shown that the abundance and diversity of fish within marine reserves increased after an effective no-take zone was established (Guénette and Pitcher 1999; Guénette *et al.* 2000; Seytre and Francour 2008). However, in practice, many MPAs are 'paper parks' (Cressey 2011) and at present suffer from inadequate control and enforcement. In the cases where MPAs are effective, the level of catch within a no-take zone should be zero and, at least for relatively sedentary species, biomass will increase (e.g. Russ and Alcala 1996, 2004). If the reserve were large enough to protect an entire stock or the majority of that stock, this would be represented in the SSP as a collapsed stock as no or very low catches would have been reported when, in fact, the stock should be classed as rebuilding.

This scenario therefore represents a case where catch-based SSPs would fail to capture the status of a stock's biomass. However, in the light of the small fraction of the world ocean effectively protected by MPAs and the relative small size of most MPAs relative to distributional ranges of commercial stocks, this scenario is not expected to greatly affect the general usefulness of the SSPs.

Increased cost of fishing

The profitability of fishing is determined to a large extent by the price of fuel (Sumaila *et al.* 2008; Abernethy *et al.* 2010), which has increased significantly over the past decade (Anon. 2008). Several studies have found that rapidly increasing fuel prices can alter the fishing patterns of vessels and thus their catch (Wilen *et al.* 2002; Venables *et al.* 2009). Abernethy *et al.* (2010), in a study on fishing vessels operating out of the port of Newlyn in south-west England found that skippers reduced fuel consumption by fishing with the flow of the tide (i.e. drifting), running at lower speeds for both steaming and fishing, operating in good weather only, remaining closer to port, reducing exploratory fishing and forgoing gear experimentation. They found that while the price of fuel increased by 359%, fish prices remained relatively stable. The extra costs were borne by the vessel owners and the crew by means of reduced wages.

Higher fuel costs, which may lead to a reduction in fishing pressure and hence a reduction in landings, could have positive effects on resource sustainability in terms of increased biomass and should drive out the least fuel-efficient (Tyedmers *et al.* 2005) and most environmentally destructive vessels (Arnason 2007). When high fuel cost induces a reduction in landings, this could result in an increase in biomass, a pattern that the SSPs would fail to capture. However, on a global scale, government fuel subsidies to the fishing sector reduce, and in some instances even negate, the reduction in effort because of higher fuel costs (Sumaila *et al.* 2008). Also the steady increase in gear efficiency will also contribute to compensate for increasing cost of fuel (Pauly and Palomares 2010).

Foreign fleets lose permission to fish in EEZ waters

Prior to the United Nations Convention on the Law of the Sea in 1982, which allowed coastal countries to establish EEZs out to 200 nautical miles, ocean-going fishing vessels had open access to the coastal waters of foreign countries. In general, after EEZ declaration, fishing by foreign vessels was to be controlled through 'access agreements', which involved the payment of a fee, usually on a per vessel and/or per tonne basis. In many developing countries, these access agreements are, in reality, often very inequitable arrangements, wherein (unmonitored) vessels end up removing large quantities of fish and adversely affecting local artisanal fishers (Kaczynski and Fluharty 2002). In developed countries, where monitoring and enforcement is often better, the exclusion of foreign fleets can cause a reduction in catches and an increase in biomass. This reduction in catch can quickly be nullified by the replacement of foreign fleets by national fleets. Therefore, the SSPs may be misleading in the short term, but once the national fishery has ramped up effort, regulated or open-access fishing patterns will apply.

An example of this scenario is the Canadian fishery for Atlantic cod. Prior to the mid-1960s, the fisheries along Canada's Atlantic coast were open to national and foreign fleets with very little restriction. The Newfoundland cod stock in particular was subject to enormous fishing pressure by foreign fleets, and biomass declined significantly (Walters and Maguire 1996), resulting in declining catches from the mid-1960s to late 1970s. In 1977, when Canada extended fisheries jurisdiction to 200 nautical miles, the Canadian domestic fishery began a significant development drive funded through government subsidies in anticipation of reaping the benefits of the displaced foreign fleets (Fig. 7c). By the late 1980s, however, fishing pressure from the domestic fleets had replaced the foreign effort completely, and the catches of cod continued on their tragic decline. Overall, the SSP would therefore correctly present the case of Atlantic cod (Fig. 7c).

Changes in the price of fish

Prices of fish can fluctuate for many reasons: scarcity, demand and changing preferences of consumers. If a species becomes scarce, and consumers still demand the fish, prices may remain high and may dictate whether fishers are willing to devote their time to fish a species at low abundance (Pinnegar *et al.* 2002). Mackinson *et al.* (1997) found that small pelagic stocks that display density-dependent catchability and are valuable will be at greater risk of collapse because high levels of fishing effort would continue to be expended even at low abundance levels. Furthermore, neither landings data nor commercial catch-per-unit-effort data (which do not account for differences in catchability) would reflect biomass.

Alternatively, declining prices of fish may lead to decreased landings if there is insufficient demand for the species, irrespective of its abundance (Pinnegar *et al.* 2006). In return, market prices rise with consumer demand (Ludicello *et al.* 1999) and when fish become more scarce (OEDC 1997). While this scenario has been advanced by several authors to question the use of catch-based metrics as indicators of stock status (e.g. Mackinson *et al.* 1997; Orr *et al.* 2004), none of them have provided an example of a once-exploited, now-abundant species left alone solely because its market price was too low. Rather, it is the combination of low market price and scarcity because of overfishing, which makes a species unprofitable to exploit and reduces catch, and hence, the SSPs would tend to reflect biomass trends.

Non-target species declines owing to restriction on a target species

Gears such as trawls and longlines catch not only their target species, but also species of lesser value or desirability. Often much or all of these by-catch species are discarded and not reported in commercial landings. However, sometimes they are landed. For example, the longline swordfish fishery (*Xiphiidae*) in south-eastern USA waters (ICCAT 2009) catches dolphinfish (or mahi mahi; *Coryphaena* spp., Coryphaenidae) as a secondary by-catch species that is marketed (Kleisner *et al.* 2010).

Swordfish have been targeted commercially off the east coast of the U.S.A. since the 1800s, and the associated by-catch of dolphinfish, a popular food fish in the USA and Caribbean, is the fourth most common landed species in the USA longline fisheries (Kleisner 2008). In 2001, NOAA's National Marine Fisheries Service implemented several large time and area closures for pelagic longline fishing in order to reduce the by-catch of juvenile swordfish and billfish (NOAA 2003; 50 CFR Part 635). In particular, the year-round closure along the Florida east coast meant that landings of swordfish essentially dropped to zero, as did the associated landing of other species such as dolphinfish.

While the overall decline in catch of swordfish is related to an actual decline in biomass, there is no indication that dolphinfish biomass has declined (Prager 2000) In this instance, the SSPs would correctly reflect the decline in swordfish catch as overfishing or collapse of the fishery because of the closure of the south-eastern USA fishery. The SSPs may fail to detect subsequent rebuilding so that the stock will still appear overfished in the SSP categorization. The accompanying decline in dolphinfish catch would not accurately reflect the biomass trend of this stock. This will mainly be a problem for species that are caught as by-catch, but that in reality are 'secondary target species'. Dolphinfish, for example, is recorded in landings from longlines, and therefore, a moratorium on long lining will affect the catch statistics of this species. However, we do not expect such cases to be frequent, precisely because 'true' by-catch species that are discarded are generally not monitored in most fisheries in the world (e.g. LeManach *et al.* 2011), and hence are not included in the catch statistics used to generate SSPs. By-catch will also cause a problem for catch-based stock status analysis if a species is 'true by-catch' for a period of time before it is officially landed and reported as a primary or secondary species because the SSP will interpret that stock as 'developing' when it may already be in an overfished state. In this case, biomass changes will be hidden behind unreported discards.

Discussion

We have highlighted the main scenarios in which SSPs could potentially present an outcome that does not properly reflect the status of stocks. Clearly, stock assessments, which are more detailed and may attempt to standardize for situations that affect catchability, will continue to remain the optimal tool for the assessment of stock status. Unfortunately, stock assessments are a limited resource, as they are currently only undertaken for a small proportion of the commercially exploited species, even in developed countries. Additionally, stocks that are assessed are generally highly valued, resilient target species that have been fished extensively for decades. In contrast, small, low-value stocks and non-resilient stocks that have not withstood the fisheries targeting them are unlikely to have warranted belated stock assessments. In the north-east Atlantic, elasmobranchs, sturgeons, shads, oysters and more recently Atlantic eel (*Anguillid* species, Anguillidae) and Atlantic salmon (*Salmo salar*, Salmonidae) are examples of fisheries that have been reduced to such low levels that no full stock assessments are made today. Hence, assessed stocks are a fundamentally biased subset of fished stocks. In contrast, the alternative to stock assessments is to use measurements that are global, such as trends in catch to approximate stock status. However, concerns about inferring stock status from catch statistics have been raised, as it can be difficult to attribute a change in catch to a corresponding increase or decrease in biomass, owing to changes in markets, social factors or management actions (Duffy 2009).

While we acknowledge that catch statistics are not a silver bullet when it comes to evaluating stock status, we argue that, currently, they do represent the best (or rather, only) method of obtaining a global picture of stock status when analysed with an understanding of the scenarios which may cause misinterpretations. Moreover, the case can be made that there are very few instances where a substantial catch decline that would ensure a move in status from 'exploited' to 'over-exploited' or 'collapsed' does not stem from a decline in the biomass

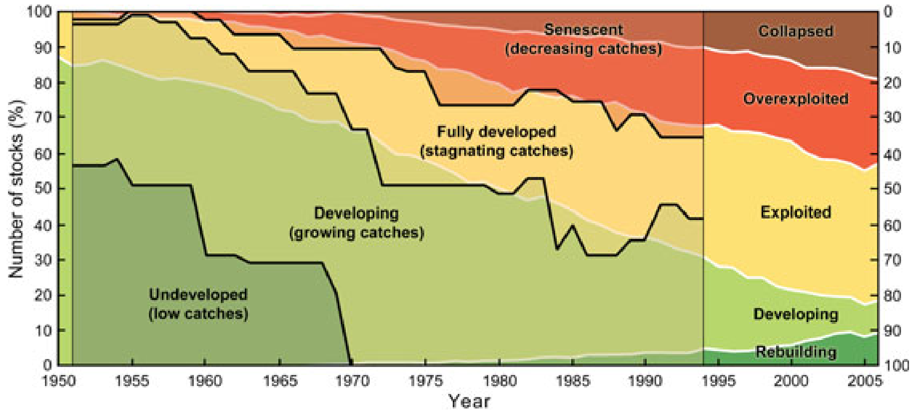

Figure 10 Overlay graph, combining the original findings of Grainger and Garcia (1996; black lines, also see Fig. 1) with an stock status plots (SSP) using the algorithm as newly defined here for global catches (white lines, also see Fig. 6). Note that the trends are very similar, with large regions of overlap. The 'senescence' category of Grainger and Garcia (1996) was too broad, that is, did not account for 'collapse' or 'rebuilding', features that contribute significantly to the reality of the trends observed in the SSPs.

of the species. Indeed, Duffy (2009) argues that 'no compelling evidence has been suggested that globally averaged catch data significantly misrepresent trends in global fish abundances'. Furthermore, Froese *et al.* (2009) found strong evidence for a link between declining catches and declining stock biomass and pointed out that if this did not apply in the majority of cases, then regulatory agencies would have managed to reduce fishing and catches without providing any reason, which does seem like a hard sell.

Here, we present a refinement of the SSP algorithm and a typology of the scenarios for which deviations in the interpretation of the plots may exist. Our improvements resolve some of the valid criticisms of the use of SSPs to infer global trends, but the results do not differ substantially from the original work of Grainger and Garcia (1996), as illustrated by Fig. 10. Indeed, the status categories in the region of overlap between the two graphs match. Thus, the simplification of the Grainger and Garcia (1996) approach initiated by Froese and Kesner-Reyes (2002) is validated by the production of similar trend lines using the presently refined SSP algorithm.

Finally, we note that the addition of a 'rebuilding' status adds an element which reflects management actions that are working to curb and reverse the over-exploitation of commercial fisheries, which was missing in earlier versions of SSPs. Also, stock status measures in terms of percentage of stocks numbers (SNSP) and percentage of catch tonnage (SCSP) help to highlight an important trend in the biodiversity of commercially exploited species, which is that we lose unproductive stocks. Thus, the number of stocks that are compromised increases over time, while the bulk of the catch still comes from stocks in the 'fully exploited' phase and which are resilient. The demonstration that the transition time between status categories is shortening should also be of interest, as it provides another dimension of global patterns of overfishing, and suggests the potential for acceleration of these patterns.

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