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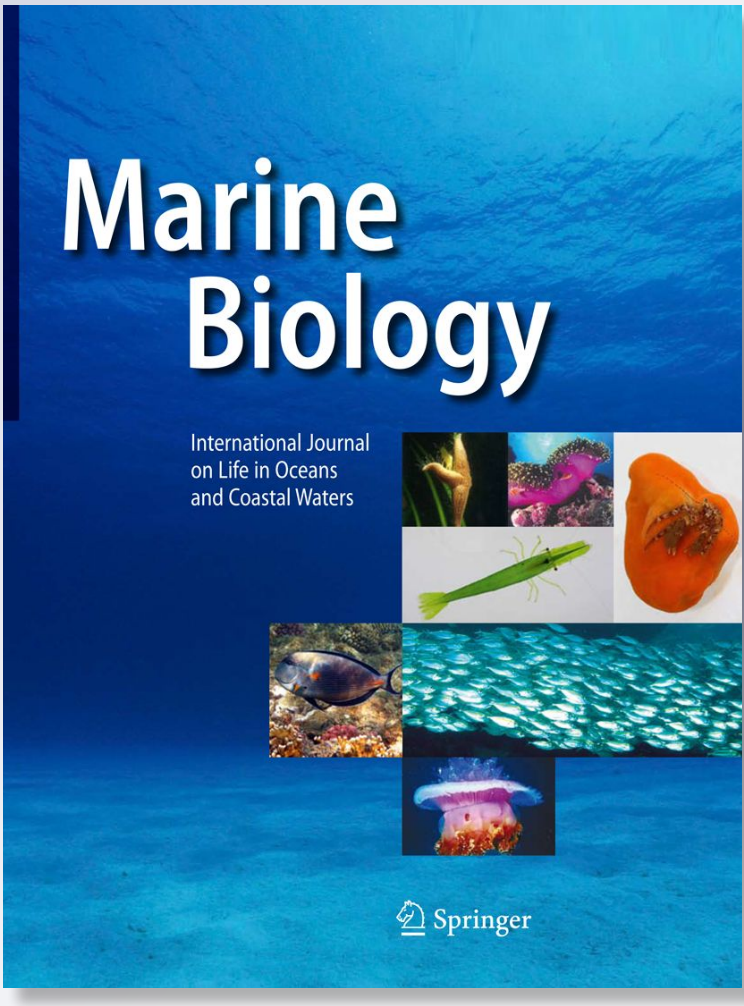

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ORIGINAL PAPER

What catch data can tell us about the status of global fisheries

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Abstract The only available data set on the catches of global fisheries are the official landings reported annually by the Food and Agriculture Organization of the United Nations (FAO). Attempts to detect and interpret trends in these data have been criticized as being both technically and conceptually flawed. Here, we explore and refute these claims. We show explicitly that trends in catch data are not an artifact of the applied method and are consistent with trends in biomass data of fully assessed stocks. We also show that, while comprehensive stock assessments are the preferred method for evaluating single stocks, they are a biased subsample of the stocks in a given area, strongly underestimating the percentage of collapsed stocks. We concur with a recent assessment-based analysis by FAO that the increasing trends in the percentage of overexploited, depleted, and recovering stocks and the decreasing trends in underexploited and moderately exploited stocks give cause for concern. We show that these trends are much more pronounced if all available data are considered.

Introduction

"Fisheries managers need to know three things: the catch, the catch, and the catch," John Gulland, then Chief of the FAO's Marine Resources Service quipped in his acceptance speech of a honorary doctorate from the University of Rhode Island (see Saila and Roedel 1980). He was serious: in most situations, it is the catch of commercial fishing vessels that constitutes the basis for estimating past and present biomass, and which then forms the basis for providing advice on next year's catch. Obviously, catch cannot be taken from zero biomass, and in most commercial species the annual catch cannot be larger than the average annual biomass. In surplus production models (e.g., Schaefer 1954), catch relative to the maximum sustainable yield (MSY) is a predictor for the relative biomasses that can support such catch in the long term, see Eq. 1.

In previous publications, we (Froese and Kesner-Reyes 2002, 2009; Froese and Pauly 2003; Pauly et al. 2008; Zeller et al. 2009; Kleisner and Pauly 2011) and others (Grainger and Garcia 1996; FAO 2010; Garibaldi 2012; Worm et al. 2006, 2007) have analyzed global catch data to gain insights into the status of global fisheries, revealing for example an increase in collapsed stocks and a decline in new stocks. These attempts were criticized by Branch et al. (2011) and categorized as "both technically and conceptually flawed" by Daan et al. (2011). Without presenting new data or insights into the status of global fisheries and without paying due attention to previous discussions of this topic (Worm et al. 2007), Branch et al. (2011) and Daan et al. (2011) conclude that reports about the critical status of world fisheries are exaggerated. Similarly, Carruthers et al. (2012) compare the methods of Froese and Kesner-Reyes (2002) and Kleisner and Pauly (2011) with surplus production assessments and find that the analyses based only on catches provide fewer correct classifications than the more informed assessment models when applied to simulated data. Here, we address this criticism as follows: We show that (1) the maximum catch (C_{max}) in a time series is highly correlated with an internationally accepted

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reference point, namely the maximum sustainable yield (MSY); (2) the trends visible in global catch data are not an artifact of the employed algorithm, as has been proposed by Wilberg and Miller (2007), Branch et al. (2011), and Daan et al. (2011); (3) the biomass trends for fully assessed stocks in the Northeast Atlantic are consistent with the trends derived from catch data analysis of these stocks; (4) only few stocks are rebuilding globally and in the Northeast Atlantic; and (5) analyses based only on assessed stocks strongly underestimate the number of collapsed stocks. We then present some improvements to the analysis of catch data and conclude with an updated analysis of the status of global fisheries.

Materials and methods

We used the original classification of stocks into categories of exploitation, based on catch relative to the maximum catch (C_{max}) of Froese and Kesner-Reyes (2002) (Table 1). We refer to this classification as the original algorithm.

Data on global capture production for 1950–2009 were obtained from http://www.fao.org in May 2011. These are landings data reported to and harmonized by FAO (Garibaldi 2012). For convenience, we refer to them in this study as FAO catch data. ISSCAAP groups of marine species were selected as in Froese and Kesner-Reyes (2002, 2009). FAO species items per marine FAO area were treated as nominal stocks. Altogether 1,953 stocks with more than 10,000 t accumulated landings in their respective time series were included in the analyses.

We introduced a new category *rebuilding* for the years in which a stock recovered from the *collapsed* status ($C < 0.1\ C_{max}$) to the *fully exploited* status ($C > 0.5\ C_{max}$) (Table 2).

Some categories require information from a preceding or subsequent year, which is obviously not available in the first and last year of a data series, respectively. We discuss these issues in the section *Dealing with boundary effects*.

For comparison of maximum catch with MSY and of catch-based analysis with biomass-based analysis, we used landings and biomass data of 50 fully assessed stocks of the Northeast Atlantic as provided by ICES (http://www.ices.dk) and respective reference points (MSY and the corresponding biomass B_{msy}) as estimated by Froese and Proelß (2010).

For the simulations of random catch data, we followed the approach used by Daan et al. (2011) and created 1,953 time series (same number as nominal FAO stocks) under the condition of a uniform distribution of random numbers between 0 and 1.

An Excel spreadsheet (193 MB) with the analysis of the FAO data is available for download at http://www.fishbase.de/rfroese/FAO_Catch_2009_MarBio.xls. The comparison between the 1950–1999 and 1950–2009 data sets is available under http://www.fishbase.de/rfroese/FAO_Catch_2009_MarBio99_3.xls. The analysis of fully assessed stocks of the Northeast Atlantic is available under http://www.fishbase.de/rfroese/BiomassMarBio.xls.

Table 1 Original criteria used by Froese and Kesner-Reyes (2002) for assigning exploitation stages to fisheries, based only on catch data (C) relative to maximum catch (C_{max})

Status of fishery	Year	C/C_{max}
Undeveloped/No info	Before $C = C_{max}$	<0.1
Developing		0.1–0.5
Fully exploited	Before or after $C = C_{max}$	>0.5
Overexploited	After $C = C_{max}$	0.1–0.5
Collapsed		<0.1

Results

Maximum catch (C_{max}) is highly correlated with maximum sustainable yield (MSY)

Froese and Kesner-Reyes (2002) propose that catches between 0.5 and 1.0 C_{max} are indicative of fully exploited stocks. Thus, they implicitly assume that the maximum sustainable yield (MSY) would normally be found within this range. That assumption is confirmed by the linear relationship between log C_{max} and log MSY shown in Fig. 1, where 98% of the variability in C_{max} is accounted for by MSY, for 50 fully assessed stocks in the Northeast Atlantic (Froese and Proelß 2010). A similar relationship was found by Srinivasan et al. (2010) for stocks from the Northwest Atlantic. Also, the median MSY/C_{max} ratio in the 50 Northeast Atlantic stocks in Fig. 1 was 0.62 (95% confidence limits, 0.56–0.70), that is, well within the range proposed by Froese and Kesner-Reyes (2002). In summary, it seems justified to assume that in a majority of fisheries, catch levels of 0.5–1.0 C_{max} are indicative of fully exploited stocks.

Trends in global catch data are not artifacts of the applied algorithm

In the following, we examine the suggested technical flaws of the original algorithm for predicting stock status from time series of catches relative to the historical C_{max}. In surplus production models, catch is a predictor of two equilibrium biomasses: either above or below the biomass that can produce the maximum sustainable yield (B_{msy}) (Eq. 1).

Table 2 Updated criteria used for assigning exploitation stages based on catches (C) relative to maximum catch (C_{max}), catches relative to *MSY*, and biomass B relative to B_{msy}. The relation between *C/MSY* and B/B_{msy} was derived from Eq. 1. No relative biomass was assigned to the *undeveloped/no info* category because lack of biomass estimates represents lack of assessment but not necessarily lack of exploitation

Status of fishery	Year	C/C_{max}	*C/MSY*	B/B_{msy}
Undeveloped/no info	Before $C \geq 0.5\ C_{max}$	<0.1	<0.2	
Developing		0.1–0.5	0.2–0.75	>1.5
Fully exploited	At/after $C \geq 0.5\ C_{max}$	>0.5	>0.75	≥0.5
Overexploited		0.1–0.5	0.2–0.75	<0.5
Collapsed		<0.1	<0.2	<0.1
Rebuilding	Years between *collapsed* and first subsequent *fully exploited*			
Final year rules				
Developing	If C_{max} occurs in the final year, increase C_{max} by 50% and set its year of occurrence as final year plus one			
Rebuilding	In the final year, accept $C > 0.28\ C/C_{max}$ as indicative of subsequent *fully exploited* status			

$$\frac{B}{B_{msy}} = 1 \pm \sqrt{1 - \frac{Y}{MSY}} \qquad (1)$$

Equation 1 shows the relationship between relative biomass (B) and relative yield (Y) in a Schaefer (1954) model.

Based on the implicit assumption that most catch time series have a clear peak and that such peaks are probably due to overshooting MSY (see above), Froese and Kesner-Reyes (2002) assume that stock biomass in years before C_{max} was above B_{msy}, and below thereafter. Consequently, *overexploited* (catch between 0.1 and 0.5 of C_{max}) and *collapsed* stocks (catch $< 0.1\ C_{max}$) would only occur after the year of the peak catch, whereas before C_{max} the same ranges would indicate *developing* and *undeveloped* stocks, respectively (Table 1).

Daan et al. (2011) repeat the approach of Branch et al. (2011), which was adopted from Wilberg and Miller (2007), where the original algorithm described above was applied to a simulated data set of randomly varying time series of numbers. Such simulated time series do not have a clear peak but rather many similar high values, with the highest value (C_{max}) appearing with equal probability somewhere between the first and the last year of the series. Under such conditions, the number of time series that, in a given year, have surpassed their maximum value increases linearly toward the end of the series. As a result, *collapsed* and *overexploited* categories, which can only occur after the year with the maximum value, show an increasing trend, while *undeveloped* and *developing* categories decline and the *fully exploited* category remains stable, in a fashion similar to the trends observed in FAO catch data (Fig. 2a). The authors of the simulations use this similarity to dismiss the usefulness of the original algorithm (Table 1) for drawing conclusions from global catch data on the status of global stocks and fisheries, although Daan et al. (2011) admit that the trends seen in real data (Fig. 2a) are steeper than those in their simulations.

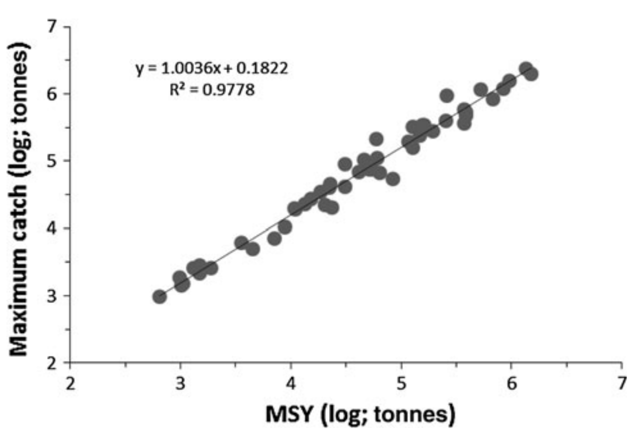

Fig. 1 Relation between maximum catch and the maximum sustainable yield (MSY), for 50 Northeast Atlantic stocks with available data (MSY taken from Froese and Proelß 2010)

Adapting the original algorithm to deal with the artificial situation of multiple, similar maximum values of simulated time series was, however, straightforward, and it corrected an inconsistency: Froese and Kesner-Reyes (2002) treat a stock as *fully exploited* once catches exceed 0.5 C_{max}, even if that happens before the year with the maximum catch. However, they consider a fishery as fully developed with no allowance for the categories *undeveloped* and *developing* only after the year with the maximum catch (Table 1). Thus, a logical simple update to the original algorithm was to assume that a fishery was fully developed from the year in which catches exceeded 0.5 C_{max} (Table 2). This update also corrects the dependency on potentially insignificant maxima in the data, such as occurred with the simulated time series.

Applying this updated algorithm to recent FAO data resulted in little change compared with the original algorithm (Fig. 2). In 15% of the time series, the start of a fully developed fishery remained where it was. In the remaining time series, it moved backward with a median change of 9 years. There was no change in the percentage of *fully*

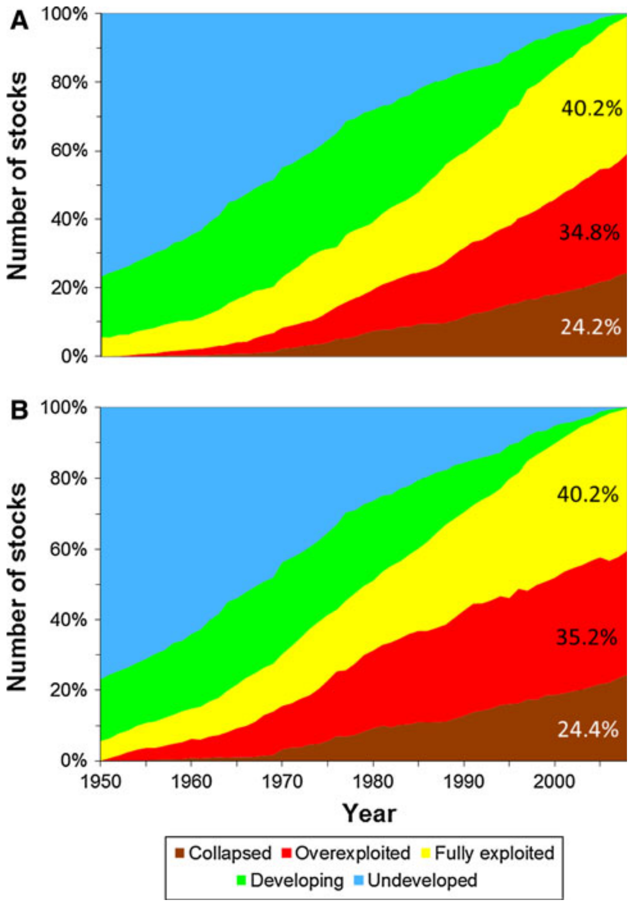

Fig. 2 FAO catch data from 1950 to 2008, as analyzed with the original algorithm of Froese and Kesner-Reyes (2002), with a fully developed fishery starting at C_{max} in (**a**), and analyzed with a fully developed fishery starting at 0.5 C_{max} in (**b**). Note that major trends remain unchanged and that the percentages in the first and final years are nearly identical between panels. Due to the earlier recognition of fully developed fisheries, there are slightly more overexploited stocks in the beginning of the time series in (**b**)

exploited stocks between the original and the updated algorithm, because the rule for this category had not changed. Near the beginning of the time series, the earlier recognition of fully developed fisheries led to a slight increase in *overfished* and *collapsed* stocks, and a corresponding slight decrease in *undeveloped* and *developing* stocks, a change that better follows observed changes in biomass (see Fig. 5). These differences disappeared toward the end of the time series. Overall, the differences are barely visible in the stock status plots (SSPs, Kleisner and Pauly 2011) constructed with the original and the updated algorithm (compare Fig. 2a, b).

However, the updated algorithm had a strong effect when applied to the simulated random data proposed by Daan et al. (2011) as baseline against which trends should be measured (Fig. 3). The similarity with the analysis of the real catch data completely disappeared. In year one, where the categories *collapsed* and *overexploited* cannot occur by definition, we see the expected random distribution of 50% *fully exploited*, 40% *developing*, and 10% *undeveloped* stocks. After a few years in which the simulated time series passed 0.5 C_{max}, the trend lines flattened and the expected random distribution of about 10% *collapsed*, 40% *overfished* and 50% *fully exploited* stocks showed. If the trends visible in Fig. 2a were indeed an artifact of the original algorithm, then Fig. 2b should be strongly different from Fig. 2a and more similar to Fig. 3. This is clearly not the case.

Daan et al. (2011) apply the most parsimonious randomization of simulated catch time series, that is, their approach includes the more restricted randomization of Wilberg and Miller (2007) and Branch et al. (2011), where a simulated value in a given year is partially dependent on the value in the previous year. Thus, the above analysis and conclusion extend also to these simulations.

In summary, the claim by Wilberg and Miller (2007), repeated by Branch et al. (2011) and Daan et al. (2011), that clearly visible trends in global catch data are artifacts of the original algorithm can be put to rest.

Dealing with boundary effects

The original algorithm has two boundary problems stemming from the fact that the maximum catch may not (yet) be included in the time series. In the first year of the time series, a stock cannot be simultaneously smaller than 0.5 C_{max} and past the start of the developed fishery, which is

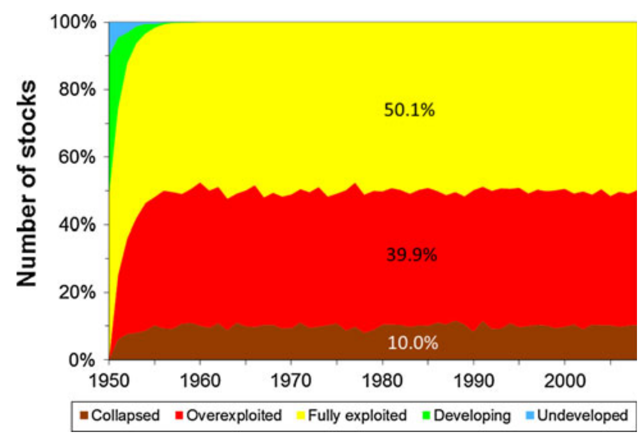

Fig. 3 The original algorithm with the change of a fully developed fishery starting at 0.5 C_{max} applied to randomly fluctuating time series of simulated catch data. As expected under such conditions, the *fully exploited* category remains unchanged with about 50% throughout the time series. The *undeveloped* and *developing* categories have about 10 and 40%, respectively, in the first year and quickly fade as the simulated data pass 0.5 C_{max}. The overexploited and collapsed categories then average about 40 and 10%, respectively, through the last 40 years. Clearly, these random data show no similarity with the reported catch data in Fig. 2

marked by catches above 0.5 C_{max}. Thus, the categories *overfished* and *collapsed* cannot occur in the first year (see Tables 1, 2). Froese and Kesner-Reyes (2002) therefore excluded the first year of the time series from their graphs. However, at the beginning of a time series these categories of overexploitation are rare, so we did not exclude the first year of the time series in the graphs presented here. Doing so did not cause a break in trends with subsequent years where all categories are present.

A more serious boundary problem occurs in the final year of the time series, where the categories *undeveloped*, *developing*, and *rebuilding* cannot occur by definition (Table 2) and thus these categories would apply to zero percent of the stocks. This would be unrealistic, as new stocks do enter the FAO data set annually, albeit in decreasing numbers (Froese and Kesner-Reyes 2009), and rebuilding of collapsed stocks is expected to happen also in more recent years, including the final year. To explore the magnitude of this problem, we compared an analysis of 1,727 stocks with global catch data from 1950 to 1999 with an analysis of the very same stocks but using the full data set that contained additional 10 years of data (2000–2009) where a maximum catch could occur. A later, higher maximum catch did indeed occur in 500 stocks (29%), and in 335 of these stocks (19%) the change was large enough so that the beginning of the fully developed phase (first year with $C > 0.5\ C_{max}$) moved to later years. This resulted in over 100 changes in stock status in 1999, especially in the categories *undeveloped*, *developing*, and *rebuilding*, which now took on values different from zero, with 1.8, 8.9, and 1.9%, respectively (see Fig. 4b).

To deal with the boundary effect, we looked at the time series that had their maximum catch in the final year of the 1950–1999 data set and we compared that maximum with the respective maximum catch in the 1950–2009 data set. The maxima from the extended data set were on average higher by a factor of 1.43 (95% CL, 1.33–1.53, $n = 176$). Based on this insight, we created a new rule to update the original algorithm for maximum catches occurring in the final year of the time series: these maxima were increased by a factor of 1.5 and the year of the beginning of the fully developed fishery was set as the final year plus one (Table 2). In other words, stocks with their maximum catch in the final year could only have the status *developing*, while previous years could be *developing* or *undeveloped*. This is similar to the procedure applied by Kleisner and Pauly (2011), who assign stocks with maximum catch in the final year to status *developing*. Our approach expands on that concept by increasing the future C_{max} by 50%, in order to give a more realistic distribution of *undeveloped* and *developing* categories in the preceding years.

Kleisner and Pauly (2011) introduced a category for *rebuilding* stocks, which they applied to all years where

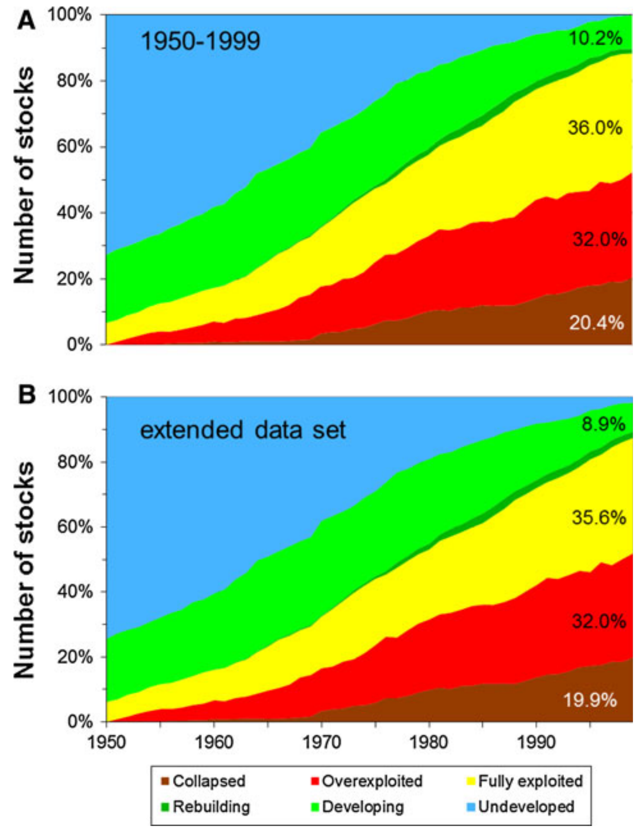

Fig. 4 FAO catch data analyzed from 1950 to 1999 with the updated algorithm. In (**a**), only data until 1999 were used. In (**b**), the years 2000–2009 where used in addition to estimate stock status until 1999 to discover boundary effects. Note that the original algorithm would have assigned zero percent to the *developing* category in the final year in (**a**), which would have led to an overestimation of the *fully exploited* category. The updated algorithm overcomes these boundary effects

catches increased above 0.1 C_{max} after a preceding status of *collapsed*. However, when looking at time series of *collapsed* stocks, we noticed that in most cases a collapse was not followed by a sustained recovery. Rather, in the majority of these stocks overfishing continued and stocks collapsed again a few years later. Thus, we decided to only count years as *rebuilding* if catches of 0.1–0.5 C_{max} resulted in reaching the *fully exploited* status of $C > 0.5\ C_{max}$ (Table 2). The definition of status *rebuilding* thus requires a subsequent year, which is obviously missing in the final year. We looked at the 31 cases in the 1950–2009 data set, which had a *rebuilding* status in 1999. We found that their average C/C_{max} ratio was 0.35 (95% CL, 0.28–0.42, $n = 31$), that is, these stocks had recovered from $C < 0.1\ C_{max}$ and were on their way to reaching $C > 0.5\ C_{max}$. We thus introduced a new rule where a stock was considered to be *rebuilding* in the final and preceding years if its C/C_{max} ratio in the final year was >0.28. Applying this rule to the 1950–1999 data set increased the percentage of rebuilding stocks in the final year from 0 to 1.4%, close to the 1.9% in the "better informed" 1950–2009 data set.

We did not try to correct the fact that *undeveloped* stocks do not contribute to the final year, although the 1950–2009 data set had 1.8% of the stocks in this category in 1999.

The comparison between the analysis of the 1950–1999 and the 1950–2009 data sets with the updated algorithm is shown in Fig. 4. Note that the better informed extended data set produced values for the categories of *collapsed* and *overexploited* stocks (18.4 + 32.1 = 50.5%) that were nearly unchanged compared with those derived from the 1950–1999 data set (19.0 + 31.6 = 50.6%), confirming the original analysis by Froese and Kesner-Reyes (2002) (20.4 + 29.3 = 49.7%; all numbers refer to percentages in the year 1998).

The new rules changed and improved the estimation of *developing* and *rebuilding* stocks, which also led to a better estimation of the category *fully exploited*, which was overestimated before in the final year when the categories *undeveloped*, *developing*, and *rebuilding* were all zero.

Due to the fact that many countries were unable to provide complete data for 2009 to FAO in time (Garibaldi 2012), the final year of catch data shows a decrease in most trends (Figs. 6, 7). To address this inadequacy in the data, we excluded the final year in Figs. 2 and 3 and masked it in Figs. 6 and 7.

In summary, existing information (relative catches in the final year) was applied to anticipate the development of catches in subsequent years, and these forecasts were then used to improve the assignment of the stock status categories *developing*, *rebuilding*, and *fully exploited*. The overall effect of these improvements is minor, and users of the method may chose to ignore them. In any case, the rules and results for the categories *collapsed* and *overexploited*, which are the most important ones in terms of policy, remain the same under the updated and the original algorithm.

How does catch data analysis compare with biomass trends in fully assessed stocks?

Froese and Proelß (2010) analyze all stocks of the Northeast Atlantic for which biomass data were available in 2008. We used their estimates of MSY and B_{msy} to compare the application of the updated algorithm to these 50 stocks with an analysis of catches relative to MSY and of biomass relative to B_{msy}. For this exercise, we associated the stock status categories with values of C/MSY and B/B_{msy}. We followed the definition of FAO (2009), where a stock is not classified as overfished as long as its reproductive capacity is not compromised. This threshold is commonly assumed to be around 0.5 B_{msy} (Froese et al. 2011). Thus, we assumed that the FAO definition of fully exploited stocks referred to stocks with biomass above 0.5 B_{msy}, realizing that this category then includes stocks that are size- or growth-overfished, where an increase in size at first capture (Beverton and Holt 1957) or an increase in biomass (Schaefer 1954) would lead to higher long-term yields. We considered stocks with biomass below 0.1 B_{msy} as collapsed. We used Eq. 1 to calculate catch levels relative to MSY that corresponded to these biomass levels (Table 2).

We then applied the C/C_{max}, C/MSY, and B/B_{msy} ranges to catch and biomass data of the 50 stocks of the Northeast Atlantic (Fig. 5). The trends revealed by the C/C_{max} algorithm are nearly identical to those which are obtained if the reference point MSY is known and applied. The trends seen in the biomass analysis are overall the same as in the catch analysis, but differ in intermediate slope. All methods result in similar amounts of overfished stocks in 2007, but the catch-based methods were late to recognize the decline in biomass throughout most of the time series. Consequently, the catch-based methods overestimated the proportion of fully exploited and developing stocks. Also, the catch-based analyses underestimated the true percentage of collapsed stocks (biomass < 10% of B_{msy}). For the other *overexploited* and *fully exploited* categories, the percentages of stock status in the final year of the analysis were very close to those derived from biomass data. The C/MSY graph suggests that the discrepancies between catch and biomass analyses are not caused by C_{max} being a poor proxy for MSY, but rather that high catches continued from these stocks while their biomass was already falling below the 0.5 B_{msy} threshold. In other words, the slow decline in catches masked the more rapid decline in biomass. Thus, contrary to the claims by Branch et al. (2011) and Daan et al. (2011), when compared with full assessments, the catch-based method did not exaggerate but rather underestimated the proportion of *collapsed* and *overexploited* stocks.

Of the 50 fully assessed stocks in the Northeast Atlantic, twelve had *collapsed* phases in their 1960–2007 biomass time series, but only two (North Sea herring and Norwegian spring—spawning herring (*Clupea harengus*)) had *rebuilding* phases where they recovered from less than 0.1 B_{msy} to more than 0.5 B_{msy}. The updated algorithm correctly identified *rebuilding* phases for these two stocks. In addition, it suggested *rebuilding* for Arctic haddock (*Melanogrammus aeglefinus*), which recovered from 0.14 B_{msy} in 1986 to 0.63 B_{msy} in 1996. However, this rebuilding was not registered by the biomass analysis because 0.14 B_{msy} was above the collapsed threshold of 0.1

B_{msy}. This discrepancy notwithstanding, we believe the new rules for *rebuilding* performed reasonably well when compared with fully assessed stocks.

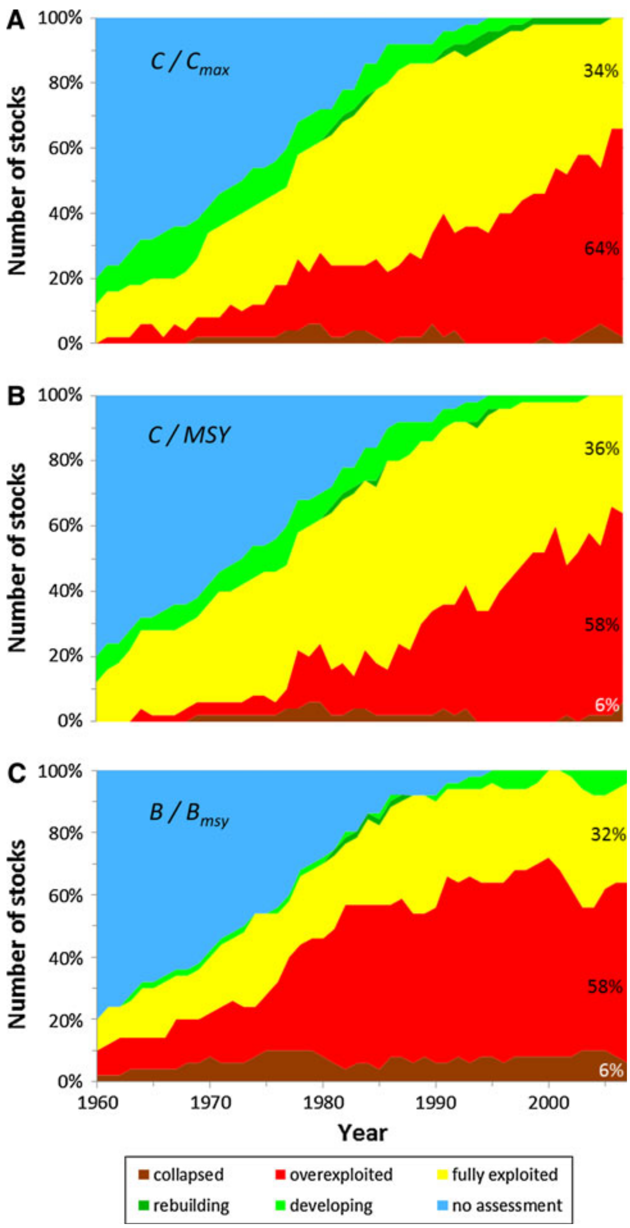

Fig. 5 Analysis of catch and biomass data for 50 stocks of the Northeast Atlantic. (**a**) Used the updated algorithm, (**b**) used the same algorithm but with MSY instead of C_{max}, and (**c**) used biomass data relative to B_{msy}. The percentages in the panels refer to the final year 2007. See Table 2 for the ranges applied to the different exploitation categories. Note that the two upper panels are nearly identical, confirming the high correlation between C_{max} and MSY. The B/B_{msy} panel depicts the same major trends as the catch-based panels, albeit with an earlier increase in overexploited stocks and a higher percentage of collapsed stocks. The "No assessment" category means that ICES did not yet provide catch and biomass data, although fishing was ongoing for most of these stocks

Trends in fully assessed stocks are not representative for the Northeast Atlantic

Full stock assessments have been proposed as the gold standard for informing fisheries policy (Worm et al. 2009; FAO 2010; Branch et al. 2011). While we obviously agree that full assessments are the preferred choice for managing individual stocks, we dispute that conclusions drawn only from fully assessed stocks are representative for a given area. In principal, stocks that are assessed are generally highly valued and fairly resilient target species that have been fished extensively for decades. In contrast, small, low value stocks, and stocks that have not withstood the fisheries targeting them (i.e., North Atlantic sturgeon) are unlikely to justify stock assessments. Hence, assessed stocks are a fundamentally biased subset of all fished stocks in that they represent high value, resilient stocks. This bias suggests a further observation: there is a fundamental problem associated with making generalizations about global stock status based solely on a sample of stocks that have survived exploitation (i.e., assessed stocks). This concern may be best illustrated by a deceivingly simple anecdote: the story of WWII engineers charged with identifying the weak spots of long-range bombers in order to better protect them. For months, the scientists studied bombers that had returned to base with damage inflicted by enemy guns and added reinforcements to the planes in the most damaged areas. However, this did not reduce bomber losses. Ultimately, a mathematician, Abraham Wald, pointed out that the analysis was fundamentally biased: it was the bombers that had not returned that contained information about their vulnerabilities, not the ones that returned, albeit damaged. His non-intuitive recommendation (Wald 1943) was to reinforce the undamaged areas of returning planes. This was implemented with great success, and the conceptual error of observation and analysis that Wald's logic corrected was subsequently termed "survivorship bias" (Burkus 2011).

To test for the occurrence of survivorship bias in fully assessed stocks, we applied the updated algorithm to 182 FAO stocks with catches reported from the Northeast Atlantic. Comparing the resulting Fig. 6 with the three analyses of fully assessed stocks from the area in Fig. 5 shows similar patterns with over 60% overexploited and collapsed stocks in the final year. However, there are important differences. Full assessments often begin well after the stocks have been exploited for some time. Consequently, the information about how many stocks were exploited historically is grossly underestimated. Also, the percentage of developing stocks is far too low, because these stocks are not yet assessed. But from a policy point of view, the strong underestimation of collapsed stocks (2–6%) is highly misleading in Fig. 5. This percentage is 32% if all stocks are considered (Fig. 6). It lies well above the global average of 24% and underlines the admitted (EC 2009) failure of European fisheries management (Froese 2011).

Discussion

The catch-based methods were developed to better understand trends in the global catch data provided by FAO. An excellent summary of the history and peculiarities of these data is given in a recent publication by Garibaldi (2012). The study cautions that "[d]ata reported for the latest year are considered provisional and may be subject to revision the following year," thus explaining the deviating trends in the final year and supporting our decision to exclude or mask that year. Also, the number of species items contributing to the global catches has to be interpreted with caution, because improved reporting of species breakdown cannot be distinguished from real changes in catch composition. We have therefore refrained from an interpretation of the increase in nominal stocks from 930 in 1950 to 1,953 in 2009, although there can be little doubt that a substantial portion of this increase is due to newly exploited stocks such as orange roughy (*Hoplostethus atlanticus*) off New Zealand and Patagonian toothfish (*Dissostichus eleginoides*) from the southern Indian Ocean. For the Northeast Atlantic, stocks with status *undeveloped* in 2000 include the octopus (*Octopus vulgaris*) and the surf clam (*Spisula solida*), which both have a long history of being exploited in the area, but their catches have been previously reported under the Family Octopidae and Class Bivalvia, respectively, thus presenting an example of improved taxonomic resolution. On the other hand, the slickhead (*Alepocephalus bairdii*) is a deep sea fish that has only recently been targeted by fisheries.

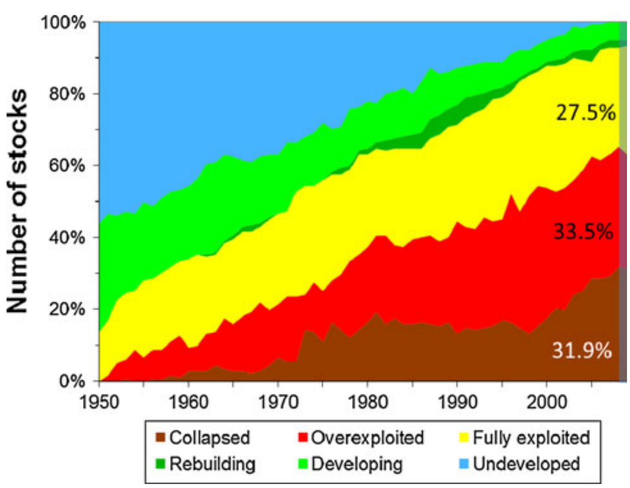

Fig. 6 The updated algorithm applied to FAO catch data for 182 nominal stocks in the Northeast Atlantic. The last year (2009) of the time series is masked because data there are incomplete. Note the lower proportion of unexploited stocks and the higher proportion of overexploited and collapsed stocks, compared to the global catch data in Fig. 7. Note also the difference with the $C/C_{\max}$ panel in Fig. 5, which only used 50 fully assessed stocks from the Northeast Atlantic: that approach underestimated the percentage of stocks that were already exploited in 1960. More disturbingly, Fig. 5 strongly underestimated the number of collapsed stocks in recent years

The aggregation of stocks by species and FAO area may result in a masking effect with respect to stock status (Garibaldi 2012). For example, in our analysis of the Northeast Atlantic, the collapse of the North Sea herring (*C. harengus*) in the 1970s was buffered by other non-collapsed herring stocks, with no collapse occurring in the time series of the combined herring catches for the area. Since collapsed stocks are fewer than non-collapsed stocks (Fig. 7), aggregation of stocks by area is more likely to mask collapsed than non-collapsed stocks. This masking provides an additional mechanism for our previous result (Fig. 5) that catch-based analysis is not prone to overestimation of collapsed stocks.

The aggregation of species items into higher taxonomic categories may also mask the status of individual stocks (Garibaldi 2012). If, for example, better taxonomic resolution in reporting leads to an *overexploited* stock being taken out of an aggregated species item with a different exploitation status, then this improved reporting would lead to an increase in the number and percentage of *overexploited* stocks, although nothing has changed in the water. Thus, the trends seen in our graphs based on FAO data reflect changes in status of individual stocks as well as better resolution in the reporting of individual stocks. Note that the effect of better taxonomic resolution on trends in percentages of exploitation status is somewhat balanced by a) a simultaneous increase in number of total stocks, b) the preferred practice of reporting catches for new, previously lumped species items backward throughout the time series, c) the occurrence of the opposite event, where previously reported species items are lumped into aggregated species items (Garibaldi 2012), and d) the fact that lumped species items with overall status *collapsed* may contribute new, separately reported stocks that are not *collapsed*. Nevertheless, users should keep in mind that trends in stock status plots based on FAO catch data are partly resulting from changes in reporting. Note that from a policy point of view, it does not matter whether the visible trends in our graphs stem in part from better reporting: even if better reporting was the only reason for the increase in *collapsed* and *overexploited* stocks, it still means that there is more unsustainable fishing ongoing than previously known and action for improving global fisheries management is therefore urgently needed.

Our data provided no support for the claim by Branch et al. (2011) and Daan et al. (2011) that many stocks with

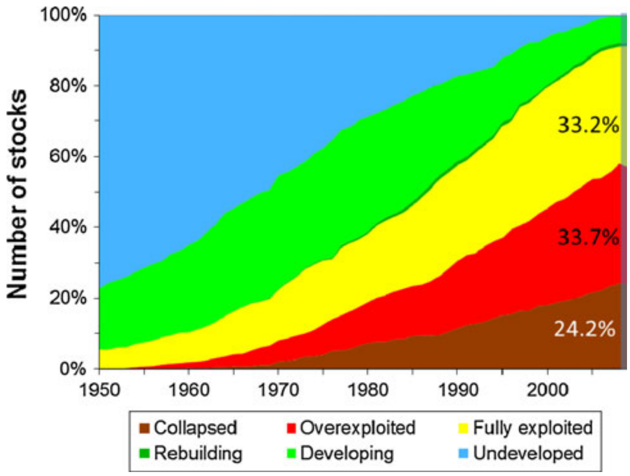

Fig. 7 The updated algorithm applied to global FAO catch data from 1950 to 2009. The last year is masked because data there are incomplete. The major trends continue those of previous analyses; however, the updated approach provides a better estimation of *developing* and *rebuilding* stocks. Note that the fraction of *developing* stocks is decreasing and the fraction of *rebuilding* stocks is small (about 1%) and not increasing

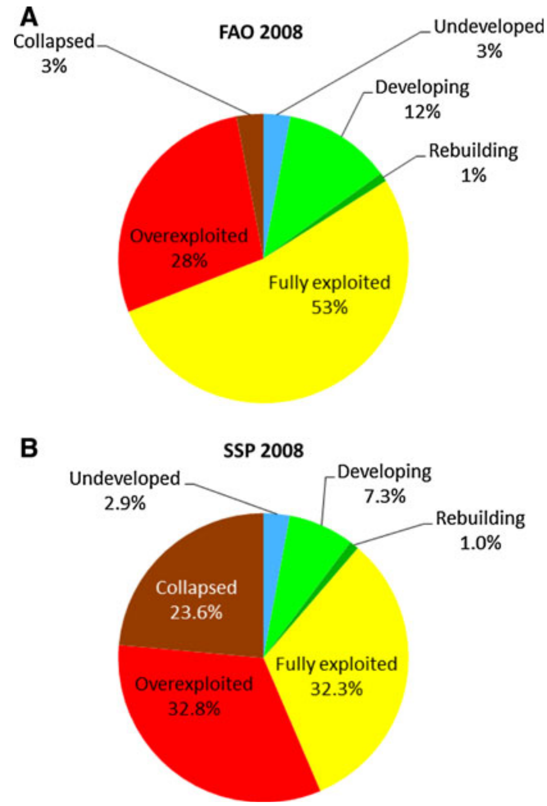

Fig. 8 Comparison of the analysis of 445 assessed stocks representing 80% of the global catches by **a** FAO (2010), and **b** the current Stock Status Plot analysis of all global catch data. While the estimates for *developing* and *rebuilding* stocks are similar between the two approaches, the FAO restriction to assessed stocks strongly overestimates *fully exploited* stocks and underestimates *collapsed* and *overexploited* stocks

low catches are actually *rebuilding* under restrictive management. The updated algorithm with its new *rebuilding* category performed reasonably well when compared with full assessments (Fig. 5). Applied to global catch data, it suggested only low percentages of stocks in that category, from 1975 onward, with no increasing trend (Fig. 7). Garcia et al. (2005) and FAO (2010) analyze over 400 global stocks and report only 1% as *rebuilding* in 2004 and 2008, respectively, very similar to our own estimates of about 1% in these years (Fig. 8).

Applying the updated algorithm to recent FAO data showed that in 2008, 24% of 1,953 FAO stocks produced less than 10% of their previous maxima, that this fraction doubled since 1990, and that its trend showed no sign of leveling off, confirming the predictions by Worm et al. (2006) and Froese and Kesner-Reyes (2009) for a business-as-usual scenario. Similarly, the fraction of stocks that produced less than 50% of a previous maximum stood at 34% in 2008, doubling in the past 20 years.

We conclude our study with a comparison of the status of global fisheries as derived here and as presented by FAO (2010) based on a subset of 445 assessed stocks representing about 80% of the global catches (Fig. 8). While the respective estimates for *undeveloped*, *developing*, and *rebuilding* stocks are fairly similar with our results, FAO (2010) strongly underestimates the number of collapsed stocks and consequently strongly overestimates the number of *fully exploited* stocks. FAO (2010) concludes with regard to their estimates: "The increasing trend in the percentage of overexploited, depleted, and recovering stocks and the decreasing trend in underexploited and moderately exploited stocks give cause for concern." Our study shows that the same trends (Fig. 7), but with more alarming slopes, result if one extends the analysis to the many stocks for which only catch data are available.

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