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Ghoti

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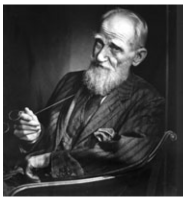

Ghoti aims to serve as a forum for stimulating and pertinent ideas. Ghoti publishes succinct commentary and opinion that addresses important areas in fish and fisheries science. Ghoti contributions will be innovative and have a perspective that may lead to fresh and productive insight of concepts, issues and research agendas. All Ghoti contributions will be selected by the editors and peer reviewed.

Etymology of Ghoti

George Bernard Shaw (1856–1950), polymath, playwright, Nobel prize winner, and the most prolific letter writer in history, was an advocate of English spelling reform. He was reportedly fond of pointing out its absurdities by proving that ‘fish’ could be spelt ‘ghoti’. That is ‘gh’ as in ‘rough’, ‘o’ as in ‘women’ and ‘ti’ as in palatial.

70th Birthday Contribution

This manuscript is a contribution to the virtual special issue celebrating the 70th birthdays of Paul Hart and Tony Pitcher, long-time collaborators and founding editors of the journal.

Plenty more fish in the sea?

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Abstract

Only in the last century did humans overwhelmingly accept that fisheries resources are finite. Consequently, ‘there are more fish still in the sea than ever came out of it’ served as a popular metaphor for unbounded expectations for half a millennium, expectations that also extended to use of the planet in general. By reconstructing historical fishing back 1200 years, we identify when this metaphor actually ceased to be true. For some of our most important stocks, it has not been true for centuries, although surprisingly, for fishes globally, it applied until the last century. We demonstrate, however, that there can still be ‘plenty more fish in the sea’ and that with effective management they provide a continuous flow of benefits for our future.

Keywords Conservation, global abundance, historical fishing, reconstruction

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Introduction

Looking ahead to a world with greater than nine billion people focuses concern on whether there are sufficient resources, particularly those required to feed everyone. Demands for wild-caught food from the marine environments are likely to grow, so it is important to know the limits to their production (Watson *et al.* 2015). The human race did not always recognize such limits to marine resources. This older belief is epitomized by the expression 'There are more fish in the sea than ever came out of it'. Consoling disappointment since 1573 (Harvey 1573), this aphorism has echoes of Huxley's confidence in the unlimited bounty of marine resources at that time (Huxley 1883). The reflection of fishers' experience in language reflects the importance of fisheries in societies throughout human history (Sahrhage and Lundbeck 1992). Cod and herring stocks of the Atlantic, for example, played a significant role in feeding European populations and even in the motivation for commerce and the exploration of new lands (Cushing 1988).

The phrase that 'there are more fish in the sea than ever came out of it' spawned variants such as 'There are plenty more fish in the sea', 'The sea is full of other fish' and 'There's more than one fish in the sea'. All are used to console and encourage one who has lost a lover (or, by transference, an opportunity) as there are plenty of others out there. Although clearly in general use before this date, the oldest recorded variant occurs in a verse letter written to the poet Edmund Spenser by Gabriel Harvey, a Cambridge Professor of Rhetoric (and noted satirist of earthquakes) in Elizabethan England (Harvey 1573):

> Tis a written veritye,
> quoth owlde Senior C.,
> all prooves on whether you speede or miss,
> in the mayne sea theres good stoare of fishe,
> and in delicate gardens and in gourgeous bowers,
> theres allwayes greate varietye of desirable flowers.
>
> speede = succeed; mayne = principal, transl. 'open sea' OED.

Although the phrase must have been in common use, it does not appear in *The Proverbs And Epigrams Of John Heywood*, 1562 or in Oswald Dykes' 1713 *English proverbs with moral reflexions*, and it is not until the 19th century that the phrase begins to appear frequently in print again. For example, 'There never was a fish taken out of the sea, but left another as good behind' (T.L. Peacock (1816) Headlong Hall). And in description of a failed scheme to transport herring from East Anglia rapidly to Billingsgate fish market in London: 'But though the project was much talked about, it never came to a head, and ultimately fell through, the projectors consoling themselves with the axiomatic reflection – there are more fish in the sea than ever came out of it'. (Sala, George Augustus (1859) Four o'clock AM – Billingsgate Market. In *Twice Round the Clock, or The Hours of the Day and Night in London*. Houlston and Wright, London. 392 pp.)

By reconstructing historical catches from two important stocks and the global oceans over several centuries, we test whether the phrase 'There are more fish in the sea than ever came out of it' can still be true. We also ask whether managers can ensure 'There are plenty more fish in the sea' and whether abundance and catches are still being sustained after centuries of fishing.

Reconstructing historical fish populations

North Sea herring

Time series of the total annual North Sea herring catches were assembled back to 1100 AD in three segments: historical catch records from the present back to 1802; from 1802 back to 1602; and annual approximations anchored on published estimates from 1100 to 1602. The historical reconstruction for North Sea herring ended in 1992, but stock assessments for more recent years show cumulative catches continuing to increase steadily and a generally increasing trend in population size since 1992 (references in Appendix S1).

North Sea Herring catches back to 1802 were assembled from regional and historical catch data (S. Mackinson, personal communication) converted to tonnes from Scotland, England, Belgium, Germany, Denmark, France and Norway (see sources in Appendix S1). From 1602 to 1850, annual catches throughout the North Sea have been assembled from commerce data (Poulsen 2008). For the overlap periods 1802 to 1850, we used other data from (S. Mackinson, personal communication) although catch amounts and trends were similar. For years with no reported catch prior to 1602, catch estimates published by (Cushing

1988) were used with about COV 15% white noise superimposed (this COV was chosen as it provided a good fit to recent catch data variation). In addition, catch adjustments were made for years when the environmental and human factors could increase herring recruitment or decrease catches (De Caux 1881; Alward 1932). Up to 50% recruitment enhancement or reduction was supported by tree ring-based estimates of annual climate fluctuations, and their confidence limits from 500 BC to the present (Büntgen *et al.* 2011). Catches were reduced up to 30% in relation to the reported severity of outbreaks of bubonic plague in north European countries (Wikipedia 2014), or episodes of naval warfare in the North Sea (Holm 2013), both societal events that are known to have reduced fishery catches (Project Gutenberg 2008).

Reconstructions without these additional factors illustrate similar long-term trends in North Sea herring (Pitcher and Lam 2014), but for this work we are interested in more accurate annual herring catch and biomass values.

In order to estimate herring biomass in relation to catches, a Fox surplus-production model was fitted by least squares to annual North Sea herring catches and VPA-estimated biomass from 1949 to 1990; these years cover a high contrast in catches (12 000 tonnes to over a million tonnes) and biomass levels (50 000–4.5 million tonnes), in a similar fishery (Burd 1991). Unfished North Sea herring biomass was consequently estimated as approx. 9 million tonnes with a rate of increase of about 0.243. Using this curve, North Sea herring biomass was estimated for each year from annual catches generated by the historical data and catch adjustment algorithm described above.

Herring biomass was converted to numbers assuming a stable age distribution over 11 age groups and using von Bertalanffy growth and length–weight parameters taken from the literature (Burd 1962; Hubold 1975). Confidence limits of the biomass to numbers conversion were also calculated.

The upper and lower confidence limits from each step in the calculations were used to place realistically broad upper and lower uncertainty envelopes on the North Sea herring catch and biomass estimates. Assuming that each step in the calculations is independent and using a Monte Carlo sensitivity analysis approach would provide a misleading impression of lower uncertainty based only on estimation error. Our approach acknowledges that the catch and biomass estimates are subject to many assumptions and uncertainties.

Newfoundland cod

Annual catch and biomass were taken from published historical analyses of the Newfoundland cod stock (Rose 2004; Hutchings and Myers 1995), with linear interpolations for missing periods (full references in Appendix S1). Cod biomass was calculated from the catches using a Schaefer surplus-production model driven by climate fluctuations (Rose 2004). Biomass was converted to numbers assuming a stable age distribution over 24 age groups, and von Bertalanffy growth and length–weight parameters found in the literature (Martin 1953). Confidence limits of the biomass to numbers conversion were also calculated. Upper and lower confidence limits from each step in the calculations were used to place realistically broad upper and lower uncertainty envelopes on the North Sea herring catch and biomass estimates.

Estimating cumulative removals from the world's oceans

Historical trends in global catches were reconstructed and compared with estimated fish abundance in the global oceans to assess whether cumulative numbers of fish caught globally exceeded global abundance.

For this analysis, it was assumed that all commercial seafood species (vertebrates and invertebrates) were 'fish'. Although comparatively easy to estimate numbers removed since 1950 by combining global commercial landings data (Watson *et al.* 2004) and estimates of mean sizes from databases such as Fishbase (Froese and Pauly 2006), this was not, however, a viable approach for the entire time period under consideration. This is because humans (*Homo sapiens*) were catching and consuming seafood. To address this, a link between population estimates and human consumption was required. This was established for the period back to the 1970s (FAO, 2014). To estimate numbers removed required the product of population, consumption per capita, the ratio of consumption to catch and the average size of the individuals removed. The method accounted for a recent increase in the numbers of fish taken which are not consumed directly but instead used for feeding aquaculture and in other animal feeds, but did not include revised estimates of mesopelagic fish abundance (Irigoien *et al.* 2014) as these are not available for human consumption. For each parameter, a range was estimated and Monte Carlo simulations (normal distribution assumed) were used to establish the confidence limits around the mean numbers taken each year. With wide margins of error, it was possible to extrapolate annual removals back to 70 000 BC based on trends in human population size (Wikipedia 2012). Cumulative totals calculated (with 95% CL) could then be compared to estimates of 'fish' numbers currently in global seas.

Predicting fish numbers in the world's oceans

Numbers of consumers in any defined size range were calculated from the primary production available to support them with a size-based model. The model estimates consumer numbers from variables that determine the rate and efficiency of energy processing. These are (i) temperature, which affects rates of metabolism and hence growth and mortality (Ernest *et al.* 2003; Brown *et al.* 2004), (ii) the size of phytoplankton and the predator to prey body mass ratio (PPMR), which determine the number of steps in a food chain (Jennings *et al.* 2008), and (iii) trophic transfer efficiency (TE), a measure of energy loss at each step in the chain (Borgmann 1987; Andersen *et al.* 2008). In summary, the model used empirical relationships between primary production and the abundance and size distribution of primary producers to predict the prey available at the base of the food chain and hence to build a size-spectrum for the consumer community. Numbers of consumers in any defined size range in the spectrum are calculated by integrating numbers between any two body mass classes, taken to be 10 g and 100 kg in this analysis. To address uncertainty, mean parameter values in the model equations were replaced with values drawn from normal or multivariate normal distributions defined by the mean, standard deviation and covariance between parameters. Model results were expressed as medians and percentiles calculated from the distribution of output values. The full model structure and model equations are described in Jennings and Collingridge (2015).

Environmental data used to force the model comprised annual mean estimates of depth integrated primary production (g C m^{-2} d^{-1}), chlorophyll (mg Chl m^{-2}) and sea surface temperature (°C) based on the years 2010, 2011 and 2012. Chlorophyll and primary production were obtained from the Mercator Ocean Project (Mercator Ocean, 2013) (Global Biogeochemical Analysis Product, BIOMER1V1 monthly 0.5° resolution) and monthly temperature data from the Mercator Ocean physical NEMO model [PSY3V3R1, after (Aumont and Bopp 2006)] at 0.25° resolution. Inputs to the size-based models were allocated to a 0.5° grid that covered the GCM domain and cells assigned a mixed layer depth (m) (Schmidtko *et al.* 2013), total depth (m) (IOC *et al.* 2003) and sea surface area (km^2) as well as being assigned to LME (University of Rhode Island/ NOAA, 2013) and FAO areas outside LME (FAO, 2013).

The main model assumptions are (i) phytoplankton production supports all production by consumers, (ii) all individuals in the size range considered are treated as accessible to fishing, (iii) surface temperatures are indicative of the temperatures experienced by producers and consumers contributing to production, and (iv) all predation and energy transfer is size-based. In relation to (i), oceanic phytoplankton are estimated to contribute 88% of total marine primary production and coastal phytoplankton 6.5%. The remaining 5.5% of primary production is contributed by microphytobenthos, coral reef algae, macroalgae, seagrasses, marsh plants and mangroves (Duarte and Cebrián 1996). Remaining production especially supports coastal and coral reef food webs, suggesting underestimation of fish numbers in these areas and slight underestimation of numbers globally. In relation to (ii), individuals of body mass 10 g to 100 kg include teleost and elasmobranch fishes, molluscs and crustaceans that are all included in the landings data. In larger size classes, some reptiles and marine mammals will be present which are not fished or not included in the catch data. Because these species are relatively large, they will make a relatively small contribution to total numbers despite a potentially larger contribution to total biomass. In relation to (iii), surface temperatures were used as a proxy for temperatures influencing the food web because the distribution of production in relation to subsurface temperatures was not known. A large proportion of primary production does occur in the mixed layer above the thermocline, or on the boundary between mixed and stratified waters, but production at higher trophic levels will take place in both areas. While temperature is not expected to have a consistent effect on predator–prey size ratios and transfer efficiency (Barnes *et al.* 2010), it does increase the production to biomass ratio (Ernest *et al.* 2003), and consequently, there will be higher abundance per unit production in cooler waters and an underestimate of abundance when a larger proportion of the abundance is exposed to cooler temperatures in deep water. Finally (iv), it is assumed that all predation and energy transfer is size-based. Although other feeding strategies are well-known to exist among larger consumers, including herbivory and parasitism, analyses of relationships between size and trophic levels in many marine food webs show that the great majority of energy flux can be attributed to size-based feeding interactions. Existing literature further discusses the strengths and weaknesses of size-based food web models for predicting abundance at body mass from primary production and for predicting structure of unexploited ecosystems (Jennings and Blanchard 2004; Jennings *et al.* 2008). The main strength of the approach for describing size and abundance in unexploited food webs is that it provides a baseline description of ecosystem structure in the absence of fishing. This baseline is not subject to the biases associated with 'historical' baselines, which are rarely based on data collected prior to fisheries exploitation and in which non-fisheries (e.g. climate change) and fisheries impacts are often confounded.

Predicting cumulative catches from fish populations in relation to unexploited biomass

To describe the relationship between stock biomass and cumulative catches, landings time series for fish populations assessed for ≥50 years were extracted from the RAM Legacy Stock Assessment Database (Ricard *et al.* 2013), version 3.0, as currently hosted at http://depts.washington.edu/ramlegac/. Estimates of unexploited population biomass are not consistently reported in the assessments in the RAM Legacy Stock Assessment Database (Ricard *et al.* 2013) and so B_0, unexploited equilibrium population biomass in the absence of fishing, was estimated as 2 × B_{MSY}, where B_{MSY} was determined from published fits of a Schaefer surplus-production model to the catch and biomass time-series data, with B_0 constrained to twice the maximum observed biomass in the time series (http://depts.washington.edu/ramlegac/). Populations for which annual catch, annual biomass and B_{MSY} estimates were not available were excluded, as were invertebrates and populations where catches were not reported by weight. The Schaefer surplus-production model, which is based on logistic population growth, usually predicts B_0 that is lower in relation to B_{MSY} than expected when more complex models can be applied. Typically, the latter models imply B_{MSY} is 35–40% of B_0 (Punt *et al.* 2013). The aim of this study was to show cumulative increases in catch of many populations relative to an unfished baseline. If the focus was on individual populations rather than comparative analysis, then approaches suited to understanding of the dynamics of the individual populations would be used for those populations for which the necessary data were available.

Age at maturity T_{mat} provided a proxy for generation time, but was only reported for some of the populations with ≥50 years assessment data on the RAM Legacy Database. Consequently, T_{mat} were extracted from Fishbase (Froese and Pauly 2006). Adoption of species' T_{mat} will be an approximation that does not account explicitly for expected changes in the life history parameters of populations of the same species across their geographical range (Beverton 1992). Changes in generation time of populations in response to fishing are not considered and would require fully age-structured analyses for each population.

Results and discussion

Catch records associated with fishing Newfoundland cod go back to the 1505, and a fitted population model driven by climate fluctuations (Rose 2004) can be used to estimate both the cumulative catch of cod (the numbers taken from the sea) and the number of cod (post-juvenile) that can currently be found in the sea. A comparison (Fig. 1a) shows that, even given wide uncertainly, we had taken more Newfoundland cod from the sea than could be found in the sea by 1635. A similar analysis for North Sea herring used catch records back to 1802 (S. Mackinson, personal communication), commerce-derived catch estimates back to 1604 (Poulsen 2008), catch reconstructions back to 1100 and a fitted population model driven by climate fluctuations, major wars and plagues. As early as 1238, more North Sea herring had been removed, with annual catches in the region of 100 million fish, than the approximately 14 billion herring in the sea (Fig. 1b). It is clear, therefore, that for some important historical fish stocks the popular saying has not been true for centuries.

'There are more fish in the sea than ever came out of it' may also be interpreted as applying to all fish, providing the greatest consolation and encouragement for those suffering loss. From 1000 to the 1500s, the cumulative numbers caught in fisheries worldwide only increased slowly (Fig. 2a), but following industrialization numbers rose far more rapidly (Fig. 2b). Numbers of fishes found in the sea, as defined by the median estimate from the size-based model, likely exceeded the cumulative numbers caught for many centuries, but, by the 1990s, humans finally removed more fish from the sea than the predicted median numbers that are found there. Consequently, the expression 'There are more fish in the sea than ever came out of it' is very unlikely to be true for the world's seas, at least for fishes weighing more than 10 g that exclude the more abundant mesopelagic fishes (Irigoien *et al.* 2014).

While there are no longer more fish found in the sea than ever came out of it, are there plenty more fish in the sea? The cumulative trends in landings reflect the long stream of benefits humans have received from the sea. Here we look back to only 1000 BC (Fig. 2a); however, prehis-

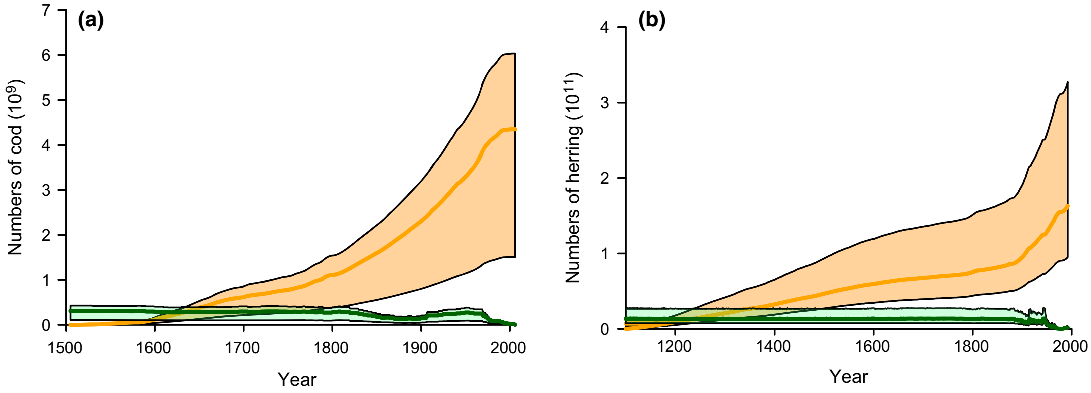

Figure 1 Numbers of cod and herring taken from global seas compared to numbers remaining. (a) Historical series for Newfoundland cod comparing cumulative catch (numbers) in orange vs. numbers in the sea (green). (b) Historical series for North Sea herring comparing cumulative catch (numbers) vs. number in the sea. [Colour figure can be viewed at wileyonlinelibrary.com]

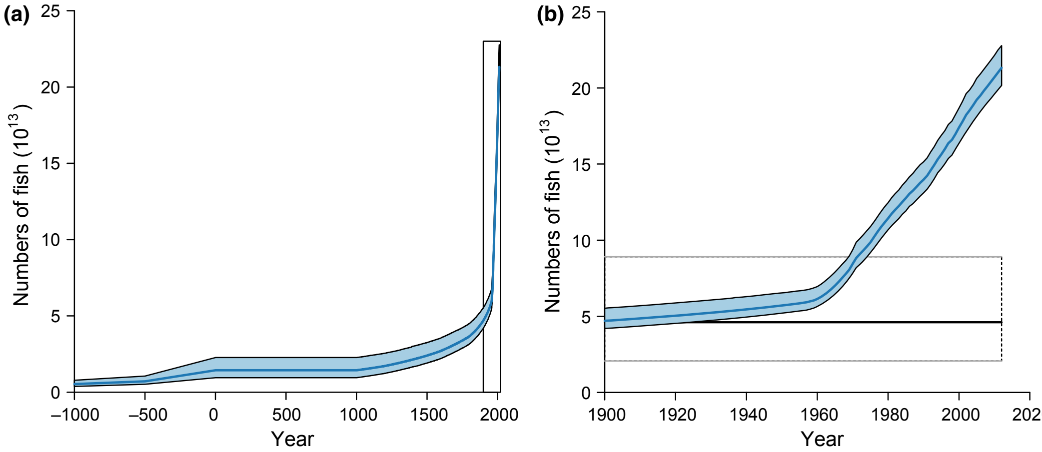

Figure 2 Numbers of fish taken from global seas compared to numbers in the sea. (a) Cumulative catch (numbers) of all fish since 1000AD (rectangle enclosed portion of time series appears in B). (b) Cumulative catch (numbers) since 1900 with horizontal lines, bold showing estimated 'fish in the sea' while faint showing 1st–3rd quartiles from simulations of predicted unfished numbers (size-spectrum modelling of fish over 10 g). [Colour figure can be viewed at wileyonlinelibrary.com]

toric humans have had an enduring relationship with marine resources (Pitcher and Lam 2014). Much has been written about fisheries depletion (Pitcher and Cheung 2013), but our association with fish yields identifies significant long-term benefits, which, although often compromised by overfishing, continue to flow from over half of the currently assessed populations that are sustainably fished, being rebuilt (Worm *et al.* 2009) or can be restored (Hilborn and Ovando 2014).

For global fish populations assessed for at least the last 50 years, cumulative catches reflect variable patterns of productivity and fisheries development. Catches may exceed estimates of unfished population abundance by a factor of ten after 1 to 20+ generations (Fig. 3). We can trace the history of our marine stewardship, and sometimes the role of environmental factors outside our control, by following each line representing the cumulative catch and status of populations in Fig. 3. Status is described as population biomass in relation to the fishery reference point, biomass at maximum sustainable yield (B_{MSY}). If we assume that ratios of $B/B_{MSY} < 0.7$ indicate populations that are well below target biomass, then over half these populations have been overfished at some time in their history. Populations that would be classified as overfished are recorded more frequently at later stages in the time series. In several cases, the status of populations has improved from $B/B_{MSY} < 0.7$ in the middle years of the time series to $B/B_{MSY} > 0.7$ (Fig. 3, blue symbols) or even $B/B_{MSY} > 1.3$ (green) in more recent years. Through generations, we have compelled nature to provide while struggling not to imperil future productivity (when the lines turn red). When motivated, effective management has shown that we can maintain or recover fish populations (Worm *et al.* 2009; Hilborn and Ovando 2014; Zhou *et al.* 2014). Maintaining our marine resources for the long term, given burgeoning human populations, with the needs and challenges they bring, will require ever stronger commitment to achieve management objectives based on a long-term and ecosystem-based view. Only then will there be a high probability of ensuring 'plenty more fish in the sea'.

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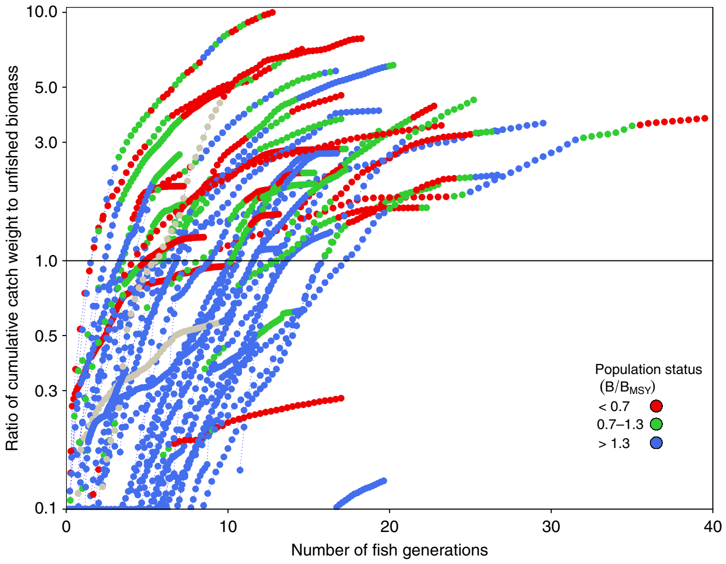

Figure 3 Flow of benefits from fish populations. Cumulative catches from fish populations fished for at least 50 years as a proportion of their unfished biomass and rebased to a proxy for generation time. Ratios exceeding one (above the horizontal line) indicate that cumulative catch has exceeded the unfished biomass. Population biomass in relation to the fishery reference point, biomass at maximum sustainable yield (B_{MSY}), is used as an indicator of population status in each year of assessment. Ratios of $B/B_{MSY} < 0.7$ (red symbols) indicate that populations are substantially overfished in relation to targets while ratios of B/B_{MSY} of 0.7–1.3 (green) and >1.3 (blue) are taken to represent population close to or below targets, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

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Author contribution

All authors conceived the ideas, undertook analysis and contributed to the writing.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1 References.