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Examining the knowledge base and status of commercially exploited marine species with the RAM Legacy Stock Assessment Database

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Abstract

Meta-analyses of stock assessments can provide novel insight into marine population dynamics and the status of fished species, but the world's main stock assessment database (the Myers Stock-Recruitment Database) is now outdated. To facilitate new analyses, we developed a new database, the RAM Legacy Stock Assessment Database, for commercially exploited marine fishes and invertebrates. Time series of total biomass, spawner biomass, recruits, fishing mortality and catch/landings form the core of the database. Assessments were assembled from 21 national and international management agencies for a total of 331 stocks (295 fish stocks representing 46 families and 36 invertebrate stocks representing 12 families), including nine of the world's 10 largest fisheries. Stock assessments were available from 27 large marine ecosystems, the Caspian Sea and four High Seas regions, and include the Atlantic, Pacific, Indian, Arctic and Antarctic Oceans. Most assessments came from the USA, Europe, Canada, New Zealand and Australia. Assessed marine stocks represent a small proportion of harvested fish taxa (16%), and an even smaller proportion of marine fish biodiversity (1%), but provide high-quality data for intensively studied stocks. The database provides new insight into the status of exploited populations: 58% of stocks with reference points (n = 214) were estimated to be below the biomass resulting in maximum sustainable yield (B_{MSY}) and 30% had exploitation levels above the exploitation rate resulting in maximum sustainable yield (U_{MSY}). We anticipate that the database will facilitate new research in population dynamics and fishery management, and we encourage further data contributions from stock assessment scientists.

Keywords Marine fisheries, meta-analysis, overfishing, population dynamics models, relational database, stock assessment

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Introduction

Marine wild capture fisheries provide 80 million tons of fisheries products (both food and industrial) annually and wild capture fisheries employ 34 million people around the world (FAO 2010). At the same time, fishing has been recognised as having one of the most widespread human impacts in the world's oceans (Halpern *et al.* 2008), and the Food and Agricultural Organization of the United Nations (FAO) estimates that 85% of fish stocks globally are fully exploited or overexploited (FAO 2010). While some fisheries have reduced exploitation rates to levels that should, in theory, promote recovery, overfishing continues to be a serious global problem (Hilborn *et al.* 2003; Worm *et al.* 2009; FAO 2010). Fisheries managers are asked to address multiple competing objectives, including maximizing yields, ensuring profitability and stability, reducing by-catch and minimizing the risk of overfishing. Given the large social and economic costs (Rice *et al.* 2003) and ecosystem consequences (Frank *et al.* 2005; Myers *et al.* 2007) of collapsed fisheries, it is imperative that we are able to learn from both successful and failed fisheries from around the world.

Global databases of fishery landings, compiled by FAO (2009) and extended by the Sea Around Us project (Watson *et al.* 2004), are valuable resources for understanding the status of, and trends in, global fisheries (e.g. Pauly and Christensen 1995; Pauly *et al.* 2002; Worm *et al.* 2006, 2009; Newton *et al.* 2007). The trade-off with these comprehensive databases, however, is that they have poor taxonomic resolution for many fisheries in developing countries, and landings data alone can be misleading when used as a proxy for stock size. Most investigations that have used these data to examine changes in fishery status (Worm *et al.* 2006; Costello *et al.* 2008) rely (either explicitly or implicitly) on the assumption that catch or landings is a reliable index of stock size. Critics have pointed out that catch can change for a number of reasons unrelated to stock size, including changes in targeting, fishing restrictions or market preferences (Caddy *et al.* 1998; Hilborn *et al.* 2007; de Mutsert *et al.* 2008). Standardizing catch by the amount of fishing effort (catch-per-unit-of-effort, CPUE) and modelling the data to account for spatial, temporal and operational factors affecting the CPUE is an improvement (Maunder and Punt 2004), but is only feasible when catch data are collected in fisheries with log book and/or observer programmes. Moreover, CPUE can still be an unreliable index of relative abundance, as it is difficult to account for all factors that influence catchability (Hutchings and Myers 1994; Harley *et al.* 2001; Walters 2003; Polacheck 2006).

Stock assessments, the most data-intensive method for assessing fisheries, consider time series of catch along with other sources of biological information such as growth, maturation, natural mortality rates, changes in size or age composition, stock–recruitment relationships and CPUE coming from different fisheries and/or from fishery independent research surveys to quantitatively estimate stock abundance (Hilborn and Walters 1992; Quinn and Deriso 1999; Cooper 2006). Because they integrate across multiple sources of information, stock assessment models should provide a more accurate picture of changes in abundance than catch data alone (Sibert *et al.* 2006), a trade-off being that their complexity renders them difficult for non-experts to evaluate.

Stock assessments are expensive to conduct, and hence are usually only done by developed nations for species of commercial importance. For example, in 2009, of the 522 federally managed exploited fish and invertebrate stocks recognised by the National Marine Fisheries Service (NMFS 2009) as exploited in US waters, only 193 or slightly over one-third were considered fully assessed. An assessment by the European Environment Agency (EEA) in 2006 indicated that the percentage of commercial landings obtained from assessed stocks (of all known landings in a region) ranged between 66–97% in northern European waters, and only 30–77% in the Mediterranean (European Environment Agency 2009). The New Zealand Ministry of Fisheries (2010) reports the status of only 117 stocks or substocks from a total of 628 stocks managed under New Zealand's Quota Management System. In Australia, 98 federally managed stocks have been assessed (Wilson *et al.* 2009) of an unknown total. The extent to which stocks are assessed elsewhere in the world is generally lower (Mora *et al.* 2009).

Despite these limitations, stock assessment is considered to be an integral component of responsible management in industrialised fisheries (Hilborn and Walters 1992), where fishing capacity can exceed the productivity of fished stocks. Effective management of these stocks requires an understanding of what the current population abundance and harvest rate are, and where these lie in relation to target or limit abundance and exploitation reference points (e.g. the exploitation rate that maximises fishery benefits or limits the risk of overfishing).

Comparative analyses of stock assessments can provide insight into the status of fisheries that is complementary to assessments of global landings, as well as providing more fundamental insight into the population dynamics of exploited species. The first database of stock assessment information, the Myers Stock-Recruitment Database, was developed by the late Ransom A. Myers and colleagues in the mid-1990s (Myers *et al.* 1995b). While the database was primarily known for its time series of stock and recruitment, it also contained time series of fishing mortality rates for many stocks; biological reference points (BRPs) were, however, largely absent. The original release version of the Myers database (Myers *et al.* 1995b) included spawning stock size and recruitment time series for 274 stocks representing 92 species as well as fishing mortality rate time series for 144 stocks. The number of entered stocks grew to approximately 509 stocks (with at least one SR pair) by 2005, of which 290 were anadromous fishes of the family Salmonidae. This database was instrumental in advancing the use of meta-analysis in fisheries science and was used to: (i) decisively show that recruitment is related to spawning stock size (Myers and Barrowman 1996), (ii) investigate potential depensation in stock–recruitment relationships (Myers *et al.* 1995a; Liermann and Hilborn 1997; Garvey *et al.* 2009), (iii) discover generalities in the annual reproductive rates of fishes (Myers *et al.* 1999, 2002b), (iv) investigate density dependence in juvenile mortality (Myers 2001; Minto *et al.* 2008), (v) develop informative Bayesian priors on steepness (Myers *et al.* 1999, 2002a; Dorn 2002) and (vi) examine patterns of collapse and recovery in exploited fish populations (Hilborn 1997; Hutchings 2000, 2001a,b).

Interest in fisheries meta-analyses has grown considerably over the past two decades, such that, there is a great need for an up-to-date stock assessment database. Yet the publicly available version of the original Myers database (Myers *et al.* 1995a) is 16 years out of date for most stocks. For stocks that were depleted in 1995, the past 16 years include valuable observations at low stock size or of a recovering population, both of which are critical for estimating population dynamics parameters such as the behaviour of the stock–recruitment relationship near the origin. In addition, there have been numerous improvements in stock assessments (improved knowledge of exploited populations and methodological development that lead to better stock estimates), and assessments have been conducted for the first time for many species.

Meta-analyses of fishery status have also been hampered by the lack of an assessment database containing BRPs [e.g. the total/spawning biomass and exploitation rate that produce maximum sustainable yield (MSY), B_{MSY} and U_{MSY}]. Knowledge of BRPs is important if stocks are to be managed for high yields that can be sustained over time (Mace 1994). Without information on reference points, previous analyses of stock assessments or catch data have instead relied upon ad hoc thresholds to define fishery status, such as the greatest 15-year decline (Hutchings and Reynolds 2004) or 10% of maximum catch (Worm *et al.* 2006). Ad hoc reference points based on some fraction of the maximum of a time series also have undesirable statistical properties and can result in false collapses when applied to inherently variable time series of catch or abundance (Wilberg and Miller 2007; Branch 2008; Branch *et al.* 2011). Complicating comparisons of fishery status is the fact that different BRPs are used in different parts of the world and even the same BRP can be used in a different manner, for example as a target or as a limit. The biomass reference point B_{MSY} is the internationally agreed legally binding reference point for managed fisheries in the United Nations Convention on the Law of the Sea and the United Nations Fish Stock Agreement, and provides a useful basis for comparing stocks.

Here, we present a new database of stock assessments for commercially exploited marine fish and invertebrate stocks. The database is inspired by that of Ransom A. Myers and is named the RAM Legacy Stock Assessment Database in honour of his pioneering contribution. This effort is the first stock assessment database to: (i) use a formal relational database structure; (ii) use source control software to organise release versions; (iii) include metadata related to the geographic location of the stock, the type of assessment model used and the original source document(s) for the assessment data; and (iv) include BRPs, in addition to stock-specific life history information.

We use the new RAM Legacy Stock Assessment Database (version 1.0, 2011) to conduct a meta-analysis of the knowledge base for commercially exploited marine stocks in terms of institutional contributions, geography, taxonomy, time span, assessment methodologies and BRPs. We then evaluate the status of all available assessed stocks globally, by management body, taxonomic grouping and trophic position. Finally, we discuss biases in the knowledge base for assessed marine stocks, highlight potential applications of the database and important caveats about its use and outline directions for future development.

Methods

The RAM Legacy Stock Assessment Database

The RAM Legacy Stock Assessment Database (hereafter, RAM Legacy database) is a relational database designed to store data from accessible current model-based fisheries stock assessments for marine fish and invertebrate populations. Time series of spawning stock biomass (SSB), total biomass (TB), recruits (R), total catch (TC) or landings (TL) and fishing mortality (F) from individual stock assessments form the core of the database. Apart from catch/landings, these time series are not raw data, but rather the output of population dynamics models; depending on the type of assessment model and the data reported, not all of these time series were available for every stock. The database also contains details about the time series data, including the age and sex of spawners, age of recruits and the ages used to compute the fishing mortality, as well as BRPs and some life history information (e.g. growth parameters, age and length at 50% maturity and natural mortality rate). Metadata for each stock assessment consists of taxonomic information about the species and the geographic location of the stock (detailed in ‘Links to related databases’), the management body that conducted the assessment and the assessment methodology. Some assessments (n = 26), particularly those for more recently developed invertebrate fisheries, were based only on CPUE time series rather than population dynamics models. While we included these in the database, the descriptions and analyses presented here include only those stocks assessed using population dynamics models.

We employed a variety of search methods in an attempt to obtain as many recent fisheries stock assessments as possible. Publicly available stock assessment reports were the primary data source and were obtained either from the website of the relevant management agency or directly from stock assessment scientists. Other assessments were obtained from the primary literature and through personal contacts at fisheries management agencies.

Database structure and quality control

The database is implemented in the open source PostgreSQL relational database management system (PostgreSQL Global Development Group 2010), and includes linked tables for all of the aforementioned data and metadata (see Figure S1). The use of a relational database improves data integrity and facilitates the development of a repeatable analytical framework. Data products that suit a given analyst's need can be automatically created and updated when new information becomes available, either through updates of existing assessments or entry of new assessments results in the database.

We employed several mechanisms to ensure database quality. During the data recording process, assessment authors were contacted where needed to clarify aspects of the assessment or to obtain more detailed data. Time series data presented only in assessment report figures were, for example, only entered into the database if the exact numbers could be obtained from the assessment author. In cases where multiple models were presented in an assessment without a preferred or best model being denoted, we attempted to ascertain which model was preferred by the stock assessment scientist, but included all model results whenever this was not possible. Once uploaded into the database, all stock assessments underwent an additional Quality Assurance/Quality Control (QA/QC) step to ensure that the entered data replicated that of the original assessment document exactly.

Links to related databases

To facilitate integration of the RAM Legacy database with related databases, such as FishBase (Froese and Pauly 2009) and the Sea Around Us global landings database (Watson *et al.* 2004), each species present in the RAM Legacy database was assigned a matching FishBase species name and species code, a matching Sea Around Us taxon code and taxonomic information from the Integrated Taxonomic Information System (ITIS) (http://www.itis.gov). Additionally, each stock was assigned to a primary (and in some cases secondary and tertiary) large marine ecosystem (LME) (Sherman *et al.* 1993). LMEs encompass the continental shelves of the world's oceans and represent the most productive areas of the oceans. Open ocean areas beyond the continental shelves are, however, not included in the LME classification; nor is the Caspian Sea, for which we have one stock. Large highly migratory oceanic species, such as tuna, were therefore assigned to new categories 'Atlantic high seas', 'Pacific high seas', 'Indian high seas' and 'Subantarctic high seas'.

The marine stock assessment knowledge base

We overview the temporal and geographic coverage of stock assessments, as well as the types of assessment models used, and BRPs estimated for all stock assessments and each management body. To evaluate the taxonomic scope of the database and identify taxonomic biases, we compare the taxonomy of assessed stocks with the diversity of (i) all marine fishes (as represented by FishBase) and (ii) marine fishes in global fisheries catches (as represented by the species available from the Sea Around Us database). To determine what fraction of world wild-capture fisheries landings come from assessed stocks, we used the Sea Around Us average global fisheries catches from the most recent 10 years of available data (1995–2004); we also discuss limitations to obtaining assessments for some of the world's major fisheries. Direct comparisons between assessments and catch data at a regional level are hampered by the geographic mismatch between stocks and FAO statistical areas or the Sea Around Us LMEs.

The status of assessed marine stocks

We evaluate the status of assessed stocks overall, by management body, by major taxonomic orders included in the database and by trophic level, using standard reference points so that all stocks are referenced to a comparable benchmark. Following Worm *et al.* (2009) and Froese and Proelß (2010), we compare the biomass and exploitation rate of stocks for the last available year in the assessment (the 'current biomass') relative to their reference points at MSY, B_{MSY} and U_{MSY}, respectively.

We recognize that MSY-related BRPs are not used by all management agencies, and that their utility as fisheries targets or limits is debated (Larkin 1977; Mace 2001), but they are the most commonly estimated BRPs and hence most easily used to compare multiple stocks. For those assessments that did not contain MSY reference points, but did include total catch and total biomass time series data, we used a Schaefer surplus production model to estimate total biomass and exploitation rate at MSY (B_{MSY} and U_{MSY}, respectively), as detailed in the Supporting Information (Figure S2). We also examined the influence of setting different upper bounds on the K parameter of the Schaefer model (ranging from 2 to 5 times the maximum observed total biomass; Figure S2).

We estimated the model parameters for the Schaefer surplus production models in AD Model Builder (ADMB Project 2009). All other analyses were conducted using the R software (R Development Core Team 2010) and additional R packages RODBC (Ripley and Lasley 2010), APE (Paradis *et al.* 2004) and KernDens (Ripley and Wand 2011). The map in Fig. 1 was created using the Generic Mapping Tools (Wessel and Smith 1991).

Results

The marine stock assessment knowledge base

In total, 331 recent stock assessments (with population dynamics models) for 295 marine fish stocks and 36 invertebrate stocks are included in the RAM Legacy database (version 1.0, 2011; Table S1). Together, these comprise time series of catch/landings for 313 stocks (95% of all assessments included), SSB estimates for 280 stocks (85%) and recruitment estimates for 274 stocks (83%) (Table S1 and Fig. 2). The median lengths of catch/landings, SSB, and recruitment time series were 39, 34 and 33 years, respectively (Fig. 2). The time period covered by 50% of assessments is as follows: catch/landings (1966–2007), SSB (1972–2007), recruitment (1971–2006), while that covered by 90% of assessments is as follows: catch/landings (1983–2004), SSB (1985–2005), recruitment (1984–2003) (Fig. 2).

Management bodies and geography

Stock assessments are derived from fisheries management bodies in Europe, North America, New Zealand, Australia, Russia, South Africa, Argentina, Peru, Iran and from eight Regional Fisheries Management Organizations (RFMOs) (Table 1). Assessments from the United States constitute by far the most stocks of any country or region ($n = 138$); assessments from the European Union's management body, the International Council for the Exploration of the Seas (ICES), constitute the second greatest number of stocks ($n = 63$). Whereas nations are responsible for managing all stocks within their EEZs, RFMOs typically focus on a certain type of species (e.g. halibut, tunas) or fisheries (e.g. pelagic high seas) within a given area and hence assess a smaller number of stocks.

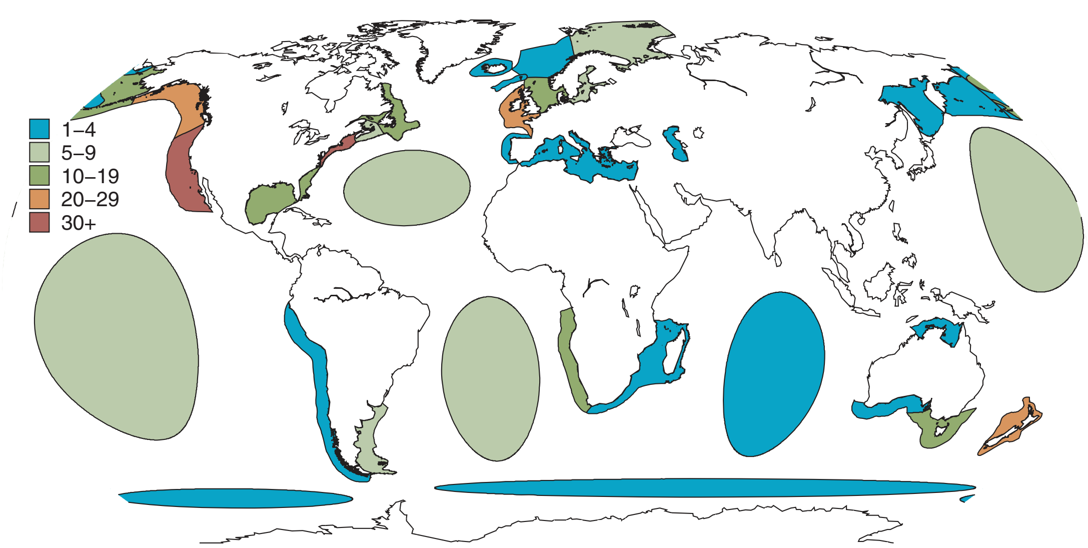


Figure 1 Map of large marine ecosystems (LMEs) and high seas areas (ovals) showing the number of stock assessments present in the database per area.

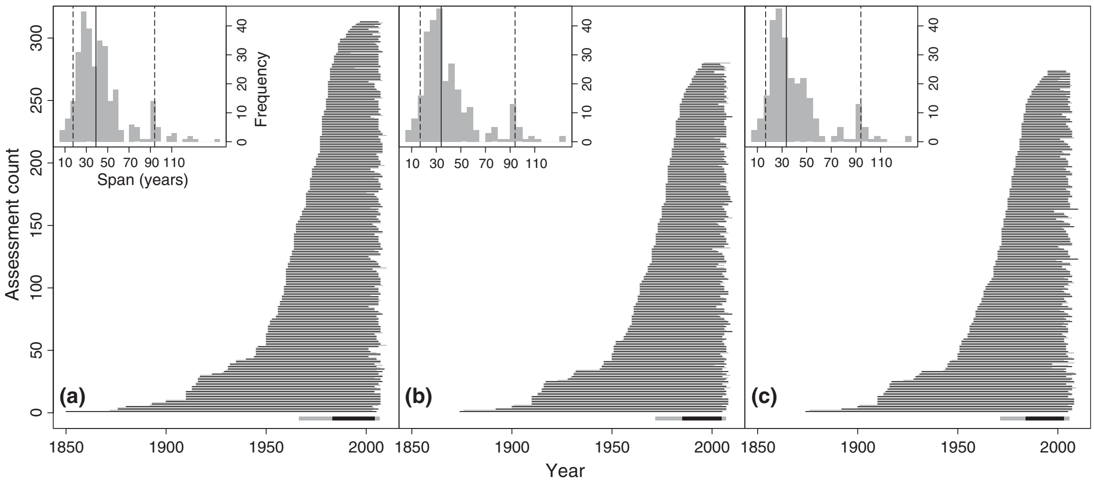


Figure 2 Temporal coverage of (a) catch/landings, (b) spawning stock biomass and (c) recruitment. The temporal coverage for individual assessments is represented by thin alternating black and grey horizontal lines in the main panels. Thick horizontal lines at the base of each main panel represent the time periods that are present in 90% (black) and 50% (grey) of all series for that data type. Subfigure histograms contain the frequency of occurrence of the various timespans without reference to time period. Solid and long-dash vertical lines within the subfigures represent the median, 2.5% and 97.5% quantiles, respectively.

Table 1 Geographic location, management body and number of assessments included in the RAM Legacy database.

Country/ocean	Management body	Acronym	No. of stocks
USA	National Marine Fisheries Service	NMFS	138
Europe	International Council for the Exploration of the Sea	ICES	63
New Zealand	Ministry of Fisheries	MFish	29
Canada	Department of Fisheries and Oceans	DFO	26
Australia	Australian Fisheries Management Authority	AFMA	17
South Africa	South African national management	DETMCM	14
Atlantic	International Commission for the Conservation of Atlantic Tunas	ICCAT	10
Northwest Atlantic	Northwest Atlantic Fisheries Organization	NAFO	8
Argentina	Consejo Federal Pesquero	CFP	6
Western and Central Pacific	Western and Central Pacific Fisheries Commission	WCPFC	5
USA	US state-level management	US State	3
Eastern Pacific	Inter-American Tropical Tuna Commission	IATTC	2
Russia	Russian Federal Fisheries Agency	RFFA	2
Antarctic	Commission for the Conservation of Antarctic Marine Living Resources	CCAMLR	1
Peru	Instituto del Mar del Peru	IMARPE	1
Indian Ocean	Indian Ocean Tuna Commission	IOTC	1
USA and Canada	International Pacific Halibut Commission	IPHC	1
Iran	Iranian national management	Iran	1
South Pacific	South Pacific Regional Fisheries Management Organization	SPRFMO	1
Southern Ocean	Commission for the Conservation of Southern Bluefin Tuna	CCSBT	1

Geographically, most assessments are of stocks from North America, Europe, Australia, New Zealand and the High Seas (Fig. 1). Few assessments were available from regions such as Southeast Asia, South America (except for six stocks from Argentina and two from the Humboldt Current LME) and the Indian Ocean (outside Australian waters) (Fig. 1). One or more assessments were available from each of 27 LMEs (of 64 globally), with the greatest number of assessed stocks coming from the Northeast US Continental Shelf ($n = 59$), the California Current ($n = 35$), the New Zealand Shelf ($n = 29$), the Gulf of Alaska (n = 27), the Celtic-Biscay Shelf (n = 26), the East Bering Sea (n = 21) and Southeast US Continental Shelf (n = 20) (Fig. 1). Assessments also came from the Caspian Sea and from four High Seas areas (Fig. 1).

Stock assessment methodologies and BRPs

The three most common assessment methods were statistical catch-at-age/length models (n = 169), virtual population analyses (VPA; n = 92) and biomass dynamics models (n = 45). Regionally, VPA is the most common assessment method in Argentina (83% of six stocks), Europe (71% of 63 assessments) and Canada (56% of 26 assessments), whereas statistical catch-at-age and catch-at-length models are more common in Australia (82% of 17 assessments), New Zealand (76% of 29 assessments) and the United States (67% of 138 assessments).

Biomass- or exploitation-based reference points were available for 262 (81%) and 224 (69%) assessments, respectively. The most commonly reported biomass-based BRPs relate to biomass at MSY (B_{MSY}), to 'limit' biomass (B_{lim}, a biomass level above which stocks should be maintained). Stocks in the United States under the management of NMFS and most of the tuna and billfish stocks assessed by RFMOs are managed using MSY-based reference points (or proxies believed to be equivalent), whereas other fisheries agencies use different BRPs, e.g. ICES have traditionally used SSB-based B_{lim} reference points.

Taxonomy

Stock assessments in the database cover 147 marine fish and 16 invertebrate species from 58 families and 20 orders (Figure S3). Five taxonomic orders (Gadiformes (n = 70), Perciformes (n = 65), Pleuronectiformes (n = 53), Scorpaeniformes (n = 41) and Clupeiformes (n = 36)) account for 80% of available stock assessments. Of these, Perciformes, the most speciose order of marine fishes are in fact underrepresented in the database (46% of all marine fish species vs. 22% of all marine fish assessments), while the other four orders are taxonomically overrepresented: Clupeiformes (2.1% of marine fishes vs. 12% in the database), Gadiformes (3.3% of marine fishes vs. 24% in the database), Pleuronectiformes (4.5% of marine fishes vs. 18% in the database), Scorpaeniformes (8.5% of marine fishes vs. 14% in the database) (Figure S3).

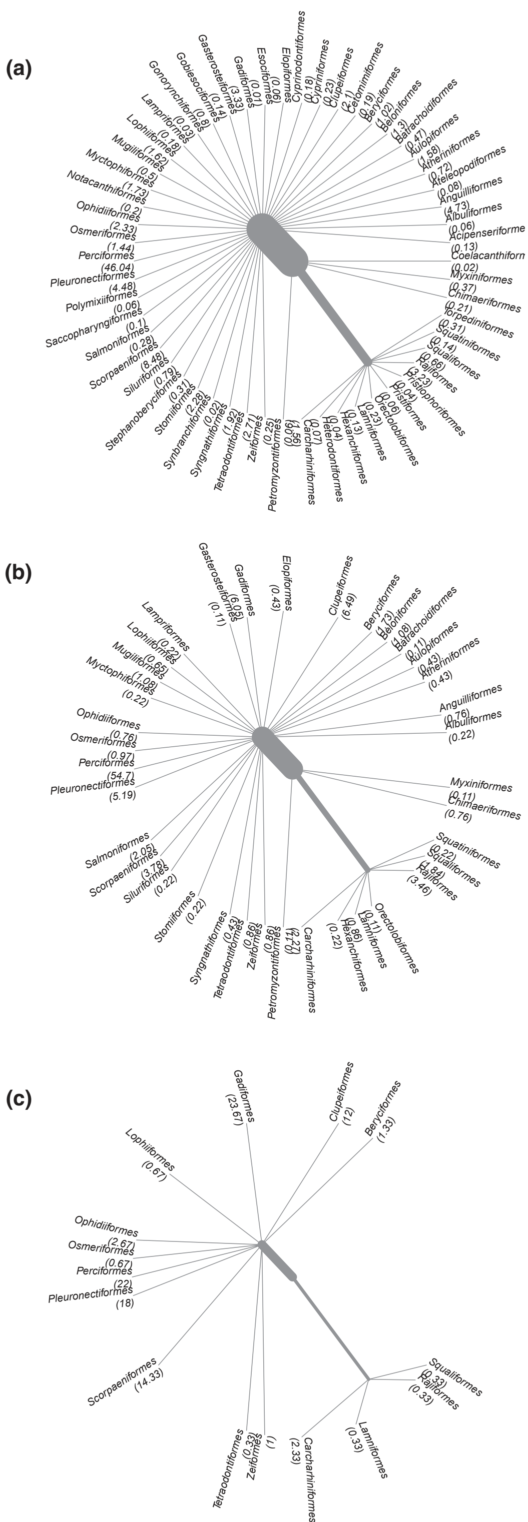
Assessed marine fish stocks constitute a relatively small proportion of harvested fish taxa (16% of fish species from the Sea Around Us database) and an even smaller proportion of marine fish biodiversity (1% of fish species in FishBase; Fig. 3). In turn, catches from the Sea Around Us database, which come from 925 species and 36 orders (Fig. 3), represent only 5% of the 12 339 species and 67% of the 54 different orders present in FishBase (Fig. 3). The diversity of harvested marine invertebrates is clearly also underrepresented in the stock assessment database and likely in stock assessments in general.

Global fisheries

Assessments were available for nine of the world's 10 largest fisheries for individual fish stocks (Table 2). Looking more broadly, the database contains assessments for 17 of the 30 largest fisheries for individual fish stocks globally, and 18 of the 40 largest fisheries globally (when including those recorded at lower taxonomic resolutions) (Table 2). Many of the fisheries not included in the RAM Legacy database, especially those recorded in the Sea Around Us database as 'Marine fishes not identified' (n = 7), occur in developing countries and have no known formal stock assessment conducted for them. From a national perspective, assessments are only included for three of the top 10 wild-caught marine fisheries–producing nations, USA, Russia and Peru (FAO 2010), with only two assessments from Russia and one from Peru. We were unable to obtain any assessments from the other top 10 yield-producing countries: China, Indonesia, Japan, India, Chile, Philippines and Burma (FAO 2010).

The status of assessed marine stocks

MSY-related reference points were available from the assessments for 112 stocks (109 fish stocks and three invertebrates) and could be estimated using surplus production models for 102 additional stocks (87 fish stocks and 15 invertebrates), for a total of 214 stocks (see Supporting Information for details). Surplus production models estimated reference points relatively well, and altering the upper bounds of the K parameter in the models did not affect the classification of any of the stocks (Figure S2, Table S2). Overall, 58% of these stocks are estimated to be below B_{MSY}, and 30% are estimated to have exploitation rates above U_{MSY}, (n = 214; Fig. 4a). Of the stocks for which biomass is currently estimated to be below B_{MSY}, 54% have had their exploitation rate reduced below U_{MSY}, suggesting potential for recovery. The remaining 46% are still exploited at rates above U_{MSY} (Fig. 4a).



The status of assessed marine stocks, as estimated from biomass- and exploitation-BRPs, varied widely amongst management bodies (Fig. 4b–h). We estimated that about half (49%) of US stocks (managed by NMFS) are above B_{MSY}, and of the 41 stocks that are below B_{MSY} almost two-thirds, (63%) have exploitation rates below U_{MSY} (Fig. 4b). In New Zealand and Australian waters, stocks managed by MFish and AFMA are above B_{MSY} in 61% and 36% of cases, respectively (Fig. 4c,d). In contrast, we estimate that most European stocks (managed by ICES) have biomasses less than B_{MSY} (81%), and over half of these stocks (59%) have exploitation rates exceeding U_{MSY} (Fig. 4e). European stocks are, however, not currently managed based on MSY reference points, but rather using limit reference points (B_{lim}, see Discussion). When considered from the perspective of the available limit reference points B_{lim} and F_{lim}, European stocks appear to be in better shape, with 52% of stocks above B_{lim} and 65% below F_{lim} (Figure S4). Most Canadian stocks (managed by DFO) also had low biomass (85% below B_{MSY}), but all of these are estimated to now have exploitation rates below U_{MSY} (Fig. 4f). For the stocks managed by RFMOs in the Atlantic (Fig. 4g), we found that six of the 10 ICCAT stocks and six of the 10 NAFO stocks were below B_{MSY}. Finally, two-thirds (four of six) of stocks managed by RFMOs in the Pacific had biomasses above B_{MSY} (Fig. 4h).

The status of marine stocks also varies substantially amongst the major assessed taxonomic orders (Fig. 5). Gadiformes and Decapoda have the highest proportions of stocks below B_{MSY} (77% and 75%, respectively), but most Gadiformes have now had

Figure 3 Comparison of the taxonomic diversity of marine species as provided by (a) FishBase, (b) the coverage of catch data as provided by the Sea Around Us database, and (c) the new RAM Legacy database (bottom panel). The middle of the circular dendrogram starts with Phylum Chordata and each subsequent branching represents a different taxonomic group (Phylum to Class to Order). The width of each line is proportional to the square root of the number of species in a branch and component percentages of each database are presented in parentheses. To facilitate the identification of the taxonomic groups that are not presented in the catch and assessment data, the FishBase branching pattern of the spoked dendrogram is maintained to generate the other two dendrograms. This figure only compares fish and elasmobranch species present in FishBase. Additional species of molluscs and arthropods are present in both the Sea Around Us and RAM Legacy databases but are not presented here.

Table 2 The world's forty largest wild-caught fisheries (constituting less than 41% of total global catches, based on average catches 1995–2004 in the Sea Around Us database), and the thirty largest fisheries of individual stocks (i.e. fisheries identified to the species level; constituting more than 32% of total global catches), including their LME, whether or not stock assessments for them are included in the RAM Legacy database, and the reason if not included (e.g. 1 = no known assessment, 2 = assessment inaccessible).

Stock rank	Individual species rank	Species (Common name, Latin name) or higher taxonomic unit	LME	In database?	Reason if not included
1	1	Peruvian anchoveta, *Engraulis ringens*	Humboldt Current	✔	
2		Marine fishes not identified	South China Sea	x	1
3		Marine fishes not identified	Bay of Bengal	x	1
4	2	Alaska pollock, *Theragra chalcogramma*	Okhotsk Sea	✔	
5	3	*Ammodytes*	North Sea	✔	
6	4	Atlantic herring, *Clupea harengus*	Norwegian Sea	✔	
7	5	Alaska pollock, *Theragra chalcogramma*	East Bering Sea	✔	
8	6	Capelin, *Mallotus villosus*	Iceland Shelf/Sea	✔	
9	7	European pilchard, *Sardina pilchardus*	Canary Current	✔	
10	8	Japanese anchovy, *Engraulis japonicus*	East China Sea	x	2
11	9	Inca scad, *Trachurus murphyi*	Humboldt Current	✔	
12		Marine fishes not identified	East China Sea	x	1
13	10	Gulf menhaden, *Brevoortia patronus*	Gulf of Mexico	✔	
14		Marine fishes not identified	Yellow Sea	x	1
15		Marine fishes not identified	Indonesian Sea	x	1
16	11	Alaska pollock, *Theragra chalcogramma*	Gulf of Alaska	✔	
17	12	Argentinean short-finned squid, *Illex argentinus*	Patagonian Shelf	x	1
18	13	Argentine hake, *Merluccius hubbsi*	Patagonian Shelf	✔	
19	14	Japanese anchovy, *Engraulis japonicus*	South China Sea	x	1
20	15	Araucanian herring, *Strangomera bentincki*	Humboldt Current	x	1
21	16	Atlantic cod, *Gadus morhua*	Barents Sea	✔	
22	17	European sprat, *Sprattus sprattus*	Baltic Sea	✔	
23	18	Atlantic herring, *Clupea harengus*	North Sea	✔	
24	19	Alaska pollock, *Theragra chalcogramma*	Arctic Ocean	x	1
25		Marine fishes not identified	Gulf of Thailand	x	1
26	20	Atlantic herring, *Clupea harengus*	Baltic Sea	✔	
27	21	Cape horse mackerel, *Trachurus capensis*	Benguela Current	✔	
28	22	Largehead hairtail, *Trichiurus lepturus*	East China Sea	x	2
29	23	Japanese anchovy, *Engraulis japonicus*	Yellow Sea	x	2
30	24	European anchovy, *Engraulis encrasicolus*	Black Sea	x	2
31	25	Chub mackerel, *Scomber japonicus*	East China Sea	x	1
32	26	Indian oil sardine, *Sardinella longiceps*	Arabian Sea	x	1
33		*Decapterus*	South China Sea	x	1
34		*Sciaenidae*	Arabian Sea	x	1
35	27	Atlantic mackerel, *Scomber scombrus*	North Sea	✔	
36	28	Largehead hairtail, *Trichiurus lepturus*	Yellow Sea	x	1
37		*Merluccius*	Benguela Current	✔	
38		Marine fishes not identified	Kuroshio Current	x	1
39	29	Alaska pollock, *Theragra chalcogramma*	Sea of Japan	x	1
40	30	Round sardinella, *Sardinella aurita*	Canary Current	x	1

their fishing mortality rate reduced below U_{MSY} (65%), while most invertebrate stocks in the order Decapoda still have excessively high fishing mortality rates ($U > U_{MSY}$ in 50%; Fig. 5a,b, respectively). In contrast, biomasses of the majority of Scorpaeniformes are above B_{MSY}, and fishing mortalities are below U_{MSY} for all but three stocks in this order (Fig. 5c). Perciformes display overall status around B_{MSY}, while Pleuronectiformes display an interesting bimodality with one mode above B_{MSY} and below U_{MSY} and another mode below B_{MSY} and above U_{MSY} (Fig. 5d,e). Clupeiformes display an overall mode below B_{MSY} but with exploitation rates reduced below U_{MSY} (Fig. 5f).

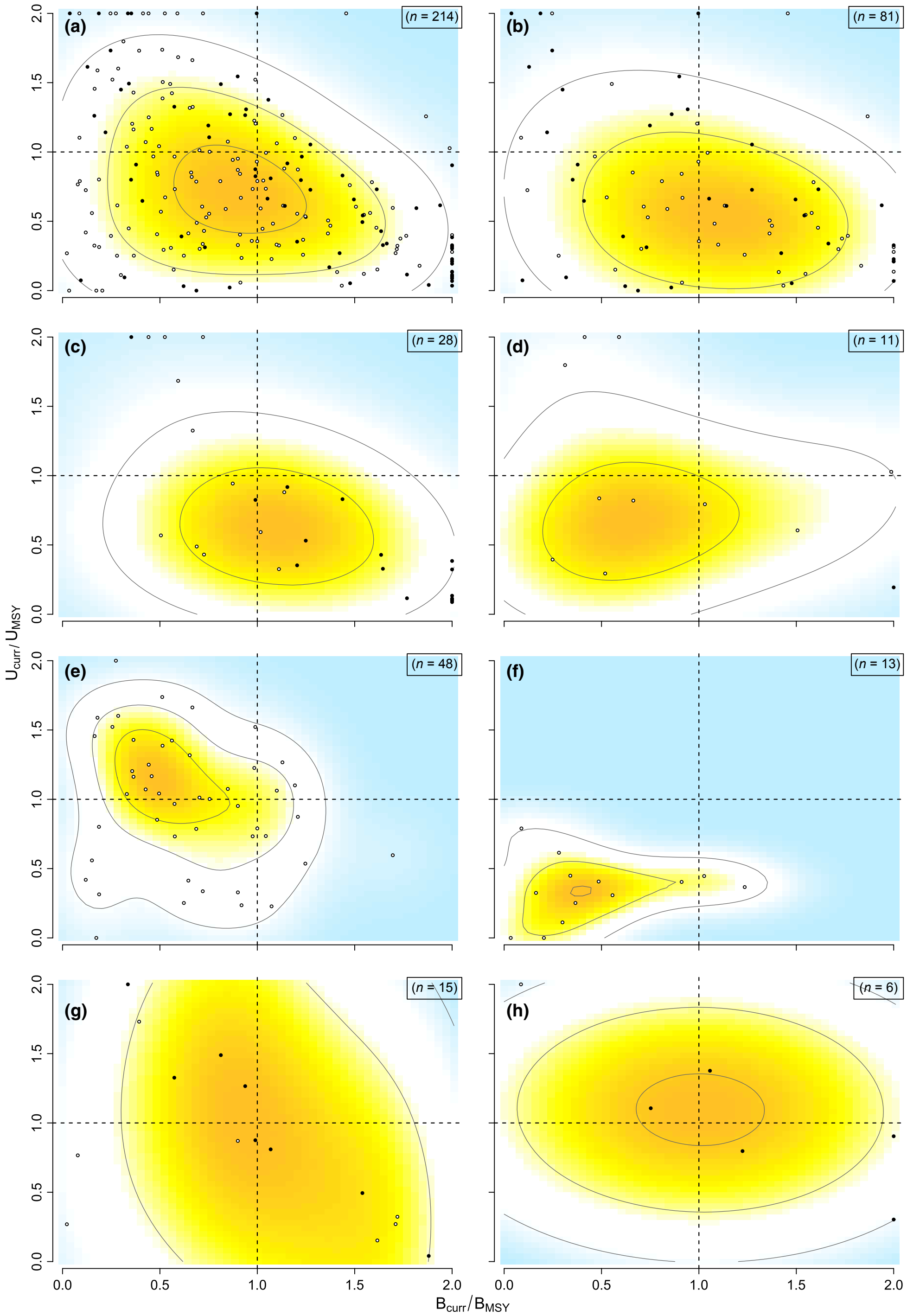


Figure 4 Current exploitation rate vs. current biomass for individual stocks from (a) all management units combined (updated from Worm *et al.* 2009) and for (b–h) individual management units (b) US, (c) New Zealand, (d) Australia, (e) Europe, (f) Canada, (g) Atlantic (multinational stocks managed by ICCAT and NATO) and (h) Pacific (including multinational stocks managed by WCPFC and SPRFMO). In each panel, exploitation rate is scaled relative to the exploitation rate expected to result in maximum susainable yield (U_{MSY}); biomass is scaled relative to B_{MSY}. Shading indicates the probability of occurrence as revealed by a kernel density smoothing function. Solid circles indicate estimates that were obtained directly from assessments; open circles indicate estimates from surplus production models.

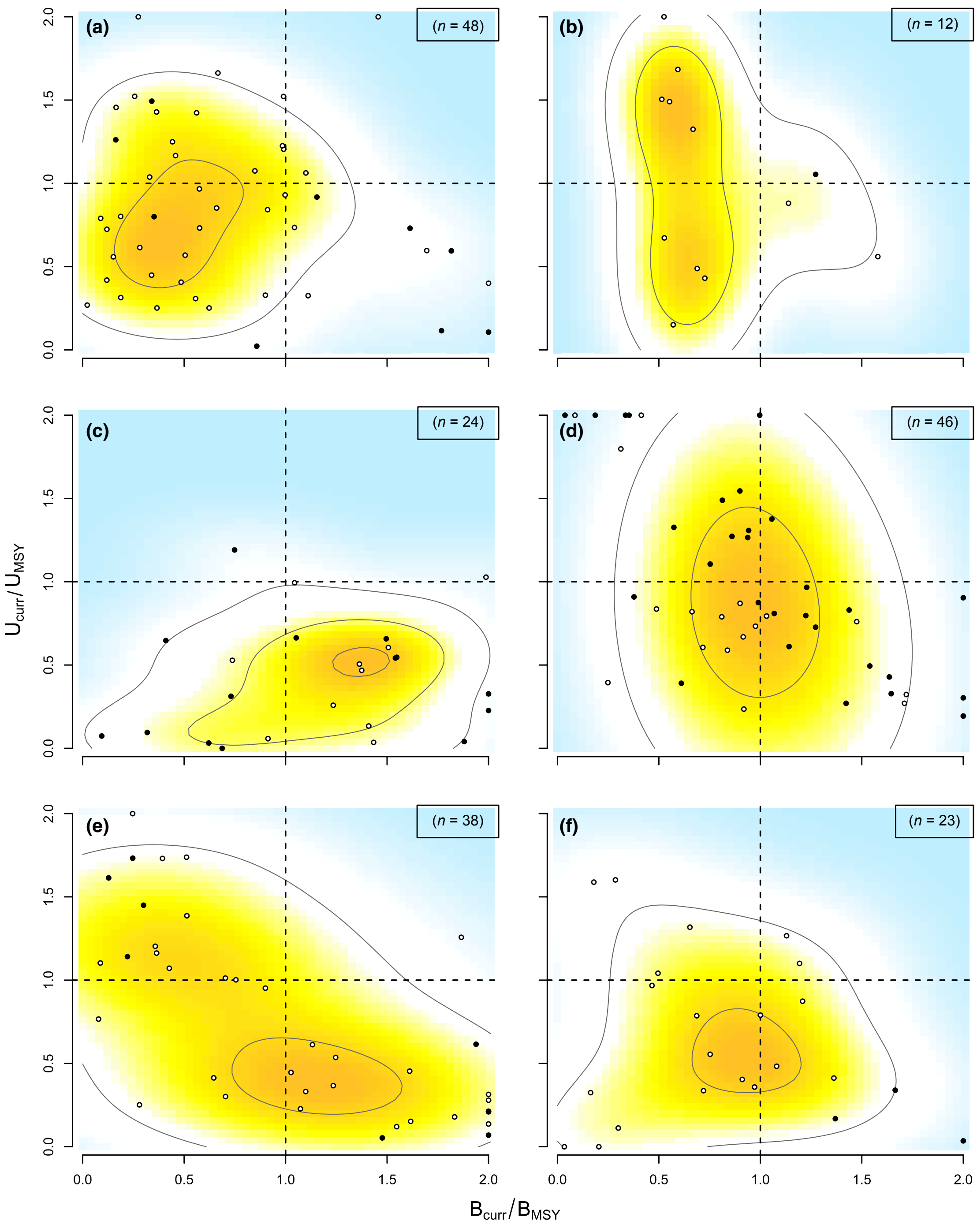


Figure 5 Current exploitation rate vs. current biomass for individual stocks from the major orders of marine fishes (a) Gadiformes, (b) Decapoda, (c) Scorpaeniformes, (d) Perciformes, (e) Pleuronectiformes and (f) Clupeiformes, in the RAM Legacy database. Plot details as in Fig. 4.

When stock status is considered from a trophic level perspective, it appears (at least for those assessed stocks with BRPs) that high trophic level stocks are no worse off than lower trophic level stocks (Fig. 6): 18 of 26 stocks (69%) with mean trophic level (MTL) between 2.0 and 3.0 had biomasses depleted below B_{MSY} (Fig. 6a), whereas just over half of higher trophic level stocks did (56% of stocks with MTL

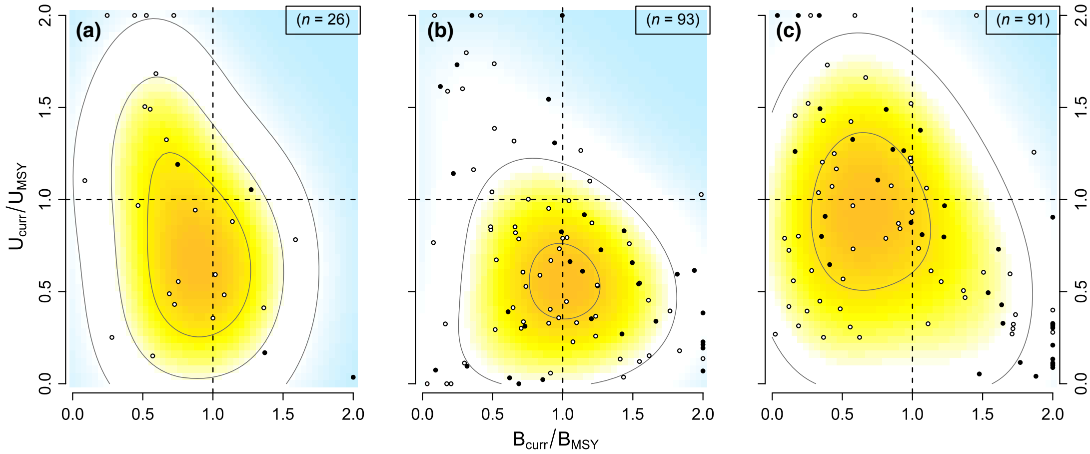


Figure 6 Current exploitation rate vs. current biomass for individual stocks from (a) low (≥2.0 to <3.0), (b) medium (≥3.0 to <4.0) and (c) high (≥4.0) trophic levels. Plot details as in Fig. 4.

between 3.0 and 4.0, 57% of stocks with MTL >4.0; Fig. 6b,c). Similarly, while almost half of the low trophic level stocks had fishing mortalities exceeding U_{MSY} (42%; Fig. 6a), only 23% of stocks with MTL between 3.0 and 4.0 (Fig. 6b) and 34% of stocks with MTL > 4.0 did (Fig. 6c).

Discussion

The marine stock assessment knowledge base

The RAM Legacy database provides detailed time series data and reference points from available stock assessments for the world's most intensively studied industrially fished marine stocks, thus providing a basis for evaluating the existing knowledge base of assessed stocks and the current status of these fisheries. In comparison to its predecessor, the Myers Stock-Recruit database, the RAM Legacy database contains 112 more stock assessments for marine species (when only those with at least one pair of stock–recruitment time series data are considered), but as of yet, no assessments for anadromous species. Other researchers have compiled authoritative datasets on Pacific salmon species, and interested readers should consult the rich literature on these species (e.g. Dorner *et al.* 2008).

Temporal, geographic and taxonomic patterns in stock assessment data

While stock assessments provide high quality and detailed information about stock abundance, the trade-off to producing these complex and data-rich assessments is that they are conducted for only a small subset of fished stocks. Thus, just as global fisheries analyses based on catch databases must be clear about the limitations of the data, meta-analyses of stock assessments must acknowledge the temporal, geographic and taxonomic biases that exist in these data, and hence in the RAM Legacy database.

Most marine stock assessments contain time series from only the past few decades (Fig. 2), whereas many industrial fisheries began long before this. Dominant age-structured assessment methodologies rely on catch-at-age data, which are often available for considerably shorter periods of time than total catch unless significant reconstruction efforts are made. Such historical reconstructions of catch-at-age data are highly uncertain (Quinn and Deriso 1999), and in many cases, the 'base case' models used for management are based only on more reliable recent catch data. For assessments used in a tactical sense and for short-term projection (e.g. to understand whether a particular quota level will result in an increase or decrease in stock size), using only reliable recent catch data may be preferable. This is particularly true for backward projection methods (e.g. VPA), which may converge on parameter estimates within the more reliable recent period and potentially benefit little from reaching further back in time. Nevertheless, a focus on only the recent history of a fishery can be seriously misleading for strategic decisions about goals and BRPs. Put simply, if we do not know what's historically possible (in terms of stock size and variability), it is hard to know where we should set our goals, and more likely that degraded ecosystem states will be perceived as natural. This 'shifting baseline' problem has been widely recognized (Pauly 1995; Sáenz-Arroyo *et al.* 2005).

Geographically, accessible stock assessments are predominantly from developed nations in north temperate regions, a limited region relative to that of all fisheries globally. Indeed, as the majority of assessed stocks are from the United States, our analysis (Fig. 4) is highly influenced by US stock status and therefore may suggest an overly optimistic view of the state of assessed stocks globally. Inclusion of new stocks from other management bodies and of stocks with longer exploitation histories will provide an interesting opportunity to see how it modifies our view on the status of world fisheries. Assessments of stocks from regions experiencing intense exploitation but with limited management institutions would provide an informative contrast to assess the state of world fisheries.

The geographic pattern of assessed stocks arises for several reasons (each of which varies geographically in its prevalence): (i) an assessment is not conducted on a stock; (ii) it is not possible to access the assessment; or (iii) the non-exhaustive collation we undertook overlooked the assessment. In general, conducting stock assessments is a costly endeavour that is restricted to developed fishing nations. Whether an assessment is conducted for a given stock depends upon many factors, including the economic value of the stock, the availability of resources to collect the data required for an assessment (which frequently includes conducting fisheries-independent research surveys) and the quantitative expertise to conduct assessments. The legal context where fisheries are prosecuted can also strongly influence the requirement for conducting stock assessments. In the United States, the Magnuson-Stevens Act defines which stocks are to be monitored and managed, hence a large number of the assessments in the RAM Legacy database are under the jurisdiction of the US National Marine Fisheries Services. The accessibility of assessments depends upon the transparency and access policies of the relevant management agencies, which also varies geographically. Our search for assessments could also give rise to geographic biases, as concerted collation efforts have only been conducted in those known assessment-rich regions. It is hoped that readers of this article can assist in correcting these biases by participating in future updates of the RAM Legacy database, in particular, by helping to expand our coverage of stocks in developing countries and for species of limited commercial interest.

Marine stock assessments also are available for a very limited subset of the accepted taxonomic coverage of marine species worldwide, and of globally exploited species (Fig. 3). Stock assessments also are heavily biased (relative to existing species) towards species within the orders Gadiformes and Clupeiformes (Figure S2). The overrepresentation of the Gadiformes and, to a lesser degree, the Clupeiformes, continues when caught and assessed taxa are compared (Fig. 3b,c). Overrepresentation of these taxa might partially reflect behavioural tendencies of these fishes to form large aggregated populations in temperate regions, which are accessible to industrial fisheries and in areas where fisheries management exists. Historical economic importance as well as the geographic distribution of the taxa in relation to areas where assessments are mandated may play important roles in determining what fished taxa are assessed. Of note is the absence of assessments for tropical species (with the exception of tunas) from the database. Inshore (e.g. estuarine species) and anadromous stocks are also are absent, as a result of our focus on federally or internationally managed marine species.

The status of assessed marine stocks

Overall, we estimate that 58% of assessed stocks (with reference points; $n = 214$) are below the biomass reference point that maximises their yield (B_{MSY}). Almost half of stocks below B_{MSY} still experience exploitation rates above those that would maximise yield. This analysis presents a slightly more optimistic outlook on assessed stocks globally than that of Worm *et al.* (2009), which used an earlier version of the database, and estimated 63% of assessed stocks were below B_{MSY} ($n = 166$ stocks). In comparison, in the latest State of the World Fisheries and Aquaculture (FAO 2010), the FAO reports that of the 445 stocks with available status reports, 15% are underexploited or moderately exploited, 53% are fully exploited, 28% are overexploited, 3% are depleted and 1% are recovering. Direct comparison with these categories is difficult, as our status is either above or below B_{MSY}, whereas the categories used by the FAO are based on stock levels compared with their unfished state.

Regional-level status of assessed marine stocks

Examining the overall status of stocks under one's jurisdiction and comparing the status of stocks amongst jurisdictions may be useful for identifying management priorities and informing various stakeholders. Most stocks under European management seem caught in a situation of long-term unsustainability ($B_{current} < B_{MSY}$; Fig. 4e, and their potential to recover is hampered by excessive exploitation rates, $U_{current} > U_{MSY}$. Our findings are in line with those of Froese and Proelß (2010), although our results are slightly more optimistic about the status of European stocks. The International Council for the Exploration of the Seas (ICES) has not historically used MSY-based reference points, and all the European stocks presented in Fig. 4e are based on Schaefer-derived values. ICES is currently transitioning to the use of MSY-based reference points, which should be fully implemented by 2015 (European Commission 2006). When looking at ICES traditional B_{lim} reference points instead, (Figure S3) the situation for European stocks appears slightly more positive, as the reference points used correspond to lower biomass levels and higher levels of exploitation, but overexploitation of depleted stocks is still common in European waters.

The situation is quite different for North American stocks and suggests that Canadian stocks are at historically low biomass levels, but are also under reduced exploitation that should promote recovery (Fig. 4f). Note that some of those stocks (most notably, cod stocks) were drastically depleted and have thus far failed to recover to the productive levels experienced in past decades. US stocks are the most numerous in our database and suggest that appropriate management measures and regulations have brought many stocks to sustainable harvest levels (Fig. 4b). Some stocks under US jurisdiction are still experiencing excessive exploitation rates and may reflect regional differences in management within the NMFS. In New Zealand, a large proportion of stocks are at relatively high biomass and low exploitation rate relative to their MSY reference points (Fig. 4c). Worm *et al.* (2009) found that the New Zealand Shelf was one of only two LMEs (the other was the California Current), in which overall multispecies exploitation rates are low enough that fewer than 10% of stocks are expected to be collapsed. Management through catch shares is widespread in New Zealand and is thought to have contributed to the relatively low exploitation rates (Worm *et al.* 2009). Nevertheless, there are number of stocks below B_{MSY} in New Zealand that are still experiencing high exploitation rates, most notably New Zealand snapper in Area 8. In Australia, the picture is similar to the global aggregate, with seven of 11 stocks thought to be below B_{MSY} and the same fraction also being exploited at levels below U_{MSY} (Fig. 4d). However, most of the stocks in Australia have MSY reference points estimated from the (relatively more uncertain) surplus production models. Stocks managed by RFMOs in the Pacific appear to be better off – both in terms of biomass and exploitation rates – than those in the Atlantic. Relatively low sample sizes in other parts of the world make it difficult to draw firm conclusions about assessed stock status.

Applications, caveats and future development of the RAM Legacy database

Applications

Over the past 2 years, while still in development, the RAM Legacy database has been used to conduct comparative analyses of fisheries status (Worm *et al.* 2009; Hutchings *et al.* 2010; Melnychuk *et al.* 2011), the utility of mean trophic level as a biodiversity indicator (Branch *et al.* 2010), the relationship between catch and stock assessment data (Branch *et al.* 2011) and the relationship between life history characteristics and the propensity for stocks to collapse (Pinsky *et al.* 2011). We anticipate that the RAM Legacy database will continue to be of utility for fisheries scientists, ecologists and marine conservation biologists, and that its public release with this publication will enable and foster further comparative analyses of marine fisheries on a variety of topics including collapse and recovery patterns, fisheries productivity and marine population dynamics.

Caveats

Stock assessment outputs (e.g. biomass time series), which constitute the majority of the new RAM Legacy database are model estimates, not raw data. Ideally, the uncertainty associated with these estimates should be carried forth in subsequent analyses. Although the database structure allows for inclusion of estimates of uncertainty (standard errors, 95% credible/confidence intervals), uncertainty estimates for time series data were typically missing from assessments and hence are not included in the current version of the database. As with any analysis, clearer inference on the strength of a signal is available when all uncertainty in the data is carried forth. Sensitivity tests to various levels of measurement error on the time series may be necessary in many investigations.

The original database developed by Ransom A. Myers was used to address a variety of ecological questions derived from stock–recruit relationships. This synthesis was possible because the VPA-type assessment models that constituted most of that database generated time series of stock and recruitment with relatively few a priori assumptions. In contrast, the forward projection methods that are common in the RAM Legacy database generally specify the form of the stock–recruit relationship, and in many cases, even fix parameters such as steepness. Stock–recruitment 'data' from such models are clearly inappropriate for straightforward meta-analysis. In general, as more assessments incorporate some type of prior information from other stocks or species (Hilborn and Liermann 1998), there is less stock-specific information available for future meta-analysis (Minte-Vera *et al.* 2005). One solution is that for stock assessments to report not only best estimates of parameters based on all available data but also stock-specific parameter estimates that do not incorporate prior information from other stocks or species.

Reference points that we have derived from surplus production models are to be interpreted with great care. For stocks with both assessment-derived and Schaefer-derived BRPs, we found that B_{MSY} estimates from surplus production models were generally lower than those obtained from assessments, particularly at high B_{MSY} values; the converse was observed for U_{MSY} (see details in Figure S2). This discrepancy stems from the fact that in the Schaefer surplus production model, MSY occurs at 50% of the carrying capacity, whereas in most age-based assessment models, yield is maximised at a lower fraction of the carrying capacity. All exploitation rate reference points, whether estimated within the assessment model or by a surplus production model, must be interpreted with caution as changes through time in size/age selectivity of the fishery also alter the exploitation rate reference points.

Future development

Future versions of the RAM Legacy database will include updated assessments for already included stocks and new marine stocks. We also aim to include freshwater and anadromous stocks, timelines of management actions per stock, as well as age-varying and length-varying data such as maturity ogives and age-disaggregated natural mortality. Time-varying aspects of the same will also be incorporated. Depending on availability, subsequent releases of the database could also include estimates of assessment uncertainty. The development of a standard for assessment reporting at the management agency level would greatly assist in the acquisition of new assessments, and hence to ensure that the database remains current. The ultimate goal for the RAM Legacy database is to provide a comprehensive stock assessment database for researchers to use results from multiple regions to assist in their own applied and fundamental research in population ecology, fisheries science and conservation biology.

Availability of the database

A copy of the database used for this manuscript is available as a single spreadsheet file and as a Microsoft Access database from the RAM Legacy website at http://fish.dal.ca. Contributions or corrections to the existing database should also be directed to the RAM Legacy website. Finally, access to the 'live' production and development versions of the database can be arranged by contacting the corresponding author.

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Supporting Information

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

Data S1. Information about database and surplus production models implementation.

Figure S1. Entity-relationship diagram of the RAM Legacy database.

Figure S2. U_{MSY} and B_{MSY} vs. U_{MSY} and B_{MSY} obtained from Schaefer model under two different constraints for the upper bound of the Schaefer K parameter.

Figure S3. Taxonomic dendrogram of the RAM Legacy database.

Figure S4. Ratio of current biomass and fishing mortality to limit biomass and fishing mortality reference points (B_{lim} and F_{lim}) for European stocks managed by ICES.

Table S1. Full list of assessments with references.

Table S2. Contingency tables for stock status classification by the Schaefer model.

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