Assessing the knowledge-base for commercially exploited marine fishes and invertebrates with a new global database of stock assessments

Alternative Title 1: A new global stock assessment database for exploited marine species

Alternative Title 2: Understanding marine population dynamics using a new global database

Suggested Running Title: A new global stock assessment database

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Abstract

Data used to assess the status of individual fish stocks varies from very little information on many of the world's artisanal fisheries, to commercial landings, research surveys, and sophisticated population dynamics models that integrate many sources of information. Previous evaluations of the state of global fisheries have used catch data, which may be poor proxies for fish stock abundances. A global compilation of stock assessment data in the mid-1990s enabled substantial syntheses of stock status; however its focus was on stock-recruitment relationships and it is now 15 years out of date. To facilitate contemporary syntheses, we have assembled a new database, the RAM Legacy Database, of the most intensively studied commercially exploited marine fish stocks, including time series of: total biomass, spawner biomass, recruits, fishing mortality, and catch; reference points; and ancillary information on the life history, management, and assessment methods for each stock. Here, we present the first overview of this database and use it to evaluate the knowledge-base for assessed marine species. Globally, assessments were assembled for 324 stocks (288 fish species representing 45 families, and 36 invertebrate species representing 12 families), including 8 of the world's 10 largest fisheries. Assessments were obtained from 18 national and international management institutions, with most coming from North America, Europe, Australia, New Zealand and the High Seas. Overall, 58% of stocks are below B_{msy}, and 30% have exploitation levels above U_{msy}. Assessed marine fish stocks comprise a relatively small proportion of harvested taxa (24%), and an even smaller proportion of marine fish biodiversity (1%).

Keywords: marine fisheries, meta-analysis, population dynamics models, relational database, stock assessment, synthesis.

Introduction

Marine wild capture fisheries provide more than 80 million tons of fisheries products (both food and industrial) per year and employ 43.5 million people (wild capture and aquaculture, (FAO, 2009b)). At the same time, fishing has been recognized 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 two-thirds of fish stocks globally are fully exploited or overexploited (FAO, 2009b). While many fisheries have reduced exploitation rates to levels that should in theory promote recovery, overfishing continues to be a serious global problem (Worm *et al.*, 2009). Fishery managers are asked to address multiple competing objectives, including maximizing yields, ensuring profitability, reducing bycatch, and minimizing the risk of overfishing. Given the enormous social and economic costs (Rice *et al.*, 2003) and ecosystems consequences (Frank *et al.*, 2005; Myers *et al.*, 2007) of collapsed fisheries, it is imperative that we are able to quickly learn from successful and failed fisheries from around the world.

Effective management of exploited fish populations generally requires an understanding of where the current size and harvest rate lie in relation to the size and rate which maximize fishery benefits or limit the risk of overfishing. This process of quantitative determination of stock status and estimation of reference points is called stock assessment. Some fisheries in developing countries have apparently provided sustainable yields for long periods of time without formal stock assessment (e.g. many community-managed fisheries in Oceania; Johannes (2002)). This has been achieved by limiting harvest rates, often through gear restrictions or seasonal or area closures. In modern industrialized fisheries, however, where fishing capacity exceeds the productivity of fished stocks, stock assessment is an integral component of responsible management (Hilborn and Walters, 1992).

The global databases of fishery landings compiled by FAO (FAO, 2009a) and synthesized by the Sea Around Us project (Watson *et al.*, 2004) have proven to be valuable resources for understanding the status of fisheries worldwide; however, catch data alone can be misleading when used as a proxy for stock size. Many papers have used these data to examine changes in fishery status (Worm *et al.*, 2006; Costello *et al.*, 2008), including changes in trophic level (Pauly *et al.*, 1998; Essington *et al.*, 2006; Newton *et al.*, 2007). Most of these analyses 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 (de Mutsert *et al.*, 2008; Murawski *et al.*, 2007; Hilborn, 2007). Standardizing catch by the amount of fishing effort (catch-per-unit-of-effort, CPUE) is an improvement, particularly when these data are modeled to account for spatial, temporal, and operational factors affecting the CPUE, but CPUE can still be an unreliable index of relative abundance since it is difficult to account for all relevant factors (Hutchings and Myers, 1994; Harley *et al.*, 2001; Walters, 2003; Polacheck, 2006).

Stock assessments consider time series of catch along with other sources of information such as: natural mortality rates, changes in size or age composition, stock-recruitment relationships, and CPUE coming from different fisheries and/or from fishery-independent surveys. 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), the trade-off being that their complexity renders them difficult for non-experts to evaluate. Without a current and comprehensive database of stock assessments, however scientists wishing to conduct comparative analyses of marine fish population dynamics and fishery status have little choice but to use problematic catch data.

The first global 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 did contain time series of fishing mortality rates for many stocks; biological reference points 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 rates time series for 144 stocks. The number of entered stocks grew to approximately 642 stocks (509 with at least one SR pair) over the period from 1995-2005. Note that anadromous fishes of the family Salmonidae comprised 290 assessments in the original database. The assessment results collated by Dr. Myers were used to: 1) decisively answer the question of whether recruitment shows any relationship to spawning stock size (Myers and Barrowman, 1996), 2) investigate potential depensation in stock-recruitment relationships (Myers *et al.*, 1995a; Liermann and Hilborn, 1997; Garvey *et al.*, 2009), 3) discover generalities in the annual reproductive rates of fishes (Myers *et al.*, 1999, 2002b), 4) investigate density-dependence in juvenile mortality (Myers, 2001; Minto *et al.*, 2008), 5) develop informative Bayesian priors on steepness (Myers *et al.*, 1999, 2002a; Dorn, 2002), and 6) examine patterns of collapse and recovery in exploited fish populations (Hilborn, 1997; Hutchings, 2001a,b) .

Although the original Myers database (Myers *et al.*, 1995b) was critical for motivating comparative analyses in fisheries science, most of the stocks are now 15 years out of date. For stocks that were depleted in 1995, the past 15 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 assessment methodologies (including important advances in statistical catch-at-age or catch-at-length models) and assessments have been conducted for the first time for many species.

Meta-analyses of fishery status also have been hampered by the lack of a global assessment database containing biological reference points (BRPs, e.g., the total/spawning biomass and fishing mortality rate that produce Maximum Sustainable Yield (MSY), B_{MSY} and F_{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 non-biological thresholds to define fishery status, such as the greatest 15-year decline (Hutchings and Reynolds, 2004) or 10 percent 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). 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.

Here we present a new global database of stock assessments for commercially exploited marine fish populations. The database is an update and extension of that developed by Ransom A. Myers, and is named the RAM Legacy database in honour of his pioneering contribution. This effort is the first global stock assessment database to:

1. Use a formal relational database structure;
2. Use source control software to organise release versions;
3. Include metadata related to the geographic location of the stock, the type of assessment model used, and the original source document for the assessment data;
4. Include biological reference points, in addition to stock-specific life history information.

We use the new RAM Legacy database (Version 1.0, 2010) to evaluate the knowledge-base for commercially exploited marine populations in terms of institutional contributions, geography, taxonomy, ecology, timespan, stock assessment methodologies and BRPs. We compare the database's taxonomic coverage to that of global fisheries catches and to global fish diversity. We then evaluate the status of assessed stocks globally, and by management body, referencing all stocks to a comparable benchmark. Finally, we discuss biases in the knowledge base for assessed marine species, highlight potential applications of the database, point out its caveats and limitations, and outline directions for future development.

Methods

The RAM Legacy database

The RAM Legacy database is a global relational database designed and developed to store data from all current and accessible population dynamics 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 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, the assessment methodology, the reference for the stock assessment document, the name of the recorder entering the assessment data, and the date the assessment was entered. Some assessments, particularly those for invertebrates, were based only on CPUE time series rather than population dynamics models. While we included these in the database (n=26), the database description and analyses presented here focus on those stocks assessed using population dynamics models.

Over the past two and a half years, we have employed a variety of search methods in an attempt to obtain all recent fisheries stock assessments. Publicly available stock assessment reports available from the internet were the primary data source. These reports 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.

Significant contributions were also made by the other members of the National Center for Ecological Analysis and Synthesis (NCEAS) working group "Finding common ground in marine conservation and management". Relevant assessment data were first transferred into a standardized spreadsheet template by a number of recorders, including ourselves, assessment authors, our NCEAS collaborators, and associated graduate students and postdoctoral researchers, and then uploaded into the relational database management system by the first author.

Database structure and advantages

The database is implemented in the Open Source PostgreSQL relational database management system (RDBMS) (PostgreSQL Global Development Group, 2009), and includes tables for the assessment metadata, time series values, time series units, and biometrics (a catch-all term for data, such as life history characteristics or BRPs, that are not part of a time series). The entity relationship diagram of the database and its component tables can be found in the Supplementary Materials.

RDBMSs form the server back-end to many applications of interest to ecologists, including web-clients and GIS software, and have a number of advantages over spreadsheet or flat text file data compilations. First, housing stock assessments in an RDBMS allows multiple users to concurrently access and extract subsets of data in an efficient and reproducible manner. Second, with the development of Application Programming Interfaces (APIs) that allow analytical softwares to directly communicate and extract data from the database, a common data environment is established, independent of one's choice of analytical software (e.g., SAS:SAS ACCESS, Matlab: Matlab/Database, R:RDBI/RODBC, Perl:DBI, etc.). Users familiar with Structured Query Language (SQL) can also query the database directly from their analytical software of choice and the same SQL query will extract the same data through each of these applications. Third, data products tailored to specific projects can be generated and stored as dynamic (i.e., continually updated) "views" within the database. These are typically rectangular, spreadsheet-like results of an expansive query of the relevant tables that can be readily read into all commonly-used analytical software. The use of views is advantageous over manipulating spreadsheets or flat text files for importing into a specific analytic software, which runs the risk of losing data integrity (e.g. multiple copies) and becomes impractical with large, non-rectangular datasets and multiple users.

Data integrity and quality control

We have employed several mechanisms to ensure that the database is of high quality. During the data recording process, assessment authors often were contacted 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 or its authors. 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. This process consisted of creating a QA/QC summary document for each assessment, containing summary details of the stock, a selection of biometrics and ratios for comparison (e.g. current status relative to BRP), and time series plots of the biomass, recruitment, and exploitation trajectories. QA/QC documents were then returned to assessment recorders and an electronic trail of subsequent correspondence was captured using a bug tracking system. Recorders were responsible for checking, and where necessary correcting, their QA/QC documents, after which all corrections were transmitted back to the operational database and a quality controlled flag was inserted to signify the assessment had passed the check. Only assessments that have passed this QA/QC step are available for subsequent analyses.

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 Project's (SAUP) 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 SAUP 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) (NOAA, 1998). 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. 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".

Assessing the knowledge-base for commercially exploited stocks

We assess the knowledge-base for commercially exploited stocks, as represented by the RAM Legacy database, using a variety of metrics. To evaluate the taxonomic scope of the database, 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 SAUP database), and discuss taxonomic biases in species included in catch data and in populations assessed using stock assessments. We evaluate the ecological scope of assessed stocks in terms of age at sexual maturity as reported in the assessments, and trophic level of those assessed stocks as reported in FishBase. We overview the types of assessment models used, and BRPs estimated, for all stock assessments and by management body. To determine what fraction of world wild-capture fisheries landings come from assessed stocks, we used the SAUP's average global fisheries catches from the most recent ten years of available data (1995-2004); we also discuss limitations to obtaining assessments for some of the world's major fisheries. Comparisons between assessments and catch data at a regional level are hampered by the geographic mismatch between stocks and FAO statistical areas or the SAUP's Large Marine Ecosystems.

Assessing the status of commercially exploited marine stocks

We evaluate the status of assessed stocks overall and by management body, using standard reference points so that all stocks are referenced to a comparable benchmark. Following Froese and Proelß (2010) and Worm *et al.* (2009), we compare the current biomass and exploitation rate of stocks relative to their MSY reference points, B_{MSY} and U_{MSY}, respectively.

We do not advocate the use of MSY targets for management, but still report MSY-related BRPs because they are the most commonly estimated BRP and can be used to compare multiple stocks. For those assessments that did not contain MSY reference points, but did include total catch ($TC_{i,s}$, $i \in 1,\ldots,n_s$) and total biomass ($TB_{i,s}$, $i \in 1,\ldots,n_s$) time series data, we used a Schaefer surplus production model to estimate total biomass and exploitation rate at MSY (TB_{MSY_s} and u_{MSY}, respectively). Surplus production of stock s in year t, $P_{s,t}$, is a commonly used measure of stock productivity, representing the amount of catch that can be taken while maintaining the biomass at a constant size, and can be calculated as:

$$P_{s,t} = TB_{s,t+1} - TB_{s,t} + TC_{s,t} \tag{1}$$

where,

$TB_{s,t}$ is the total biomass of stock s in year t

$TC_{s,t}$ is the total catch of stock s in year t

We fit a Schaefer surplus-production model, which is based on a logistic model of population growth to the catch and total biomass time series data. The predicted surplus production in each year in the Schaefer model is given by:

$$\hat{P_{s,t}} = \frac{4mTB_{s,t}}{K} - 4m\left(\frac{TB_{s,t}}{K}\right)^2 \tag{2}$$

where,

m is the maximum sustainable yield, equal to $rK/4$

K is the carrying capacity or equilibrium total biomass in the absence of fishing (Hilborn and Walters, 1992)

We estimated the model parameters (m and K) using maximum likelihood in AD Model Builder (ADMB Project, 2009) assuming that the residuals $\epsilon_{s,t} = P_{s,t} - \hat{P_{s,t}}$ were normally distributed. For the Schaefer model, B_{MSY} is simply $0.5K$, and the harvest rate that results in maximum sustainable yield, u_{MSY}, is m/B_{MSY}. Carrying capacity was constrained to be less than twice the maximum observed total biomass.

Finally, we discuss potential applications of the database, point out its limitations and caveats about its use, and outline directions for future development.

Statistical analyses and plot generation were conducted with the R Environment for Statistics and Graphics (Development Core Team, 2009) using the packages *RODBC* (Ripley *et al.*, 2009), *KernSmooth* (original by Matt Wand. R port by Brian Ripley., 2009), *xtable* (Dahl, 2009), *ape* (Paradis *et al.*, 2004), *gsubfn* (Grothendieck, 2010), *IDPmisc* (Ruckstuhl *et al.*, 2009), and *doBy* (with contributions from Kevin Wright and Leidi., 2010). Figure 1 was generated using the Generic Mapping Tools (Wessel and Smith, 1991).

Results

The knowledge-base for commercially-exploited marine stocks

In total, 324 recent stock assessments for 288 marine fish and 36 invertebrate populations are included in the RAM Legacy database (Version 1.0, 2010; Table S1). Together these comprise time series of catch/landings for 308 stocks (95%), SSB estimates for 271 stocks (84%), and recruitment estimates for 269 stocks (83%) (Table S1).

Management bodies and geography

Stock assessments are derived from fisheries management bodies in Europe, the United States, Canada, New Zealand, Australia, Russia, South Africa and Argentina (Table 1). Also included are assessments conducted by eight Regional Fisheries Management Organizations (RFMOs), in the Northwest Atlantic, Atlantic, Pacific and Indian Ocean (Table 1). Assessments from the United States comprise by far the most stocks of any country or region (n=139); assessments from the European Union's management body, the International Council for the Exploration of the Seas (ICES), comprise the the second greatest number of stocks (n=63). Whereas nations are responsible for managing all populations 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.

Most assessments come from North America, Europe, Australia, New Zealand and the High Seas, while there are few from regions such as Southeast Asia, South America, and the Indian Ocean (outside Australian waters) (Figure 1). Assessments were available for 31 LMEs, with the greatest number of assessed stocks coming from Northeast U.S. Continental Shelf (n=58), California Current (n=35), New Zealand Shelf (n=29), Gulf of Alaska (n=26), Celtic-Biscay Shelf (n=26), East Bering Sea (n=22) and Southeast U.S. Continental Shelf (n=20) (Figure 1).

Taxonomy

Assessments for 157 species from 57 families and 20 orders are included in the database (Figure 2). Five taxonomic orders (Gadiformes (n=67), Perciformes (n=62), 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 (46.04% of all marine fish species vs. 19% of all marine fish assessments), while the other four orders are taxonomically overrepresented: Clupeiformes (2.1% of marine fishes vs. 11% in the database), Gadiformes (3.3% of marine fishes vs. 21% in the database), Pleuronectiformes (4.5% of marine fishes vs. 17% in the database), Scorpaeniformes (8.5% of marine fishes vs. 12% in the database) (Figure 3).

Assessed marine fish stocks in the RAM Legacy database comprise a relatively small proportion of harvested taxa (24% of fish species from the SAUP database) and an even smaller proportion of marine fish biodiversity (1% of fish species in FishBase; Figure 3). In turn, catches from the SAUP database, which come from 649 species and 36 orders (Figure 3), represent only 5% of the 12339 species and 67% of the 54 different orders present in FishBase (Figure 3). The diversity of harvested marine invertebrates is clearly underrepresented in the stock assessment database and likely in stock assessments in general.

Ecology

Assessed species span a range of ecological traits. Some life-history information (e.g. growth, maturity, fecundity) is available for 288 of the collated assessments. In some cases, this information is derived from biological studies, while in other cases life-history parameters represent model assumptions (e.g., natural mortality = 0.2) or model estimates. The trophic level of assessed species ranged from 2 to 4.5 with a mean of 3.7, with no apparent relationship between trophic level and stock status (Figure 4).

Timespan

The median lengths of catch/landings, SSB, and recruitment timeseries were 38, 34, and 33 years, respectively (Figure 5). The time period covered by 90% of assessments is: catch/landings (1967-2007), SSB (1972-2007), recruitment (1971-2006), while that covered by 50% of assessments is: catch/landings (1983-2004), SSB (1985-2005), recruitment (1984-2003) (Figure 5).

Stock assessment methodologies and BRPs

The three most common assessment methods were Statistical catch-at-age/length models (n=164), Virtual Population Analyses (n=90) and Biomass dynamics model (n=45). Regionally, Virtual Population Analysis (VPA) is still the most common assessment model for ICES (71% of 63 assessments), DFO (59% of 22 assessments) and Argentina's CFP (83% of 6 assessments), whereas statistical catch-at-age and -length models are more common for NMFS (66% of 139 assessments), AFMA (81% of 16 assessments) and MFish (76% of 29 assessments).

Biomass- or exploitation-based reference points were available for 257 (81%) and 222 (69%) assessments, respectively. The most commonly reported biomass-based BRPs relate to biomass at MSY (e.g. B_{msy}), to "limit" biomass (e.g. B_{lim}) and to "precautionary approach" biomass (e.g. B_{pa}). Biomass and exploitation of US stocks under the management of NMFS must follow MSY-based reference points whereas other fisheries agencies use different BRPs.

Global Fisheries

Assessments were available for 8 of the 10 largest fisheries for individual fish stocks globally (Table 2). Assessments for Peruvian anchoveta, the world's largest fishery, and for Japanese anchovy in the East China Sea (the eighth largest species for an individual stock, and tenth overall) were not accessible. Looking more broadly, the database contains assessments for 16 of the 30 largest fisheries for individual fish stocks globally, and 17 of the 40 largest fisheries globally (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 SAUP 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 2 of the top 10 wild-caught marine fisheries producing nations, U.S.A. and Russia (FAO, 2009b), with only two assessments from the latter. We were unable to obtain any assessments from the other top 10 countries: China, Peru, Indonesia, Japan, Chile, India, Thailand, Philippines (FAO, 2009b).

The status of commercially exploited marine stocks

To evaluate stock status, we single out stocks where both a biomass BRP and an exploitation BRP are available. Of the 241 stocks presented in Figure 6, 66 come directly from assessments and 175 come from surplus production model fits. To identify potential biases arising from using BRPs derived from surplus production models we computed a contingency table of status classification for stocks that have both assessment- and Schaefer-derived BRPs (Table S2). Surplus production models correctly classified ratios of current biomass to BRPs in 71% of cases (for 67 of 95 assessments) and 63% of cases for exploitation BRPs (for 37 of 59 assessments).

Overall, 58% of stocks are estimated to be below their biomass-related MSY BRP, that is $B_{curr} < B_{msy}$, and 30% are above their exploitation-related MSY BRP, $U_{curr} > U_{msy}$ (n=241 stocks total; Figure 6). Of the stocks for which biomass is currently estimated to be below B_{msy}, 53% have had their exploitation rate reduced below U_{msy}, suggesting potential for recovery (Figure 6). The remaining 47% of these stocks however, still have excessive exploitation rates (Figure 6). Encouragingly, 42% of all stocks are estimated to be above B_{msy}, and 94% of the stocks above B_{msy} also have $U_{current}$ below U_{msy}.

The status of exploited marine stocks, as estimated from biomass- and exploitaion-BRPs, varied widely depending on the management body (Figure 7). Most European stocks (managed by ICES) have biomasses less than B_{msy} (79%), and over half of these stocks (61%) still have exploitation rates exceeding U_{msy}. Canadian stocks (managed by DFO) also had low biomass (79% $< B_{msy}$), but all but one of these has had its exploitation rate reduced below U_{msy}. In contrast, about half (49%) of U.S. stocks (managed by NMFS) are estimated to still be above B_{msy}, and of the 45 stocks that are below B_{msy} 58% have exploitation rates below U_{msy} (Figure 7). In the New Zealand and Australian waters, stocks managed by MFish and AFMA are above B_{msy} in 61% and 42% of cases, respectively. For the stocks grouped as “Atlantic” in Figure 7 we found that 5 of the 10 ICCAT stocks and 5 of the 10 of NAFO stocks were below B_{msy} .

Discussion

The knowledge-base and status of commercially exploited marine stocks

The RAM Legacy Database provides detailed time series and point data from available stock assessments for the world's industrial marine fisheries, thus providing a basis for evaluating the existing knowledge-base and current status of these fisheries. Accessible stock assessments are predominantly from developed nations in north-temperate regions, and tend to cover only the past few decades, typically a significantly shorter period than that for which the stock has been exploited. The taxonomic makeup of available assessments is a very limited subset of the accepted taxonomic coverage of marine species worldwide, and of globally exploited species. Most notably (with the exception of tunas), assessment-based knowledge is not available for coral reef and other tropical fishes. Inshore (e.g. estuarine species) and anadramous populations are also noteworthy in their absence (as a result of our focus on federally or internationally managed marine species) and, as such, any assessment of global status of exploited populations must be interpreted only for that subset of exploited species for which assessments are present in the database.

In its latest State of the World Fisheries and Aquaculture (FAO, 2009b), the FAO reports that 20% of stocks are underexploited, 52% are fully exploited, 19% are overexploited and 1% is recovering from depletion. The ambiguous classification of stocks as "underexploited", "fully exploited" and "overexploited" makes comparisons of our results with those from the FAO difficult. Our estimates are that almost 60% of stocks are below the biomass reference point that maximises their yield. Almost half of stocks that are below B_{msy} still experience exploitation rates that are above those that would maximise yield. Our results also provide evidence that appropriate fisheries management measures can curtail over-exploitation and that stocks can recover. For depleted stocks, recovery requires strongly articulated legislation, potentially difficult short- to medium-term regulations to decrease fishing mortality, protection of habitat through area closures and recovery targets with well-defined timelines. For stocks that exist in areas beyond national jurisdiction, nation members of various Regional Fisheries Management Organisations must treat international regulations as bindings agreements that must be fulfilled.

Biases in the knowledge-base for commercially exploited marine stocks

Geographic bias

Bias in the geographic scope of the RAM Legacy database (relative to that of all fisheries globally) may arise for several reasons, all of which vary geographically in their prevalence: 1. an assessment is not conducted on a stock; 2. it is not possible to access the assessment; or 3. the non-exhaustive collation we undertook overlooked the assessment. Whether an assessment is conducted for a given stock depends upon a multitude of factors, including the economic value of the stock, the availability of fiscal resources to collect the data required for an assessment (which frequently includes conducting fisheries-independent research surveys) and the expertise to conduct assessments. In general, conducting stock assessments is a costly endeavour that is restricted to wealthy fishing nations. 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. How accessible assessments are for entry 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, and that the development of this database will encourage greater transparency amongst fishing nations.

Taxonomic bias

Related to geographic bias is the taxonomic bias in those species that are known, caught and assessed. At a broad level the Gadiformes and Clupeiformes occupy disproportionate taxonomic representation in the catch compared to overall species occurrence (Figure 3, panels a and b). Taxonomic biases at this level may reflect behavioural tendencies of the over-represented species in the catch to form large aggregated populations in temperate regions that are readily accessible to fishing. Consumer preferences may also be an important determinant of what taxonomic groups are more likely to be caught. The over-representation of the Gadiformes and, to a lesser degree, the Clupeiformes, continues when caught and assessed taxa are compared (Figure 3, panels b and c).

Historical economic importance as well as the geographic distribution of the taxa in relation to mandated assessments may play important roles in determining what fished taxa are assessed. Even in developed countries, however, not all stocks are assessed. For example, in 2007, of the 528 fish and invertebrate stocks recognized by the National Marine Fisheries Service (NMFS), only 179, or slightly over one-third, were fully assessed (National Marine Fisheries Service, 2008). An assessment by the European Environment Agency (EEA) in 2006 indicated that the percentage of commercial landings obtained from assessed stocks ranged between 66-97 percent in northern European waters and 30-77 percent in the Mediterranean (European Environment Agency, 2009). The New Zealand Ministry of Fisheries reports the status of 117 stocks or sub-stocks out of a total of 628 stocks managed under New Zealand's Quota Management System (New Zealand Ministry of Fisheries, 2009). In Australia, 98 federally managed stocks have been assessed (Wilson *et al.*, 2009) out of an unknown total. The extent to which stocks are assessed elsewhere in the world is currently unknown.

Temporal bias

Most of the assessments in the RAM Legacy database contain time series of 30 years or less whereas industrial fishing began long before this. Dominant age-structured assessment methodologies typically 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 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 don't know what's historically possible (in terms of stock size), it's hard to know where we should set our goals. This "shifting baseline" problem has been widely recognized (Pauly, 1995; Sáenz-Arroyo *et al.*, 2005), but is still apparent in the relatively short time series of most assessments.

Future applications of the RAM Legacy database

We anticipate that this new database will be of utility for fisheries scientists, ecologists, and marine conservation biologists interested in conducting comparative analyses of global fisheries status, collapse and recovery patterns, fisheries productivity or marine population dynamics. In addition to the initial aim of providing reliable access to time series information about stocks, we hope to also stimulate research in the relationships of life-history characteristics and their relation to exploitation. The RAM Legacy database contains the corresponding species codes to the Sea Around Us Project and FishBase, thus facilitating researchers' use of a global fisheries data "toolkit" to address questions on the relationships between life history attributes and resulting population dynamics in an exploited setting.

Caveats and limitations

Stock assessment outputs (e.g. biomass time series), which comprise the majority of the new RAM Legacy database are model estimates, not raw data. 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), because these estimates were typically missing from assessments, either because they weren't produced by the assessment model (e.g. non-bootstrapped VPA assessments) or the focus of the assessment document was on central tendency (e.g. mean biomass) not the associated uncertainty, they have not been included in this first version of the database. Note that this view of assessment uncertainty is changing with the advent of MCMC approaches to Bayesian inference for assessments, bootstrap methods, statistical catch-at-age models (ADMB Project, 2009) and a general focus on uncertainty (Walters and Maguire, 1996). As with any analysis, clearer inference on the strength of a signal is available when all uncertainty in the data is carried forth. This represents a difficulty for synthetic analyses of fisheries data in that in an ideal world one would access the raw data for each stock and carry forth the uncertainty at all levels of the analysis. In the case of assessments, the raw data is typically catch-at-age matrices and potentially survey indices. To understand the fleet characteristics and survey stratification schema for each stock in a potentially global meta-analysis would be extremely time consuming and error-prone. Instead, the expert opinion of those researchers most familiar with the data, stock assessment authors, is used, while recognizing that without accompanying uncertainty estimates the strength of conclusions drawn may be weakened.

While the database provides detailed trends for individual stocks, it will never have the geographic and taxonomic coverage provided by catch statistics. Assessment results will also never replace the essential role played by fisheries-independent scientific surveys in determining abundance, biomass and diversity trends in marine living resources.

BRPs derived from surplus production models are to be interpreted with great care. For stocks where both were available we found that Schaefer-derived B_{msy} were systematically higher than those obtained from assessments. This stems from the fact that under 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.

The original database developed by Ransom A. Myers was used to address a variety of ecological questions derived from stock-recruit relationships. This was possible because the VPA-type assessment models that comprised most of that database generated time series of stock and recruitment with relatively few a priori assumptions. Forward projection methods generally specify the form of the stock-recruit relationship, and in many cases even fix parameters (infinitely dense point prior) 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. One solution is 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.

Future development

We anticipate that the RAM Legacy database will continue to grow with hitherto unentered stocks e.g. freshwater and anadramous populations, particularly the Salmonidae that comprised 45% of the stocks in the original Myers Stock Recruitment Database, and updated assessments for already included stocks. Future versions of the database will also include timelines of management actions per stock, as well as age-varying and length-varying data such as maturity ogives and age-disaggregated natural mortality. Depending on availability, subsequent releases of the database could also include estimates of assessment uncertainty. Future database products will include management-agency-level reports containing summaries of all stocks within their remit. 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. For example, ICES assessments have a very regular standard, including agreed-upon reference points and regular estimate reporting. This makes the process of data collation much more routine than unstandardized documents where the recorder trawls through a report for the relevant information. ICES also has a central database of assessments for stocks of the region. Certainly different stocks and regions require different formats but basic output tables, consisting of total and spawning biomass, recruitment, catch/landings, estimated fishing mortality over vulnerable age groups, associated measures of uncertainty, and commonly-used reference points would streamline the process immensely. A process whereby the assessment spreadsheets are filled out at each assessment meeting would facilitate the process even further and be the least error prone method. In return, the assessment scientists can access results for a global collation of assessments to further their own research initiatives in population assessment and management. The ultimate goal 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

Contributions or corrections to the existing database, as well as requests to use the database (subject to standard "Fair Use" policies), should be directed to the corresponding author.

Acknowledgments

We sincerely thank all of the fisheries scientists whose assessments form the basis of this new global database. We are also grateful for the database contributions, advice, and support of Trevor Branch, Jeremy Collie, Laurence Fauconnet, Mike Fogarty, Rainer Froese, Ray Hilborn, Jeff Hutchings, Simon Jennings, Heike Lotze, Pamela Mace, Michael Melnychuk, Ana Parma, Renée Préfontaine, Kate Stanton, Reg Watson, Boris Worm, Dirk Zeller, and the financial support of the National Science Foundation through an NCEAS Working Group, the Natural Sciences and Engineering Research Council (NSERC) of Canada, the Canadian Foundation for Innovation, the David H. Smith Conservation Research Fellowship, the Schmidt Research Vessel Institute, and the Census of Marine Life (CoML/FMAP).

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Tables

Table 1: Number of assessments included in the RAM Legacy database

Country/Ocean	*Management Body*	*Acronym*	*No. stocks*
Australia	Australian Fisheries Management Authority	AFMA	16
Multinational	Commission for the Conservation of Antarctic Marine Living Resources	CCAMLR	1
Argentina	Consejo Federal Pesquero	CFP	6
South Africa	South African national management	DETMCM	14
Canada	Department of Fisheries and Oceans	DFO	22
Multinational	Inter-American Tropical Tuna Commission	IATTC	2
Multinational	International Commission for the Conservation of Atlantic Tunas	ICCAT	10
Multinational	International Council for the Exploration of the Sea	ICES	63
Multinational	Indian Ocean Tuna Commission	IOTC	1
Multinational	International Pacific Halibut Commission	IPHC	1
New Zealand	Ministry of Fisheries	MFish	29
Multinational	Northwest Atlantic Fisheries Organization	NAFO	9
USA	National Marine Fisheries Service	NMFS	139
Russia	Russian Federal Fisheries Agency	RFFA	2
Multinational	South Pacific Regional Fisheries Management Organi-	SPRFMO	1

Table 2: The world's forty largest wild-caught fisheries (comprising less than 41% of total global catches, based on average catches 1995-2004 in SAUP database), and the thirty largest fisheries of individual stocks (i.e. fisheries identified to the species level; comprising 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 is not based on a population dynamics model, 3=assessment inaccessible).

Stock Rank	*Stock Number*	*Species (Common name, Latin name) or higher taxonomic unit*	*LME*	*In Database?*	*Reason if not included*
1	1	Peruvian anchoveta, *Engraulis ringens*	Humboldt Current	x	3
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	✓	

Continued on next page

Stock Rank	*Individual species rank*	*Species (Common name, Latin name) or higher taxonomic unit*	*LME*	*In Database?*	*Reason if not included*
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	3
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 ofAlaska	✓	

Continued on next page

Stock Rank	*Individual species rank*	*Species (Common name, Latin name) or higher taxonomic unit*	*LME*	*In Database?*	*Reason if not included*
17	12	Argentinean short-finned squid, *Illex argentinus*	Patagonian Shself	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	?
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	?
25		Marine fishes not identified	Gulf of Thailand	x	1

Continued on next page

Stock Rank	*Individual species rank*	*Species (Common name, Latin name) or higher taxonomic unit*	*LME*	*In Database?*	*Reason if not included*
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	?
29	23	Japanese anchovy, *Engraulis japonicus*	Yellow Sea	x	?
30	24	European anchovy, *Engraulis encrasicolus*	Black Sea	x	?
31	25	Chub mackerel, *Scomber japonicus*	East China Sea	x	?
32	26	Indian oil sardine, *Sardinella longiceps*	Arabian Sea	x	1
33		*Decapterus*	South China Sea	x	?
34		*Sciaenidae*	Arabian Sea	x	?

Continued on next page

Stock Rank	*Individual species rank*	*Species (Common name, Latin name) or higher taxonomic unit*	*LME*	*In Database?*	*Reason if not included*
35	27	Atlantic mackerel, *Scomber scombrus*	North Sea	✓	
36	28	Largehead hairtail, *Trichiurus lepturus*	Yellow Sea	x	?
37		*Merluccius*	Benguela Current	✓	
38		Marine fishes not identified	Kuroshio Current	x	?
39	29	Alaska pollock, *Theragra chalcogramma*	Sea of Japan	x	?
40	30	Round sardinella, *Sardinella aurita*	Canary Current	x	?

Figures

Figure legends

Figure 1. Global map of Large Marine Ecosystems (LMEs) and High Seas Areas (ovals) showing the number of stock assessments present in the database for each area.

Figure 2. Taxonomic coverage of assessed marine species present in the RAM Legacy database. The circle located near the middle of the circular dendrogram represents kingdom Animalia and each subsequent branching represents a different taxonomic group (Kingdom to Phylum to Class to Order to Family to Genus to Species). The width of each line is proportional to the square root of the number of assessments in the database. The outermost lines represent species and the number of lines is the number of assessments for each species. The names of multi-assessment species are not repeated on the outermost portion of the dendrogram but continue counter-clockwise from the first entry. Note that branch lengths are chosen for graphical purposes and do not convey phylogenetic distance.

Figure 3. Comparison of the taxonomic diversity of marine species as provided by FishBase (top panel), the coverage of catch data as provided by the Sea Around Us Project (SAUP) database (middle panel) and the new RAM Legacy database (bottom panel). 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.

Figure 4. Mean trophic level (obtained from FishBase) of the assessed species, grouped by their B/B_{msy} and U/U_{msy} ratios.

Figure 5. 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 which 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.

Figure 6. Current exploitation rate versus current biomass for 241 individual stocks. Exploitation is scaled relative to that which should allow maximum sustainable yield (U_{msy}); biomass is scaled relative to B_{msy}. Shades of grey indicate probability of occurrence as revealed by a kernel density smooth function. Solid circles indicate B_{msy} and U_{msy} that were obtained directly from assessments; open circles indicate that they were estimated from surplus production models.

Figure 7. Current exploitation rate versus biomass for individual stocks grouped by management unit. The panel labelled "Atlantic" comprises ICCAT and NAFO. Plot details as in Figure 6.

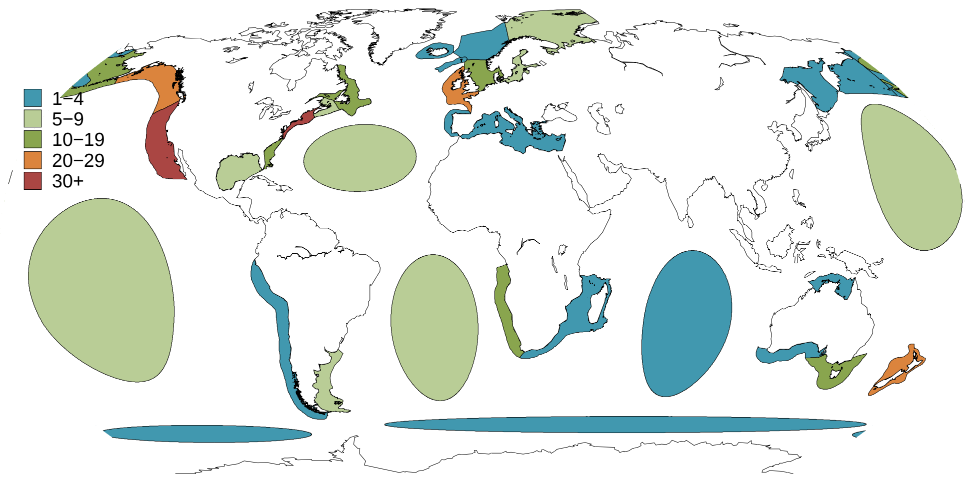

Figure 1:

Figures

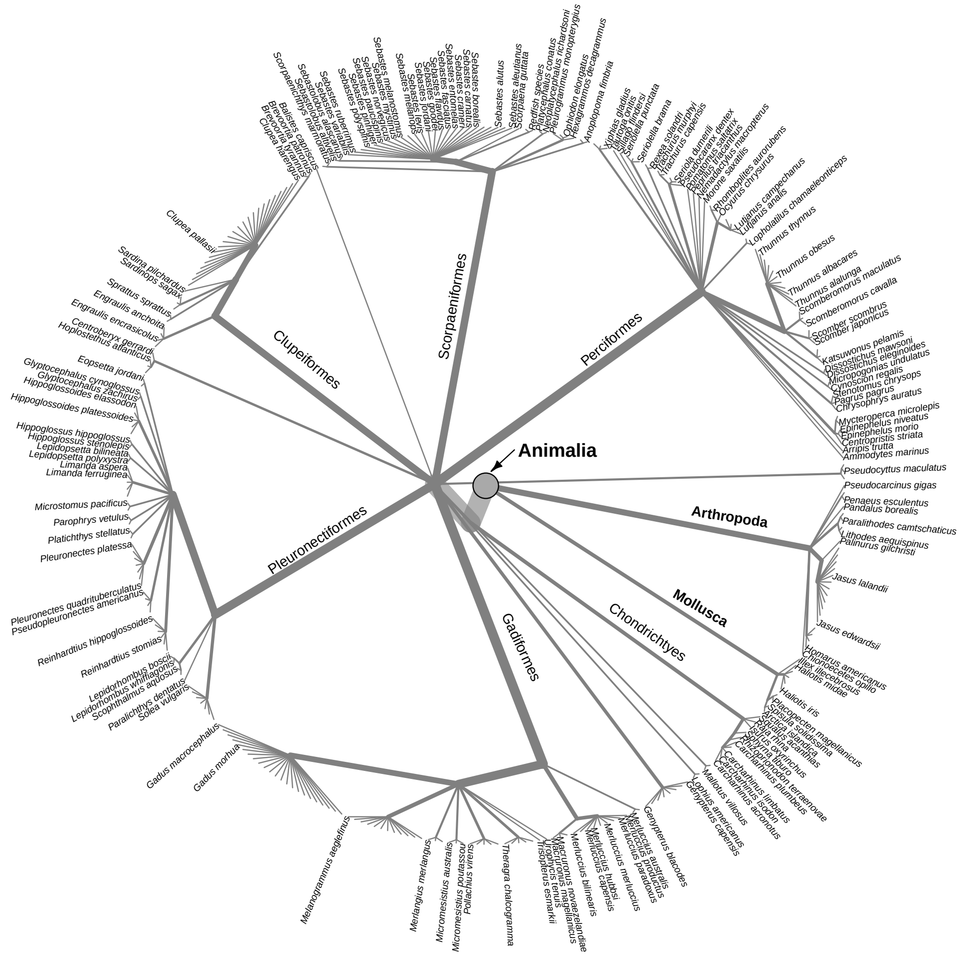
Animalia
Arthropoda
Mollusca
Chondrichtyes
Gadiformes
Pleuronectiformes
Clupeiformes
Scorpaeniformes
Perciformes

Figure 2:

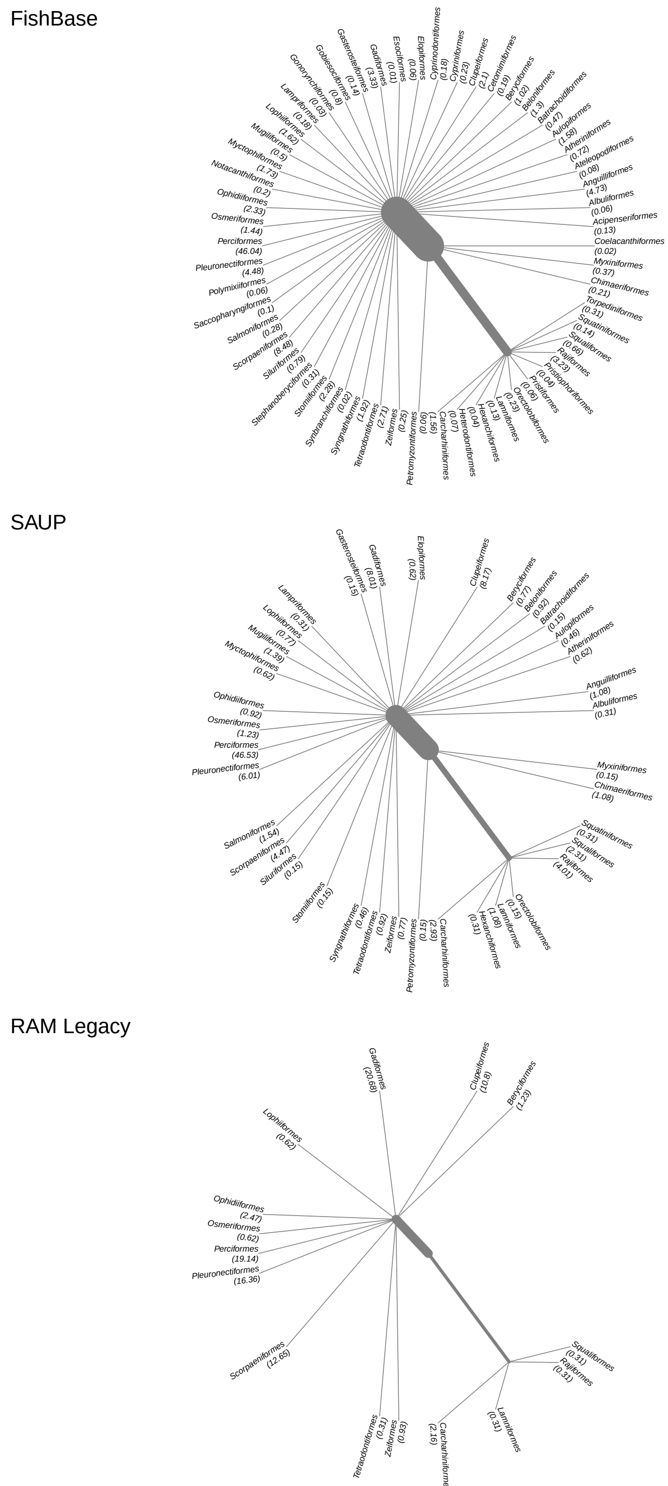
FishBase
SAUP
RAM Legacy
Gadiformes (20.68)
Clupeiformes (10.8)
Beryciformes (1.23)
Lophiiformes (0.62)
Ophidiiformes (2.47)
Osmeriformes (0.62)
Perciformes (19.14)
Pleuronectiformes (16.36)
Scorpaeniformes (12.65)
Squaliformes (0.31)
Rajiformes (0.31)
Tetraodontiformes (0.31)
Zeiformes (0.93)
Carcharhiniformes (2.16)
Lamniformes (0.31)

Figure 3:

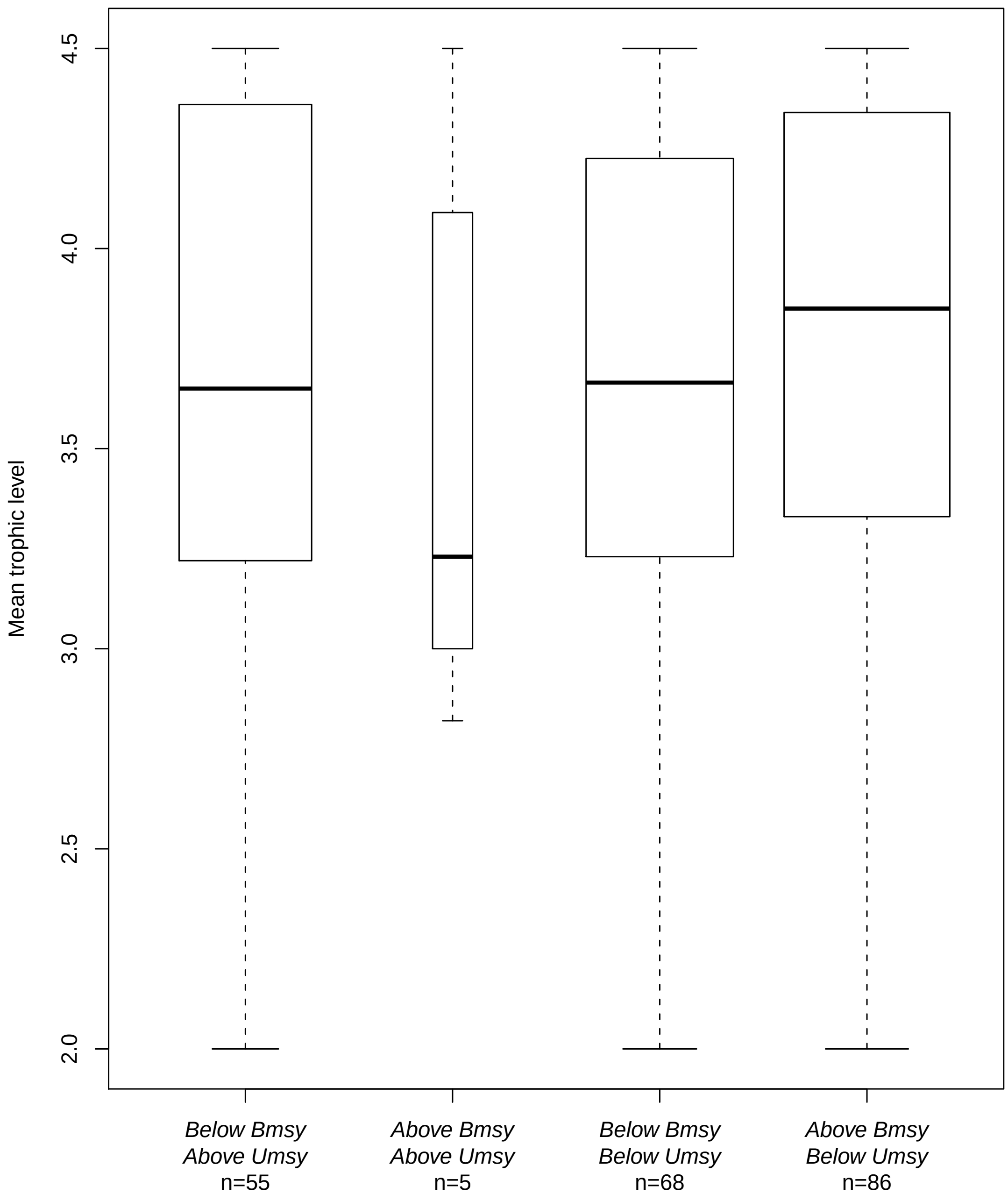
4.5
4.0
3.5
3.0
2.5
2.0
Mean trophic level
Below Bmsy
Above Umsy
n=55
Above Bmsy
Above Umsy
n=5
Below Bmsy
Below Umsy
n=68
Above Bmsy
Below Umsy
n=86

Figure 4:

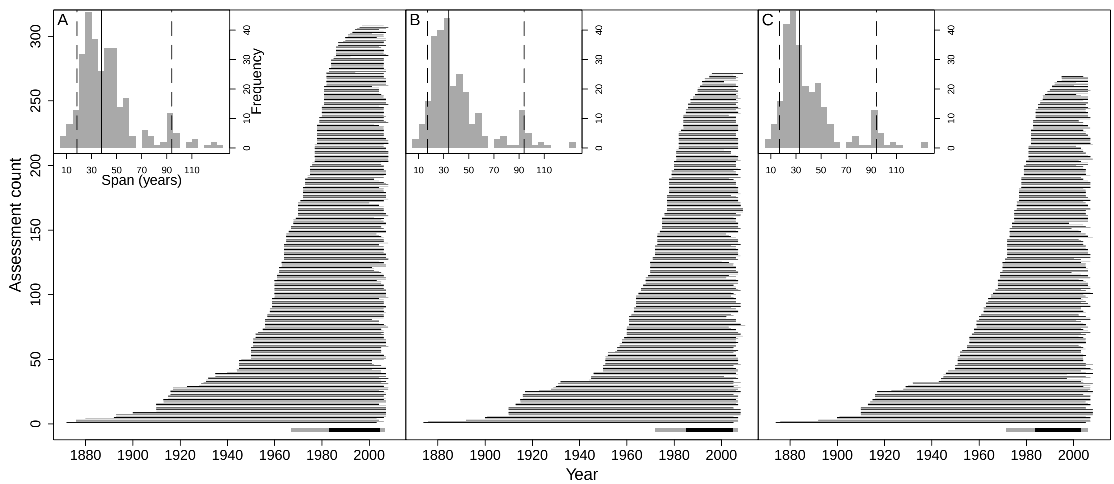

Figure 5:

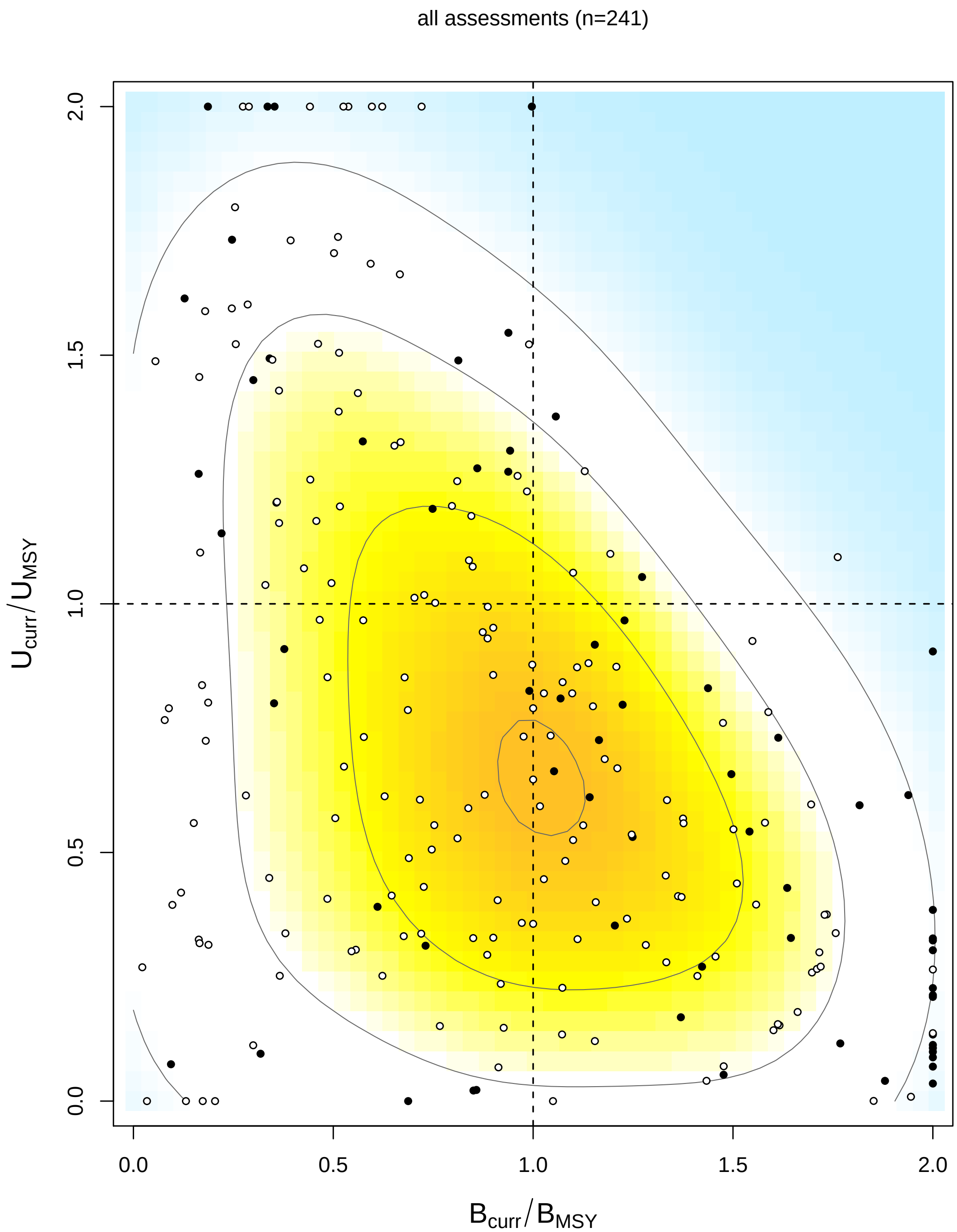

Figure 6:

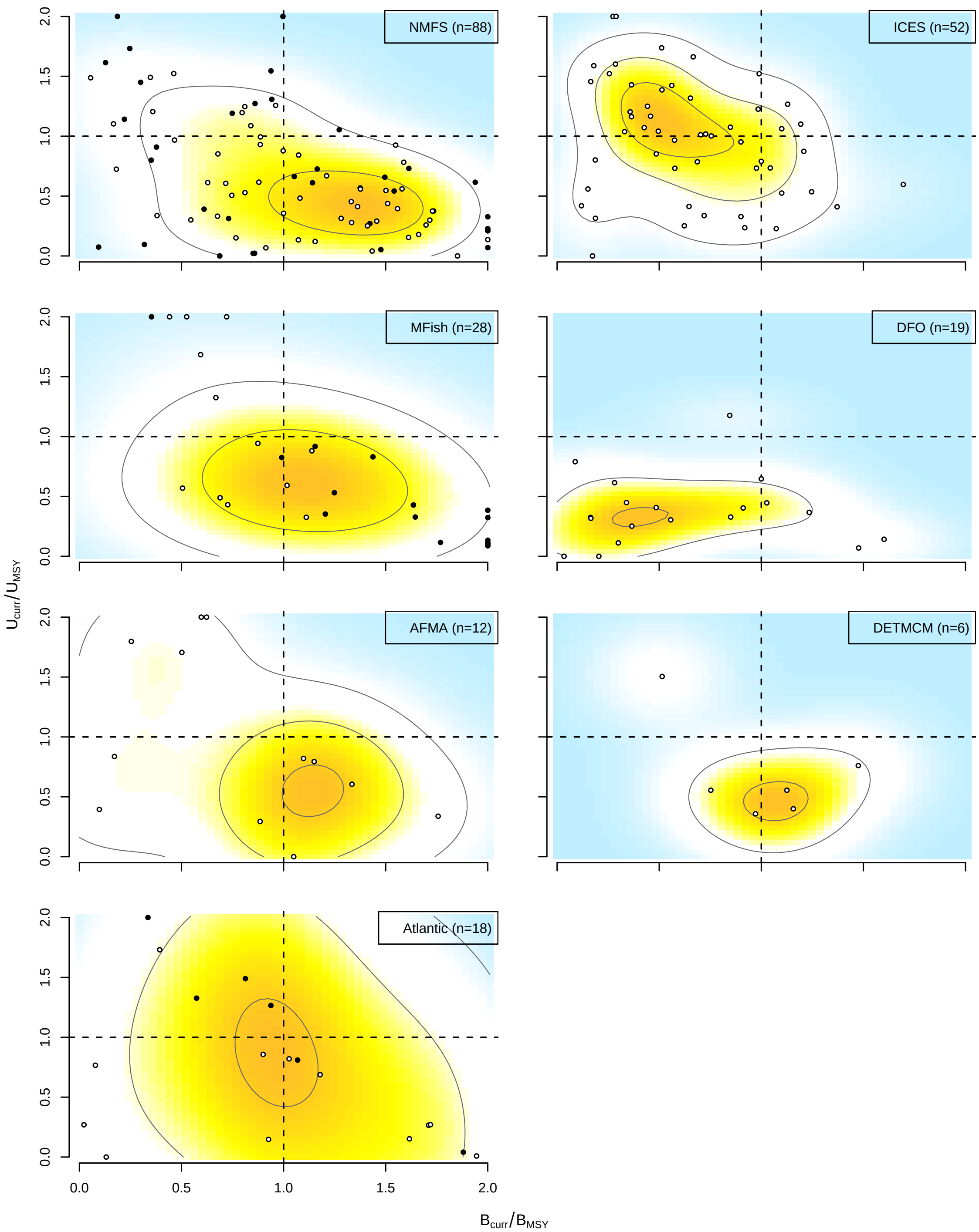
NMFS (n=88)
ICES (n=52)
MFish (n=28)
DFO (n=19)
AFMA (n=12)
DETMCM (n=6)
Atlantic (n=18)
U_{curr}/U_{MSY}
B_{curr}/B_{MSY}
0.0
0.5
1.0
1.5
2.0

Figure 7: