




LETTER

Applying a New Ensemble Approach to Estimating Stock Status of Marine Fisheries around the World

Andrew A. Rosenberg¹, Kristin M. Kleisner², Jamie Afflerbach³, Sean C. Anderson⁴, Mark Dickey-Collas^{5,6}, Andrew B. Cooper⁷, Michael J. Fogarty⁸, Elizabeth A. Fulton^{9,10} , Nicolás L. Gutiérrez¹¹ , Kimberly J.W. Hyde¹², Ernesto Jardim¹³, Olaf P. Jensen¹⁴, Trond Kristiansen¹⁵, Catherine Longo¹⁶, Carolina V. Mente-Vera¹⁷, Cólín Minto¹⁸, Iago Mosqueira¹³, Giacomo Chato Osio¹³, Daniel Ovando¹⁹, Elizabeth R. Selig^{20,21}, James T. Thorson²², Jessica C. Walsh⁷ , & Yimin Ye¹¹

¹ Center for Science and Democracy, Union of Concerned Scientists, 2 Brattle Square, Cambridge, MA, 02138, USA

² Environmental Defense Fund, 18 Tremont St., Ste. 850, Boston, MA, 02108, USA

³ National Center for Ecological Analysis and Synthesis, University of California Santa Barbara, 735 State Street, Santa Barbara, CA 93101, USA

⁴ School of Aquatic and Fishery Sciences, University of Washington, Box 455020, Seattle, WA 98195, USA

⁵ International Council for the Exploration of the Seas, H. C. Andersens Boulevard 44–46, DK 1553 Copenhagen, Denmark

⁶ National Institute of Aquatic Resources, Danish Technical University, Jægersborg Alle 1, 2920 Charlottenlund, Denmark

⁷ School of Resource and Environmental Management, Simon Fraser University, Burnaby, BC, V5A 1S6, Canada

⁸ Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 166 Water St., Woods Hole, MA 02543, USA

⁹ CSIRO Oceans & Atmosphere, Castray Esplanade, Hobart, Tasmania, 7001, Australia

¹⁰ Centre Marine Socioecology, University of Tasmania, Hobart, Tasmania, 7001, Australia

¹¹ Food and Agriculture Organization, Via del Terme di Caracalla 00153, Rome, Italy

¹² Northeast Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Narragansett, Rhode Island 02882, USA

¹³ European Commission, DG Joint Research Center, Directorate D – Sustainable Resources, Unit D.02 Water and Marine Resources, Via Enrico Fermi 2749 21027 Ispra, VA, Italy

¹⁴ Department of Marine & Coastal Sciences, Rutgers University, 71 Dudley Rd., New Brunswick, NJ 08540, USA

¹⁵ Institute of Marine Research, P.O. Box 1870 Nordnes, Bergen 5817, Norway

¹⁶ Marine Stewardship Council, Marine House, 1 Snow Hill, London EC1A 2DH, UK

¹⁷ Nupelia-State University of Maringá, Oceanographic Institute, University of São Paulo, Brazil

¹⁸ Galway-Mayo Institute of Technology, Marine and Freshwater Research Centre, Dublin Road, Galway, H91 T8NW, Ireland

¹⁹ Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, USA

²⁰ Conservation International, 2011 Crystal Drive, Suite 500, Arlington, VA 22202, USA

²¹ Norwegian Institute for Water Research, Gaustadalléen 21, 0349 Oslo, Norway

²² Fisheries Resource and Monitoring Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2725 Montlake Blvd. East, Seattle, WA 98112, USA

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Correspondence

Andrew A. Rosenberg, Union of Concerned Scientists, 2 Brattle Square, Cambridge, MA, 02138, USA. Tel: +617-301-8010; Fax: +617-864-9405. E-mail: arosenberg@ucsusa.org

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Abstract

The exploitation status of marine fisheries stocks worldwide is of critical importance for food security, ecosystem conservation, and fishery sustainability. Applying a suite of data-limited methods to global catch data, combined through an ensemble modeling approach, we provide quantitative estimates of exploitation status for 785 fish stocks. Fifty-three percent (414 stocks) are below B_{MSY} and of these, 265 are estimated to be below 80% of the B_{MSY} level. While the 149 stocks above 80% of B_{MSY} are conventionally considered “fully exploited,” stocks staying at this level for many years, forego substantial yield. Our results enable managers to consider more detailed information than simply a categorization of stocks as “fully” or “over” exploited. Our approach is reproducible, allows consistent application to a broad range of stocks, and can be easily updated as new data become available. Applied on an ongoing basis, this approach can provide critical, more detailed information for resource management for more exploited fish stocks than currently available.

Introduction

The overexploitation of wild-capture marine fisheries directly impacts ecosystem health and the food security, livelihoods, and cultural identities of coastal communities worldwide (Garcia & Rosenberg 2010; Costello *et al.* 2012; FAO 2014; Inniss *et al.* 2016). The failure to sustainably manage some fisheries has resulted from many factors including deficient institutional capacity and inadequate data collection, leading to the lack of regular evaluations of stock exploitation status. Quantitative stock assessments are generally only available for relatively “data-rich,” commercially important stocks predominantly fished by developed countries. Recent studies of marine fisheries exploitation status in developed regions of the world have demonstrated that significant progress has been made in managing marine fisheries (e.g., Worm *et al.* 2009; Ricard *et al.* 2012; Fernandes & Cook 2013; Hilborn & Ovando 2014). However, much less is known about many smaller- or lower-valued stocks and stocks fished in both developed and developing regions of the world.

Recent estimates of the current state and future trajectory of marine stocks (Pauly *et al.* 1998; Worm *et al.* 2009; Garcia & Rosenberg 2010; Anderson *et al.* 2012; Costello *et al.* 2012, 2016; Thorson *et al.* 2012; FAO 2014) show that many of the world’s fisheries are below biologically sustainable biomass levels relative to widely accepted reference points. Stocks in data-limited regions are often in even poorer condition than stocks in data-rich regions (e.g., Costello *et al.* 2012). For these important marine resources, managers may at best only have a gross characterization of status, which provides little guidance for new policy action. Here, we apply a consistent, easily repeatable method for estimating more detailed quantitative estimates of stock status across both data-rich and data-limited fisheries.

Currently, there are two primary sources of information used to estimate the status of fish stocks (Thorson *et al.* 2012). The first source comes from abundance estimates derived from analytical stock assessments, developed by fisheries scientists around the world over the last 60 years (Beverton & Holt 1957; Hilborn & Walters 1992; Quinn & Deriso 1999). The data requirements for these sorts of quantitative stock assessment are substantial and are usually restricted to commercial fisheries where there is the analytical capacity to apply complex stock assessment models. There is a comprehensive compilation of fish stock assessments maintained in the RAM Legacy database (<http://ramlegacy.org>, Ricard *et al.* 2012). Most stocks included in this database are from North America, Europe, and developed countries in other regions, while small-scale fisheries and those in developing countries, are underrepresented.

The second source of information used to infer fisheries stock status around the world comes from the United Nations Food and Agriculture Organization (FAO) landings database. The FAO conducts a regular stock status review (FAO 2014) focusing on biological overexploitation as defined in most fishery-related international treaties (e.g., United Nations Fish Stocks Agreement) and classifies stocks into three categories based on expert opinions: underexploited, fully exploited (including stocks that are notionally within 20% above or below the biomass that would support maximum sustainable yield, B_{MSY}), and overexploited. While the FAO stock status review includes more stocks than the RAM Legacy database, therefore, providing a more comprehensive picture of stock status, the methods used to evaluate fisheries are more heterogeneous and less transparent than the stock assessments found in the RAM Legacy database. In particular, the reliance on expert judgment to determine these status estimates means that they are harder to reproduce, even with a systematic methodology (FAO 2014). Similarly, the estimates are categorical, which means they are less quantitative than those from a traditional stock assessment and may provide limited guidance for management decisions.

There are two major ways to improve estimates of individual stock status at the global level: (1) through improvements to the data and technical capacity available to quantitatively assess fisheries at the local level and (2) through further refinements to methodologies that use widely available data (e.g., globally available landings data). The first option requires substantial new resources and expertise. The second option is more immediately attainable and a range of new approaches has recently been developed (e.g., Vasconcellos & Cochrane 2005; Berkson *et al.* 2011; Costello *et al.* 2012; Carruthers *et al.* 2014), which have fewer data requirements than traditional quantitative stock assessments. Here, we focus on these approaches, which require a time series of removals (catches) and basic life history information. This enables us to obtain more complete global coverage of stock status than more data-intensive quantitative stock assessment models, although these methods are still subject to many limitations.

In particular, estimates of exploitation status by catch-only methods can be biased and highly uncertain largely due to required simplifying assumptions. Rosenberg *et al.* (2014) demonstrated the strengths and weaknesses of four catch-only models using a full factorial simulation framework, which evaluated their performance under different combinations of life-history traits, initial depletion, effort dynamics, and length of the catch time series.

A recent development in data-limited stock assessment methods has been to combine the estimates of

Table 1 Numbers of “stocks” (i.e., fished taxa) per FAO statistical area under each data filter applied and regional B/B_{MSY} status estimates

| FAO Area | Original no. of stocks in FAO: 3,630 total | Filter: species-level taxa: 2,621 total | Filter: >20 years and >1,000 t of catch: 785 stocks | Median B/B_{MSY} for stocks in analysis | Percentage of Stocks in analysis with $B/B_{MSY} < 1$: 414 stocks |
|-----------------------------|--|---|---|---|--|
| FAO Stocks | 100% | 69.9% | 66.1% | NA | 52.7% |
| Arctic Sea | 7 | 5 | NA | NA | NA |
| Atlantic, Antarctic | 40 | 29 | NA | NA | NA |
| Atlantic, Eastern Central | 281 | 176 | 63 | 1.05 | 0.44 |
| Atlantic, Northeast | 379 | 269 | 96 | 0.95 | 0.57 |
| Atlantic, Northwest | 211 | 158 | 60 | 0.82 | 0.70 |
| Atlantic, Southeast | 194 | 122 | 33 | 0.84 | 0.76 |
| Atlantic, Southwest | 250 | 161 | 54 | 1.03 | 0.43 |
| Atlantic, Western Central | 247 | 157 | 52 | 0.84 | 0.67 |
| Indian Ocean, Antarctic | 51 | 34 | NA | NA | NA |
| Indian Ocean, Eastern | 219 | 108 | 55 | 1.13 | 0.29 |
| Indian Ocean, Western | 322 | 202 | 40 | 1.14 | 0.33 |
| Mediterranean and Black Sea | 255 | 163 | 51 | 1.02 | 0.49 |
| Pacific, Antarctic | 24 | 13 | NA | NA | NA |
| Pacific, Eastern Central | 190 | 111 | 31 | 1.00 | 0.52 |
| Pacific, Northeast | 110 | 80 | 26 | 0.98 | 0.54 |
| Pacific, Northwest | 223 | 131 | 90 | 0.82 | 0.67 |
| Pacific, Southeast | 203 | 121 | 46 | 0.91 | 0.59 |
| Pacific, Southwest | 209 | 126 | 38 | 1.02 | 0.47 |
| Pacific, Western Central | 215 | 96 | 50 | 1.10 | 0.34 |

Median B/B_{MSY} and probability of B/B_{MSY} pertain to stocks with species-level taxonomic resolution and with catch time series longer than 20 years and more than 1,000 t of annual median catch. The first value in the last column is the ‘percentage of all stocks across all regions with $B/B_{MSY} < 1$ ’ in analysis.

exploitation status, B/B_{MSY} , where B is current stock biomass and B_{MSY} is the biomass estimated to result in maximum sustainable yield from multiple catch-only models in a superensemble (Anderson *et al.* 2017 and Supporting Information). A superensemble (Krishnamurti *et al.* 1999) is “super” because it combines the estimates from multiple models by calibrating them on a dataset with known or trusted properties—in this case the simulated dataset from Rosenberg *et al.* (2014). Estimates from multiple models, here of B/B_{MSY} , are calibrated to known values via a regression model. This allows for both weighting the individual models based on their accuracy and exploiting the covariance between individual models to generate more accurate and less biased estimates of B/B_{MSY} . The superensemble approach is common in the weather and climate forecasting where, for example, it has been used to improve predictions of wind and precipitation in Asian monsoons (Krishnamurti *et al.* 1999) and improve global surface temperature forecasts (Berliner & Kim 2008).

Here, we quantitatively estimate current biomass of global fisheries relative to B_{MSY} , for stocks in the FAO database. We aim to provide a more comprehensive assessment of global and regional stock status by implementing a superensemble approach to combine status estimates obtained from four different catch-only models.

Methods

We applied the four catch-only methods tested in Rosenberg *et al.* (2014) to 785 FAO stocks, subject to the criteria described in Table 1. We applied one empirical model, the panel regression approach (PRM) developed by Costello *et al.* (2012), and three mechanistic models, which all assume the same population dynamics, but make different assumptions about uncertainty and the dynamics of fishing effort:

- (1) The catch-MSY (C_{MSY}) model of Martell & Froese (2012), which includes assumptions about resilience.
- (2) The catch-only-model with sampling-importance resampling (COMSIR) developed by Vasconcellos & Cochrane (2005).
- (3) The state-space catch-only model (SSCOM) developed by Thorson *et al.* (2013).

Further details on the models are presented in the Supporting Information and Table S1. To obtain global estimates of stock status for all stocks, we combined the estimates from the four models using a superensemble (Supporting Information). The superensemble method goes well beyond simply averaging across individual method estimates. Our superensemble calibrated a combination of the four individual model estimates of B/B_{MSY} via a

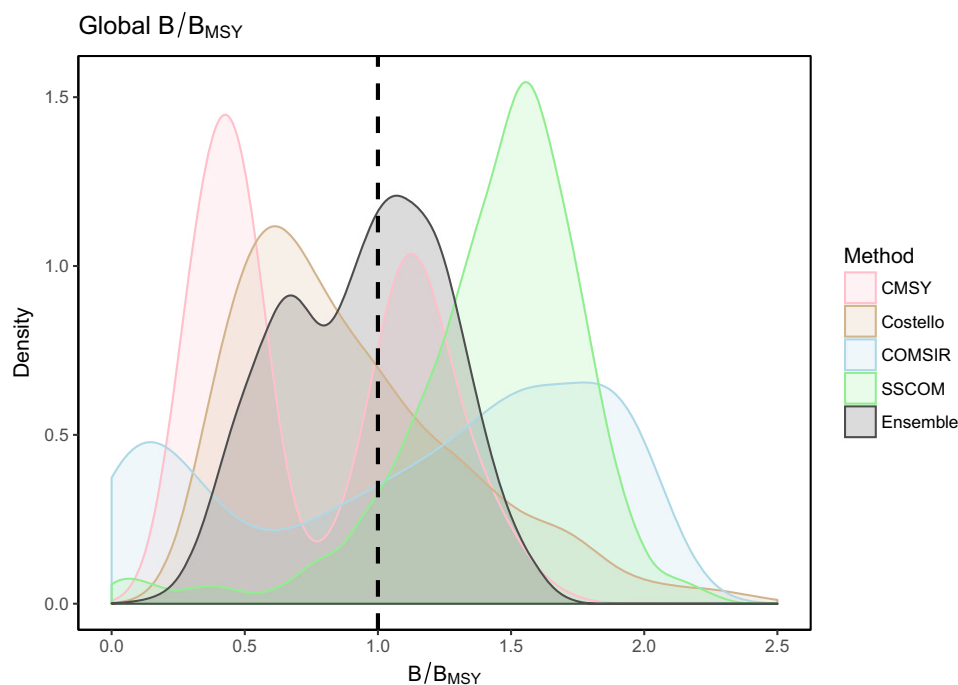


Figure 1 Global distribution of B/B_{MSY} status for 785 analyzed stocks estimated by each data-limited method and the superensemble approach.

random forest method (Breiman 2001) fitted to a dataset of nearly 6,000 simulated fish stocks with known B/B_{MSY} (Anderson *et al.* 2017). Random forests are a machine learning approach that allow for nonlinear relationships between the predictors (the individual model estimates) and the response (the superensemble estimate) and interactive effects between the individual model estimates while being relatively robust to overfitting (Breiman 2001, Figure S1). Previous analyses showed that a random forest superensemble consistently had the best or among the best performance characteristics when compared to other possible superensemble regression models (Anderson *et al.* 2017). The superensemble outperformed the individual models in cross-validation on simulated data with, for example, a median absolute proportional error in B/B_{MSY} of 0.32 compared to 0.42–0.56 for the individual models (Anderson *et al.* 2017).

Estimating stock status

We computed density plots to explore the distribution of stock status globally and within each FAO statistical region through 2013. We also compared our global estimates of status to other global estimates of status (Table S2). Additionally, we compared our approach to traditional stock assessment estimates by matching stocks in the RAM Legacy database with those in the FAO catch

database where possible. In some cases, there are multiple RAM stocks that match a single “stock” from the FAO database (e.g., tuna stocks or Atlantic cod). In these cases, we matched the RAM stock status estimate to each FAO region to which it could logically correspond. We also compared the status estimates for RAM Legacy assessed stocks with the status of previously unassessed stocks from the FAO catch database.

Results

Global patterns

At the aggregate global level, the median B/B_{MSY} status of exploited stocks is 0.97, such that 414 stocks (52.7%) are estimated to be below the B_{MSY} reference point based on a superensemble of data-limited models (Table 1, Figure 1). Of these, 265 (64% of those below B_{MSY}) are estimated to be below 80% of the B_{MSY} level, which is the FAO (State of World Fisheries and Aquaculture) SOFIA definition of “overexploited.” Therefore, for the 149 stocks between B_{MSY} and 80% of B_{MSY} , significant yield may be foregone, but the current advice under FAO is that they are fully exploited, and unfortunately, no real policy change would be called for.

The superensemble was employed to deal with individual biases in each of the models, but underlying

patterns could still be detected. For example, in addition to a primary mode slightly above B/B_{MSY} (Figure 1), the superensemble estimated many stocks to have a B/B_{MSY} below 1, producing a second mode at $B/B_{MSY} = 0.65$. We investigated the distributions of the underlying data-limited models to understand the cause of this bimodality and found that the C_{MSY} and COMSIR models were mainly responsible for this pattern in the estimates (see Supporting Information section *S1.5, Sensitivity analyses*, Figure S2). In a sensitivity analysis for C_{MSY} , we found that the bimodality was due to the prior distributions assigned to the final year depletion, which are based on the catch trajectories (Figure S3). This bimodality carries forward into the superensemble estimates. However, the overall results do not change if each model is removed individually from the superensemble (Figure S2). The SSCOM method frequently estimated stocks to be underexploited relative to B_{MSY} (Figure 1). The ensemble partly accounts for potential systematic bias through the relative weightings, but these estimates of higher biomass still affect the overall pattern.

Regional patterns

For 8 of the 15 FAO regions, over 50% of the stocks were estimated to be below B_{MSY} (Table 1, Figure 2). This is particularly striking in the northern hemisphere regions, where most stocks are estimated to be below the biomass that would support MSY (Figure 2). The exception to this pattern was the Mediterranean and the Black Sea, where more stocks were above B_{MSY} . Similarly, the majority of stocks in the South Atlantic and South Pacific regions were below B_{MSY} .

In the Atlantic, all of the FAO areas have a median value for estimated stock status below B_{MSY} , except eastern-central Atlantic and southwest Atlantic (Table 1) but with substantial variation in status among stocks within each region. Similarly, the northeast Pacific, northwest Pacific, and southeast Pacific regions have a median estimated status below B_{MSY} while the southwest Pacific, eastern-central Pacific, and western-central Pacific have a median status at or above B_{MSY} (Table 1). The eastern and western Indian Ocean regions are in better condition with only around one-third of the stocks below B_{MSY} . The superensemble estimated that stocks in the western Indian Ocean have the highest median status of all FAO areas (median = 1.14). The long tails on the distribution of stock status for all regions indicates that there are some stocks that are only lightly exploited, and others heavily exploited, with regard to recent catch trends.

Within all of the regions a substantial number of stocks are estimated to be within 20% below B_{MSY} such that

they would be classed as “fully exploited” in previous studies (Figure 2).

Comparisons with other methods

Direct comparison of the ensemble estimates for stocks that are also included in the RAM Legacy database (i.e., a comparison of assessed RAM to assessed ensemble stocks) show that for most regions our methods are slightly more pessimistic concerning stock status than analytical stock assessments (Figure S4). This is also the case when comparing estimates of the status of assessed stocks contained in the RAM Legacy database with estimates using the ensemble method for those stocks without analytical assessments contained in the FAO data we utilized (Figure 3; i.e., a comparison of assessed RAM to unassessed stocks). However, many more stocks can be considered using the catch-only methods than can be analytically assessed by traditional methods.

Discussion

Our results suggest that the overall status of fisheries globally is near the biomass capable of producing maximum sustainable yield (Table 1). However, according to the FAO SOFIA definitions and methodology of expert opinion, 36% of these stocks would have been classified as “fully exploited,” rather than “overexploited.” From a manager’s point of view, perhaps no action would be needed to improve management of a fully exploited stock, under the FAO SOFIA categorical status assessments. However, the more quantitative estimates provided in this study highlight the possible need for management action for many of these taxa.

Our results overall are broadly consistent with other studies that have attempted to provide a global picture of fishery status using a variety of methods (Table S2). A key advantage of using this approach is that it does not require a wholesale change in estimation method each time a new method becomes available. Our methodology can be easily repeated as new information becomes available, it is objective, and can incorporate new methods as part of the superensemble. Combining estimates from different methods in a consistent reproducible manner may provide more stability in the advice for managers. Additionally, the superensemble approach is more robust than typical model averaging because the superensemble does not simply average across individual method estimates of status. Instead, it uses those estimates as input to a new statistical model that is then trained on known status, which is a key advantage of this approach.

Recent requirements to set scientifically based catch limits in several countries (Rosenberg *et al.* 2009) and

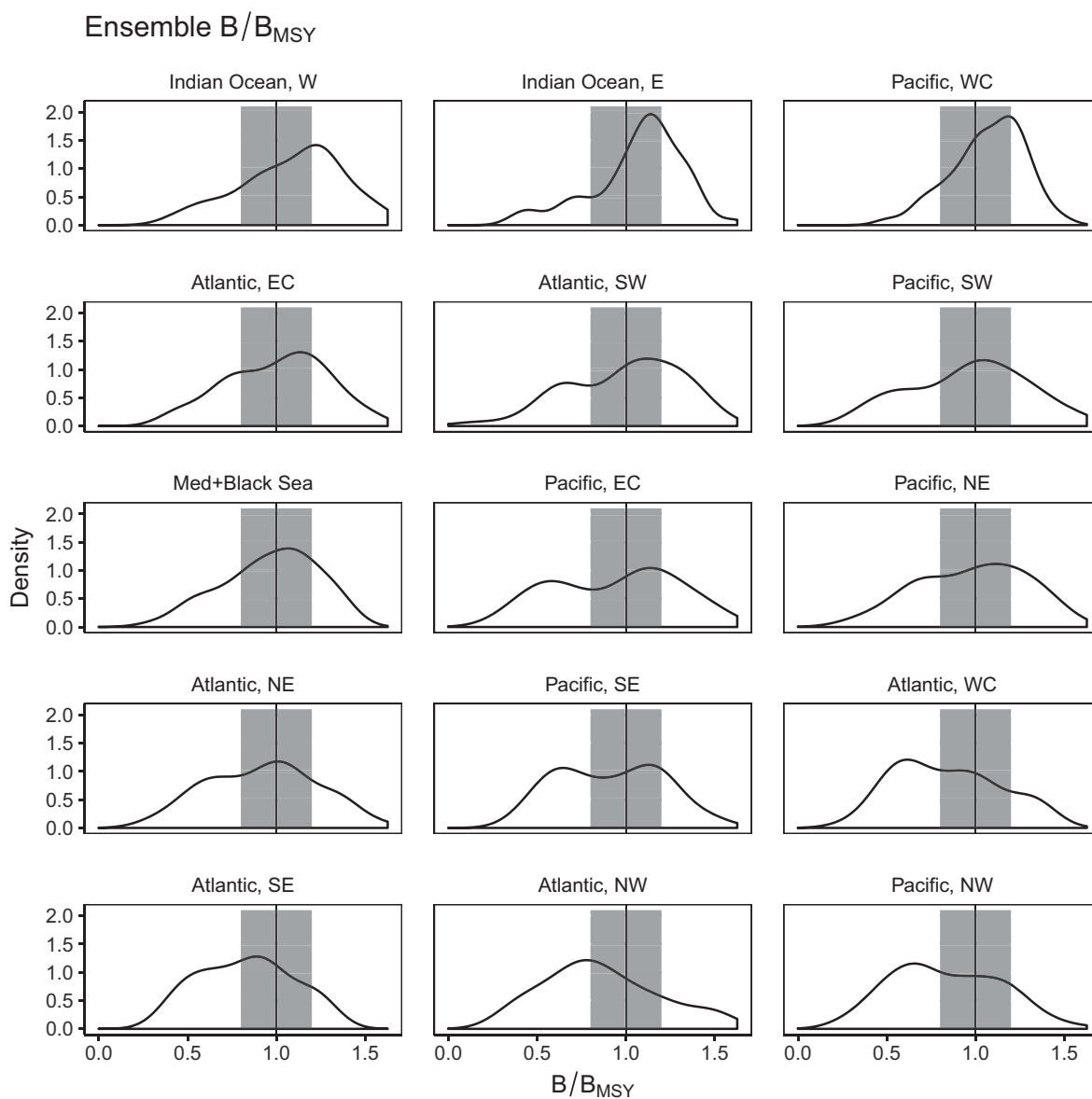


Figure 2 Regional distribution of B/B_{MSY} status for analyzed stocks estimated by the superensemble approach. Black vertical lines indicate $B/B_{MSY} = 1$ with dark gray bars indicating $\pm 20\%$ around this point.

growing consumer demand for sustainably managed seafood products (Gutierrez *et al.* 2012) have spurred an emerging field of methods for estimating overfishing thresholds and setting catch limits for stocks with limited data (e.g., Berkson *et al.* 2011; Carruthers *et al.* 2014). Stock status is not the sole input guiding management, but it should provide a key indication of whether a stock is in a safe operating space. Indeed, there is broad consensus among management authorities worldwide that managing stocks toward values within the range of MSY is an important guidepost for achieving fisheries sustain-

ability as shown by the UN Fish Stocks Agreement under the Law of the Sea.

Often, the status of quantitatively assessed stocks is used to infer the status of unassessed stocks. However, several studies (Worm *et al.* 2009; Costello *et al.* 2012, 2016; Ricard *et al.* 2012) have shown that this inference may be seriously flawed. In consequence, continued overexploitation of unassessed stocks, often by small-scale fisheries, has led to significant loss in benefits to people (Inniss *et al.* 2016). Our results are generally more pessimistic regarding stock status than full stock

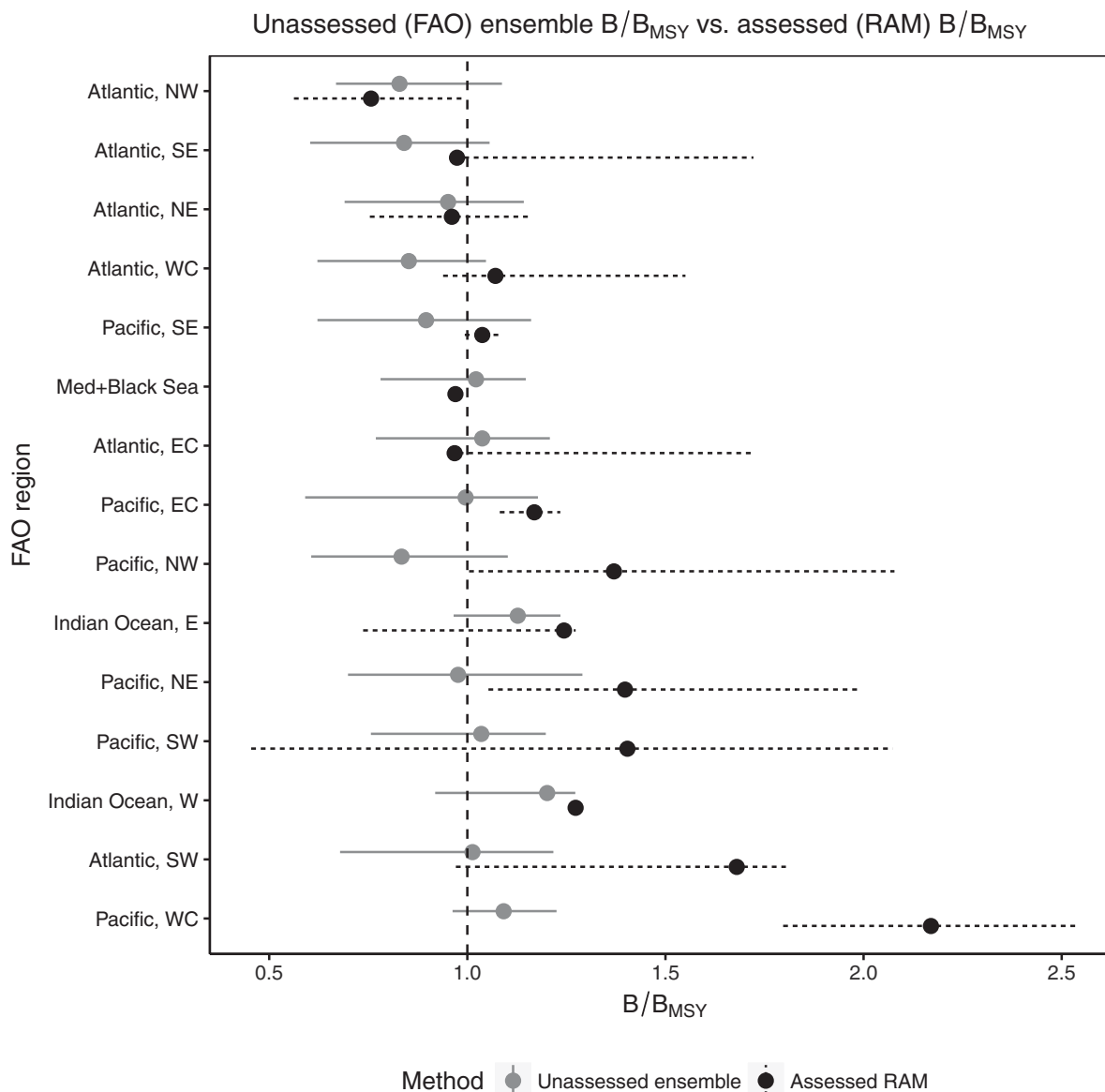


Figure 3 Comparison of B/B_{MSY} estimates by FAO area for unassessed versus assessed stocks. Assessed B/B_{MSY} was calculated as the median of the B/B_{MSY} estimates from stocks in the RAM Legacy database. Unassessed B/B_{MSY} was calculated as the median of the B/B_{MSY} estimates determined by the superensemble approach for all stocks without a RAM database analog. The estimates are ordered by decreasing median assessed B/B_{MSY} estimates.

assessments (Figures 3 and S4). These differences may be due to better management of assessed stocks as well as any methodological differences, though ascribing the effect to either cause is not a simple matter. We recognize that our methods and all stock assessments are limited by the time series of catch information available and the dynamics of that catch. If large declines in abundance occurred prior to the start of the data series for a given stock, an incorrect impression of stock status will be obtained.

Although our approach provides an important step toward quantitative and replicable estimates of stock

status for a larger set of fished stocks than has been the case in the past, there are still many limitations to using this information for stock-specific or even regional advice. These include the high variability of the estimates, the need for longer time series of data, limited life history information for many stocks, and the difficulties of assigning prior distributions, particularly given the problem of bimodality in some of the distributions of our estimates. The simulation testing described in the Supporting Information and Rosenberg *et al.* (2014) can help explore these issues but does not resolve them. There are

fundamental data limitations that are inherent to the problem we are addressing. In particular, the superensemble method as applied here is trained on simulation results, and therefore may not capture other features in the dynamics of real populations including the impact of factors such as climate change. Key potential areas for future improvement include better informed prior distributions for final status in different regions, including priors that account for the characteristics of fishery resources in different regions (Cope *et al.* 2015), inclusion of existing survey and fishery data (Thorson *et al.* 2012), and evaluation of how well these models inform management strategies for data-limited fisheries.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Table S1. Summary of variables used in the modified panel regression model (mPRM).

Table S2. Comparison of estimates of stock status from various recent studies illustrating the different definitions and numbers of "stocks" evaluated.

Figure S1. Individual model and spectral density covariate contributions to the random forest superensemble (random forest partial dependence plots).

Figure S2. Violin plots showing median, interquartile range and distribution of B/B_{MSY} estimates from ensemble models that exclude each model in turn.

Figure S3. Illustration of the variability in the B/B_{MSY} estimates from CMSY when the priors on initial and final depletion are varied, with an example of stocks from the Pacific Southwest and Pacific Northeast FAO regions.

Figure S4. Comparison of B/B_{MSY} estimates by FAO area for assessed RAM stocks and assessed stocks in the ensemble.

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