Fisheries management impacts on target species status

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Edited by Juan Carlos Castilla, Universidad Catolica de Chile, Santiago, Chile, and approved November 17, 2016 (received for review June 18, 2016)

Fisheries management systems around the world are highly diverse in their design, operation, and effectiveness at meeting objectives. A variety of management institutions, strategies, and tactics are used across disparate regions, fishing fleets, and taxonomic groups. At a global level, it is unclear which particular management attributes have greatest influence on the status of fished populations, and also unclear which external factors affect the overall success of fisheries management systems. We used expert surveys to characterize the management systems by species of 28 major fishing nations and examined influences of economic, geographic, and fishery-related factors. A Fisheries Management Index, which integrated research, management, enforcement, and socioeconomic attributes, showed wide variation among countries and was strongly affected by per capita gross domestic product (positively) and capacity-enhancing subsidies (negatively). Among 13 management attributes considered, three were particularly influential in whether stock size and fishing mortality are currently in or trending toward desirable states: extensiveness of stock assessments, strength of fishing pressure limits, and comprehensiveness of enforcement programs. These results support arguments that the key to successful fisheries management is the implementation and enforcement of science-based catch or effort limits, and that monetary investment into fisheries can help achieve management objectives if used to limit fishing pressure rather than enhance fishing capacity. Countries with currently less-effective management systems have the greatest potential for improving long-term stock status outcomes and should be the focus of efforts to improve fisheries management globally.

resource management | stock assessment | fisheries enforcement | fishery subsidies | marine conservation

Studies in recent years have yielded divergent views of the status of marine populations and recommendations for how the world's fisheries should best be managed (1–6). Although scientists are generally unanimous in calling for stronger management, some proposed solutions involve widespread establishment of marine reserves (4), whereas others involve greater investment in management structures, such as stock assessments and enforcement of catch or effort limits (6–8), or in reforms of fishing fleets toward rights-based management (1). Fisheries management systems involve a wide array of policies and regulations to meet conservation and socioeconomic objectives (5, 9, 10). These aspects vary within and among countries, target species, and fishing fleets. Given the great diversity in fisheries management systems, it has not been clear which specific management characteristics lead to success across systems, but it seems increasingly clear that successful attributes involve the capacity to limit fishing pressure (1, 2, 6–8, 11).

We used expert surveys to characterize attributes of research, management, enforcement, and socioeconomics of fisheries management systems in 28 major fishing countries that collectively account for >80% of global total catch. We specified survey criteria as to whether these attributes play an effective role in limiting fishing pressure for target species. We quantified geographic, economic, and fishery-related influences on the management system, and in turn quantified how management attributes individually affect recent status and trends of stock size and fishing mortality.

Survey responses from fishery experts showed high variability among 28 countries in research, management, enforcement, and socioeconomics dimensions of management systems, as well as in stock status (Fig. 1). Values for each dimension are weighted means of several criteria, with answers of 0, 0.5, or 1 reflecting the degree to which a criterion was met for each of 10 species in the country. Survey responses were correlated among research, management, enforcement, and socioeconomics dimensions ($r = 0.66$–0.82) (Fig. S1*A*) and were averaged with equal weighting to obtain a Fisheries Management Index (FMI) for each returned survey ($n = 191$) (Fig. S2*A*), which were subsequently aggregated by country. FMI is an indicator of the effectiveness of management systems at meeting objectives. Survey responses were weighted by confidence scores in answers provided for individual questions and self-assigned level of expertise; sensitivity analyses considered alternative weighting schemes. Countries with high FMI values included the United States, Iceland, Norway, Russia, New Zealand, South Africa, and Canada; Myanmar, Thailand, Brazil, China, and Bangladesh had the lowest FMI values among countries (Fig. 1).

To explain variation in country FMI values, we considered the background and self-assigned expertise of respondents (Fig. S3), as well as geographic, economic, and fishery-related factors (*SI Materials and Methods*, Fig. S4, and Table S1). Of 12 numerical covariates considered in a mixed-effects model, three of the most influential factors involved monetary investment into management systems. Per capita gross domestic product (GDP) had the strongest effect on FMI (Fig. S5*A*), with mean FMI values ranging from 0.42 to 0.83 at the lowest and highest values of per capita GDP, respectively (Fig. 2 and Fig. S6). This finding suggests that countries with greater wealth generally have greater capacity for investment in management, although many other factors will also contribute to the extent of potential investments. Second, countries with greater reported catches in exclusive economic zones (EEZs) had greater FMI, suggesting that with greater landed value derived from fisheries resources, countries invest more to

Significance

There is broad public interest in the health of our oceans and marine life at local, national, and international levels. In recent years there has been increasing concern about whether our fisheries can sustainably provide seafood without overfishing fish stocks. Several papers have described the global status of fish populations (i.e., their abundance and exploitation rates) and have hypothesized influences of fisheries management, but this report is unique in being a comprehensive analysis of how specific management attributes (which are numerous and operate simultaneously) affect population status across oceans, countries, and taxonomic groups. Our report integrates management policies and population ecology to assess sustainable harvesting outcomes of target species in marine fisheries; results have important global food security implications.

Author contributions: M.C.M., E.P., M.E., and R.H. designed research; M.C.M., E.P., M.E., and R.H. performed research; M.C.M. analyzed data; and M.C.M. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1609915114/-/DCSupplemental.

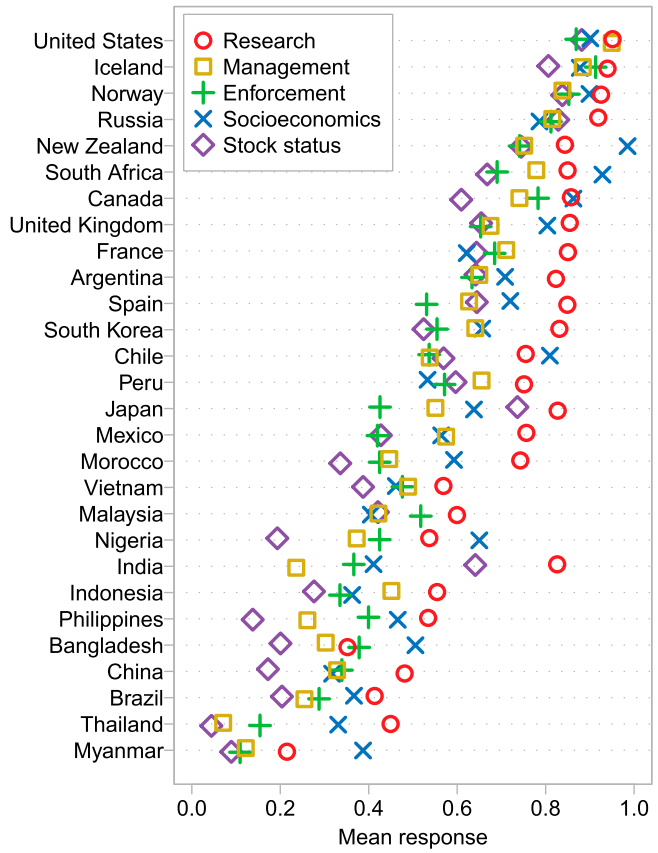

Fig. 1. Summarized survey answers by dimension and country. Responses are weighted by both respondent expertise and confidence in individual answers provided, and are adjusted for observed differences among respondent background categories. Countries (n = 28) are sorted by FMI values, a composite of research, management, enforcement, and socioeconomics dimensions.

better manage those resources. Third, the ratio of beneficial ["good" (12)] subsidies (i.e., investment in research, management, and enforcement) to landed value positively influenced the FMI, as expected. In contrast, the ratio of capacity-enhancing ["bad" (12)] subsidies to landed value negatively influenced FMI (Fig. 2); this association was the strongest of all predictors, with the exception of per capita GDP. The strong association of capacity-enhancing subsidies with poor management outcomes is consistent with concerns raised previously (3, 12–14).

The proportion of landings recorded as miscellaneous "not elsewhere included" species groups in the United Nations Food and Agriculture Organization (FAO) landings database was a negative indicator of FMI (Fig. 2 and Figs. S5*A* and S6). Countries with more developed management systems are often better prepared to collect landings data at a higher taxonomic resolution, but this also highlights the correlative nature of these data. Respondent background categories were treated as random intercepts; government managers and scientists tended to give higher FMI (conditional modes, 0.70–0.72), whereas individuals from environmental nongovernmental organizations (NGOs) and external organizations, such as the FAO, tended to give a lower FMI (0.63–0.64) than respondents from the fishing industry and from universities (0.65–0.68), which were intermediate (Fig. 2 and Fig. S5*B*). All respondents providing answers for countries >35° absolute latitude had an FMI > 0.5, whereas values for countries 0–35° were more variable (Fig. 2). Tropical fisheries are more often mixed-species fisheries compared with temperate fisheries, presenting additional challenges for research and management (5, 15). The full model with 12 fixed-effect covariates and random intercepts for respondent background explained 61% of the variability in logit-transformed FMI values. Alternative weighting and adjustment schemes were considered (Fig. S7) and observed results were robust to alternatives (Figs. S1*B* and S2*B* and Table S2).

We quantified effects of 13 fisheries management attributes on four stock status criteria: current biomass status, trend in biomass, current fishing mortality, and trend in fishing mortality (*SI Materials and Methods*). These four criteria involved management targets, consisting of whether biomass or fishing mortality were currently in or trending toward desirable states (Dataset S1). Random forest analyses suggested that 3 of the 13 management attributes considered were particularly important, with strong positive influence: the extensiveness of stock assessments influenced all four stock status variables; the strength of fishing pressure limits influenced the current status and trend in fishing mortality; and the comprehensiveness of enforcement programs influenced the trends in biomass and fishing mortality (Fig. 3). This analysis supports arguments that a crucial key to successful fisheries management is the implementation of science-based limits on catch or fishing effort coupled with adequate enforcement of those limits (6–8, 11, 16). Management attributes with weaker influence on stock status criteria for target species included body size or age data, landings data, and protection of sensitive habitats; influence of other management attributes was intermediate (Fig. 3).

Of the four stock status measures considered, trend in fishing mortality may be the best indicator of future stock status. Trends in fishing pressure were positively associated with the level of transparency and stakeholder involvement in the management process and with the absence of capacity-enhancing subsidies (Fig. 3). This finding suggests that greater stakeholder engagement within governance frameworks can improve sustainable harvesting outcomes for targeted species, consistent with arguments from previous studies (15, 17, 18).

Characterizing fisheries management systems across countries is challenging considering the wide variety of management approaches used. Relative FMI values among countries were similar to those of some related studies but contrast sharply with others. Pitcher et al. (19) evaluated many of the same countries in their adherence to principles, indicators, and steps toward implementation of ecosystem-based fisheries management (EBFM). Strong correspondence between EBFM performance and FMI values was observed (r = 0.63–0.70; see Fig. 4*A* for the aggregate measure), except for Russia, which had high FMI but low EBFM performance. The expertise required to complete FMI surveys meant that respondents typically completed a survey for only the country in which they work; we cannot rule out self-scoring biases that may differ among countries. Our estimates for Russia were in line with those of Mora et al. (20), who also used surveys to characterize several aspects of fisheries management across countries. Overall correspondence with FMI values was lower (r = 0.44), partly because of China having a low FMI but having the highest value of management effectiveness in Mora et al. (20) among the countries that overlapped between studies. There was little correlation (r = 0.15) between country FMI and the Food Provision Index from Wild Capture Fisheries (a component of the Ocean Health Index, OHI), which assesses the amount of wild-caught seafood that can be sustainably harvested (21) (Fig. 4*A*).

Observed differences among studies partly reflect the variety of criteria included in each overall index. Our survey criteria focused primarily on target species, whereas EBFM criteria (19) placed greater emphasis on ecosystem-level values, structure, function, and change (Table 1 and Fig. S8). Criteria strongly overlapped between studies in some attributes (fishery management plan, protection of sensitive habitats, community involvement), but other attributes were only considered in one or the other study depending on overall focus. Some of our criteria in other attributes (limits on fishing pressure, capacity to adjust fishing pressure, fisheries

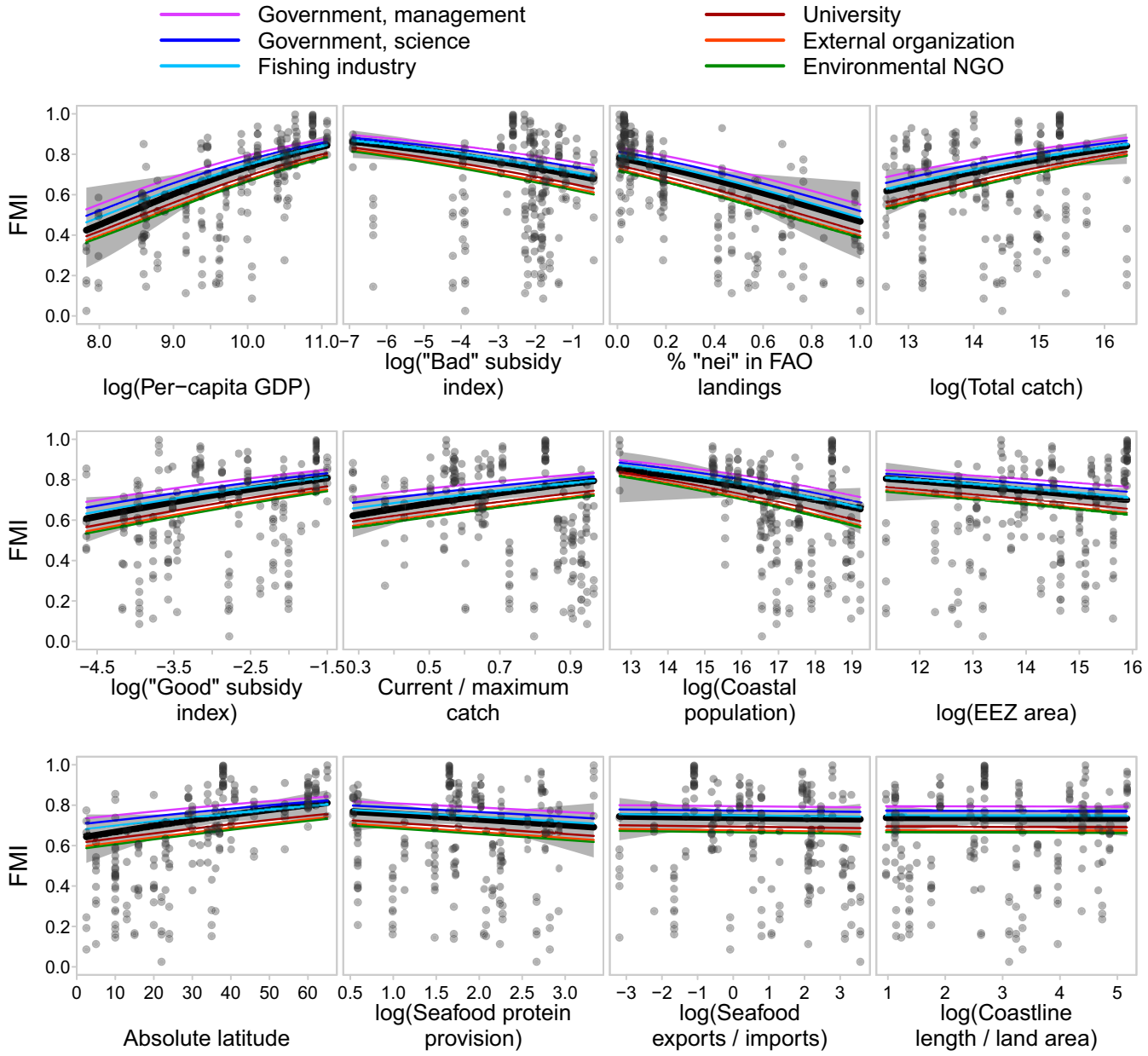

Fig. 2. Influences of country-level factors on FMI values. Data points show FMI values for each respondent and country (n = 191 surveys), weighted by confidence in individual answers provided. Black lines show overall best fits with 95% confidence bands in gray, weighted by respondent expertise. Best-fit lines for respondent background categories are overlaid. Panels are sorted left to right by absolute values of t-statistics for predictor variables.

enforcement) strongly overlapped with survey questions for management effectiveness (20) (Table 1 and Fig. S8). Although our study and that of Mora et al. (20) both focused on the effectiveness of fisheries management systems and covered similar topics, the correspondence between index values for overlapping countries was less than expected. The wording of survey criteria may partly explain differences: our criteria specified not only whether various management instruments were in place, but whether they were effective at limiting fishing pressure. Differences may also arise from the sampling unit at which questions were posed: answers to our survey criteria were given for specific target species, whereas answers to questions in Mora et al. (20) were given for the entire country; the stock-specific approach may simplify responses. Overall aims and attributes covered differed substantially between our country FMI and the Food Provision Index from Wild Capture Fisheries (21) (Table 1). The latter index consists primarily of the OHI "Fisheries Status" component; this component more closely resembles our stock status attribute, which is not included in the calculation of FMI values to better distinguish management characteristics from their effects on target species. A significant advantage of the FMI survey over previous studies is that data were collected for individual fisheries. In this paper we aggregate results to the country level, but more detailed analyses will consider differences among taxa.

There was little correlation between the present study's stock status values and either the OHI Fisheries Status (21) or the Environmental Performance Index (EPI) "Fish Stocks" measure [from Sea Around Us Project (22)] of the fraction of stocks overexploited or collapsed (inverted in Fig. 4*B*, such that increasing values represent increasingly desirable states). These other measures rely on catch-based methods, which have received recent criticism for poorly representing stock status (23, 24). Answers provided in FMI expert surveys about current status and trends of stock size and

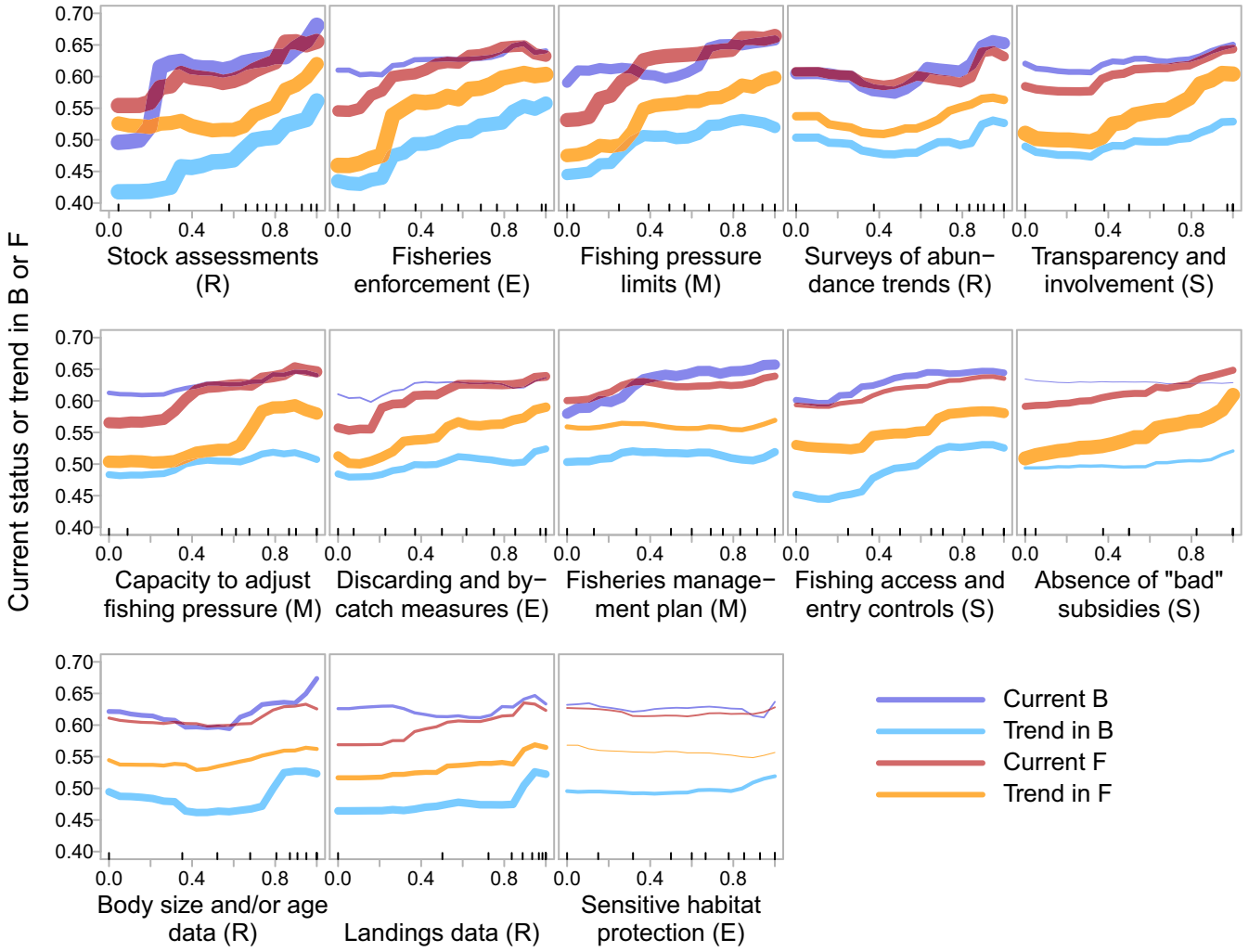

Fig. 3. Effects of fisheries management attributes in research (R), management (M), enforcement (E), and socioeconomics (S) dimensions on the current status and trends of biomass (B) and fishing mortality (F). Higher values of response variables indicate increasingly desirable states or trends toward desirable states with respect to management targets (i.e., high values of F do not indicate $F > F_{MSY}$, but rather $F \leq F_{MSY}$). Line thicknesses are proportional to predictor variable importance scores from random forest analyses for each response variable. Panels are sorted left to right by the sum of standardized variable importance scores across all four response variables. Response and predictor variables are weighted by confidence in individual answers. All variables range from 0 to 1, but vertical axes are truncated. Rug marks at bottom show deciles of predictor variable values.

fishing mortality reflect the opinions of individuals most familiar with national fisheries management systems and their managed fish stocks.

The high diversity of fisheries management systems mirrors the diversity across regions, target species, and fishing fleets. There is no single management strategy or tactic that will yield success in

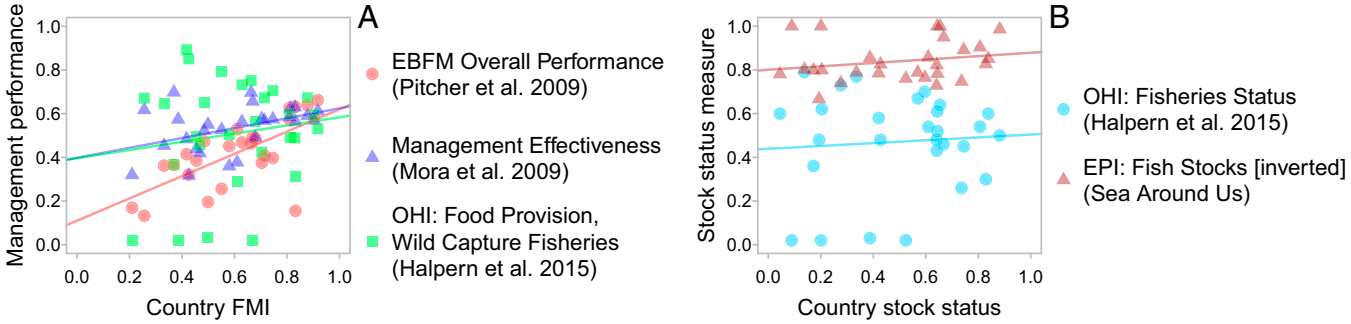

Fig. 4. Comparison of country FMI or stock status values with published indices of fisheries management or status. (*A*) EBFM overall performance [Pitcher et al. (19)] ($r = 0.68$), overall management effectiveness in EEZs [Mora et al. (20)] ($r = 0.44$), and OHI–Food Provision from Wild Capture Fisheries [Halpern et al. (21)] ($r = 0.15$) compared with FMI, by country. (*B*) OHI–Fishery Status (21) ($r = 0.07$), and EPI–Fish Stocks, using Sea Around Us Project estimates (22) ($r = 0.21$, inverted such that greater values suggest lower percent overfished stocks) compared with stock status values ($n = 28$). Best-fit lines are shown for each comparison.

Table 1. Overlap of fisheries management and related attributes considered in the present study and three previous studies

Dimension	Attribute	Fisheries Management Index	Ecosystem-based management [Pitcher et al. (19)]*	Management effectiveness in EEZs [Mora et al. (20)]†	Wild capture fisheries food provision (Halpern et al. (21)]‡
Research	Landings data	3		1	
	Body size or age data	3		1	
	Surveys to monitor trends in abundance	3	2 **(1)**		
	Stock assessments	5	1	3 **(1)**	
	Skills and training in fishery science			1	
Management	Fishery management plan	3	5 **(2)**		
	Effective limits on fishing pressure	3	2 **(1)**	2 **(2)**	
	Capacity to adjust fishing pressure	3	2 **(1)**	3 **(3)**	
	Number or proportion of species regulated			1	
	Recreational fishing extent and regulations			6	
	Artisanal fishing extent and regulations			5	
Enforcement	Fisheries enforcement	4		4 **(2)**	
	Protection of sensitive habitats	3	3 **(3)**		4
	Discarding and by-catch measures	3	1 **(1)**	2 **(1)**	
	Frequency of corruption and bribery			1	
Socioeconomics	Controls on access and entry into fishery	3		1	
	Transparency and community involvement	3	9 **(3)**	1 **(1)**	
	Subsidies	2	1	1 **(1)**	
	Pressures to increase catch			1	
	Other overcapacity			2	
Stock status	stock status	5	1 **(1)**	1	1 **(1)**‡
Other	Ecosystem structure, function, and change		3	1	
	Ecosystem values		3		
	Ecological risk assessment		1		
	Research and information priorities		1		
	Fisher education and training		1		
	Fishing methods			8	4
	Foreign fleet agreements			1	
	Pollution and environmental variables			1	2
	Alien species and mariculture escape				2
	Worldwide Governance Indicator				2
	IUCN assessments				1

The number of criteria, survey questions or component variables associated with each attribute is listed for each study. Boldfaced numbers in parentheses for previous studies indicate the number of criteria, questions, or variables that strongly overlap with FMI survey criteria. Individual criteria or survey questions from previous studies may be associated with more than one attribute category of the present (FMI) study. See Fig. S8 for further details of overlap.

*Criteria include 5 EBFM principles, 6 EBFM indicators, and 12 EBFM implementation steps (Fig. S8), which together contribute to an overall performance score (19).

†Most of 22 survey questions (mainly with the exception of fishing methods, recreational fishing, and artisanal fishing) contribute to an overall management-effectiveness score (20).

‡Component variables of status (1 component), pressures (12 components), and resilience (5 components) contribute to this OHI goal (21). Wild-capture fisheries food provision scores are weighted heavily toward the Fisheries Status component, which is associated with the stock status attribute of the present study.

all cases, but the findings presented here suggest broad support for the importance of establishing and enforcing science-based catch or effort limits to the sustainable harvesting of marine populations. Countries in which management systems are currently less effective at meeting conservation and socioeconomic objectives have the greatest potential for improving long-term stock status outcomes and should be the focus of efforts to improve fisheries management globally.

Materials and Methods

Fishery experts from diverse backgrounds were invited to complete a survey characterizing the management systems for 10 species in their country of familiarity. Institutional review board approval was not required for these surveys and Respondents were given the option of being acknowledged for their contribution or remaining anonymous; see *SI Extended Acknowledgments* for a list of expert survey participants. A total of 191 surveys were completed by 182 individual respondents; the number of returned surveys per country ranged from 2 to 17 (mean = 6.8). This range represented an overall 41% response rate from 467 invitations originally extended. Survey responses for research, management, enforcement, and socioeconomics dimensions were aggregated into a Fisheries Management Index. Variation among countries in the FMI was attributed to geographic, economic, and fishery-related influences using mixed-effects models. In turn, the influence of management-related attributes on the current status and trends in stock abundance and fishing pressure were evaluated using random forests. See *SI Materials and Methods* for details and Dataset S1 for the survey file listing specific attributes and criteria within each dimension.

ACKNOWLEDGMENTS. We thank respondents for completing fisheries management surveys. Respondents wishing to be acknowledged are listed in the *SI Extended Acknowledgments*, and we equally thank those wishing to remain anonymous. We also thank C. Anderson, P. Mace, C. de Moor, A. Parma, T. Branch, T. McClanahan, Y. Ye, H. Kurota, F. Abdelmalek, R. Pelc, J. Wilson, C. Szuwalski, C. Costello, M. De Alessi, L. Viggiano, and J. Banobi for

providing comments on the initial survey template and conducting trial surveys; K. Ono for translating the survey into French; three anonymous reviewers for providing helpful comments; and members of the National Center for Ecological Analysis and Synthesis–Science for Nature and People Partnership group "Measuring the Status of Fisheries and Factors Leading to Success" for comments on analyses. Support for this work was provided by the David and Lucile Packard Foundation and by the Walton Family Foundation.

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