AMBIO 2013, 42:910–922
DOI 10.1007/s13280-013-0447-x

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Exploring Patterns of Seafood Provision Revealed in the Global Ocean Health Index

Kristin M. Kleisner, Catherine Longo, Marta Coll, Ben S. Halpern, Darren Hardy, Steven K. Katona, Frédéric Le Manach, Daniel Pauly, Andrew A. Rosenberg, Jameal F. Samhouri, Courtney Scarborough, U. Rashid Sumaila, Reg Watson, Dirk Zeller

Abstract Sustainable provision of seafood from wild-capture fisheries and mariculture is a fundamental component of healthy marine ecosystems and a major component of the Ocean Health Index. Here we critically review the food provision model of the Ocean Health Index, and explore the implications of knowledge gaps, scale of analysis, choice of reference points, measures of sustainability, and quality of input data. Global patterns for fisheries are positively related to human development and latitude, whereas patterns for mariculture are most closely associated with economic importance of seafood. Sensitivity analyses show that scores are robust to several model assumptions, but highly sensitive to choice of reference points and, for fisheries, extent of time series available to estimate landings. We show how results for sustainable seafood may be interpreted and used, and we evaluate which modifications show the greatest potential for improvements.

Keywords Indicator · Status · Assessment · Fisheries · Mariculture · Aquaculture · Seafood · FAO

INTRODUCTION

One of the most important contributions of a healthy ocean is seafood, fundamental for nutrition of a quarter of the world's population, and a source of livelihoods for millions (FAO 2012; Sumaila et al. 2012). However, globally the status and trends of many exploited and cultivated marine species are not directly assessed (Trujillo 2008; Costello et al. 2012), and it is unclear whether current catch and harvests can be sustained. An additional challenge is to place the provision of seafood within the context of other benefits people draw from oceans. Fisheries and mariculture are almost invariably considered separately and independently from other ocean-based human activities, thus neglecting interactions and cumulative impacts among sectors.

The Ocean Health Index (hereafter, the 'Index', Halpern et al. 2012), was developed to assess the health of human–ocean coupled systems through the lens of benefits to people. It measures the current status and likely future state of ten goals, including Food Provision, which we define here to be seafood obtained from a country's waters from either wild capture fisheries or mariculture. In this definition we only consider total catch and harvest coming from the waters of a given region and we do not account for imports and exports or what this tonnage may be used for. Our desire was to evaluate the potential productivity with respect to seafood in that given region. Current production was measured relative to a sustainable production reference point.

This Index was initially applied globally (Halpern et al. 2012), and here we explore patterns in the Food Provision goal, which is intended to assess the ability of a country to fully, yet sustainably, catch, or culture seafood. For example, a country with fisheries that are overfished scores poorly because catch is below full ecosystem production potential. This approach to assessing food provision is a departure from some traditional fisheries indicators that focus on exploitation rates under current management rather than historical loss of potential benefits (current good management is incorporated in the Index's likely future state, reflecting the potential for resource rebuilding). Similarly, the mariculture model compares current harvest to potentially achievable harvest, thus differing

Electronic supplementary material The online version of this article (doi:10.1007/s13280-013-0447-x) contains supplementary material, which is available to authorized users.

from assessments focused solely on economic performance or environmental impacts.

Sustainable seafood, within the Food Provision model, is defined as seafood fished or farmed in a way that allows for steady or increased production over time without compromising the ability of future seafood production. Yet such production can have unwanted tradeoffs with other coupled human–ocean health goals. The tradeoff between Food Provision and other goals becomes apparent in the overall Index, and in the likely future state of relevant goals, such that improvements in goals like Biodiversity or Sense of Place may come at a cost to Food Provision. This conceptual approach may produce different patterns from those generated by other analyses focused solely on seafood provision. Here, we explore how this unique approach, and modifications to its assumptions, methods, reference points, and data quality, affect patterns of results for Food Production and use that information to suggest improvements for future global and regional assessments.

MATERIALS AND METHODS

Full details of the fisheries (Eqs. S1–S3) and mariculture models (Eqs. S5–S6) and scores from the original fisheries and mariculture sub-goals are reported by 'Index reporting units' in the Electronic Supplementary Material, Table S1. Index reporting units aggregated several EEZ components (e.g., the U.S. Index region is composed of the EEZs for the U.S. east coast, U.S. west coast, the U.S. Gulf of Mexico, Alaska, and Hawaii, see Halpern et al. 2012 for a complete listing of EEZs per Index reporting unit). Here we focused only on scores for 'status', i.e., the current state of each sub-goal, rather than overall goal scores (i.e., including trends, pressures, and resilience) to allow for easier comparison of our results to other fisheries measures. Fisheries and mariculture scores range from 0 (either where exploitation exceeds the sustainable reference point by 200 % or more or where, in contrast to historical levels, currently there is no fishing or cultivation) to 100 (fishing close to the reference point or maximum cultivation given the area to do so).

Patterns in Global Fisheries and Mariculture

We used Spearman's rank order correlation coefficients to investigate the relationships between sub-goal status scores and: (1) economy (economic impact of fisheries index (EIF), Dyck and Sumaila 2010); (2) demography (Human Development Index (HDI), UNDP 2011); (3) governance (fishery management effectiveness survey, Mora et al. 2009); (4) three measures of sustainability: percentage of rebuilt stocks and percentage of overexploited and collapsed stocks as determined from landings-based assessments of stock status (Kleisner et al. 2013), and percentage of landings from habitat-damaging fisheries (i.e., bottom trawls and dredges); and (5) geography (mean latitude). We hypothesized that sub-goal scores would be higher for more developed countries, typically at higher latitudes with stronger economic reliance on sustainable seafood.

The fisheries indicator was designed to score highest when catch was close to the reference point, $mMSY_R$ (defined as 75 % of $mMSY \pm 5$ % buffer; see Electronic Supplementary Material), and to decline with catch above or below this value (see Eq. S3, Electronic Supplementary Material). Because the intent was to measure food provision with respect to sustainable production potential, rather than the performance of current fisheries management efforts, catch below this reference range was penalized regardless of whether the cause was under- or over-exploitation. We explored separately how EEZs that fish under versus over $mMSY_R$ were correlated to the five metrics described above and to: (6) cumulative human impacts (Halpern et al. 2008); (7) population within 100 km of the coastline (CIESIN 2012); and (8) loss in secondary production due to fishing (the L-index; Coll et al. 2008). We hypothesized that countries fishing below $mMSY_R$ due to under-utilization may have lower populations, lower impacts, and lower loss of secondary production while the opposite may be true of countries fishing above $mMSY_R$ due to overexploitation.

Sensitivity Analyses

Selection of model parameters for global assessment required many assumptions. We present sensitivity analyses addressing the main assumptions (Table 1; full details in the Electronic Supplementary Material). Firstly, we tested sensitivity to the choice of reference point. For fisheries, we examined how the proportion of *mMSY* that was selected (i.e., 75 %) and the width of buffer (±5 %) around $mMSY_R$ affected results (see *Reference point* in Electronic Supplementary Material). We also examined how use of a catch time series beginning in 1950 (i.e., earlier years not available) affected estimates of *MSY* when compared to indices that were 10, 20, or 30 years shorter. We used these results in a five-step process to estimate the probability that *mMSY* may have been underestimated in each country (see *Landings time series* in Electronic Supplementary Material). For mariculture, for which we lacked estimates of sustainable harvest equivalent to $mMSY_R$ for fisheries, we explored consequences of using coastal population density rather than coastal area for standardizing production values by potential cultivable area (see Eq. S9, Electronic Supplementary Material), under the assumption that mariculture could be developed as a function of

population and/or that there are logistic limitations to farm development linked to presence of infrastructures, access and locally available workforce that may be approximated by local population density.

Secondly, we explored how choice of coefficients to account for data quality (fisheries) or sustainability (mariculture) affected results. For fisheries, the completeness of taxonomic reporting (T_C; Eq. S4, Electronic Supplementary Material) of a country's catch was used to approximate its quality of monitoring, which is one component of sustainability. To compute this proxy, we determined that species were accessible to fishing if biological distribution areas overlapped at least 10 % of the EEZ of the country in question. We tested the effect of 1, 5, 20, and 30 % overlap. For the mariculture model (Eq. S6, Electronic Supplementary Material), the sustainability coefficient (S_M) used three indicators from the Mariculture Sustainability Index (MSI; Trujillo 2008), and included a place-holder value for countries missing sufficient MSI data. We examined the change in scores if all 13 MSI indicators (Table S4) were included and also if 'place-holder' countries were eliminated. Results for all sensitivity tests presented here are at a finer resolution (i.e., EEZ and sub-EEZs are not aggregated as they were in Halpern et al. (2012)) to provide easier interpretation of patterns.

While global landings data allowed for a standardized analysis of fisheries across all countries, there were inherent limitations due to data quality (Pauly et al. 2013b). Landings were mapped by the *Sea Around Us* project (Watson et al. 2004) to infer landings of both domestic and foreign vessels in each EEZ. Here, we examined nine countries with the highest reported landings, representing 50 % of the landings globally (excluding High Seas: Canada, Chile, China, India, Japan, Norway, Peru, the UK, and the US), to determine the effect of mapping inaccuracies on fisheries status estimates. We computed the domestic proportion of landings within an EEZ and also determined whether the landings allocated to foreign EEZs within an FAO area was a significant proportion of the total landings for each of these countries. By examining these proportions we identified EEZs where scores were likely to be influenced by mapping inaccuracies.

RESULTS

Patterns in Global Fisheries and Mariculture

Economy, demography, sustainability, and geography showed stronger relationships with fisheries scores than did governance metrics. Fisheries scores (Table S2, Electronic Supplementary Material) were generally higher for countries with a higher EIF (0.26, $P = 0.0008$; Fig. 1a) and a higher HDI (0.31, $P < 0.001$; Fig. 1b). There was a significant positive correlation with the proportion of rebuilding stocks (0.33, $P < 0.001$), and a significant negative correlation with the proportion of trawling or dredging gears used (−0.26, $P < 0.001$). In general, countries at

Table 1 Sensitivity analyses for various sub-goal components and indication of their effect on the overall scores. 'NA' refers to lack of change in both the average sub-goal score and the rank order of scores

Component tested	Model	Sensitivity analysis	Influence
Place-holder score for countries with insufficient data	Fisheries	Removal of 0.25 as a proxy score	NA
Reference point	Mariculture	Replacing area-based reference point with coastal population	Scores are on average 82 times higher
Reference point	Fisheries	Replace optimum between 70 and 80 % of mMSY with 55–95 % of mMSY	For countries fishing below the original reference point, scores are lower when 95 % of the reference point is used. Countries fishing in the range of 0 to −5 % of the original reference point score on average 23 % lower. Countries fishing in the range of 0 to +5 % of the original reference point score on average 18.5 % lower
Reference point	Fisheries	Replace ±5 % buffer with ±10 %, ±15 %, ±25 %	NA
Reference point	Fisheries	Likelihood of peak in landings time series occurring prior to 1950	Scores are on average 2 times higher
Taxonomic reporting correction factor	Fisheries	Minimum overlap of a species range of 1, 5, 20, and 30 % to consider a species as occurring in that EEZ	1 % overlap: 18 % decrease in scores; 5 % overlap: 8 % decrease in scores; 20 % overlap: 14 % increase in scores; 30 % overlap: 32 % increase in scores
Sustainability coefficient	Mariculture	All MSI indicators (13) as opposed to just three	NA

lower latitudes tended to have lower fisheries scores (0.16, $P = 0.04$; Fig. 2a). There were no significant correlations with other metrics (Table S3).

Economy, demography, sustainability, and geography, similar to fisheries, showed stronger relationships with mariculture scores than did governance metrics. Countries with economies more reliant on fisheries tended to have more sustainable mariculture (0.45, $P < 0.001$; Fig. 1a) and a weak, but significant correlation with HDI (0.19, $P = 0.044$) and latitude (0.28, $P = 0.0025$). There was also a significant negative correlation with the proportion of trawling or dredging gears used (−0.22, $P = 0.0215$). No other significant correlations existed with the other metrics (Table S3, Electronic Supplementary Material). In general, the highest mariculture scores were in Asia (Table S1, Electronic Supplementary Material, Fig. 2b), which is correlated to the distribution of global production levels (see Fig. 1.1 in Branch et al. 2013). Many countries that had low scores for fisheries, such as China, scored high for mariculture. The lowest scoring countries were generally small island states and countries in Africa.

Examination of under- versus over-exploitation relative to $mMSY_R$ (Fig. 3a; correlations in Table S3, Electronic Supplementary Material) revealed that many countries in the Asia-Pacific region were fishing well above the reference point, as were Ireland, Venezuela, Algeria, Peru, Yemen, and the Maldives, and others. In contrast, in Canada, Russia, many South Pacific islands, and several countries in Central America, fishing was well below $mMSY_R$ (blue regions in Fig. 3a). Regions that performed best using the approach taken here (i.e., fishing within the 5 % buffer around $mMSY_R$, shown in light colors in Fig. 3a) included Australia, Japan, Portugal, the US east coast, and Finland.

Demography and sustainability showed stronger relationships with scores for countries fishing above $mMSY_R$ than did economic, governance, geographic, or population metrics. For countries with fisheries yields exceeding our estimate of $mMSY_R$, the extent of overfishing was higher in countries where the Human Development Index was lower (−0.41, $P < 0.001$), indicative of potential overfishing in EEZs of less developed countries. There was also a negative correlation with the percentage of collapsed or overexploited stocks (−0.31, $P = 0.007$) and a significant positive correlation with human impacts (0.16, $P = 0.048$).

Sustainability, geography, and population showed stronger relationships with scores for countries fishing below $mMSY_R$ than did demographic, economic, or governance metrics (Table S3, Electronic Supplementary Material). Countries with fisheries yields far below our estimate of $mMSY_R$ tended to have lower proportions of collapsed and overexploited stocks (−0.60, $P < 0.001$), occur at higher latitudes (0.25, $P = 0.026$), have higher human impacts (0.25, $P = 0.026$), have larger coastal populations (0.35, $P = 0.0014$), and greater values of the L-index (0.58, $P < 0.001$). These results suggest that countries 'underfish' for different reasons.

Sensitivity Analyses

Reference Point

Changes in fisheries status for each EEZ with respect to the fraction of *mMSY* that is set as a reference point (i.e., 75 %**mMSY*) are presented in Table S5 (Electronic Supplementary Material). On average, fisheries status was higher with a reference point closer to *mMSY* lower with a reference point farther from *mMSY* (Fig. 4), implying that countries tended to harvest close to or slightly above *mMSY*. Across all scores, fisheries status decreased by an average of 8.5 % (percent change range: −100 to +40.2 %)

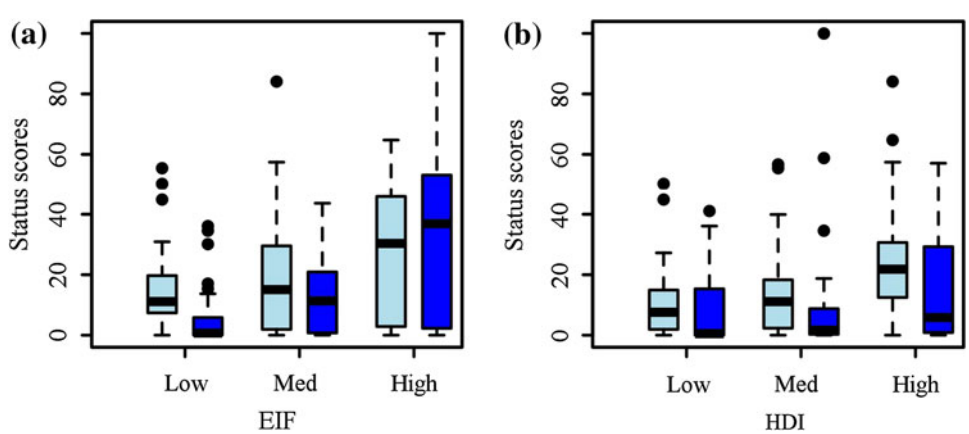

Fig. 1 Boxplots of fisheries (*light blue*) and mariculture (*dark blue*) status versus **a** economic impact factor (EIF) and **b** Human Development Index (HDI)

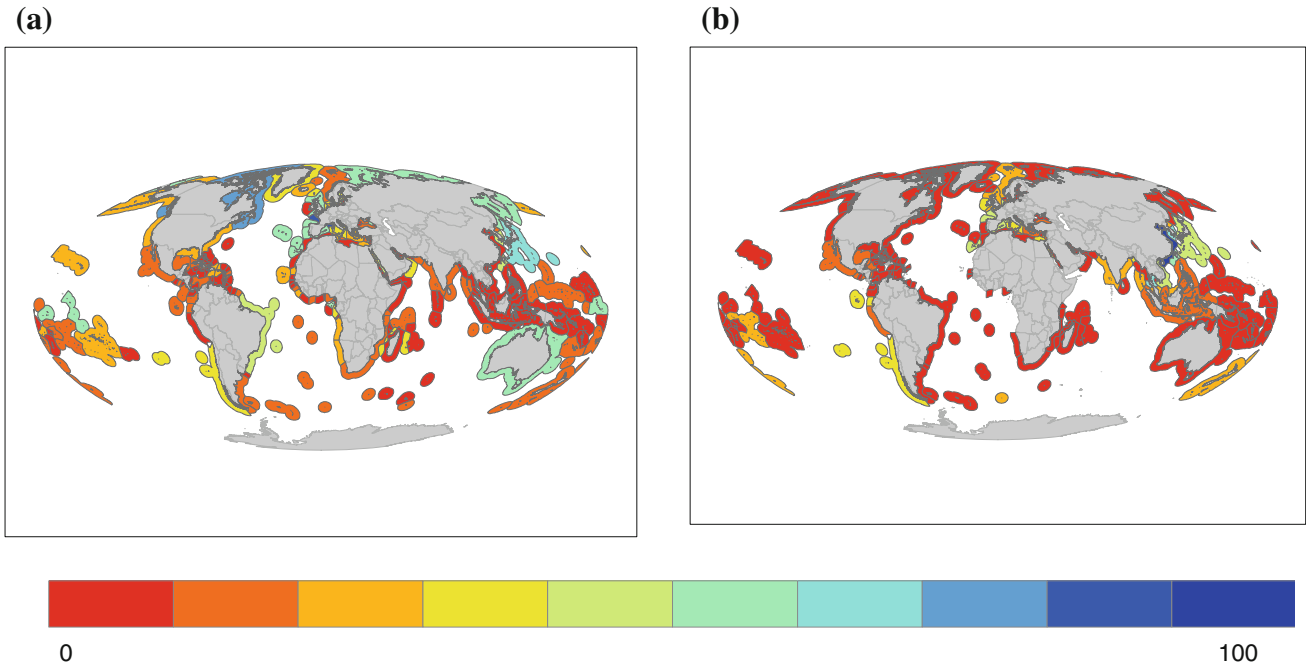

Fig. 2 Sub-goal scores for **a** fisheries and **b** mariculture. Higher scores in *dark blue*, lower scores in *red*

and 8.7 % (percent change range: −100 to 20.4 %) with fractions of *mMSY* set at 55 and 65 %, respectively. Status increased by an average of 19.6 % (percent change from −15.9 to 733.1 %) and 33.5 % (percent change from −24.8 to 1311.9 %) with fractions of *mMSY* set at 85 and 95 %, respectively. Looking more closely at the changes within the EEZs of the nine largest fishing countries (Table S6, Electronic Supplementary Material), we see a shift in the fishing relative to the reference point: EEZs fishing more than 40 % above 75 %**mMSY* fish closer to a 95 %**mMSY* reference point, EEZs fishing slightly above or just under 75 %**mMSY*, will fish under a 95 %**mMSY* reference point. EEZs in the U.S. score best under a 95 %**mMSY* reference point, likely because they are have adopted a precautionary *MSY* approach.

For mariculture, incorporating coastal population into the reference point resulted in significant differences among the highest scoring countries (Table S2, Electronic Supplementary Material). The maximum score was based on the country with the highest ratio of production to coastal population (Norway, followed by China). China had the greatest mariculture production globally, but also the second largest coastal population in the world, after India. Thus, the use of coastal population to scale production lowered China's status nearly 40 points below Norway, which had a much smaller population relative to production. Canada, with the largest coastal zone in the world but relatively few people scored ninth. Several other countries also scored higher, including New Zealand, Iceland, Belize, Denmark, French Polynesia, Seychelles, Greece, and New Caledonia.

Landings Time Series

Figure 3 illustrates the sensitivity of fisheries status to the assumption that peak catch falls within the landings time series. In most countries, status changed dramatically (Fig. 3d vs. 3b) due to changes in reference points (Fig. 3c vs. 3a), with the exception of Brazil, India, and countries in SE Asia. In these areas, the time series available very likely included the peak.

Taxonomic Precision of Landings

With a reduction in requirements for overlap between species ranges and EEZs from 10 % (Fig. S3c, g Electronic Supplementary Material) to 5 or 1 %, status scores for many countries improved by 30–50 % with notable increases for Australia, Japan, and Canada (Fig. S3f, h, Electronic Supplementary Material). Scores of many island nations in SE Asia remained low, a likely indication of low reporting quality in combination with high species diversity. Countries that scored 0 for fisheries status due to current landings being 200 % over $mMSY_R$ (e.g., China, Peru, Algeria) remained low because T_C has no effect in these cases. All T_C scores declined with a 5 % overlap (mean decline = 18 %, max = 56 %) or 1 % overlap (mean decline = 8 %,

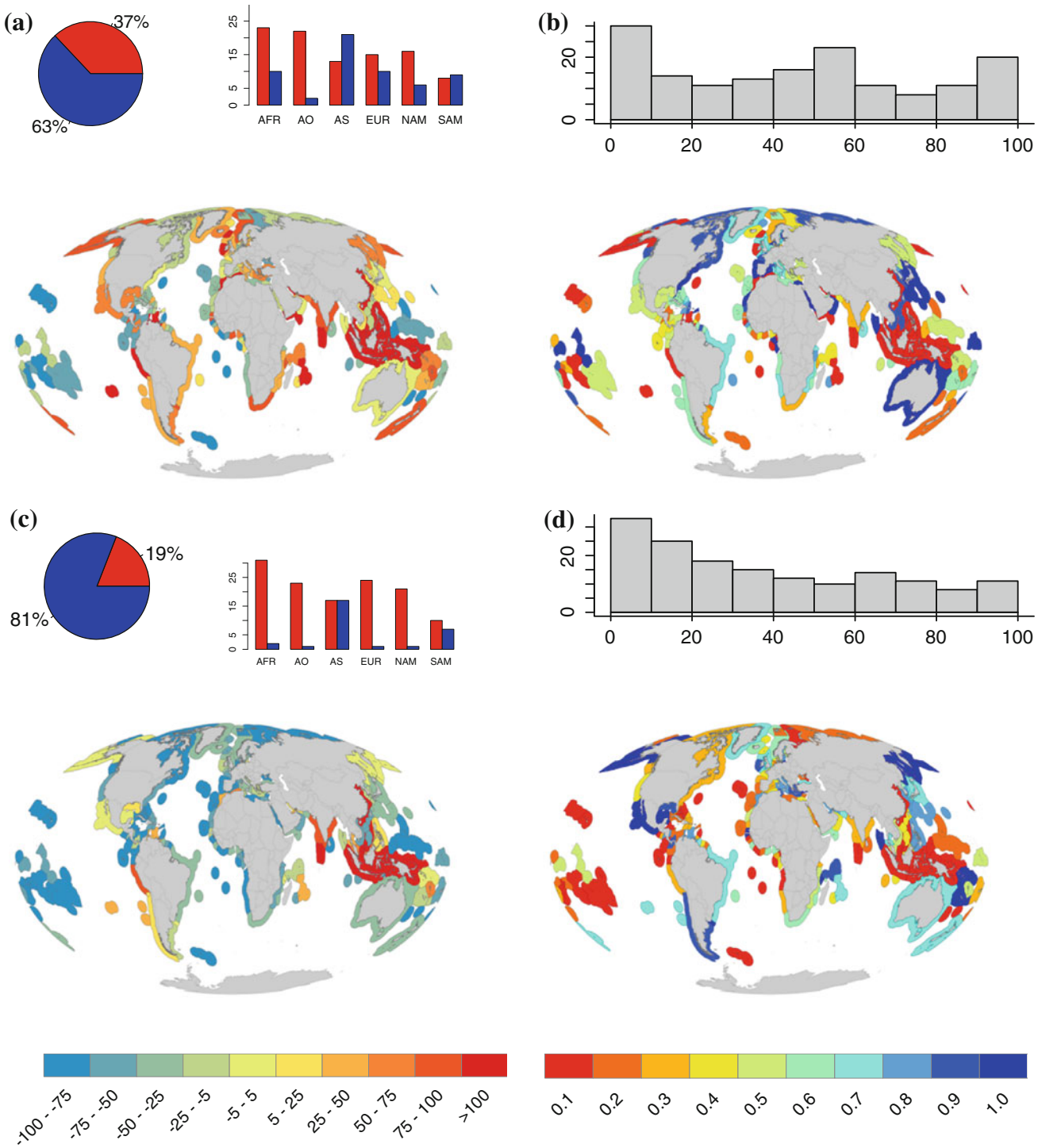

Fig. 3 Maps of distance from *mMSY* (**a**, **c**) and fisheries status (**b**, **d**). *Top panels* are based on original reference point, while *bottom panels* are calculated using MSY values plus the value δ. *Pie charts* and *barplots* in panels **a** and **c** illustrate the proportions, globally and by continent, of countries over-fishing (*red*) versus under-fishing (*blue*), respectively (AFR = Africa, AO = Australia & Oceania, AS = Asia, EUR = Europe, NAM = North America, SAM = South America). Histograms **b** and **d** illustrate the distribution of scores under *mMSY* and for $mMSY + \delta$. Histogram **d** illustrates a skew toward lower scores (due to more countries fishing below $mMSY + \delta$). We assume a 95 % probability that the error in potentially underestimating *mMSY* is less than δ. Note that when evaluating distance from *mMSY*, the 'best' countries are those that range between −5 and +5 % of the reference point (*pale green*), whereas a status score of 1 (*dark blue*) is highest

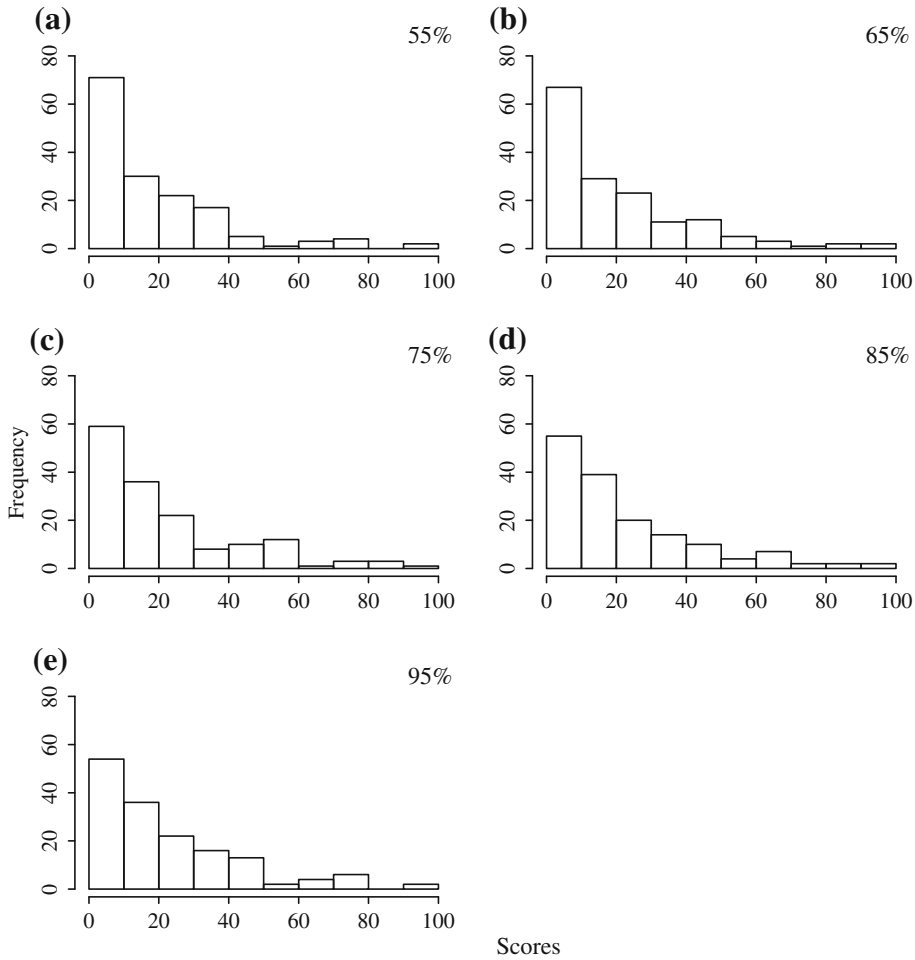

Fig. 4 Histograms of scores calculated with different proportions of the reference point: **a** 55 %, **b** 65 %, **c** 75 % (original proportion), **d** 85 %, and **e** 95 %

max = 67 %; Fig. 5). T_C scores increased with overlaps set at 20 % (mean increase = 14 %, max = 133 %) or 30 %, (mean increase = 32 %, max = 187 %; see Fig. S3a, c, e, g, Electronic Supplementary Material). However, there was an increasingly pronounced band of lower T_C scores at lower latitudes, which may be a result of higher diversity fish communities in the Tropics or a result of reporting errors (Fig. S3e, g, Electronic Supplementary Material).

Spatial Mapping of Landings

Spatial mapping of landings for the nine top fishing countries suggested that the effects of foreign fleets in domestic waters, and landings from foreign EEZs, had inconsistent effects on fisheries scores (Table S7, Electronic Supplementary Material). Several examples illustrated where mapping of catch may influence fisheries status scores. In FAO area 21 in the NW Atlantic, both the US and Canada primarily fished domestically (Canada 89 % and US 86 %). The US also had landings from Bermuda's and Greenland's EEZs. However, these landings were relatively low compared to domestic catches. Thus, even if they were mapped to the wrong location, they would not have a large effect on US or Bermuda scores since they represented 4 % of total landings in Bermuda's EEZ. There may be a more significant impact on Greenland's status as approximately 24 % of its landings were due to US landings. In FAO area 87 (SE Pacific), approximately 90 % of Chilean catches were attributed to the Chilean EEZ and the High Seas, and an additional 5 % to Chilean territorial holdings. Therefore, the score for Chile or its territorial holdings would not be strongly affected. In the NE Pacific, FAO area 67, Canada had relatively high landings within the Alaskan EEZ according to mapped landings. A large portion of these landings was Alaska pollock (*Theragra chalcogramma*), likely too high given that Canada was only minimally

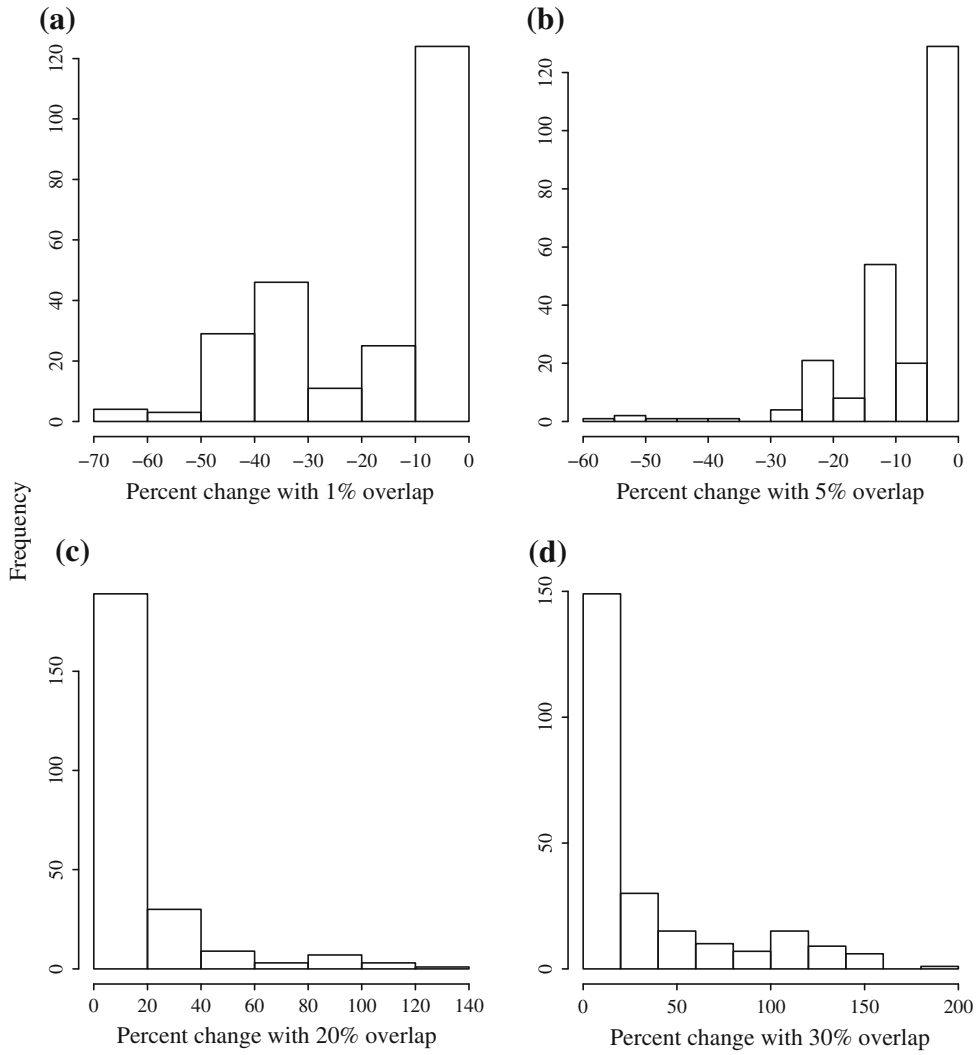

Fig. 5 Histograms of percent change in scores using minimum overlaps of **a** 1 %, **b** 5 %, **c** 20 %, and **d** 30 % for calculating the numerator of the taxonomic reporting correction factor and illustrating the decrease in scores with a lower threshold for overlap and increase in scores with a higher threshold for overlap

involved in that fishery. This allocation may have increased the landings in Alaska, resulting in landings that were too high (and well above the reference point, i.e., a lower score). In the western and eastern Indian Ocean (FAO areas 51 and 57, respectively), India's landings were allocated completely domestically and the amount of foreign landings was very small. In this case, a mapping error was less likely and scores would not be affected. In FAO region 71 (western central Pacific), only 12 % of China's landings were allocated to the Chinese EEZ. However, Chinese landings from FAO 71 were likely to be significantly underreported (Pauly et al. 2013a), probably due to mis-reporting to FAO rather than an error in catch allocation. Since China's score was zero, reflecting landings that were over 200 % of the reference point, higher landings would likely still result in a lower score.

DISCUSSION

We present here Food Provision results from the Ocean Health Index's first global scale implementation, and critically review the modeling approaches used and data quality issues encountered. The intent is to reveal and investigate observed patterns, highlight caveats, and discuss areas for potential future modifications.

Overall, global food provision scored very low, nearly 40 points below the highest score of 100. Wild-capture fisheries mostly drove scores since contributions of fisheries and mariculture were weighted by percentage of tonnage produced and fisheries catch was higher in most EEZs. A geographic and social gradient was evident, with high latitude, developed countries, and countries with higher economic importance of fisheries

(EIF, Dyck and Sumaila 2010) scoring highest. Comparison of fisheries scores with independent measures of past and current exploitation status gave mixed results. There was some level of concordance with both proportion of rebuilding stocks and proportion of catch from habitat-damaging gears, which tended to be negatively correlated with fisheries scores. However, other proxies such as management effectiveness showed no correlation.

The Index penalizes countries that obtain wild-capture seafood both above and below the reference point range, so results may be explained by separating the two types of countries. Countries with more collapsed and overexploited stocks were associated with landings that were above the reference point. Since the bulk of landings come from fully exploited stocks, rather than overexploited or collapsed stocks (Kleisner et al. 2013), this may indicate that the collapses are from many small stocks, indicating a potential reduction in biodiversity. Additionally, these locations were significantly (though weakly) correlated with indicators of cumulative human impact levels, loss in secondary production due to fishing (i.e., L-index), and under-development. On the other hand, countries with landings below the reference point seemed to be those managing their resources conservatively or otherwise avoiding strong fishing effort. They tended to be at low latitudes, have lower coastal population densities, lower human impacts, higher proportions of rebuilt stocks, and lower proportions of collapsed/overexploited stocks. These countries were penalized in the Food Provision model for having available resources that are not fully utilized to provide food. However, this may have penalized some countries for being precautionary, which is not ideal.

Many countries that scored poorly for fisheries scored well for mariculture. For example, the overall Food Provision scores of 63 for both China (mariculture status: 100; fisheries status: 0 because current fishing exceeds MSY_R by 200 %) and Canada (mariculture status: 2.1; fisheries status: 71.8) were achieved very differently (Halpern et al. 2012). China scored highest due to its extremely high mariculture production. However, it was the only country scoring above 75, and only 3 of the 169 Index reporting units scored over 50. If the EIF index is a proxy for the economic importance of all seafood, its positive correlation with mariculture scores (as well as fisheries catch) suggests that in countries with low fisheries scores and high mariculture scores, mariculture provided an alternative source of protein when commercial fisheries were degraded (Edwards 1997), or there was greater economic incentive to switch from commercial fisheries to cultured seafood (Bostock et al. 2010). There was no latitudinal pattern, but most high mariculture scores were in East Asia. Mariculture scores were also particularly low in countries with large coastlines and low population densities, such as the US and Russia. Countries that scored lowest with respect to both fisheries and mariculture had very low EIF, likely reflecting preference for non-seafood protein and livelihoods, and/or a lack of managerial requirements to establish mariculture (Charles et al. 1997).

The Index framework simultaneously evaluated fisheries and mariculture performance on the same scale, combining them by relative production (Eqs. S7–S8). However, choice of reference points can affect scores and thus interpretations both within and between the sub-goals (Samhouri et al. 2012). For the fisheries sub-goal, it was very difficult to derive an accurate estimate of *mMSY*. Our estimate was obtained using a catch-based method for calculating single-species *MSY*s for each stock, summing across all stocks, and reducing this value by 25 % to account for multi-species interactions (Link et al. 2012). Some data limitations may have caused poor estimates of *MSY* and, consequently, *mMSY*. The estimate of *MSY* required that the time-series capture the full fishing history of the stock including the true peak catch. Our analyses suggested this may not be possible in all cases (Fig. 3), as many countries achieved peak catch prior to the beginning of the reported landings time-series. Additionally, poorer taxonomic reporting in earlier decades may preclude detection of the peak. The mapping of catch may also cause mis-estimation of peaks in catch and thus *MSY*. However, our explorations suggested that the catch allocation is robust for many of the major fishing countries, although countries with extensive distant-water fisheries may still pose an issue if their catches are assigned incorrectly.

Another influential parameter in the fisheries status was the taxonomic correction factor, T_C, intended to capture whether a country is reporting landings at a high taxonomic resolution. Different choices in the calculation can have significant effects on the overall score. However, in the absence of a large-scale independent assessment of landing statistics, we feel that 10 % is a suitable threshold.

MSY is often intended as a limit rather than a target, and lower reference points are adopted in management for precautionary reasons. The appropriateness of *mMSY* as a multispecies limit is difficult to assess even in data-rich locations, and is not often used in management. Therefore, there were no established practices on how to use *mMSY* when setting a reference point. We explored the sensitivity of results to our choice of a 25 % reduction of *mMSY*. Setting the reference point closer to *mMSY* in most cases had the effect of increasing the scores, suggesting many countries were above, but close to, the reference point. If we underestimated the 'true' but unknown reference point, we may have artificially reduced the scores of countries that

could be performing well, while rewarding countries that may be fishing too little with respect to maximum sustainable multispecies yields.

For mariculture, the reference point was intended to measure maximum sustainable harvest, initially based on the highest recorded production relative to coastal area (Halpern et al. 2012). This reference point assumed that larger amounts of seafood could be produced sustainably by developing all coastal area currently uncultivated. The key to this increased development would be that it must be done in a sustainable manner (as reflected by the sustainability coefficient). A different conceptual approach tested here scaled mariculture production to coastal population, under the assumption that mariculture would be developed as a function of population and/or that reduced local population creates logistic constraints to farm development through lack of infrastructure, access, and locally available workforce. Using local population density as the reference point produced very different rankings, shifting Asian countries towards slightly lower values and raising the scores of locations such as Canada and Norway. Other possible approaches to setting reference points may be equally or more valid, such as assuming that mariculture would be preferentially developed away from population centers and/or driven by countries' economic status. We currently know little about true values of maximum sustainable mariculture. To our knowledge, carrying capacity of mariculture has so far only been explored for bivalves (Byron et al. 2011).

Currently, the fisheries model does not consider whether a given country is fishing unsustainably in the EEZs of other countries, on the High Seas, or whether it is importing fish from countries that do not have sustainable fishing practices. If the fisheries sub-goal included a penalty for a country's distant-water fleet behavior, some of the current top scoring countries might see a decline in their scores. Additionally, information on consumer preferences for seafood from wild capture fisheries versus mariculture or the performance of global seafood markets and prices was not included in these goals. The incorporation of such data or other indices that address these topics (e.g., Villasante et al. 2012) could be important areas for future exploration and improvement within the fisheries model and the overall Index. Moreover, fisheries scores did not reflect whether catch in a given EEZ was consumed locally or exported. This is important, as it meant that while the fisheries sub-goal could contribute to a measure of food security at the global level, it did not measure food security within a country; this would have required estimates of internal consumption and seafood trade that are complex to evaluate (Smith et al. 2010). Nonetheless, food provision scores could provide information to assess country-level food security was this information available and this could indeed be a worthwhile avenue for future research.

The Index was designed to provide a conceptual framework, adaptable according to the scale, data, and knowledge of the region to which it is applied. The Food Provision goal followed this rationale and was intended as a synthetic measure of long-term, multispecies sustainable production that integrated across multiple dimensions of sustainability (e.g., harvest practices, pressures, resilience). As such it differed from expectations based on more traditional measures. Firstly, it simultaneously assessed mariculture and fisheries, by combining each sub-goal status score into a single Food Provision index based on the relative contribution (tonnage produced) from each sector. Although this uncovered interesting patterns, direct comparison required an understanding of their reference points. Furthermore, since low fisheries scores can represent both under- and overfishing, fisheries status scores did not correspond to traditional stock assessments. For example, a score of 100 for fisheries was not an indication that current biomass is equivalent to the biomass that would produce *MSY*, i.e., B_{MSY}, contrary to what some authors thought (Branch et al. 2013), and that therefore the Food Provision "index should be about the same as dividing global catches by global MSY". Rather, a score of 100 indicated the ability to sustainably and optimally deliver seafood now and in the future, which was captured through use of recent trends, cumulative pressures placed upon fisheries from human activities, and resilience provided to the systems from various social, ecological, and governance factors. Setting the food provision reference points requires understanding the purpose of the indicator and the societal objectives it was designed to inform (e.g., whether to fully exploit available resources or favor a use that was more precautionary or prioritizes other benefits). For example, an alternative approach that may have posed fewer data and modeling issues, would have been to focus on total global seafood production, regardless of country (e.g., Costello et al. 2012). However, this perspective ignores the critical question of how specific countries are doing over time and relative to one another, and would not be informative of spatial patterns. An understanding of regional patterns is key if national governments and international organizations wish to understand sustainable seafood production potential and how current production varies globally. Therefore, though availability of adequate data and functional understanding of many ecosystems remains a challenge, it was paramount to provide an initial assessment, pending the availability of better data and improved methods. Another conceptual departure from more traditional measures was that measures of sustainability were incorporated throughout the Index both in calculation of delivery of individual benefits and in interactions across goals. This

must be kept in mind when exploring the Food Provision results separately, as we have done here.

CONCLUSION

Here we acknowledge several limitations of the indicators used. We showed that the indicators were most sensitive to the choices in the percentage of *mMSY* set as the reference point (i.e., $mMSY_R$), the algorithm for the calculation of T_C, the length of the landings time-series and, at least in some cases, the spatial allocation of landings. Our explorations suggested several improvements that may be applied to future global calculations. For example, reported landings quality is not likely to improve in the near future, but the use of reconstructed catches (Zeller and Pauly 2007) is a promising option. Additionally, the improvement of catch data in countries such as China, which has a huge presence in global fisheries, both due to its domestic and foreign fishing activities, could help to reduce the overall bias in the Food Provision model due to mis-reporting. Currently the estimation of the fisheries reference point is limited by the availability of robust methods to estimate exploitation status globally. The search to validate and improve such methods is an ongoing effort within fisheries science, and these improvements could be incorporated as they become available (Costello et al. 2012; Martell and Froese 2012; Thorson et al. 2012). We also highlight the current lack of an analogous reference point to *MSY* for mariculture. However, using mariculture harvest per-capita as a reference point, instead of per potentially cultivated area, may be an improvement, pending advances in quantifying optimum carrying capacity and longer-term sustainability. Finally, at regional scales, a better understanding of system capacity, may enable the use of fisheries reference points based on stock assessments, or setting mariculture targets based on local management objectives, which would aid comparability between the sub-goals beyond a simple relationship based on production levels and would provide useful information for national governments to better utilize their seafood resources. Thus, the Ocean Health Index represents a useful and adaptive framework, utilizing the best data available, that can assist governments and international organizations in better understanding and comparing seafood production between regions.

Acknowledgments Beau and Heather Wrigley provided the founding grant for the original Ocean Health Index work. Additional financial and in-kind support was provided by the Pacific Life Foundation, the Thomas W. Haas Fund, the Oak Foundation, the Akiko Shiraki Dynner Fund, Darden Restaurants Inc. Foundation, Conservation International, New England Aquarium, National Geographic, and the National Center for Ecological Analysis and Synthesis (NCEAS). This is a contribution from the NCEAS Ecosystem Health Working Group and the *Sea Around Us* project, a collaboration between The University of British Columbia and The Pew Charitable Trusts. We thank A. Tavakolie for assistance with some of the indices. MC was supported by a Marie-Curie CIG Fellowships and a research contract of the *Ramon y Cajal* program of the Spanish Government.

REFERENCES

Bostock, J., B. McAndrew, R. Richards, K. Jauncey, T. Telfer, K. Lorenzen, D. Little, L. Ross, et al. 2010. Aquaculture: Global status and trends. *Philosophical Transactions of the Royal Society B-Biological Sciences* 365: 2897–2912.

Branch, T.A., D.J. Hively, and R. Hilborn. 2013. Is the ocean food provision index biased? *Nature* 495: E5–E6.

Byron, C., J. Link, B. Costa-Pierce, and D. Bengtson. 2011. Calculating ecological carrying capacity of shellfish aquaculture using mass-balance modeling: Narragansett Bay, Rhode Island. *Ecological Modelling* 222: 1743–1755.

Charles, A.T., R.F. Agbayani, E.C. Agbayani, M. Agüero, E.T. Belleza, E. González, B. Stomal, and J.-Y. Weigel. 1997. Aquaculture economics in developing countries: Regional assessments and an annotated bibliography. FAO Fisheries Circular No 932, Rome, Italy, FAO, 401 pp.

CIESIN. 2012. National aggregates of geospatial data collection: Population, landscape, and climate estimates, Version 3 (PLACE III). NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY

Coll, M., S. Libralato, S. Tudela, I. Palomera, and F. Pranovi. 2008. Ecosystem overfishing in the ocean. *PLoS ONE* 3: e3881.

Costello, C., D. Ovando, R. Hilborn, S.D. Gaines, O. Deschenes, and S.E. Lester. 2012. Status and solutions for the world's unassessed fisheries. *Science* 338: 517–520.

Dyck, A.J., and R. Sumaila. 2010. Economic impact of ocean fish populations in the global fishery. *Journal of Bioeconomics* 12: 227–243.

Edwards, P. 1997. Sustainable food production through aquaculture. *Aquaculture Asia* 2: 4–7.

FAO. 2012. The State of World Fisheries and Aquaculture. Rome, Food and Agriculture Organization of the United Nations, 197 pp.

Halpern, B.S., S. Walbridge, K.A. Selkoe, C.V. Kappel, F. Micheli, C. D'Agrosa, J.F. Bruno, K.S. Casey, et al. 2008. A global map of human impact on marine ecosystems. *Science* 319: 948–952.

Halpern, B.S., C. Longo, D. Hardy, K.L. McLeod, J.F. Samhouri, S.K. Katona, K. Kleisner, S.E. Lester, et al. 2012. An index to assess the health and benefits of the global ocean. *Nature* 488: 615–620.

Kleisner, K., D. Zeller, R. Froese, and D. Pauly. 2013. Using global catch data for inferences on the world's marine fisheries. *Fish and Fisheries* 14: 293–311.

Link, J.S., S. Gaichas, T.J. Miller, T. Essington, A. Bundy, J. Boldt, K.F. Drinkwater, and E. Moksness. 2012. Synthesizing lessons learned from comparing fisheries production in 13 northern hemisphere ecosystems: Emergent fundamental features. *Marine Ecology-Progress Series* 459: 293–302.

Martell, S., and R. Froese. 2012. A simple method for estimating MSY from catch and resilience. *Fish and Fisheries*. doi:10.1111/j.1467-2979.2012.00485.x.

Mora, C., R.A. Myers, M. Coll, S. Libralato, T.J. Pitcher, R.U. Sumaila, D. Zeller, R. Watson, et al. 2009. Management effectiveness of the world's marine fisheries. *PLoS Biology* 7: e1000131.

Pauly, D., D. Belhabib, R. Blomeyer, W.W.L. Cheung, A.M. Cisneros-Montemayor, D. Copeland, S. Harper, V.W.Y. Lam, et al. 2013a. China's distant-water fisheries in the 21st century. *Fish and Fisheries*. doi:10.1111/faf.12032.

Pauly, D., R. Hilborn, and T.A. Branch. 2013b. Does catch reflect abundance? *Nature* 494: 303–306.

Samhouri, J.F., S.E. Lester, E.R. Selig, B.S. Halpern, M.J. Fogarty, C. Longo, and K.L. McLeod. 2012. Sea sick? Setting targets to assess ocean health and ecosystem services. *Ecosphere* 3: 41.

Smith, M.D., C.A. Roheim, L.B. Crowder, B.S. Halpern, M. Turnipseed, J.L. Anderson, F. Asche, L. Bourillon, et al. 2010. Sustainability and global seafood. *Science* 327: 784–786.

Sumaila, U., W. Cheung, A. Dyck, K. Gueye, L. Huang, V. Lam, D. Pauly, T. Srinivasan, et al. 2012. Benefits of rebuilding global marine fisheries outweigh costs. *PLoS ONE* 7: 1–12.

Thorson, J.T., T.A. Branch, and O.P. Jensen. 2012. Using model-based inference to evaluate global fisheries status from landings, location, and life history data. *Canadian Journal of Fisheries and Aquatic Science* 69: 645–655.

Trujillo, P. 2008. Using a mariculture sustainability index to rank countries' performances. In *A comparative assessment of biodiversity, fisheries, and aquaculture in 53 countries' Exclusive Economic Zones Fisheries Centre Research Reports 16(7)*, ed. J. Alder, and D. Pauly. Vancouver: University of British Columbia.

UNDP. 2011. *Human Development Report 2011, sustainability and equity: A better future for all*, 178 pp. New York: Palgrave Macmillan

Villasante, S., D. Rodríguez, M. Antelo, M. Quaas, and H. Österblom. 2012. The Global Seafood Market Performance Index: A theoretical proposal and potential empirical applications. *Marine Policy* 36: 142–152.

Watson, R., A. Kitchingman, A. Gelchu, and D. Pauly. 2004. Mapping global fisheries: Sharpening our focus. *Fish and Fisheries* 5: 168–177.

Zeller, D., and D. Pauly (eds.). 2007. Reconstruction of marine fisheries catches for key countries and regions (1950–2005). *Fisheries Centre Research Reports* 15(2): 163.

AUTHOR BIOGRAPHIES

Kristin M. Kleisner (✉) (Ph.D. in Marine Biology and Fisheries) is a postdoctoral research fellow for the *Sea Around Us* project at the Fisheries Centre at the University of British Columbia. Her research interests include measuring the effects of fishing on marine resources, the development and testing of global data-poor stock assessment techniques and indicators of ecosystem health. Her past work included the development of geospatial techniques for assessing highly migratory fish stocks and the assessment of suitable areas for temporal–spatial fishing area closures for red snapper in the Gulf of Mexico.
Address: Fisheries Centre, University of British Columbia, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada.
e-mail: k.kleisner@fisheries.ubc.ca

Catherine Longo (Ph.D. in Marine Sciences) is Assistant Project Scientist for the Ocean Health Index project (www.oceanhealthindex.org), at the Institute of Marine Science of the University of California, Santa Barbara. Her research interests include ecosystem services, ecosystem indicators for marine management, fisheries multispecies assessments, biodiversity theory and metabolic theory.
Address: National Center for Ecological Analysis and Synthesis (NCEAS), 735 State Street, Suite 300, Santa Barbara, CA 93101, USA.
e-mail: longo@nceas.ucsb.edu

Marta Coll (Ph.D. in Animal Biology, Plant Biology and Ecology) is a Researcher at the Institute of Marine Science (ICM-CSIC) of the Spanish Scientific Council (Barcelona, Spain). Her research interests focus on understanding patterns and processes that characterize marine ecosystems and, in particular, changes of, and threats to, marine biodiversity. She studies population, community and food-web dynamics linked with human activities (such as fisheries, climate change, eutrophication, and invasive species), and how these translate into changes in ecosystem structure and functioning, and services that humans obtain from the ocean.
Address: Department of Marine Renewal Resources, Institute of Marine Science, Passeig Marítim de la Barceloneta, n° 37-49.08003, Barcelona, Spain.
e-mail: mcoll@icm.csic.es

Ben S. Halpern (Ph.D. in Marine Ecology) is a Professor at the Bren School of Environmental Science and Management at University of California, Santa Barbara and Chair in Marine Conservation at Imperial College London. His research interests include marine ecology, conservation biology, and ecosystem-based management.
Address: Bren School of Environmental Science and Management, University of California, 552 University Rd., Santa Barbara, CA 93106, USA.
e-mail: halpern@bren.ucsb.edu

Darren Hardy (Ph.D. in Environmental Science and Management) is a GIS Software Engineer at Stanford University, where he develops geospatial digital library and data management technologies. His interdisciplinary research focuses on geospatial data analysis, discovery, and management, and crowd-sourcing geographic information.
Address: Digital Library Systems & Services, Stanford University Libraries, Stanford, CA 94305, USA.
e-mail: drh@stanford.edu

Steven K. Katona (Ph.D. in Biology) is managing director of the Ocean Health Index project for Conservation International. Previously he was a founding faculty member, then president at College of the Atlantic in Bar Harbor, Maine, where his laboratory pioneered collaborative studies on individual photo-identification of humpback and finback whales to study their distribution, abundance and population stock sub-structure. His Ph.D. dissertation was the first demonstration that diffusible sex pheromones stimulated the sexual behavior of copepods and contact sex pheromones probably regulated species-specific mating.
Address: Conservation International, Betty and Gordon Moore Center for Science and Oceans, 2011 Crystal Drive, Suite 500, Arlington, VA 22202, USA.
e-mail: skatona@conservation.org

Frédéric Le Manach (Ph.D. student) studies at the University of British Columbia's Fisheries Centre, and at the French Research Institute for Development (IRD). His research focuses on international fishing access agreements.
Address: Fisheries Centre, University of British Columbia, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada
e-mail: f.lemanach@fisheries.ubc.ca.
Address: Institut de Recherche pour le Développement, UMR212 Ecosystèmes Marins Exploités, Avenue Jean Monnet, BP 171, Sète cedex 34203, France.

Daniel Pauly (Ph.D. in Fisheries Biology) is a Professor of Fisheries at the Fisheries Centre, University of British Columbia, Vancouver. His current research interests focus on documenting the impact of fisheries and global warming on marine ecosystems worldwide.

Address: Fisheries Centre, University of British Columbia, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada.
e-mail: d.pauly@fisheries.ubc.ca

Andrew A. Rosenberg (Ph.D. in Biology) is the director of the Center for Science and Democracy within the Union of Concerned Scientists. He is the author of scores of peer-reviewed studies and reports on fisheries and ocean management and has published on the intersection between science and policy making.
Address: Center for Science and Democracy, Union of Concerned Scientists, 2 Brattle Square, Cambridge, MA 02138, USA.
e-mail: arosenberg@ucsusa.org

Jameal F. Samhouri (Ph.D. in Ecology and Evolutionary Biology) is a Research Fisheries Biologist at the U.S. National Oceanic and Atmospheric Administration's (NOAA's) Northwest Fisheries Science Center. His research focuses on the science needed to support ecosystem-based management of the ocean, with particular attention to trade-offs and thresholds related to alternative conservation and management decisions.
Address: Conservation Biology Division, Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2725 Montlake Blvd E, Seattle, WA 98115, USA.
e-mail: jameal.samhouri@noaa.gov

Courtney Scarborough (M.S. in Environmental Science and Management) is a Project Scientist at the National Center for Ecological Analysis and Synthesis (NCEAS). Her research interests lie at the intersection of innovative marine science and applied management solutions.
Address: National Center for Ecological Analysis and Synthesis (NCEAS), 735 State Street, Suite 300, Santa Barbara, CA 93101, USA.
e-mail: scarborough@nceas.ucsb.edu

U. Rashid Sumaila (Ph.D. in Economics) is Professor and Director of the Fisheries Economics Research Unit, Fisheries Centre, the University of British Columbia. He specializes in bioeconomics, marine ecosystem valuation and the analysis of global issues such as fisheries subsidies, illegal fishing and the economics of high and deep seas fisheries. He also studies how emerging threats to the ocean, e.g., climate change and oil spills, are likely to impact the economics of fisheries worldwide.
Address: Fisheries Centre, University of British Columbia, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada.
e-mail: r.sumaila@fisheries.ubc.ca

Reg Watson (Ph.D in Parasitology) is a Professor at the Institute for Marine and Antarctic Studies as the University of Tasmania, Australia. His research maps global fisheries catch, effort and seafood sourcing, and their interactions with marine ecosystems. He collaborates in global studies of marine biodiversity, economics of fishing, and impacts on birds and mammals, with aims of developing better ways to assess the health, of exploited marine systems, the impacts of climate change, and the social consequences of mismanagement.
Address: IMAS, University of Tasmania, Private Bag 49, Hobart, TAS 7001, Australia.
e-mail: rwatson@ecomarres.com

Dirk Zeller (Ph.D. in Marine Ecology) is a marine biologist and fisheries scientist, and is the Senior Researcher and Project Manager of the *Sea Around Us* project, Fisheries Centre, University of British Columbia. His research interests include global catch reconstructions and associated Illegal, Unreported and Unregulated fishing, ocean governance and policy, as well as resource economics.
Address: Fisheries Centre, University of British Columbia, 2202 Main Mall, Vancouver, BC V6T 1Z4, Canada.
e-mail: d.zeller@fisheries.ubc.ca