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Concern about the collapse of overexploited fish populations and the safety of consuming seafood can complicate determining what types of fish are best to eat. In recent years, public attention has become increasingly focused on oceanic environmental contaminants, which may be toxic to seafood consumers in sufficient doses. Laudable education campaigns have been established to inform consumers about seafood choices that are sustainable, and to provide information on which fish are deemed safe for human consumption. We found that unsustainable seafood items also present higher health risks (as indexed by mercury concentrations) and do not necessarily provide greater health benefits (as indexed by omega-3 fatty acid concentrations) as compared with sustainable seafood items. Our results have broad implications for identifying effective approaches for informing consumers about the health risks and benefits of different seafood choices, while simultaneously addressing the ecological consequences of fishing and fish farming.

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Seafood is generally a healthful food option that brings many benefits (Figure 1; Dorea 2005; McMichael and Butler 2005). It is rich in high-quality proteins, vitamins, and minerals, and some species contain high levels of long-chain omega-3 fatty acids, namely eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) (Meyer *et al.* 2003). Numerous studies show that consumption of fatty fish and fish oils can lead to safer pregnancies (Olsen *et al.* 1993; Buck *et al.* 2003), lower cardiovascular disease risk (Siscovick *et al.* 1995; Bouzan *et al.* 2005; König *et al.* 2005), and other health benefits (Simopoulos 1991). However, some types of seafood, particularly large, long-lived, or top predator species, often contain higher concentrations of mercury (Hg) or organohalogen compounds such as polychlorinated biphenyls (PCBs). At elevated levels, these contaminants present risks to human health, particularly to the developing fetus and young children (NRC 2000). Methylmercury and other contaminants bioaccumulate in the body over time and biomagnify through the food chain (Rasmussen *et al.* 1990; Cabana *et al.* 1994; Watras *et al.* 1998). Thus, long-lived species (eg orange roughy [*Hoplostethus atlanticus*], Chilean seabass [*Dissostichus eleginoides*], and groupers [*Epinephelus* and *Mycteroperca* spp]), as well as high trophic level predators (eg sharks, king mackerel [*Scomberomorus cavalla*], swordfish [*Xiphias gladius*], and other billfish), generally have relatively high tissue concentrations of contaminants such as Hg (Burreau *et al.* 2006; Burger and Gochfeld 2011). Many top predator species are also vulnerable to overfishing, given their life-history characteristics (Branch *et al.* 2010; Pinsky *et al.* 2011).

In a nutshell:

- Studies of consumer response to seafood awareness campaigns indicate that health attributes of seafood are often a considerably more important factor in purchasing decisions than whether the species was harvested sustainably
- We present the first quantitative examination of associations between sustainability and human health-oriented seafood rankings, as well as consistency across seafood sustainability rankings
- We found that the more sustainable items were also consistently safer to consume
- A plausible explanation for this pattern is that large or long-lived fish tend to accumulate larger amounts of mercury and are more susceptible to overfishing

Overfishing is the primary cause of global declines among marine fish populations (Myers and Worm 2003; UNEP 2007). Various sustainable seafood awareness campaigns have been established to educate consumers and promote responsible fishing and farming practices. Although surveys have consistently shown that these efforts have raised awareness, it is difficult to measure their direct effect in terms of changing fishing or farming practices (Jacquet *et al.* 2010). Several of these seafood awareness programs have included suggestions for "best choices" based on contaminant levels and omega-3s in addition to ecological sustainability. For example, Environmental Defense Fund began denoting fish with elevated Hg or PCB levels on its Seafood Selector guide in 2004 and added special designations for high-omega-3 species in 2006. Similarly, the Monterey Bay Aquarium (MBA) released a "Super Green" list of seafood items that are high in omega-3s, are low in Hg or PCBs, and are caught sustainably (Monterey Bay Aquarium 2009).

There are many knowledge gaps regarding the relative health risks and benefits of seafood. For example, with information about omega-3s only, consumers may undermine health objectives by eating highly contaminated fish. Mercury intake and exposure risk are difficult to esti-

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Figure 1. *Consumers buying seafood need to balance health-related information about omega-3 fatty acids and mercury content with messages about the importance of choosing sustainably harvested or produced fish and shellfish.*

mate because seafood Hg concentrations can be highly variable, even within a species (Sunderland 2007). Health benefits associated with eating fish may be higher if alternatives include protein sources that are higher in saturated fat. In addition, despite similar scoring methodologies and a high level of agreement, some discrepancies remain between various sustainable seafood decision guides (Roheim 2009; Jacquet *et al.* 2010). Therefore, there are cases where it may be difficult for a non-specialist to make an informed decision based on one criterion alone. For instance, the current Seafood Watch iPhone (Apple Inc) application from MBA lists 27 different tuna entries with health and ecological recommendations that range from "Best" to "Avoid". Although the collective body of information reflects the complexity of the global seafood market, it has the potential to confuse conscientious consumers (Jacquet *et al.* 2010), who may then inadvertently ignore well-intended information or make partially informed choices.

There is a need to balance ecological risks associated with unsustainable production or harvesting (eg greater risk of fishery collapse), health risks of excessive contaminant exposure, and benefits obtained from increased fish consumption (eg omega-3 intake). Consumers are getting mixed health messages about how much fish to eat (eg eat seafood for omega-3s versus avoid seafood because it is contaminated) or may believe that they should avoid fish from a sustainability standpoint. Given previous research that suggests consumers are more interested in the health attributes of seafood than sustainability (Roheim 2009), one may predict that a consumer facing this trade-off will usually opt for healthful over sustainable seafood. Here, we compare seemingly disparate consumer metrics (sustainability, omega-3 levels, and Hg concentrations) associated with seafood consumption and evaluate consistency in eco-ranking schemes to identify broadly accepted consumer recommendations.

Methods

Human health indices

We developed an ecological and health matrix based on an extensive literature review (WebTable 1). We use Hg as the metric for health risk because of the large body of evidence demonstrating that Hg poses a health risk, for both acute and chronic low-level exposures (NRC 2000). Other contaminants in seafood, such as PCBs, also have associated health risks, but concentrations of these contaminants in marine fish (Storelli *et al.* 2007; Webster *et al.* 2009) and their health-related consequences (Johnson *et al.* 1999; McKelvey *et al.* 2010) are less well understood as compared with those of Hg. We use omega-3 fatty acid concentrations as the metric for health benefit because of the well-documented health benefits associated with its consumption (Simopoulos 1991; Olsen *et al.* 1993; Siscovick *et al.* 1995; Buck *et al.* 2003; Bouzan *et al.* 2005; König *et al.* 2005). Although there is also evidence that selenium (Se) may have a protective effect against Hg toxicity (Berry and Ralston 2008), the evidence is inconsistent across studies and likely depends on the relative concentrations and chemical forms of Hg and Se (Khan and Wang 2009; Dang and Wang 2011). Moreover, as with PCBs, there is a much smaller knowledge base regarding Se concentrations in commercial fish as compared with that of Hg and omega-3 fatty acid concentrations.

Indices of sustainability

Because quantifying the sustainability of seafood is not straightforward, we used multiple metrics of sustainability in our analyses, to reflect the varying approaches – online and in the literature – to measuring sustainability. These include the MBA and Blue Ocean Institute (BOI) -derived sustainability rankings, fishery vulnerability data from FishBase (Froese and Pauly 2010), and a global meta-analysis of fisheries performance through the use of population size (B/B_{MSY}, hereafter "B_{relMSY}") and fishing mortality (μ/μ_{MSY}, hereafter "μ_{relMSY}") relative to estimates of maximum sustainable yield (MSY) (Worm *et al.* 2009). Below, we describe the methods used to standardize and calculate each of the indices used in our analyses.

MBA/BOI rankings

These rankings are specifically designed for consumer use and include both wild caught and farmed fish on an equivalent numerical or color-coded scale. Although characterized by minor differences in scoring and weighting, the two schemes are generally consistent across major scoring categories. For wild fisheries, MBA and BOI both assess life history, population levels, bycatch, gear impacts on habitat, and management effectiveness. For farmed fish, both guides include risk assessments of feed use, potential for escapes, incidence of disease and parasites, extent of pollution and habitat impacts, and effectiveness of management efforts (Monterey Bay Aquarium 2009; Blue Ocean Institute 2009). For our analysis, we downloaded all MBA and BOI sustainability rankings from their public websites as of October 2011. For all seafood items with an MBA ranking, 219 and 225 had Hg and omega-3 fatty acid concentration data, respectively, at the time of analysis. This dataset includes records from both wild and farmed seafood items. Below, we analyze the combined dataset rather than isolating the wild stocks, to ensure that our conclusions about the comparison of MBA and BOI are general. As we will show, our results are statistically indistinguishable, whether we include farmed fish or not.

Fisheries performance indices

To consider additional metrics of global fisheries sustainability, we analyzed data on harvest rate and biomass for the period 2005–2009 (from the supplementary online materials for Worm *et al.* 2009, reflecting stock assessments from 2001–2009). These data (1) include estimates of B_{relMSY} and μ_{relMSY} relative to the commonly used fisheries benchmark of MSY and (2) represent a fraction of the stocks analyzed with the seafood ranking data described above and do not include assessments of farmed fish. For example, popular seafood items like Pacific salmon (*Oncorhynchus* spp) – which would likely be good choices in terms of healthfulness and sustainability – are absent from this study (Worm *et al.* 2009). In addition, unlike the MBA/BOI ranking systems described above, fisheries performance data (eg μ_{relMSY} or B_{relMSY}) do not include effects on ecosystem quality (eg bycatch, habitat impacts) – additional factors that may be important for some consumers.

Vulnerability

As an alternate metric of fishery sustainability, we obtained vulnerability values for each species according to scientific name from FishBase (Froese and Pauly 2010). Vulnerability values represent the inherent ability of a given species to respond to fishing pressures, which can be used as an indicator of extinction risk. These values were derived from life-history and ecological metrics, including maximum length, fecundity, and mortality, and the uncertainty associated with these factors (Cheung 2005). Vulnerability values represent vulnerability to fishing pressures and thus only apply to wild populations. Therefore, we do not include farmed fish in any analysis that relies on the vulnerability data.

Analyses

Consistency in eco-rankings

To examine consistency in eco-rankings between MBA and BOI, we assigned scaled numeric ranks to BOI and MBA classifications. For the MBA list we assigned scores of 1, 2, and 3 to Green, Yellow, and Red risk categories, respectively. Unlike MBA, BOI has five risk categories (Green, Light green, Yellow, Orange, and Red), based on raw numeric scores ranging from 0 to 4. We thus binned the BOI raw scores into three equally sized categories and assigned these categories scores of 1, 2, and 3, accordingly. In particular, BOI raw scores of 0–1.33 (BOI Orange and Red categories) were assigned a scaled score of 3, BOI raw scores of 1.34–2.66 (BOI Yellow and Light green categories) were assigned a scaled score of 2, and BOI raw scores of 2.67–4 (BOI Green category) were assigned a scaled score of 1. We then calculated pairwise differences in scaled numeric ranks (ie $d = MBA_{score} - BOI_{score}$) and tested the null hypothesis H_0: $d = 0$ using a one-sample t test. Scaled MBA scores were higher on average ($\bar{d} = 0.18$, standard deviation = 0.62, $t = 3.86$, degrees of freedom [df] = 177, $P < 0.0001$); however a large fraction (104 of 178) of the scaled scores were identical ($d = 0$). Thus, the indices for a majority of seafood items were the same but, where the two schemes differ, MBA was more conservative.

Sustainability and health

We employed three approaches to evaluate relationships between ecological and health metrics. First, we used MBA risk categories (Red, Yellow, and Green) in a one-factor analysis of variance to compare (1) mean Hg concentrations and (2) mean omega-3 fatty acid concentrations. Datasets for Hg and omega-3 fatty acid were skewed and exhibited unequal variance among classes of MBA risk. These violations of parametric statistical approaches were rectified by log-10 transforming mean Hg and mean omega-3 values. Hence, our analyses below rely on transformed data. Second, we examined correlations between Hg levels and omega-3 concentrations across the entire dataset. Third, we examined the relationship between global fisheries performance (μ_{relMSY} and B_{relMSY}), contamination (Hg concentrations), and health benefits (omega-3 concentrations). To do this, we used principal components analysis (PCA) to group seafood items in terms of orthogonal components of the variance based on these three categories. We conducted our analysis with PCA because harvest and biomass are co-linear; hence we could not analyze their correlation with Hg and EPA-DHA independently. PCA removes the dependence and constructs new variables that are orthogonal.

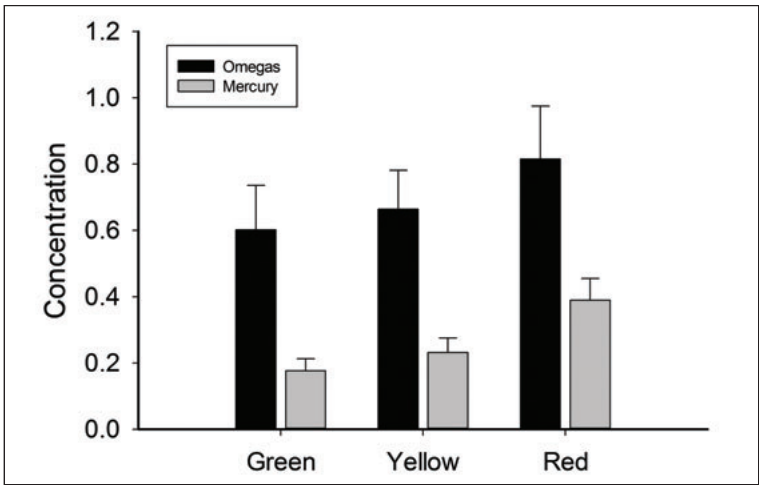

Figure 2. *Mercury (in parts per million) and omega-3 fatty acid concentrations (in grams per 100 grams) for Monterey Bay Aquarium (MBA) Seafood Watch rankings as of May 2011: Red (Avoid), Yellow (Good Alternatives), and Green (Best Choices). Bars are means and whiskers are one standard error. MBA ecological risk categories differ significantly in mean Hg concentrations (*F *= 4.88, df = 2216,* P *< 0.005) but not in mean omega-3 concentrations (*F *= 1.69, df = 2222,* P *> 0.15). The MBA Red category (ie high ecological risk) had significantly higher Hg concentrations than the other two ecological risk categories (*F *= 5.23, df = 1217,* P *< 0.025), whereas mean omega-3 concentrations were not significantly different between the Red and other categories (*F *= 3.27, df = 1223,* P *> 0.05). Thus, seafood items with high ecological risk do not have greater health benefits on average (as indexed by omega-3 fatty acid concentrations) but do present greater health risks on average (as indexed by Hg concentrations).*

Our PCA of the relationships between sustainability, contamination, and health benefits relies on a multivariate analysis that includes μ_{relMSY} and B_{relMSY} as additional proxies for sustainability. Here, we began with an initial dataset of 112 records for individual stocks with unique estimates of μ_{relMSY} and B_{relMSY} (Worm *et al.* 2009). However, not all of these records were associated with unique records for Hg or EPA–DHA concentrations. For many species, we had unique values for μ_{relMSY} and B_{relMSY} for multiple stocks and/or methods of harvest, but only a single value at the species level for all stocks for Hg and omega-3 concentrations. Because these stocks could not be treated as independent records in our PCA, we collapsed multiple records (where present for a single species) into average values, yielding a total of 44 records for which there were unique (ie independent) quantitative measures of Hg, EPA–DHA, μ_{relMSY}, and B_{relMSY}. We then performed a PCA on these four variables (after log-10 transformation of all four). To examine the sensitivity of our results to alternate metrics of sustainability, we also performed a PCA on our vulnerability metric from FishBase (Froese and Pauly 2010), contamination (Hg concentrations) and health benefits (omega-3 concentrations). As above, we used PCA to group fish species/stocks in terms of orthogonal components of the variance based on these three categories.

Results

Ecological risk categories differed significantly in mean Hg concentrations (Figure 2; *F* = 4.88, df = 2216, *P* < 0.005) but not in mean omega-3 concentrations (*F* = 1.69, df = 2222, *P* > 0.15). The MBA Red category (ie high ecological risk) had significantly higher Hg concentrations than the other two ecological risk categories (Red versus Yellow + Green; *F* = 5.23, df = 1217, *P* <0.025). In contrast, mean omega-3 concentrations were not significantly different between the Red versus Yellow + Green categories (*F* = 3.27, df = 1223, *P* > 0.05). Findings were similar and not significantly different when we analyzed wild seafood items separately from farmed seafood items. Ecological risk categories of wild stocks alone differed significantly in mean Hg concentrations (*F* = 7.19, df = 2195, *P* <0.001) but not in mean omega-3 concentrations (*F* = 0.93, df = 2206, *P* > 0.35). Thus, "unsustainable" seafood items pose higher health risks (as indexed by Hg concentrations) and do not appear to have greater health benefits (as indexed by omega-3 fatty acid concentrations).

The PCA results for the other risk estimates corroborate results from our univariate analyses on the larger dataset above. This analysis also suggests reasonably unambiguous groups of fish based on Hg, omega-3, and sustainability (Figure 3). For example, the first two principal components explained nearly 65% of the variation in the data (WebTable 2). The first component (PC1) loaded positively with Hg and μ_{relMSY} and negatively with B_{relMSY}. The second principal component (PC2) loaded negatively with Hg and positively with omega-3 (WebTable 3). Our analyses of alternative metrics of sustainability (using vulnerability from FishBase in place of μ_{relMSY} and B_{relMSY}) show the same patterns; the first two components explained > 80% of the variance in risk metrics (WebTable 4). The first component loaded negatively with all three risk metrics, whereas the second component loaded positively with omega-3 concentration and negatively with Hg concentration and vulnerability (WebTable 5; WebFigure 2). Collectively, these results suggest that vulnerable fish stocks/species are also associated with high Hg levels and lower omega-3 concentrations (albeit the latter relationship is not statistically significant).

In general, high (positive) scores for PC1 indicate species with low B_{relMSY} or high μ_{relMSY} and high Hg, and represent species that are ecologically vulnerable and pose human health risks (species listed in the Red group in WebTable 1). Examples include bluefin and other species of tuna (*Thunnus* spp), swordfish, and several species of Pacific rockfish (*Sebastes* spp). Similarly, there is a group with high-magnitude *negative* PC1 scores that represent good consumer choices for health and sustainability criteria (species listed in the Green group in WebTable 1). We used PC2 as an indicator of species with high omega-3 relative to Hg. The stocks with high PC2 scores have high ratios of omega-3 to Hg concentrations (Hg can still be high in these stocks).

Our results indicate that stocks with negative scores for PC1 and high positive scores for PC2 are the most likely to maximize health benefits of omega-3s while minimizing risks for the health of consumers (Hg) or the stock. Species with high PC2 scores include Atlantic mackerel (*Scomber scombrus*), bluefin tuna (*Thunnus thynnus*), European anchovy (*Engraulis encrasicolus*), Pacific herring (*Clupea pallasi*), and sablefish (*Anoplopoma fimbria*). However, because the PCA groups stocks as Green based on the combination of sustainability (high) and Hg (low), in a few cases we overestimate sustainability because of very low Hg (eg blue king crab [*Paralithodes platypus*]), and in other cases we overestimate threat because of high harvest rate rather than low Hg (eg winter flounder [*Pseudopleuronectes americanus*]). Finally, comprehensive metrics were limited for some species (eg Pacific herring, bluefin tuna), and, as a result, their PCA scores may shift as more data become available. For example, while Pacific herring might be expected to be sustainable given life-history traits, our results indicate a near-zero PC1 score and conflicting values for Hg and biomass (both low). Additionally, results for both Pacific herring and several species of rockfish based on PC1 scores should be considered with caution given that Hg values for several different species were identical.

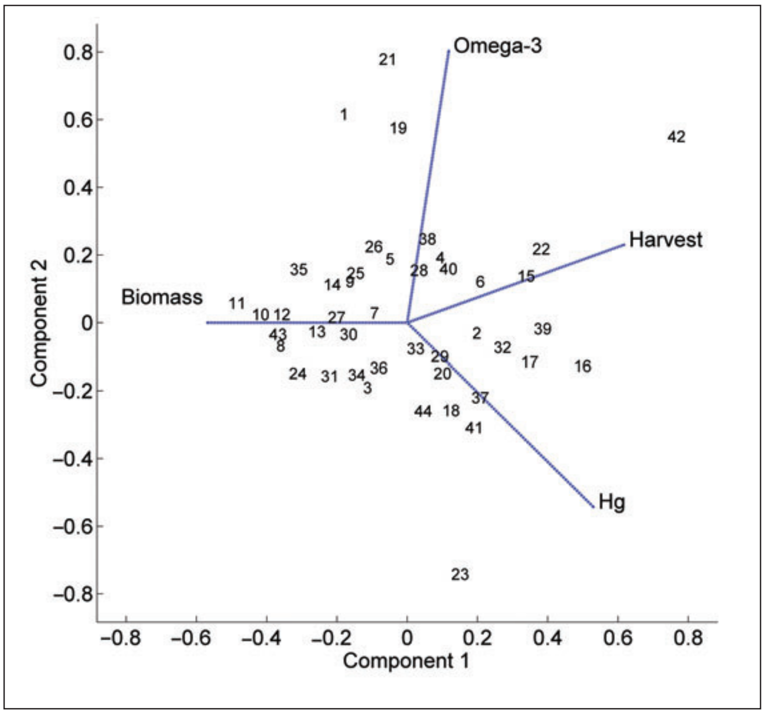

Figure 3. *Biplot of components 1 and 2 from PCA for four risk metrics (*μ_{relMSY}*,* B_{relMSY}*, Hg, and omega-3 concentrations). Key of species: (1) European anchovy, (2) Atlantic cod, (3) Pacific cod, (4) blue king crab, (5) red king crab, (6) snow crab, (7) tanner crab, (8) plaice (Alaska), (9) American plaice, (10) Pacific arrowtooth flounder, (11) English sole, (12) flathead sole, (13) Pacific rock sole, (14) yellowfin sole, (15) winter flounder, (16) yellowtail flounder, (17) gag grouper, (18) haddock, (19) Pacific herring, (20) American lobster, (21) Atlantic mackerel, (22) Spanish mackerel, (23) orange roughy, (24) Atlantic ocean perch, (25) Alaska pollock, (26) Atlantic pollock, (27) black rockfish, (28) blue rockfish, (29) bocaccio rockfish, (30) canary rockfish, (31) chilipepper rockfish, (32) cowcod rockfish, (33) darkblotched rockfish, (34) northern rockfish, (35) Pacific ocean perch, (36) widow rockfish, (37) yelloweye rockfish, (38) black cod sablefish, (39) swordfish, (40) albacore tuna, (41) bigeye tuna, (42) bluefin tuna, (43) skipjack tuna, and (44) yellowfin tuna.*

Discussion

We found a clear association between sustainability and Hg concentration for all metrics of sustainability. Species deemed unsustainable have significantly higher levels of Hg but do not have higher long-chain omega-3 fatty acid concentrations (Figure 2). Thus, if consumers make decisions aimed at minimizing Hg exposure, they will also tend to buy more sustainable seafood but will not necessarily increase intake of desirable omega-3s. Results from PCA through the use of fishery performance indices (Worm *et al.* 2009) corroborate these simple univariate analyses and allow us to delineate groups of fish based on human health (ie Hg, omega-3) and sustainability (μ_{relMSY} and B_{relMSY}; Figure 4; WebTables 2 and 4). Our first principal component can be used to identify seafood items that both are ecologically vulnerable and pose human health risks (eg bluefin tuna, orange roughy; WebTable 3). Here, vulnerable stocks are those with low B_{relMSY}, high μ_{relMSY}, or both. With few exceptions, species with negative PC1 scores have lower biomass, higher harvest rates, and higher Hg concentrations, but not significantly different omega-3 concentrations than species with positive PC1 scores (Figure 3). Our second principal component corresponds to stocks that have conflicting Hg and omega-3 concentrations. Within the group of stocks with high vulnerability (as indicated by PC1) there is a trend toward higher omega-3 concentrations (as indicated by PC2), but this increase in omega-3s is almost always offset by increase in Hg (Figure 3). Including both biomass and fishing mortality provides a more robust indicator of sustainability than each of these metrics alone. For example, some species have low harvest rates because they are heavily regulated as a result of high historical fishing pressure and low current biomass (relative to MSY).

Our PCA offers a rich set of results that provide some insight for consumers. First, of the 44 species in our database that have quantitative measures of μ_{relMSY}, B_{relMSY}, Hg, and omega-3, there is an unmistakable group (with

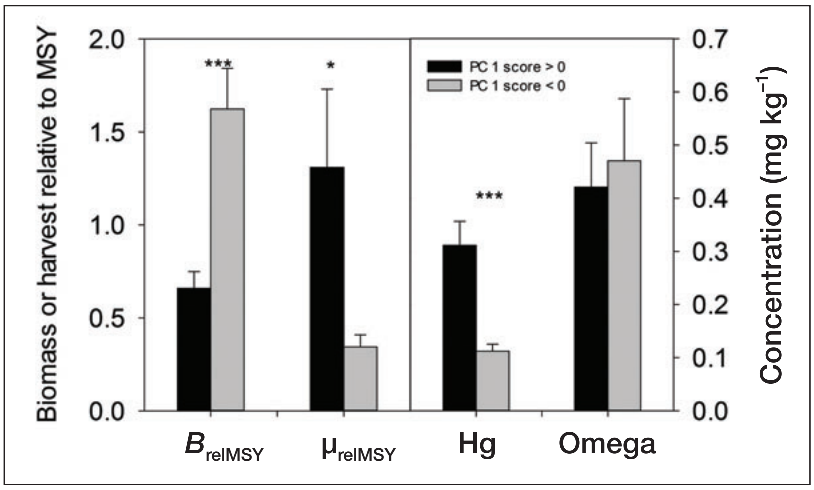

Figure 4. *Average biomass and harvest relative to maximum sustainable yield (MSY) (B_{relMSY}, μ_{relMSY}) and average mercury (Hg) and omega-3 (Omega; EPA+DHA) concentrations for seafood items with positive and negative scores for the first principal component (PC1). Negative scores for PC1 were associated with fish that pose little health risk by exposure to Hg and are sustainable, whereas positive scores for PC1 were associated with fish that have high levels of Hg and are not sustainable (high harvest, low biomass relative to MSY). Error bars are standard errors based on species-level variation (see WebTable 1). Asterisks indicate significant differences in two-sample* t *tests assuming unequal variances at the* $P < 0.005$ *(***) or* $P < 0.05$ *(*) level.*

high PC1 scores) that represent poor consumer choices *both* in terms of ecological sustainability and human health. Within this group, two species (swordfish and orange roughy; WebTable 1) contain mean Hg concentrations that exceed 0.5 parts per million (ppm), the regulatory maximum set by many countries (reviewed in Burger and Gochfeld 2011). Seven species contain mean Hg levels that exceed the US Environmental Protection Agency criterion of 0.3 ppm. Whether or not health consequences result from consuming fish with elevated Hg concentrations depends on many factors, including body weight and the amount of fish consumed. Moreover, some of these same species, notably bluefin tuna, have very high omega-3 relative to Hg. These fish (with high PC2 scores) have substantial health benefits in terms of omega-3 fatty acid concentrations but may not be good choices in terms of Hg and sustainability. Note that several potentially good choices (eg Pacific salmon) are absent from our database. These species likely would have low PC1 scores and high PC2 scores reflecting good consumer choices, depending on the stock. We therefore find support for the notion that human health and ecological sustainability go hand-in-hand – some highly vulnerable stocks also carry a health risk; however, this message is not broadly applicable according to metrics of population biomass (B_{relMSY}) that do not account for the broader ecosystem impacts of fishing.

The correlation between Hg and sustainability rankings is likely because MBA/BOI rankings are in part derived from life-history characteristics. These metrics are based on intrinsic characteristics of fish species that are strongly related to fish Hg concentrations. Specifically, large-bodied, long-lived, or high trophic level species – often highly susceptible to overfishing – tend to have high Hg concentrations due to bioaccumulation over time and biomagnification through the food web. The link between Hg and sustainability is demonstrated by the high PC1 score of most tuna species. However, there are clear exceptions to the link between sustainability and other health metrics. Omega-3s do not bioaccumulate and biomagnify to the same extent as methylmercury (Kainz *et al.* 2006, 2008), which may explain why we see no consistent relationship with omega-3 levels and sustainability rankings.

Our analyses provide a powerful tool for seafood consumers to make choices and for policy makers to make recommendations based on multiple preferences. Consumers can use the sustainability rankings to simplify decisions in choosing fish that are both eco-friendly and relatively healthful. While our results suggest that people should eat more of the sustainable alternatives to boost omega-3 intake (because omega-3 values are slightly lower on average in these sustainable fish than in the less-sustainable choices), further research should address whether increased demand could be met without compromising sustainability.

On average, seafood items with greater ecological impacts also present higher health risks (as indexed by Hg concentrations) and do not necessarily provide higher health benefits (as indexed by omega-3 fatty acid concentrations). While there are some important exceptions (eg blue rockfish [*Sebastes mystinus*] is classified as unsustainable but has low Hg), in general, consumers who choose to eat low Hg seafood are more likely to be choosing sustainable seafood at the same time. Moreover, consumers can obtain recommended amounts of omega-3 fatty acids by eating more low-omega-3 fish that are also defined as sustainable and low in Hg (Mozaffarian and Rimm 2006). Our analyses suggest that there are many seafood items that are good ecological choices and pose few health risks (low Hg). Our framework could be used to incorporate additional factors, such as other nutrients or environmental contaminants that are important to consumers. The simplicity of the close association between Hg concentration and sustainability should help to inform consumers and policy makers about good seafood choices. Broad dissemination of the message that sustainable fish pose fewer risks will allow citizens to enjoy the benefits of healthful seafood while simultaneously contributing to better fishing and farming practices.

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WebTable 1. PCA scores from analysis for all seafood items in Worm *et al.* (2009)* and corresponding Hg, omega-3 fatty acid concentrations, listed by descending PC1 scores

Species	*Stock*	*Biomass*	*Harvest rate*	*Hg*	*Omega-3*	*PC1*	*PC2*	*PC3*	*PC4*
Bluefin tuna	Eastern Atlantic	0.34	9.38	0.22	1.173	3.82	2.15	–1.89	1.13
Yellowtail flounder	Georges Bank	0.22	1.14	0.46	0.245	2.06	–0.72	0.60	–0.13
Swordfish	Mediterranean	0.94	1.26	0.95	0.754	1.85	–0.27	–1.04	–1.75
Spanish mackerel	US South Atlantic	0.47	0.91	0.45	1.341	1.61	0.81	–0.02	–1.57
Gag grouper	US Gulf of Mexico	1	1.99	0.39	0.247	1.44	–0.56	–1.22	0.08
Winter flounder	Southern New England–Mid Atlantic	0.16 (0.09–0.23)	1.56 (1.1–2.02)	0.09	0.245	1.38	0.60	1.03	1.51
Cowcod rockfish	Southern California	0.09	0.08	0.24	0.286	1.21	–0.38	2.51	–0.30
Snow crab	US Bering Sea	0.55	1.49	0.16	0.372	0.98	0.45	–0.22	0.47
Yelloweye rockfish	US Pacific Coast	0.83	0.61	0.6	0.286	0.97	–1.05	–0.30	–1.06
Atlantic cod	Canada–Iceland–New England–Norway–Russia	0.34 (0.02–0.83)	1.07 (0.27–2.4)	0.11 (0.11–0.66)	0.184	0.85	–0.20	0.54	0.93
Albacore tuna	North Atlantic–South Pacific	1.64 (0.81–2.46)	1.2 (0.91–1.49)	0.33	0.862	0.73	0.54	–1.28	–1.12
Bigeye tuna	Western Pacific	1.05	1.38	0.28	0.1	0.70	–1.32	–0.82	0.73
Haddock	Georges Bank–Gulf of Maine	0.99 (0.98–1)	0.99 (0.65–1.23)	0.31	0.131	0.58	–1.22	–0.56	0.26
Orange roughy	Southeast Australia	0.48	0.29	0.55	0.019	0.56	–3.67	0.67	0.77
American lobster	Rhode Island	0.61	0.73	0.21	0.17	0.47	–0.73	0.16	0.32
Bocaccio rockfish	US Southern Pacific Coast	0.32	0.1	0.26	0.286	0.45	–0.56	1.30	–0.61
Black cod	Alaska–US Pacific Coast	1.04 (1.02–1.05)	0.68 (0.66–0.69)	0.2	1.0565	0.31	0.99	–0.38	–1.07
Pacific herring	British Columbia	0.32 (0.03–0.91)	0.17 (0–0.4)	0.07	1.658	–0.18	2.16	1.45	–0.62
Red king crab	Norton Sound–Pribilof Islands–Bristol Bay	1.39	1.05	0.09	0.413	–0.24	0.77	–0.60	0.47
Pacific cod	Alaska/British Columbia	1.1 (1.04–1.14)	0.63 (0.18–0.93)	0.13	0.13	–0.30	–0.70	–0.24	0.79
Tanner crab	US Bering Sea	0.79	0.15	0.16	0.372	–0.40	–0.01	0.51	–0.51
Atlantic pollock	Northeast Arctic–Faroe Plateau–North Sea–New England	1.02 (0.56–1.7)	0.69 (0.3–0.97)	0.08	0.421	–0.46	0.78	–0.11	0.36
Alaskan pollock	Eastern Bering Sea	0.92	0.94	0.05	0.165	–0.63	0.28	–0.05	1.57
Atlantic mackerel	Northeast Atlantic	0.98	0.73	0.04	2.299	–0.64	2.93	–0.03	–0.22
American plaice	New England	0.7	0.3	0.07	0.245	–0.73	0.21	0.65	0.58

Continued

WebTable 1. – *continued*

Species	*Stock*	*Biomass*	*Harvest rate*	*Hg*	*Omega-3*	*PC1*	*PC2*	*PC3*	*PC4*
Canary rockfish	US Pacific Coast	0.86	0.04	0.14	0.286	–0.74	–0.23	0.61	–0.34
Black rockfish	US Pacific Coast	1.84 (1.45–2.23)	0.36 (0.19–0.53)	0.13	0.286	–0.89	–0.11	–0.44	–0.13
Yellowfin sole	Bering Sea and Aleutian Islands	2	0.69	0.08	0.245	–0.98	0.19	–0.70	0.60
European anchovy	South Africa	0.97	0.36	0.04	1.449	–1.01	2.31	0.32	–0.22
Rock sole	Bering Sea and Aleutian Islands	2.03 (1.03–3.02)	0.33 (0.21–0.45)	0.11	0.245	–1.10	–0.19	–0.46	0.04
Pacific Ocean perch	Alaska and US Pacific Coast	0.88 (0.69–1.7)	0.14	0.06	0.286	–1.25	0.46	0.67	0.51
Ocean perch	Newfoundland–Labrador Shelf	1.91	0	0.14	0.215	–1.33	–0.64	–0.06	–0.39
Alaska plaice	Bering Sea and Aleutian Islands	2.2	0.06	0.13	0.245	–1.39	–0.43	–0.26	–0.36
Flathead sole	Bering Sea and Aleutian Islands	1.83	0.18	0.08	0.245	–1.49	0.04	–0.11	0.26
Skipjack tuna	Central Western Pacific	4.38	0.31	0.12	0.263	–1.56	–0.27	–1.18	–0.26
Arrowtooth flounder	Bering Sea and Aleutian Islands	3.26 (2.7–3.8)	0.26 (0.21–0.31)	0.08	0.245	–1.78	0.02	–0.73	0.21
English sole	US Pacific Coast	3.83 (1.23–6.24)	0.22 (0.06–0.37	0.06	0.245	–2.09	0.14	–0.78	0.32
Blue king crab	Pribilof Islands–St Matthew Island	0.77	0	0.09	0.413	0.52	0.66	2.94	0.21
Yellowfin tuna	Central Western Pacific	1.22	0.8	0.28	0.1	0.19	–1.49	–0.57	0.37
Blue rockfish	California	0.75	1.55	0.07	0.286	0.18	0.79	–0.33	1.32
Darkblotched rockfish	US Pacific Coast	0.73	0.29	0.24	0.286	0.09	–0.50	0.34	–0.53
Widow rockfish	US Pacific Coast	0.88	0.05	0.24	0.286	–0.34	–0.64	0.45	–0.81
Northern rockfish	Bering Sea and Aleutian Islands	1.42	0.13	0.24	0.286	–0.55	–0.65	–0.10	-0.82
Chilipepper rockfish	US Southern Pacific Coast	1.96	0.03	0.24	0.286	–0.89	–0.73	–0.27	–1.00

Notes: For each species, stocks are separated by dashes in the corresponding column for stock. Parentheses indicate ranges of values for multiple stocks for each mean value. We also provide a consumer recommendation category (red, green, or gray) based on values of our first principal component (PC1). Red choices (generally, PC1 scores > 0.2) are those that have high Hg and score low on sustainability metrics (because of either high harvest or low biomass) relative to other choices. Green choices (generally, PC1 scores <0) are those that have low Hg and are more sustainable based on the same metrics. Gray choices indicate species for which the two metrics do not align well (eg either high Hg and healthier populations, or low Hg and depleted populations), including several rockfish species with aggregated Hg concentrations. Here, healthful choices may not indicate sustainability or a sustainable choice may have relatively high Hg levels. Note also that biomass and harvest estimates may have changed since estimates were published in Worm *et al*. (2009).

* Worm B, Hilborn R, Baum JK, *et al*. 2009. Rebuilding global fisheries. *Science* **325**: 578–85.

WebTable 2. Variance associated with the principal components extracted from harvest, biomass, omega-3, and Hg data

Metric	*Component 1*	*Component 2*	*Component 3*	*Component 4*
Standard deviation	1.17	1.10	0.91	0.77
Proportion of variance	0.34	0.30	0.21	0.15
Cumulative proportion	0.34	0.65	0.85	1.00

WebTable 3. Loadings of risk metrics with each principal component (variables: biomass, harvest, omega-3, and Hg)

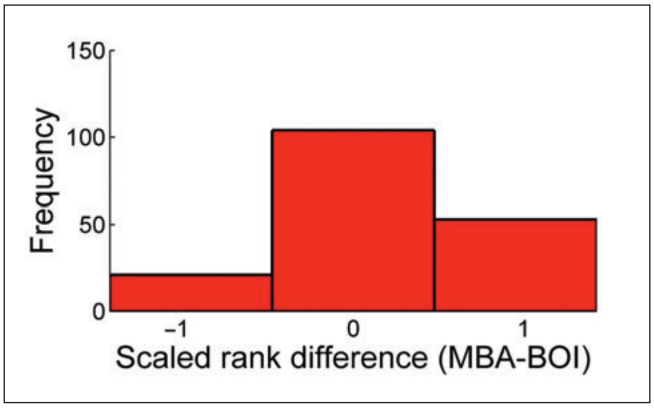
Risk metric	*Component 1*	*Component 2*	*Component 3*	*Component 4*
Harvest	0.617	0.23	–0.576	0.485
Biomass	–0.569	–	–0.797	–0.179
Hg	0.53	–0.543	–0.176	–0.627
Omega-3	0.118	0.803	–	–0.583

WebTable 4. Variance associated with the three principal components extracted from FishBase (vulnerability), omega-3, and Hg data

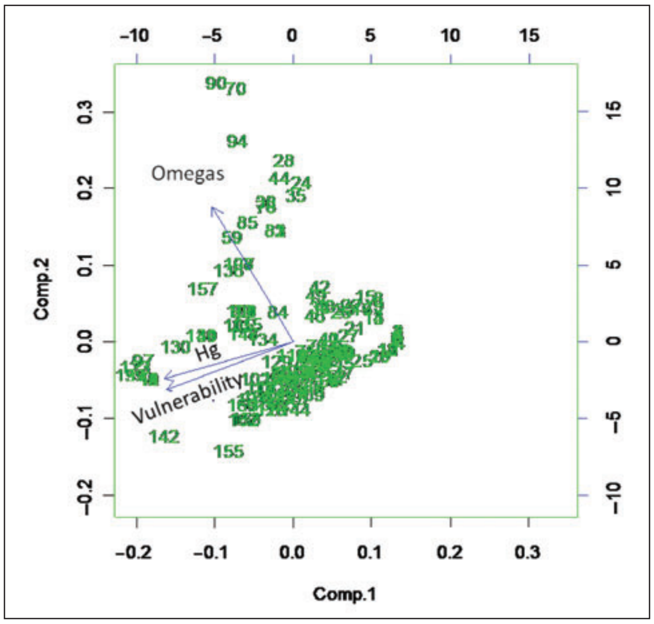
Metric	*Component 1*	*Component 2*	*Component 3*
Standard deviation	1.24	0.95	0.75
Proportion of variance	0.51	0.298	0.188
Cumulative proportion	0.515	0.81	1.0

WebTable 5. Loadings of risk metrics with each principal component for vulnerability data (variables: vulnerability, omega-3, and Hg)

Risk metric	*Component 1*	*Component 2*	*Component 3*
Omega-3	–0.407	0.912	–
Hg	–0.652	–0.249	–0.717
Vulnerability	–0.640	–0.326	0.696



WebFigure 1. *Histogram of differences in scaled scores of ecological risk (d = $\mathrm{MBA_{score}} - \mathrm{BOI_{score}}$). Each bar is the frequency of a single value for differences in scaled scores.*



WebFigure 2. *Biplot of components 1 and 2 from PCA of three risk metrics (Hg and omega-3 concentrations, and alternative vulnerability metric from FishBase).*