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Sustaining seafood for public health

Leah R Gerber¹, Roxanne Karimi², and Timothy P Fitzgerald³

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.

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 (e.g., orange roughy [Hoplostethus atlanticus], Chilean seabass [Dissostichus eleginoides], and groupers [Epinephelus and Mycteroperca spp.]), as well as high trophic level predators (e.g., 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).

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).

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.

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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 Balston 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 ($\mu/B_{MSY}$, hereafter “$\mu_{relMSY}$”) 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 \( B_{\text{relMSY}} \) and \( \mu_{\text{relMSY}} \) 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 \( \mu_{\text{relMSY}} \) or \( B_{\text{relMSY}} \)) 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 \( d = \text{MBA}_{\text{score}} - \text{BOI}_{\text{score}} \)) 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 (\( \mu_{\text{relMSY}} \) and \( B_{\text{relMSY}} \)), 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.
Our PCA of the relationships between sustainability, contamination, and health benefits relies on a multivariate analysis that includes \( \mu_{\text{MSY}} \) and \( B_{\text{relMSY}} \) as additional proxies for sustainability. Here, we began with an initial dataset of 112 records for individual stocks with unique estimates of \( \mu_{\text{MSY}} \) and \( B_{\text{relMSY}} \) (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 \( \mu_{\text{MSY}} \) and \( B_{\text{relMSY}} \) 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, \( \mu_{\text{MSY}} \), and \( B_{\text{relMSY}} \). 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 \( \mu_{\text{MSY}} \) and negatively with \( B_{\text{relMSY}} \). 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 \( \mu_{\text{MSY}} \) and \( B_{\text{relMSY}} \)) 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 \( B_{\text{relMSY}} \) or high \( \mu_{\text{MSY}} \) 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 sustain-

![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 (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 (\( F = 3.27, df = 1223, P > 0.05 \)). 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 \( \mu_{\text{MSY}} \) and negatively with \( B_{\text{relMSY}} \). 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 \( \mu_{\text{MSY}} \) and \( B_{\text{relMSY}} \)) 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 \( B_{\text{relMSY}} \) or high \( \mu_{\text{MSY}} \) 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 sustain-
ability 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 [Pleuronectes 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.

## 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 ($\mu_{\text{relMSY}}$ and $B_{\text{relMSY}}$; 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 $B_{\text{relMSY}}$ high $\mu_{\text{relMSY}}$ 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 $\mu_{\text{relMSY}}$ $B_{\text{relMSY}}$ Hg, and omega-3, there is an unmistakable group (with
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related to fish Hg concentrations. Specifically, large-bodied, intrinsic characteristics of fish species that are strongly
life-history characteristics. These metrics are based on
likely because MBA/BOI rankings are in part derived from
for the broader ecosystem impacts of fishing.

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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
roughly; WebTable 1) contain mean Hg concentrations
that exceed 0.5 parts per million (ppm), the regulatory maxi-
num 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 rela-
tive to Hg. These fish (with high PC2 scores) have substan-
tial health benefits in terms of omega-3 fatty acid concen-
trations 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; how-
ever, this message is not broadly applicable according to
WebTable 1). Asterisks indicate significant differences in two-sample t tests assuming
unequal variances at the P<0.005 (***) or P<0.05 (*) level.

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 concen-
trations) and do not necessarily provide higher health ben-
efits (as indexed by omega-3 fatty acid concentrations).
While there are some important exceptions (eg blue rock-
fish [Sebastes mystus] 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 recom-

dended 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 associ-
ation 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 con-
tributing to better fishing and farming practices.

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Aquarium), J Sabo (Arizona State University), and J
Senko (Blue Ocean Institute) for insightful comments on

Figure 4. Average biomass and harvest relative to maximum sustainable yield
(MSY) (B<sub>relMSY</sub>, H<sub>relMSY</sub>) 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 Web-
Table 1). Asterisks indicate significant differences in two-sample t tests assuming

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References


Aquat Sci 47: 262–70.

Baltic Sea and the northern Atlantic Ocean.


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Baltic Sea and the northern Atlantic Ocean.


**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

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

*Continued*
### WebTable 1. – continued

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

**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).

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

<table>
<thead>
<tr>
<th>Metric</th>
<th>Component 1</th>
<th>Component 2</th>
<th>Component 3</th>
<th>Component 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation</td>
<td>1.17</td>
<td>1.10</td>
<td>0.91</td>
<td>0.77</td>
</tr>
<tr>
<td>Proportion of variance</td>
<td>0.34</td>
<td>0.30</td>
<td>0.21</td>
<td>0.15</td>
</tr>
<tr>
<td>Cumulative proportion</td>
<td>0.34</td>
<td>0.65</td>
<td>0.85</td>
<td>1.00</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Risk metric</th>
<th>Component 1</th>
<th>Component 2</th>
<th>Component 3</th>
<th>Component 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvest</td>
<td>0.617</td>
<td>0.23</td>
<td>–0.576</td>
<td>0.485</td>
</tr>
<tr>
<td>Biomass</td>
<td>–0.569</td>
<td>–</td>
<td>–0.797</td>
<td>–0.179</td>
</tr>
<tr>
<td>Hg</td>
<td>0.53</td>
<td>–0.543</td>
<td>–0.176</td>
<td>–0.627</td>
</tr>
<tr>
<td>Omega-3</td>
<td>0.118</td>
<td>0.803</td>
<td>–</td>
<td>–0.583</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Metric</th>
<th>Component 1</th>
<th>Component 2</th>
<th>Component 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation</td>
<td>1.24</td>
<td>0.95</td>
<td>0.75</td>
</tr>
<tr>
<td>Proportion of variance</td>
<td>0.51</td>
<td>0.298</td>
<td>0.188</td>
</tr>
<tr>
<td>Cumulative proportion</td>
<td>0.515</td>
<td>0.81</td>
<td>1.0</td>
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</table>

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

<table>
<thead>
<tr>
<th>Risk metric</th>
<th>Component 1</th>
<th>Component 2</th>
<th>Component 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omega-3</td>
<td>–0.407</td>
<td>0.912</td>
<td>–</td>
</tr>
<tr>
<td>Hg</td>
<td>–0.652</td>
<td>–0.249</td>
<td>–0.717</td>
</tr>
<tr>
<td>Vulnerability</td>
<td>–0.640</td>
<td>–0.326</td>
<td>0.696</td>
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</tbody>
</table>

WebFigure 1. Histogram of differences in scaled scores of ecological risk (d = MBAcore – BOIcore). 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).