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LETTER

Financial and Ecological Implications of Global Seafood Mislabeling

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Abstract

Consumers and regulators influence conservation of marine finfish by controlling harvest demand and availability. Consumer power to choose sustainably-harvested species is threatened by seafood mislabeling, which may be a product of fraud or human error. Here we examined the prevalence of mislabeling, and its financial and ecological implications, by compiling and analyzing an international dataset of DNA barcoding studies of marine finfish ($n = 43$). On average, DNA-identified species sold were less expensive (−2.98% ex-vessel price) and more sustainable (+3.88% IUCN status) than species listed on their label; thus, mislabeling had a net positive impact on the conservation status of sold species. However, ecological impacts of some frequently mislabeled taxa were potentially severe, suggesting eco-conscious consumers may want to avoid certain genera. Mislabeling may be reduced by increasing traceability and identification of seafoods, particularly at points in the chain-of-custody beyond ports, where the majority of mislabeling occurred.

Introduction

Marine finfish are often managed to balance conflicting conservation and harvest objectives (Rosenberg *et al.* 1993). Market-based seafood governance allows consumers to reconcile these interests. In theory, eco-labeled products can enable consumers to select “sustainable” seafoods, shifting market demands away from species of conservation concern (Erwann 2009). The sustainable seafood movement has recently precipitated widespread use of certification programs, whereby fisheries are evaluated and the products of qualifying suppliers are advertised to consumers as “sustainable.” Indeed, major retailers such as Wal-Mart and Tesco have prioritized sourcing seafood from sustainable fisheries, including many that are vetted through certification programs. However, market-based efforts to alleviate fishing pressure on threatened species could be undermined by merchants (e.g., processors, fish markets, restaurants) mislabeling seafood items (Jacquet *et al.* 2010), for example by presenting species of conservation concern as alternative, “sustainable” options. To understand whether seafood mislabeling places imperiled species at further risk, we must examine factors that influence mislabeling and their potential impacts.

Mislabeling is thought to be common (30% of samples; [Pardo *et al.* 2016]), but its financial and ecological implications are unclear. Mislabeling may affect consumer finances (e.g., low-value species concealed as high-value species [Carvalho 2011; Cawthorn *et al.* 2012]) or health (e.g., poisoning from ciguatera and tetrodotoxin [Cohen *et al.* 2009; Garcia-Vazquez *et al.* 2010]). The primary ecological concern is that illegally-caught or vulnerable fish species are mislabeled to avoid detection or reap premiums for eco-labeled seafood (Wong & Hanner 2008). Mislabeling cause and effect could be linked: for example, if mislabeling is accidental, the effects of mislabeling on fished species and consumers could be minimal.

However, we hypothesize intentional mislabeling may introduce systematic bias in seafood replacement. If seafood is mislabeled to increase profit or replace scarce, high-value fish with plentiful, cheap alternatives, mislabeling may systematically cheat consumers financially but have enduring neutral or even positive ecological effects. Mislabeling could also shift consumer perception about the rarity of certain items (Hall *et al.* 2008), creating a false impression of sustainability. Finally, if items are mislabeled to appear more sustainable (Wong & Hanner 2008; Miller & Mariani 2010), mislabeling may exacerbate depletion of vulnerable species or create economic incentives for illegal fishing.

Here we ask if mislabeling results in substitution of lower-value species for higher-value ones, conceals species of lower conservation status, or substitutes plentiful finfish for rarer ones. Understanding whether mislabeling is primarily an issue of ecological status or economic fraud can suggest how urgently it should be tackled and by whom.

Methods

We compiled mislabeling information from DNA barcoding studies, species status information from the IUCN Red List, and price information from a global price index (Melnychuk *et al.* 2016). We calculated bootstrapped statistics for the difference in price and IUCN status across labeled (what item is listed as by retailer) and true (DNA detected identity) items to determine whether mislabeling appeared to lower the value or conservation status of what was served compared to what was ordered. We also examined whether the prevalence or consequence of mislabeling varied across genera, and correlated total production volume (fisheries and aquaculture; FAO 2014) with mislabeling proportions. Next, we constructed simple generalized linear models to examine which covariates (i.e., labeled genus, country of origin, purchase location) best predicted mislabeled proportion across five genera of commonly-consumed finfish.

Assembling barcoding data

We assembled barcoding data on seafood from peer-reviewed publications by searching Web of Science (WoS) and Google Scholar for papers that contained the topics "barcod,*" "seafood," and "mislabeling." We also included data from an FDA study that tested seafood samples at U.S. ports and a barcoding study performed by students in an undergraduate genetics course. From this original set (45 papers), we included only papers which (1) studied finfish (2) included raw barcoding data, and (3) reported sample sizes, resulting in 43 papers totaling 6754 samples. Samples were recorded at the highest resolvable taxonomic level (e.g., if sample sequences or label aligned with more than one species within the same genus, it was considered to be resolved to genus level). In total, 2145 samples (31.76%) were resolved to the genus level, 31 samples (0.46%) were resolved to the family level, and the remaining samples were resolved to a species level.

Conservation status

We evaluated whether true species were of greater conservation concern than labeled species using the most recent IUCN Red List Categories and Criteria (IUCN 2015). This conservation status is calculated based on a standardized extinction risk assessment. We chose IUCN conservation status, rather than criteria based on fishery stock assessments (e.g., FAO's review [2011]; and the RAM database [Ricard *et al.* 2012]); first, because many species in our sample were not covered by other assessments (IUCN: 6354 samples, RAM: 3061, FAO: 3378), and second, because we cannot resolve the catch locations of sampled seafood items, which is required to match items to the unique population (stock) fish originate from. IUCN Red List status correlates with and is slightly more conservative than stock assessment-based sustainability indices (Davies & Baum 2012). For labeled seafood products resolved to the family or genus level, we calculated IUCN status as the average status across species and tested sensitivity to this by removing genera- and family-only IUCN status estimates.

Price information

To compare value between labeled and true items, we compiled estimates of price for each species. Ex-vessel prices were reconstructed for each species (ASFIS_species entity) in the FAO catch database (Melnychuk *et al.* 2016). Ex-vessel price estimates represent amounts earned by fishers, which we used as a proxy for consumer price. Although consumer price and ex-vessel prices are not equivalent, ex-vessel price provides a lower bound on consumer price, and consumer price indices for seafood are only available for a small sample of countries (Dhyne *et al.* 2006). Compiled ex-vessel prices were based on export prices of all product types of species in the global FAO commodity export database, aggregated and weighted by product quantity (Melnychuk *et al.* 2016). Previous studies have constructed databases of ex-vessel prices for fin fish (e.g., Sumaila *et al.* 2007; Swartz *et al.* 2010). Here, we used Melnychuk *et al.* (2016) because it provides a weighted mean global price. These data provided different prices for each year; our samples were matched to price by year, so that price differences reflect the difference at the time of purchase.

Summary statistics

We bootstrapped the dataset 1000 times and collated summary statistics, including (1) proportion of mislabeled items, and (2) difference in IUCN stock status, and (3) percentage of ex-vessel price per kilo between labeled and true items. IUCN stock status was assigned integer values ("Critically Endangered": 0, "Endangered": 1, "Vulnerable": 2, "Near Threatened": 3, "Least Concern": 4; "Data Deficient" statuses were excluded) to calculate the status differences between labeled and true items. We calculated status of true and labeled items for alternative metrics (FAO Fisheries and Aquaculture Department, Marine and Inland Fisheries Service 2011; Ricard *et al.* 2012) similarly (see Supplementary Methods). To examine for publication bias in mislabeling proportion, we created a funnel plot (Møller & Jennions 2001). This plot suggested our dataset is not clearly biased toward or against publication of studies with a larger proportion of mislabeled items, but the data are considerably heterogeneous in mislabeling proportion across study (Figure S6). This heterogeneity supported a more in-depth examination of these statistics. For each of these analyses, we calculated summary statistics for genera that had more than 10 unique fish products.

Linear Models

Generalized linear models (GLM) were used to compare probabilities that a fish was mislabeled across countries, fish taxa labels, and purchase sources using a reduced set of genera. Models were constructed utilizing a beta-binomial response distribution, because overdispersion was detected in the data. The response variable was whether or not an item was mislabeled. Because there was not sufficient replication within taxa across our entire dataset, we modeled mislabeling only for the five most commonly consumed genera of finfish in the United States: Atlantic and Pacific salmon, tuna, catfish, and cod (Centers for Disease Control and Prevention [CDC] & National Center for Health Statistics [NCHS] 2010). We considered the fixed effects of genus and purchase location (levels: distributor, port, grocery, fish market, restaurant, sushi restaurant) on mislabeling in these five genera.

GLMs were fit using the gamlss package in R version 3.2.3. Akaike's Information Criterion (AIC) was used for model selection across the following suite of models. The full model is described in Equation (1), whereas alternative models and their associated AIC values are described in Table S2.

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1 \text{Genus} + \beta_2 \text{Country} + \beta_3 \text{Source} + \epsilon \quad (1)$$

where p refers to mislabeled probability, β_i represents the respective coefficient, genus represents the genus of the sample, country refers to the country from which the sample was obtained, and source refers to where the product was purchased.

Results

On average, true species were of improved conservation status (+0.038 increase in IUCN category, 95% bootstrapped confidence interval: 0.019-0.062; Data corrected on 4/20/17), lower cost (true item has 97.02% value of labeled item; 95.88–98.02%), and higher global production (adjusted $R^2 = 0.12$, $P = 0.009$) compared to labeled species. That is, mislabeling resulted in serving items of lower value but improved or equivalent conservation status. Total global production and mislabeled proportion were negatively correlated, providing some evidence mislabeling relates to seafood supply (Figure 1).

In contrast to overall trends, some labeled genera were frequently substituted, and more highly-endangered fish were detected than labels suggested (Figures 2 and 3). Some taxa were mislabeled in more than 50% of samples, including the family Sciaenidae (croakers, 100% mislabeled), the genera Acipenser (sturgeons, 82.35%), Pangasius (shark catfish, 90.24%), Mustelus (smooth-hound sharks, 77.78%), Argyrosomus (genus of croakers, 74.12%), Perca (perches, 63.24%), Seriola (amberjacks, 57.58%), Lutjanus (snappers, 67.56%), and Genypterus (cusk-eels, 50.42%). However, excluding snappers and cusk-eels, data for these taxa were taken from fewer than 100 samples, suggesting these numbers may be skewed due to low sample sizes. In addition, only 19 samples were labeled as "critically endangered" species, whereas 54 samples were genetically identified as "critically endangered" (Table S3), suggesting that mislabeling may conceal the sale of some highly-endangered fish. Conversely, 55 samples were labeled as "endangered" but genetically identified as "vulnerable," suggesting some species of higher conservation status were substituted for endangered menu items.

The monetary and conservation impacts of mislabeling varied across taxa. Items of lower conservation status and lower cost were substituted for snappers (true species had 65.13% price and −0.99 of a category improvement in IUCN status compared to labeled species). In some other genera, however, items with lower cost and improved

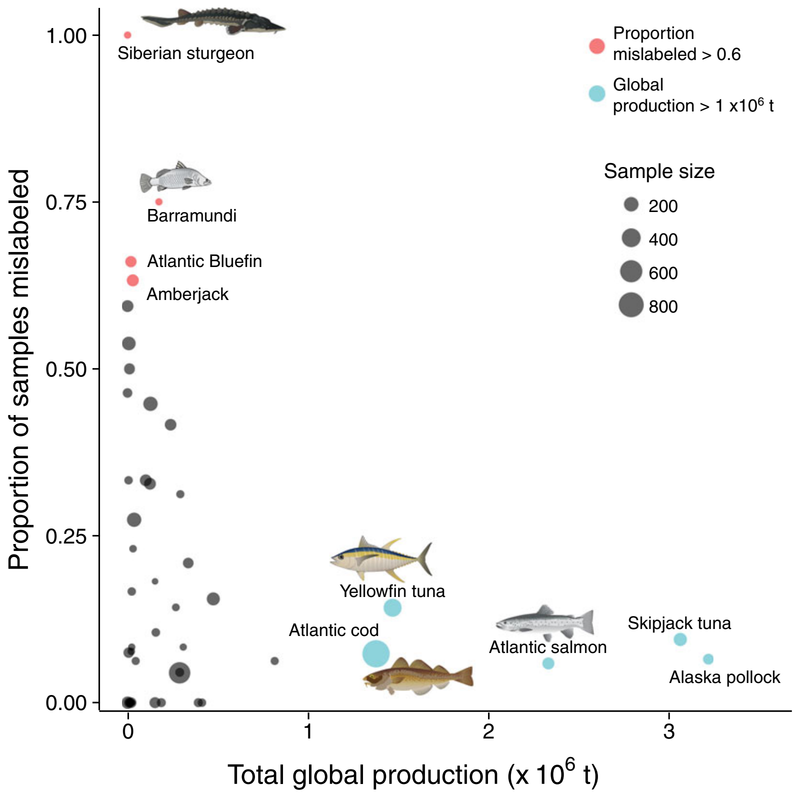

Figure 1 Relationship between weighted mislabeled proportion and global production. Fish images are courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

conservation status were substituted, including tuna (49.92%, +0.03), grouper (85.08%, +0.88) and flounder (92.34%, +0.83 Analysis corrected 4/20/17). Items of lower conservation status were substituted for eel (−1.33), smooth hound (−0.73), and croaker (−0.33; Figure 2), but prices were not available for these genera. Several labeled genera were substituted with higher value items; these included dolphinfish (131.94%), skipjack tunas (107.23%), and tunas (105.58%, +0.12).

Bootstrapping indicated an overall median mislabeling portion of 13.12% (95% quantile: 11.37–15.02%), which was lower than the weighted average across samples (23%). This suggests that several influential outliers inflate the overall mean proportion of mislabeling (i.e., the distribution of mislabeling proportion estimates is right-skewed). Our estimate is also lower than the mean mislabeling proportions reported by other large published studies on seafood mislabeling (32–51%: Cox *et al.* 2013; 30%: Pardo *et al.* 2016) though the mean of mislabeled proportion across studies in our analysis (35%) is closer to previously reported estimates, suggesting studies with smaller sample sizes may report a higher proportion of mislabeling.

When examining predictors of mislabeling across the top five genera consumed in the United States, the chosen GLM supported purchasing location as the second most influential predictor of mislabeling, after the null model (Figure. 5). That is, although no factor was a particularly strong predictor of mislabeling, retail source may explain some variation in mislabeling probability, compared with alternative models including predictors for the genus and country where samples were purchased (analysis corrected 4/20/17). Among sources, distributors had the highest probability of serving mislabeled items (mean = 0.184, SD = 0.136) whereas port samples had the lowest probability of being mislabeled (mean = 0.046, SD = 0.047). Samples from distributors displayed a wide range of variability in mislabeling probability; sushi restaurant (mean = 0.168, SD = 0.072) and market (mean = 0.174, SD = 0.048) samples had high probabilities of mislabeling, but narrower confidence intervals.

Discussion

These findings highlight that generally mislabeling results in sale of items of better conservation status and nearly equivalent price, and that regulators may be able to target specific genera (e.g., sturgeon) to mitigate the worst implications of mislabeling. We found, on average,

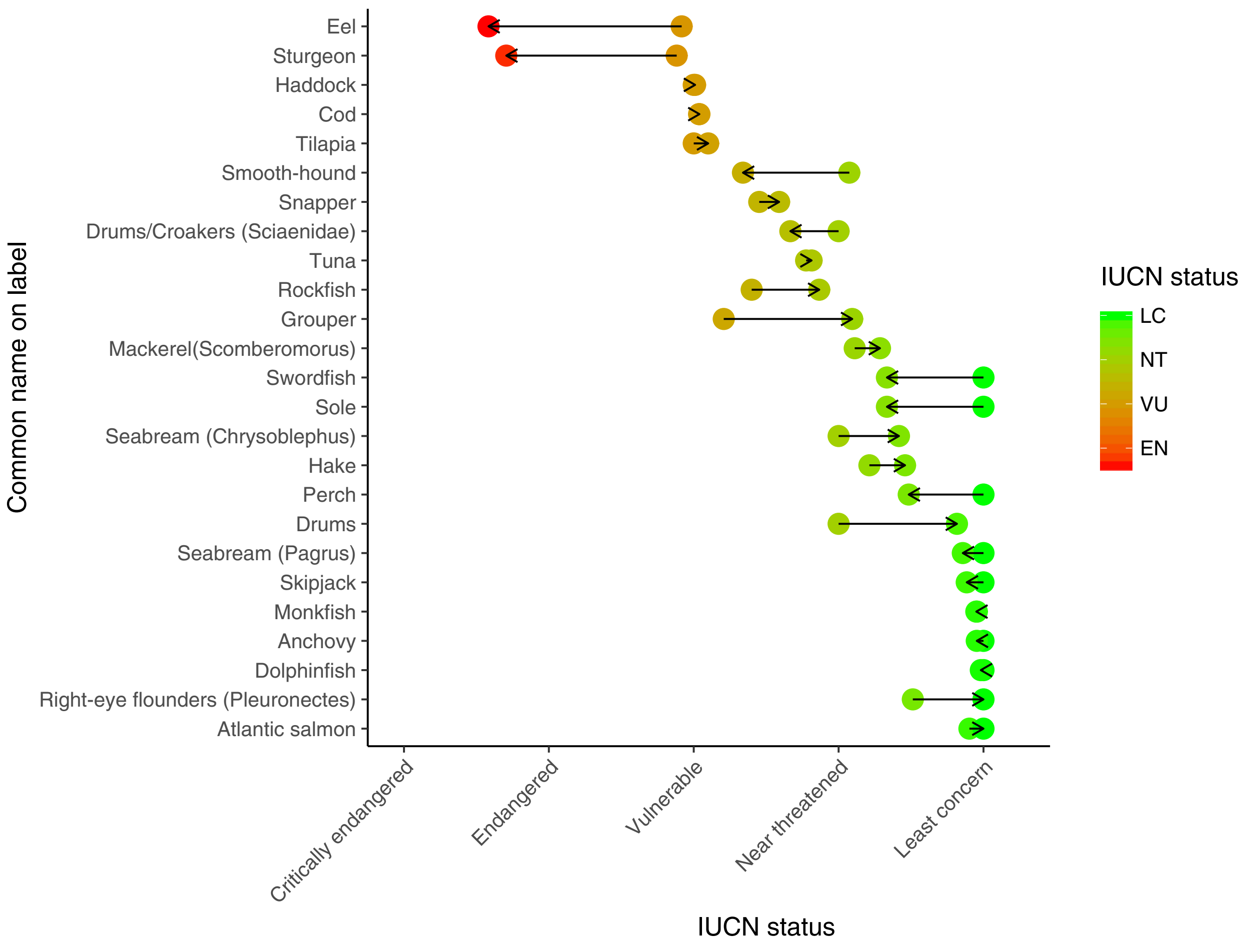

Figure 2 IUCN status of ordered seafood item (beginning of arrow) and true seafood item (end of arrow). Colors represent mean IUCN status of each. The majority of genera had no difference in IUCN status between labeled and true items; these are removed from the figure.

true species were of slightly lower cost (−2.98% global ex-vessel price) and higher conservation status (+3.88% IUCN status) than labeled finfish. From a consumer perspective, this suggests mislabeling may not mislead people into eating less sustainable seafood. Our study also highlights that mislabeling effects are highly disparate by genus. For example, several genera were substituted with items of lower IUCN status (e.g., eel, sturgeon smooth-hound) and some genera were substituted with lower cost items (e.g., wahoo, swordfish, grouper). However, other genera (e.g., dolphinfish, skipjack) were substituted with higher cost items, suggesting mislabeling in some species may occur accidentally or because there is a low supply of desirable menu items. In addition, global production was inversely correlated with proportion mislabeled, consistent with the hypothesis that highly productive fisheries are subject to more scrutiny (i.e., regulation enforcement, seafood certification; e.g., Calahan *et al.* 2014).

By combining mislabeling probabilities with price and sustainability information at a broad scale, we take the first step toward integrating mislabeling probability, ecological risk, and economic loss information on seafood. A large body of guidance on seafood sustainability (i.e., seafood certification schemes, consumer guides) exists, but may be undermined if consumer trust in such metrics is eroded by reports of mislabeling. Seafood guides (e.g., the Monterey Bay Aquarium's Seafood Watch® guide) allow consumers to assess the conservation consequences of their seafood choices, but do not integrate mislabeling information. Our study may supplement such guides, to provide consumers with guidance on not only the status of the labeled item, but also the status of items frequently substituted for that label. This is a first step towards the

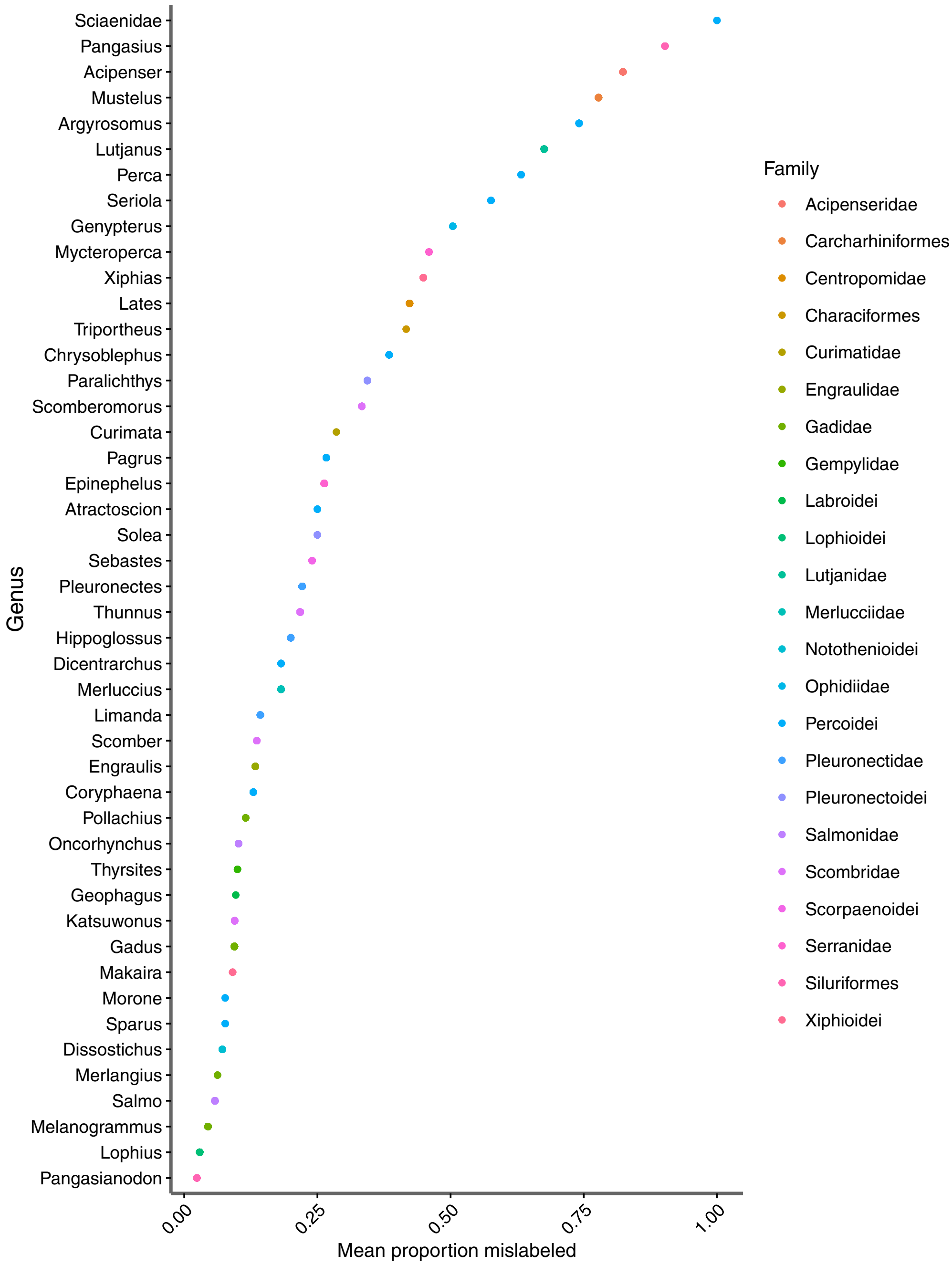

Figure 3 Weighted mean proportion of samples mislabeled by genus. Several genera with 0 samples mislabeled not included in figure.

ultimate consumer guide: a standardized risk assessment (De Lange *et al.* 2010), combining the probability of receiving a mislabeled item with the expected loss due to mislabeling. Adequate replication across species and taxa would be needed to ensure mislabeling probability was calculated in a more statistically rigorous way than was possible in this analysis.

One solution to reduce mislabeling is to increase traceability of seafood through the supply chain. For example, businesses have opted into the Gulf Seafood Trace program, which allows consumers to trace the origin of their seafood, enabling consumers to buy authentic products and businesses to protect their brands (Miller *et al.* 2014). Regulatory (i.e., mandated) traceability

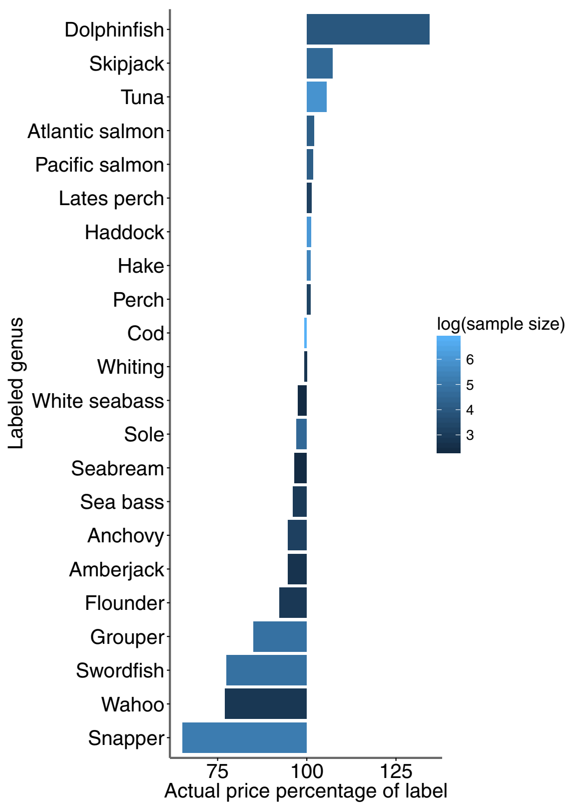

Figure 4 Price difference percentage (ex-vessel price of true identity of item/ex-vessel price of labeled item). Color represents sample size on logarithmic scale. Ex-vessel prices are taken from Melnychuk et al. 2016.

programs may also be effective in combating mislabeling, particularly in contexts of international supply chains that are more opaque (Bailey *et al.* 2016). Disparate mislabeling probabilities between port samples and consumer outlets (e.g., restaurants, groceries), as in Miller *et al.* (2012), suggest mislabeling occurs primarily at outlets rather than ports or processors; thus, it may be most beneficial to improve the traceability of products at outlets. Overall, our results support strict chain of custody standards that track food through the supply chain, such as those used by certification programs (e.g., Marine Stewardship Council; Jacquet & Pauly 2008), as well as efforts to track seafood importation (Pramod *et al.* 2014; Watson *et al.* 2015). Increasing traceability aligns with other desirable outcomes for the seafood industry, such as facilitating the recall of contaminated products (Bailey *et al.* 2016).

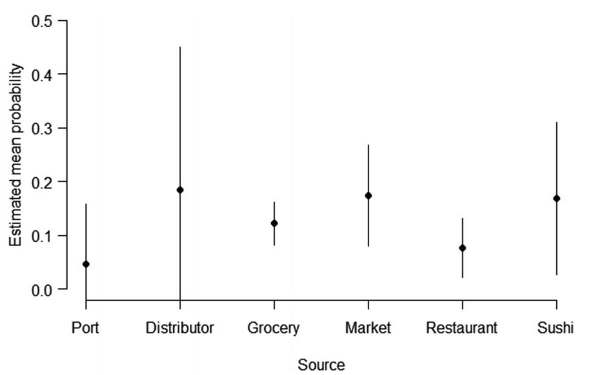

Figure 5 Estimate of mislabeling probability and 95% confidence interval by purchase location (source) from generalized linear model on data from Atlantic and Pacific salmon, cod, tuna, and catfish samples.

Uncertainty in this study must be considered in the interpretation of our findings. Our analysis suggests seafood mislabeling is relatively common (13.12%; [11.37–15.02%]), but less common than estimates reported in previous studies (35%, Pardo *et al.* 2016). Disparity in these estimates may occur because we included gray literature, where mislabeling may be less common due to publication bias. We found no evidence of publication bias, but studies detecting a high proportion of mislabeled seafood may be more likely to be published than studies detecting no mislabeling ("file drawer effect"; Møller & Jennions 2001). In addition, uncertainty may have been introduced via averaging of IUCN statuses across species when species-specific identification was not provided, as well as using a single metric per species when in reality, different populations of the same species may have disparate conservation statuses. Our sensitivity analysis excluding genus-level IUCN statuses provided similar estimates of conservation status differences, and using population-level FAO- and RAM-derived species statuses yielded qualitatively similar results (true items had +0.091 FAO difference, −0.049 RAM difference from labeled). This suggests our overall conclusion, that mislabeling does not impact or increases conservation status of consumed items, is robust.

Despite scientific agreement that fisheries can benefit from consumers making informed choices about their seafood, empirical relationships between sustainability certification programs and fishery statuses are lacking, and one potential culprit is mislabeling (Jacquet *et al.* 2010). For the seafood sustainability movement to succeed (i.e., improve statuses of fisheries) where other eco-advertising campaigns have failed (e.g., "greenwashing" in the 1990s; Jacquet *et al.* 2010), its credibility must be maintained in part through the ability of consumers to purchase accurately labeled products. This may be achieved through certification programs or government regulations that identify and trace seafood from point of capture to consumer purchase; our results suggest prioritizing identification and traceability at points in the chain-of-custody beyond ports, where the majority of mislabeling occurred. More broadly, plans to reduce mislabeling must consider potential effects on international trade: measures to increase accuracy of labels will likely require resources that are more limiting in the developing world, which supplies most of the international seafood trade yet struggles to afford certification programs (Sampson *et al.* 2015; Bailey *et al.* 2016). Although regulatory reform to reduce mislabeling may ultimately empower consumer populations to shift market demands away from imperiled species, understanding mislabeling estimates and their outcomes in the meantime can provide consumers with more information on which to base their seafood choices.

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Supporting Information

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

Table S1. List of studies included in meta-analysis

Table S2. GLM models fit and AIC weights

Table S3. Numbers of labels and true IDs in each IUCN global conservation status category

Figure S1. Mislabeling definition.

Figure S2. Mean proportion of mislabeled items across sources.

Figure S3. Proportion of samples mislabeled by country.

Figure S4. Status difference vs. price difference for all the samples for which we found both price and status information.

Figure S5. Two visualizations of a NMDS plot describing the true composition of fish labeled as salmon, tuna, and whitefish.

Figure S6. Funnel plot to examine publication bias. Each point represents one study, with the number of genera in each study included as a covariate.

Figure S7. Difference between labeled (start of arrow) and true (end of arrow) status of seafood items, as based on aggregated values from FAO (2011).

Figure S8. Difference between labeled (start of arrow) and true (end of arrow) status of seafood items, as based on aggregated RAM B/B_{msy} values.

Figure S9. Difference between labeled (start of arrow) and true (end of arrow) status of seafood items, as based on aggregated RAM U/U_{msy} values.

Figure 6. Shannon diversity in Labeled species (Blue) vs Actual species (Red). Line thickness represents sample size. Australia and Hong Kong have no difference in diversity between labels and true species.

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