Consequences of seafood mislabeling for marine populations and fisheries management

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Over the past decade, seafood mislabeling has been increasingly documented, raising public concern over the identity, safety, and sustainability of seafood. Negative outcomes from seafood mislabeling are suspected to be substantial and pervasive as seafood is the world's most highly traded food commodity. Here we provide empirical systems-level evidence that enabling conditions exist for seafood mislabeling in the United States (US) to lead to negative impacts on marine populations and support consumption of products from poorly managed fisheries. Using trade, production, and mislabeling data, we determine that substituted products are more likely to be imported than the product listed on the label. We also estimate that about 60% of US mislabeled apparent consumption associated with the established pairs involves products that are exclusively wild caught. We use these wild-caught pairs to explore population and management consequences of mislabeling. We find that, compared to the product on the label, substituted products come from fisheries with less healthy stocks and greater impacts of fishing on other species. Additionally, substituted products are from fisheries with less effective management and with management policies less likely to mitigate impacts of fishing on habitats and ecosystems compared with the label product. While we provide systematic evidence of environmental impacts from food fraud, our results also highlight the current challenges with production, trade, and mislabeling data, which increase the uncertainty surrounding seafood mislabeling consequences. More integrated, holistic, and collaborative approaches are needed to understand mislabeling impacts and design interventions to minimize mislabeling.

food fraud | seafood mislabeling | seafood trade | species substitution

Seafood mislabeling has been increasingly documented over the past decade, raising public concern over the identity, safety, and sustainability of seafood (1). One challenge to addressing mislabeling of seafood is that it can take a variety of forms, including misrepresentation of species, farmed versus wild sourcing, and geographical origin. Furthermore, seafood is the world's most highly traded food commodity (2) with complex and opaque seafood supply chains that enable product mislabeling globally (3). Among food commodities, seafood has been identified as a commodity particularly vulnerable to misrepresentation. For example, the European Parliament identified fish and fish products as the second highest category of foods at risk for fraud (4). Media coverage (1) and European Union and US seafood traceability policies have raised awareness of mislabeling, but implementation and enforcement remain challenging and mislabeling continues to be widely documented (3, 5).

The current evidence for impacts of mislabeling is limited, equivocal, and largely anecdotal with empirical, systems-level evidence lacking (3, 6). Most work to date has focused on wild-caught fishery population impacts, with multiple researchers and practitioners hypothesizing that mislabeling generates negative population impacts (7–10) and therefore can threaten sustainable development goal targets (11). A primary mechanism through which mislabeling is hypothesized to result in negative population impacts is enabling the sale of illegal, unreported, and unregulated (IUU) products that could not be sold otherwise, thus reducing the health of fish populations (12–15). Another mechanism through which negative impacts could occur is the substitution of higher-value products with lower-value products that may have less healthy populations or are more poorly managed (8, 14). Substitutions can also undermine purchasing behavior consumers may engage in that supports sustainable fisheries (10).

Other research claims that substitute products are, on average, of equal or lesser conservation concern than the expected products (i.e., product on the label) they replace (16). Indeed, there are explanations for why the substitute product may be from a fishery with the same or better population or management status than the expected and therefore not result in negative outcomes for marine populations or support poorly managed fisheries. This could occur if products are accidentally mislabeled due to supply chain complexities (17). To the extent better population or management outcomes are not always associated with higher value or lower availability, motivations can be economic and include replacing higher-value with lower-value or lower-availability with higher-availability products (14).

We developed a systems-level methodological approach to characterize enabling conditions for population and management consequences of seafood mislabeling. We focused on the

Significance

The consumption of an important food source, seafood, has increased over the past half century. It is now the most globally traded food commodity and its supply chains are often complex and opaque. Contemporaneous with the growth of overall production, evidence of seafood product mislabeling has become ubiquitous. We show that enabling conditions exist for mislabeling to generate negative impacts on marine populations and to support consumption of products from poorly managed fisheries. More holistic approaches that include consumer and industry engagement, well-designed and targeted testing, and regulatory traceability programs could reduce seafood mislabeling and improve transparency related to impacts of seafood product consumption.

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United States since it is the world's largest seafood importer by value (20) and there are sufficient data available on mislabeling in the United States and on marine population and management outcomes in fisheries where US consumption originates.

Our first analysis combined and synthesized data from multiple sources to identify mislabeling pairs and estimate their mislabeled apparent consumption for use in the second two analyses. The starting point is 246 pairs (a pair is a unique combination of an expected product that corresponds to the product label and a substitute product which is the product identified through testing) of seafood products that have been documented to be involved in mislabeling in the United States (3). We used these data to estimate the quantity of mislabeled seafood consumption associated with each pair, which we refer to as mislabeled apparent consumption—an expansion of the term apparent consumption used to refer to estimates of seafood consumption. We calculated the mislabeled apparent consumption by multiplying estimated apparent consumption for the expected product, calculated using trade and production data, and pair mislabeling rates estimated using a statistical model adopted from ref. 3. We also used trade and production data to calculate the percentage of each product that is imported and to identify farmed products.

We conducted a second analysis focused on the origin of pair products. Specifically, we examined whether substitute products are more likely to be imported than the expected product on the label.

For the third analysis, we used the Monterey Bay Aquarium Seafood Watch program assessment scores for wild-caught products to examine whether there are systematic differences between expected and substitute products. Examining the pairs using data on production method, we identified pairs containing both a wild-caught expected and a substitute product. We linked the products in these pairs to scores for two factors associated with population outcomes: impacts on the target species and impacts on other species (i.e., bycatch). We also used scores for two factors associated with management design and scope: management effectiveness and habitat and ecosystem impacts. The assessments cover 80 to 85% of the US and Canadian seafood markets (21), providing a standardized scoring of products from different fisheries and species groups.

Results

Our systems-level approach allowed us to evaluate whether enabling conditions exist for US seafood mislabeling to result in negative impacts through substituted products being associated with worse population outcomes or management approaches than the expected products on the label. In our first analysis we estimated the mislabeling rates and mislabeled apparent consumption for documented mislabeling pairs (Fig. 1). In aggregate, the documented pairs associated with mislabeling in the United States led to 190,000 to 250,000 tonnes of mislabeled product in live weight equivalents being sold yearly in the US

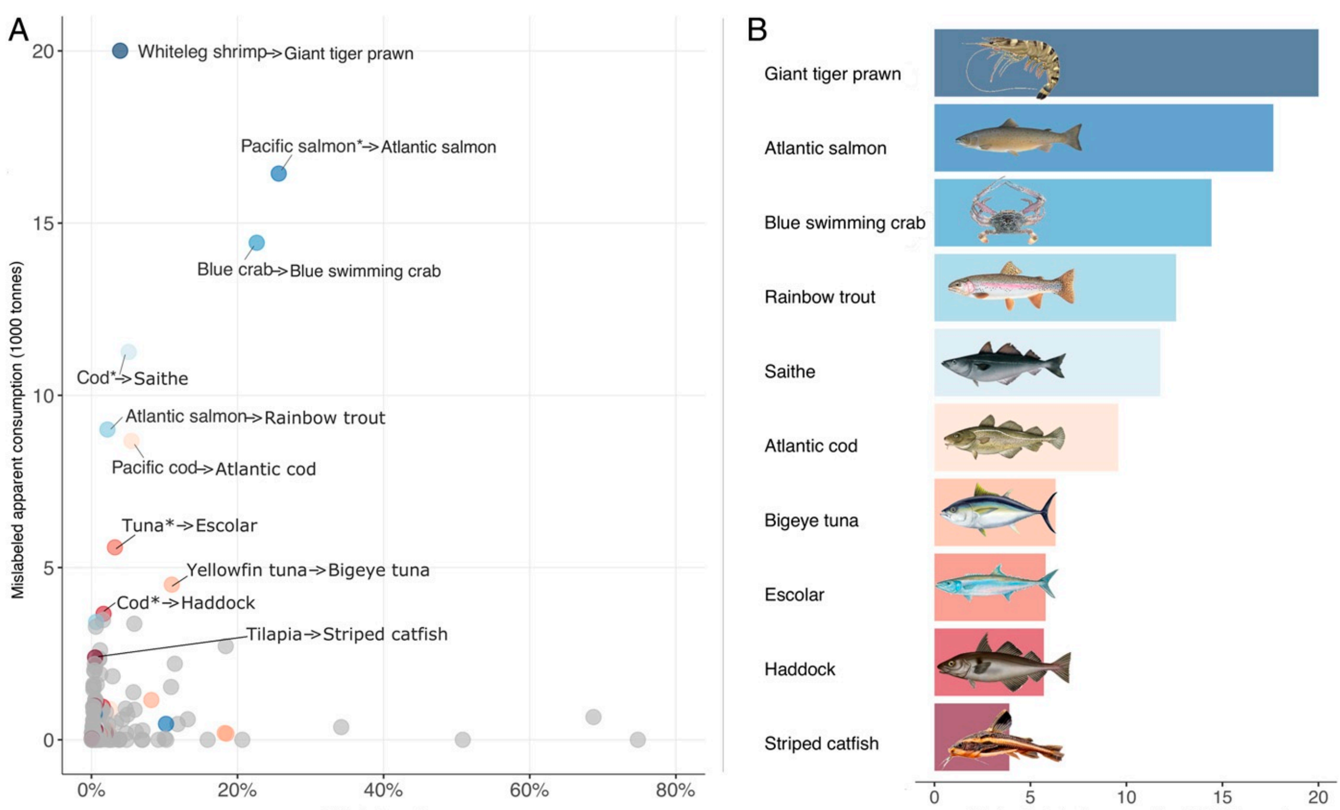

Fig. 1. Mislabeling and apparent consumption for the US seafood supply. (*A*) Estimated mislabeling rates and mislabeled apparent consumption for pairs of seafood products where the expected product has been tested for mislabeling in the United States. The horizontal axis is the mode mislabeling rate for each pair, while the vertical axis is the resulting apparent mislabeled consumption. Products with high rates have low consumption and vice versa. The majority of pairs have relatively low rates and low consumption. Pairs with high mislabeled apparent consumption are labeled to show the expected and substitute products (expected → substitute). Colored points represent pairs that contribute to the substitute products that have the highest total mislabeled consumption in *B*. (*B*) Of the substitute products that have been identified in the United States, the top 10 make up 55% of the total estimated mislabeled consumption. The total mislabeled consumption for each substitute product is calculated by grouping the pairs by substitute product and summing the mislabeled apparent consumption. The expected products Pacific salmon*, Cod*, and Tuna* represent more than one species. Common names follow Fishbase (18) and Sealifebase (19).

market or 3.4 to 4.3% of apparent consumption (the estimates vary based on the set of mislabeling pairs used; *Materials and Methods*). We also found that substitution of giant tiger prawn for whiteleg shrimp is responsible for more mislabeled apparent consumption than any other product, driven by the fact that Americans eat more of it than any other seafood product (*SI Appendix*, Fig. SI-1). In many instances a substitute product is documented as having been substituted for multiple expected products. In our database, for example, striped catfish (also called pangasius) is a substitute for 12 different products.

Our second analysis examined whether substitute products are more likely to be imported than the expected product they replace. The analysis is motivated by work that has shown the US imports a substantial amount of its seafood (over 60%) (22) and that the geographic origin of seafood products can reveal information about environmental outcomes and the strength of policies associated with the environmental impacts of production. For example, the United States has successfully implemented several policies to address overfishing, minimize bycatch, and improve stock status (23). In contrast, many countries that export seafood to the United States have relatively weaker governance and therefore a greater likelihood of negative direct and indirect fisheries impacts, such as overfishing and high levels of bycatch (24). The United States is also known to have stricter environmental laws related to aquaculture production than many other seafood-exporting countries (25). For our pairs of seafood products where mislabeling has been documented, the percentage of substitute product imported is 28% higher than the percentage imported of the expected products they replace ($P < 0.02$; *SI Appendix*, Table SI-4). However, a substitute product was most likely to originate from the United States (40%) compared to any other single country, followed by Canada (10%), Indonesia (7%), Chile (6%), and India (4%; Fig. 2). These results suggest that understanding impacts of mislabeled seafood in the US market requires understanding production outside the United States.

Further examination of the mislabeling product pairs suggested that production method is another factor that requires consideration when examining impacts of mislabeling. Despite aquaculture now comprising roughly half of global seafood production with further expansion expected (26, 27), its role in mislabeling has not been addressed in a systematic way in the literature. This is likely due in part to the lack of ubiquitous and inexpensive testing techniques that can differentiate wild-caught and aquaculture products. Therefore, we identified mislabeling pairs that include a potentially farmed expected or substitute product based on Food and Agriculture Organization of the United Nations (FAO) data on production methods used in the country of origin of the shipment. Our analysis suggested that production method is an important consideration in mislabeling as these pairs are responsible for about 40% of mislabeled apparent consumption in the United States (Fig. 3). This set of pairs consisted of some where both the expected and substitute products can be produced via aquaculture (e.g., rainbow trout labeled as Atlantic salmon) and others where only the substitute is likely produced via aquaculture (e.g., Atlantic salmon labeled as chinook salmon). Given that environmental impacts from aquaculture products are inherently different from those from wild-caught seafood (28–30) and relatively understudied (27), we did not attempt a comparative analysis. However, this is a rich area for future work as the aquaculture consumption associated with mislabeling is driven by a few products; specifically, we estimated that giant tiger prawn and Atlantic salmon were the top two substitute species by volume. Furthermore, production has been determined to generate environmental impacts that can vary by species and location (30).

Our third analysis assessed the relative performance of the expected and substitute fisheries for the approximately 60% of US mislabeled apparent consumption from documented pairs where both products are wild caught. Below we provide further detail on the results for the population and management scores.

Population. To examine the comparative performance of expected and substitute species in terms of population impacts, we used Seafood Watch's scores for two factors: impacts on the target species and impacts on other species. The scores for impacts on the target species are based on target species abundance and fishing mortality, which are arguably the most common measures of the health of fished stocks and have been used to assess fishery ecological outcomes (31, 32). The scores for impacts on other species are based on multiple factors including abundance, fishing mortality, and discards (21). Bycatch and discards are also well-established fisheries outcomes (33).

We found that substitute product fisheries received lower scores than those of expected products, suggesting that substitute fisheries, on average, performed worse in terms of impacts on the target fish stock and on other species. Specifically, on average, 14% of substitute product scores for impacts on target

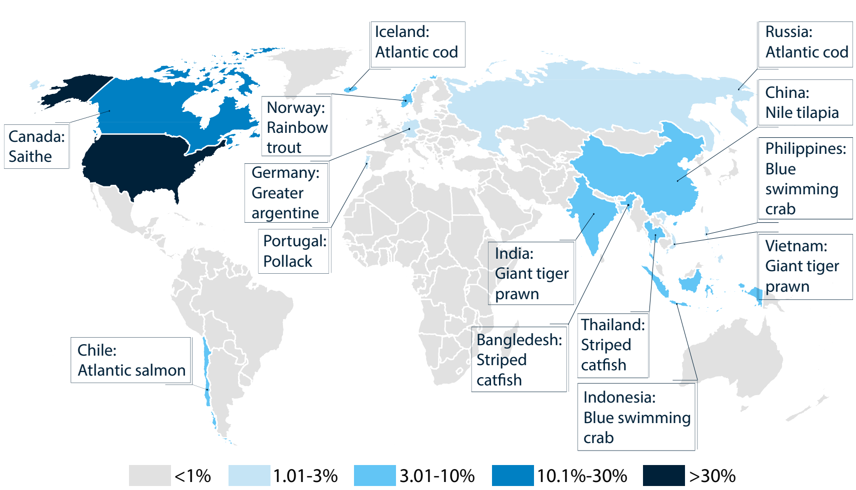

Fig. 2. The estimated countries of origin of substitute products involved in seafood mislabeling occurring in the United States. Countries where the origin of substitute products represents >1% of US mislabeled apparent consumption are shaded blue. The products listed represent the most common substitute by volume for each country. Substitute products from the United States and Canada are responsible for about half of the estimated mislabeled consumption. Common names follow Fishbase (18) and Sealifebase (19).

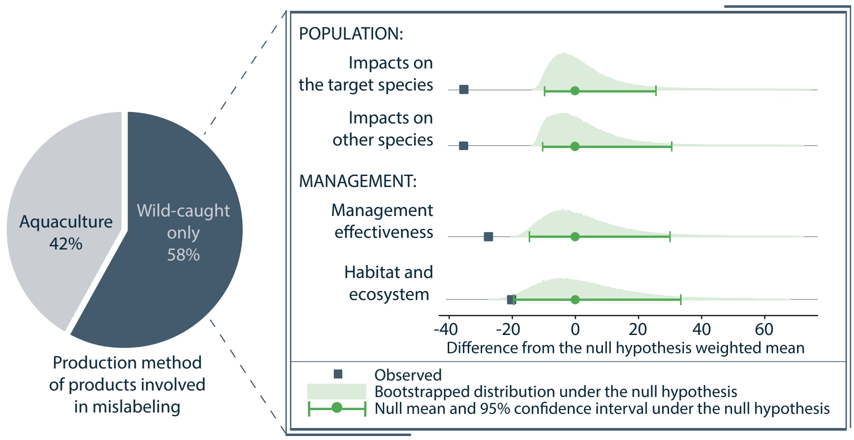

Fig. 3. Estimated production method and population and management performance of seafood products involved in mislabeling. Approximately 40% of estimated mislabeled apparent consumption involves seafood products that can be produced via aquaculture (i.e., >1% of the expected or substitute product is farmed). The remaining about 60% of consumption involves exclusively wild-caught seafood products. For pairs exclusively involving wild-caught products, we compare the 95% confidence interval of the bootstrapped distribution under the null hypothesis that there is no difference between substitute products' Seafood Watch scores and their corresponding expected product scores. Across all four scores, substitute product scores are consistently worse than expected product scores ($P \leq 0.04$). See *Materials and Methods* for information on the statistical tests.

species were higher than the scores for the product they replace. Additionally, 14% of substitute product scores for the impacts on other species were higher than the scores for the products they replace. The observed percentages are significantly lower than 50%, which corresponds to the null hypothesis that there is no difference in scores between expected and substitute products (the difference from the null is -36% and P value ≤ 0.01 for each case; Fig. 3 and *SI Appendix*, Table SI-3).

Management. We also examined the comparative performance of expected and substitute species in terms of their management approaches. Management effectiveness scores account for attributes including strategy for responding to changing circumstances, data collection, enforcement and compliance, and stakeholder inclusion (21). The habitat and ecosystem score includes consideration of the destructiveness of permitted gears on ocean habitats, the seafloor, or associated biological communities; efforts to mitigate gear impacts; and the extent to which ecosystem-based fisheries management (EBFM) has been implemented (21). Rather than focusing on the current status of species populations, scoring well on these metrics suggests the fishery and ecosystem should be productive in the longer run.

We found that, on average, 22% of substitute product scores for management effectiveness were higher than the scores for the product they replace and 30% of substitute scores for habitat and ecosystem impact were higher than those of the product they replace. Although these results are statistically significant ($P \leq 0.01$ and $P \leq 0.04$, respectively), the magnitude of the difference from the null hypothesis is lower and the distribution is wider than for the population metrics (Fig. 3 and *SI Appendix*, Table SI-3). This may be because some of the management criteria, and EBFM in general, are newer concepts in fisheries management relative to the more established tracking of target stock status and impacts on other species (34).

Discussion

The systems-level methodology we developed results in empirical evidence for the presence of enabling conditions for seafood mislabeling to precipitate negative impacts on marine populations and support poorly managed fisheries. Our approach advances the literature beyond the prior focus on rates of substitution (10, 16, 35), confirming previous claims that mislabeling rates alone are insufficient to inform the characterization of seafood mislabeling and its potential impacts (3, 6). In fact, mislabeling rates did not correlate with apparent mislabeled consumption (Fig. 1; Spearman ρ -0.1; $P = 0.21$; see *SI Appendix* for additional detail). This suggests that focusing solely on seafood products with high mislabeling rates obscures the substantial quantity and potential impacts of seafood mislabeling with relatively low mislabeling rates but substantial apparent consumption of products.

Our conclusions, however, should be viewed through a lens of uncertainty for several reasons. First, the apparent consumption estimates assume there is no measurement error in trade and production data, those data do not include mislabeled products, and all mislabeling occurs after the port of entry. This is certainly not the case for some products and at least eight studies have documented mislabeling at ports of entry (3). Second, the granularity of product names within import and production data is variable and sometimes poor, which limits its utility and increases the need for simplifying assumptions (22). Third, we rely on Seafood Watch scores as indicators of population health and management effectiveness due to their broad coverage. Future work could explore robustness of our findings to other ratings systems (36) or evaluation methods. For example, using indicators precludes assessment of quantities of mislabeled product relative to fishery size and impacts on harvest quantities and marine populations or habitats, which could be explored with other methods. Finally, mislabeling data are often challenging with respect to estimating rates, resulting in the exclusion of many products (3). We were forced to combine global mislabeling rate estimates with US apparent consumption data to estimate mislabeled apparent consumption, increasing the uncertainty of our results (*SI Appendix*). For example, despite its high consumption, few mislabeling studies have sampled shrimp in the United States, all of which have small sample sizes (3, 37–39). Using its global mislabeling estimate (i.e., 5%), however, results in the highest estimate of US mislabeled apparent consumption (Fig. 1). Until more US-based data become available, global estimates are justified, since current evidence suggests that overall mislabeling rates do not differ across countries (3).

Our methodology and findings also highlight avenues for future mislabeling research. First, our analysis included all documented mislabeled product pairs in the United States, but more testing and public dissemination of results is needed to understand the coverage of current testing of products and implications for mislabeling impacts. A second key area in need of further work is understanding the role of aquaculture in mislabeling, which would benefit from the deployment of forensic tools in addition to DNA barcoding that can differentiate production method and provenance within the same product (40). Furthermore, while substituting a farmed for a wild-caught product results in an immediate change in wild-caught consumption by a specific consumer, a comprehensive assessment of impacts of these substitutions requires a better understanding of socioeconomic factors and comparable production impact measurements (41).

Results of our analyses also suggest there are latent benefits to increasing efforts to bridge the current gap between the relatively siloed seafood sustainability movement with its emphasis on consumer- and industry-driven certification and traceability (36), seafood mislabeling testing and rate estimation efforts (3), and regulatory traceability programs. Doing so would promote the development of best practices to properly characterize mislabeling, develop more effective programs to reduce it, and increase the ability to monitor the effectiveness of interventions targeting seafood fraud. These steps could improve the credibility of information available to consumers related to marine population status and management as well as other aspects of sustainable fisheries such as social and economic factors (32) and support sustainable purchasing efforts (42). Although conceptual synergies exist, multiple challenges must be overcome, such as data collection, access, and compatibility. Thus, more coordination is needed among diverse stakeholders to codevelop data-driven investment and research to support and design policies and consumer engagement programs aimed at minimizing mislabeling and reducing its negative impacts.

Materials and Methods

Mislabeled Apparent Consumption Associated with Mislabeling Pairs. Our first analysis resulted in estimates of mislabeled apparent consumption for each documented pair of expected and substitute products in the United States. We first identified mislabeled pairs using the database from Luque and Donlan (3). Following ref. 3, we refer to the product on the label as the expected product and the actual product, which differs from that on the label, as the substitute. Some products can be both an expected and a substitute product. For our primary analysis, we included 246 pairs with 50 samples tested globally and where the expected product had been tested in the United States. We refer to these mislabeling pairs as the US 50+ pairs. We report results from sensitivity testing using two other datasets in *SI Appendix*.

For each unique expected and substitute product pair we estimated the quantity of mislabeled seafood consumption associated with the pair, which we refer to as mislabeled apparent consumption. The mislabeled apparent consumption is calculated by multiplying estimated apparent consumption for the expected product by the mislabeling rate estimated for the pair (6). We calculated the apparent consumption in live weight equivalents as the sum of production and imports minus exports of each product. To calculate the apparent consumption we used 2016 production data from the FAO, 2016 trade data from the US National Oceanic and Atmospheric Administration's National Marine Fisheries Service (43), and product-specific mass conversion ratios corresponding to the processing a product has undergone from the European Market Observatory for Fisheries and Aquaculture Products (44). We estimated substitution rates for each pair with a metanalysis approach, using a Bayesian hierarchical model and the resulting mode for each pair, the most credible value (3). We linked mislabeling rate estimates with US apparent consumption estimates at the lowest taxonomic level possible. We calculated the percentage of US apparent consumption that is mislabeled as the estimated mislabeled consumption associated with each of the three sets of pairs divided by total estimated US apparent consumption. See *SI Appendix* for more detail on the apparent consumption calculations, mislabeling rate estimates, and database linkages.

Origin, Production Method, and Seafood Watch Scores Associated with Mislabeling Pairs. We augmented the mislabeling pair data with information on product origin, production method, and Seafood Watch scores. For each expected and substitute product involved in mislabeling we first estimated the percentage of that product's US apparent consumption that is imported and the percentage of apparent consumption that is farmed. We used the trade and production data to estimate these percentages. Additional details on the calculations and summary statistics are available in *SI Appendix*.

We then identified pairs with products that are potentially farmed. Using the data on production method, we first identified products with greater than 1% of estimated apparent consumption that is farmed. We deemed these products as those that can be produced via aquaculture. We then identified any pairs with at least one product meeting these criteria, which are then excluded from the analyses using the Seafood Watch scores.

Finally, we linked the products from pairs with wild-caught expected and substitute products to Seafood Watch score data. We used scores from the Monterey Bay Aquarium Seafood Watch program, which undertakes scientific assessments of fisheries units to provide seafood recommendations to consumers. We used four scores from Seafood Watch assessments: 1) management effectiveness, 2) impacts on species under assessment (i.e., target species), 3) impacts on other species under assessment (i.e., bycatch), and 4) impacts on habitat and ecosystem. Seafood Watch fishery assessments vary in their specificity (21). Some assessments focus on a product with a global scope, regardless of the origin of production. Many reports, however, are specific to a particular fishery, using a specific type of gear, and located in a specific country or region. For cases where the United States imported a product from multiple fisheries units, we calculated a weighted average score where the weights corresponded to the estimated apparent consumption from each unit that produces the product and has a Seafood Watch score. Additional information on the Seafood Watch score calculations is available in *SI Appendix*.

Statistical Methods. Analyses two and three are based on statistical tests using the mislabeling pair and mislabeled apparent consumption data. For both analyses, results in the main text relied on the US 50+ pairs dataset. Results of robustness checks, including analyses with the additional datasets, are presented in *SI Appendix*. For each analysis we were limited to pairs where both the expected and the substitute product had the associated data available. For our second analysis, we focused on pairs for which we could calculate the percentage of the apparent consumption derived from imports. For our third analysis, we focused on wild-caught product pairs with Seafood Watch scores for expected and substitute products.

For both analyses, we used bootstrapping to simulate a distribution of test statistics around a null hypothesis. Bootstrapping allowed us to relax the normality assumption present in parametric hypothesis testing (45). Because our bootstrapped distributions were skewed, we used a bias corrected and accelerated (BCa) procedure which corrects confidence intervals for bias (45). We resampled with replacement from the observed set of pairs. Each resampled set had the same number of observations as the original sample. We calculated the test statistic for each resampled set and repeated the procedure to create a distribution of test statistics. To simulate the distribution of test statistic values under the null hypothesis, we shifted the value of each observation by the difference between the null test statistic value and the observed test statistic value. This forced the mean of the bootstrapped test statistics to the null hypothesis value.

For the second analysis, the test statistic was the weighted mean difference in import percentage between substitute and expected products in a product pair (substitute product percentage less the expected product percentage). We weighted observations by the estimated mislabeled apparent consumption tonnage of the pair. Our null hypothesis was that, on average, there is no difference in import percentages of apparent consumption for expected and substitute products. We bootstrapped, with replacement, the difference in imported percentage for each pair along with the weight.

For the third analysis, we identified pairs that contained products where over 1% of estimated apparent consumption was derived from aquaculture sources. We dropped all pairs where this was true for either the expected or the substitute product. We also required Seafood Watch scores for both the expected and the substitute product. We were able to estimate scores for about 84% of the total mislabeled consumption associated with the wild-caught pairs. Our null hypothesis was that there was no difference, on average, between the Seafood Watch scores of expected and substitute product pairs. The test statistic was the weighted proportion of substitute products with higher scores than their associated expected products. Since the scores are ordinal, the difference between 2 and 3 does not necessarily have the same meaning as the difference between 3 and 4. Thus, we focused on the relative magnitude between the two scores by creating an index equal to one if the substitute product score was greater than the expected product score, zero if the substitute score was lower, and one-half (i.e., the value equal to our null hypothesis) if they were exactly equal. We compared the observed value for each score to null distributions obtained from bootstrapping. Specifically, we examined whether our observed values fell within the 95% BCa confidence interval of our null distribution and calculated the associated *P* value.

Data Availability. All study data are included in this article and *SI Appendix*.

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