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Examining Seafood Fraud Through the Lens of Production and Trade: How Much Mislabeled Seafood Do Consumers Buy?

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Contents

1. Introduction

Seafood is one of the world's most-traded food commodities, with an estimated export value of $142 billion in 2016 (FAO 2017b). Because of its economic importance, the wide variety of products traded, and often murky and complex supply chains, there are numerous opportunities for seafood mislabeling. Incentives for deliberate mislabeling, or fraud, include the opportunity to take advantage of price differentials between two species, the potential profits from circumventing catch limits on wild-caught stocks, and the desire to gain market access for illegally landed seafood. Forensic analysis of seafood taken from wholesalers, restaurants, and grocery stores in the United States has demonstrated that a cheaper or more abundant product is sometimes mislabeled as a more expensive or less available one (Hsieh et al. 1995; Cline 2012; Warner et al. 2013). A better understanding of the scale and nature of seafood mislabeling is important for improving regulatory efforts and consumer engagement programs aimed at minimizing its societal costs.

Seafood mislabeling studies have focused almost exclusively on mislabeling rates—the percentage of mislabeled seafood product in a given sample. Though obviously important, these data alone cannot characterize the magnitude of the problem. For example, an extremely popular product with a low rate of mislabeling could yield a larger total quantity of mislabeled product than a frequently mislabeled product with limited consumer demand. So the important, and perhaps underappreciated, question is, *How much mislabeled seafood do consumers buy*? And secondarily, though outside the scope of this report, *Are there ecological harms of this mislabeling*?

In this report, we cannot answer the questions directly; rather, we discuss their importance and how production, import, and export data can be integrated with mislabeling rates to provide insights into seafood fraud.

We use two commonly consumed, economically relevant examples to illustrate our approach: 1) farm-raised Atlantic Salmon (*Salmo salar*) mislabeled as wild-caught Pacific salmon (*Oncorhynchus spp.*), and 2) Pacific Cod (*Gadus microcephalus*) and Alaska Pollock (*G. chalcogrammus*) mislabeled as Atlantic Cod (*G. morhua*).[1] These are widely traded fish species, commonly sold in stores and presented on restaurant menus across the United States.

We also discuss how data on production method and origin can provide insights into the potential ecological and socioeconomic consequences of mislabeling.
We conclude by highlighting research needs that will enable the development of reasonably precise and accurate estimates of mislabeled fish consumption.

2. Potential Consequences of Seafood Mislabeling

Our analysis is motivated by the premise that policymakers and the fisheries industry need a better understanding of mislabeling and its social and environmental costs to design and implement effective traceability policies and consumer engagement programs (e.g., seafood rating systems). The advent of food forensics, such as DNA barcoding, has spurred research on seafood mislabeling over the past decade (Pardo et al. 2016). The majority of research has focused on developing forensic tools and documenting mislabeling ad hoc for a particular species or geography. Consequently, our current understanding of seafood mislabeling is largely limited to idiosyncratic studies without consistent methodologies or metrics. The general characterization of seafood mislabeling is limited, and even less is known about its ecological and societal harms. For example, the environmental effects of farm-raised fish are different from wild fisheries, and the health of fish stocks often varies drastically across countries and regions. Because potential effects may vary by seafood product, production method, and country of origin, production and trade data, when coupled with forensic sampling for mislabeling, are likely to yield insights on the scope of the problem.

Seafood mislabeling can precipitate several market and fiscal effects. When lower-quality, lower-priced seafood products are substituted for more desirable, higher-priced products, consumers unknowingly pay more than they should (Cline 2012; Doukakis et al. 2012; Gordoa et al. 2017). The price differential can be substantial: for example, selling cheaper substitutes for caviar from the Beluga sturgeon (*Huso huso*) can increase profit margins to the seller by fivefold (Birstein et al. 1998; Doukakis et al. 2012; Fain et al. 2013; Ludwig et al. 2015). Fraudulent seafood producers and marketers profit from such substitutions, disadvantaging and undercutting honest players in the market (Ugochukwu et al. 2015). Prevalence of mislabeling might also undermine consumers' confidence in the food industry and regulatory programs (FAO 2018b) and weaken their support for sustainable seafood certification.

Seafood fraud also deprives governments of revenue when importers mislabel and substitute a species to avoid tariffs (Stiles et al. 2011). Striped catfish (*Pangasionodon hypophthalmus*), often known as swai or panga in seafood markets, provides an example of mislabeling to avoid regulation. After the United States imposed a 40 percent antidumping tariff on swai and panga imports from Vietnam in 2003, prosecutions for mislabeling of the species may have increased (Environmental Crimes Section Monthly Bulletin 2009, 2010, 2011; DOJ 2011, 2012); one case, settled in 2009, involved the illegal import of 4,500 metric tons of swai, representing approximately 12 percent of that year's imported volume, and $12 million in avoided duties (DOJ 2009; NOAA Fisheries 2017).

Environmental concerns about seafood mislabeling include the increased harvest of substitute species that are or might become endangered or overexploited. Several mislabeling studies have documented the substitution of threatened or endangered species for products from sustainable fisheries (Doukakis et al. 2012; Palmeira et al. 2013; DiPinto et al. 2015). Mislabeling could thereby hamper management efforts to rebuild overexploited fisheries stocks. In the notable “Codfather” criminal case, fishing mogul Rafael Carlos of New Bedford, Massachusetts, bragged to undercover IRS agents that he had mislabeled 300,000 pounds of overfished American plaice (*Hippoglossoides platessoides*) as haddock (*Melanogrammus aeglefinus*) (Fraser 2016). This amount was around 10 percent of the total annual catch limit for American plaice set by the New England and Mid-Atlantic Fishery Management Councils (NOAA Fisheries 2016, 2017) and likely led to overharvest of the species. Rafael was subsequently sentenced to nearly four years in prison for multiple offenses, including fraud and tax evasion involving 800,000 pounds of mislabeled fish (Goldfarb 2017a, 2017b).

Seafood mislabeling has also generated concerns about human health. The high oil content and indigestible wax esters in species belonging to the family Gemphylidae can cause keriorrhea, an intestinal disorder (Ling et al. 2009; Aldsworth 2017). This family includes oilfish (*Ruvettus pretiosus*) and escolar (*Lepidocybium flavobrunneum*), which is sometimes mislabeled as “white tuna” in sushi (Lowenstein et al. 2009; Warner et al. 2013; Arnett 2016). The extent of fish-induced keriorrhea from mislabeling, however, remains unknown. Much less frequent but more serious are incidences of tetrodotoxin poisoning from inadvertent consumption of puffer fish (species in the order Tetraodontidae) (Cohen et al. 2009). Possible increased mercury consumption due to mislabeling of tuna and other species has also been documented (Lowenstein et al. 2010; Marko et al. 2014). To date, however, the extent of human health risks is equivocal (Pappalardo et al. 2017).

In sum, despite numerous anecdotal examples of economic, environmental, and human health harms from seafood mislabeling, the extent and details of these impacts are unknown. Insights into the actual volumes of mislabeled seafood consumed are a necessary first step in understanding the potential consequences of seafood fraud.

3. Mislabeling in the United States: Salmon and Cod

We combined data on mislabeling rates, imports, exports, and production for two commercially important US seafood products that are known to be sometimes mislabeled: Pacific salmon and Atlantic Cod. Mislabeling necessarily involves two products: the *expected* product (i.e., the species that appears on the menu or supermarket label) and the *substitute* product (i.e., the true identity of a mislabeled product). Fundamental to our analysis is the recognition that the potential magnitude of mislabeled seafood consumed in the United States depends on both the mislabeling rates and the availability of the expected and substitution products.

With production and trade data, it is possible to calculate US apparent consumption (i.e., consumption based on labels in trade and production data). We can use these data to provide insights into the total volumes of seafood involved in mislabeling.[2] We follow the United Nations Food and Agriculture Organization (FAO) convention and define apparent consumption as the sum of the total quantity of products produced in a country added to the quantity imported, minus exports (FAO 2017). With good estimates of rates and quantities, by combining production and trade data with available mislabeling information, one can develop estimates of the total amount of mislabeled fish consumed (see Box 1). The quantity of mislabeled product on the market is a function of the mislabeling rate and the quantity of the expected product. Intuitively, even with a high mislabeling rate, very little expected product would result in a very low quantity of mislabeled substitute.[3] Conversely, high volumes of an expected product could result in substantial quantities of a mislabeled product on the market—even with a low mislabeling rate.

Our goal is not to provide definitive estimates of mislabeled seafood consumption; that would require additional work, since mislabeling rate estimates are often highly variable. Rather, we provide a framework for estimating the amount of mislabeled seafood consumed and illustrate how combining different types of data can provide insights into seafood mislabeling, including the scale and nature of possible socioeconomic and environmental harms.

3.1 Pacific Salmon

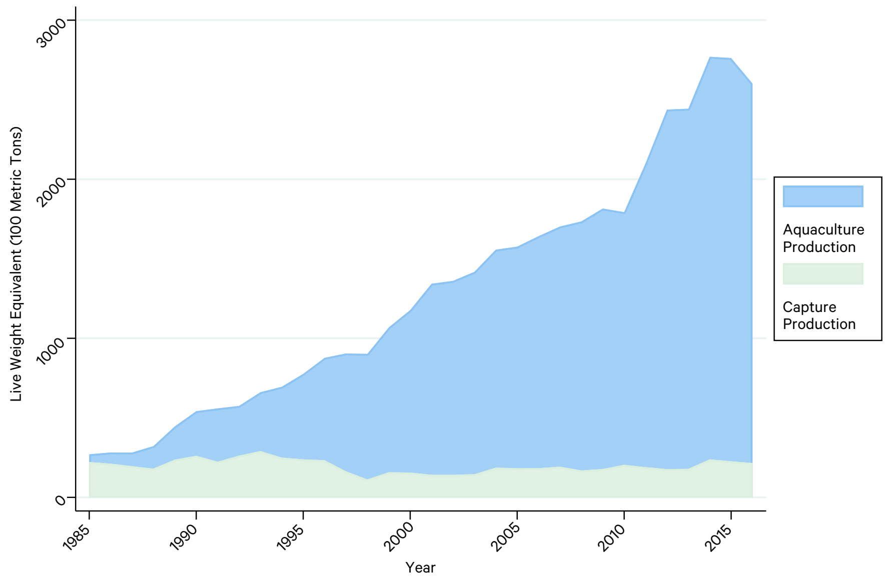
Marketers have strong incentives to substitute farm-raised Atlantic Salmon for wild Pacific salmon.[4] Atlantic Salmon is cheaper, more abundant, and available year-round. Further, at least in some US locations, seafood consumers prefer wild over farmed salmon and are willing to pay higher prices (Roheim et al. 2012). In the United States and Canada, where Pacific and Atlantic Salmon are both common in the market, mislabeling has been documented in multiple cities, with widely varying rates (Table 1). Pacific salmon prices vary significantly across species and time (Knapp et al. 2007). The documented mislabeling often involves substitution of cheaper farmed Atlantic or other wild Pacific salmon species for expensive Pacific salmon species, such as Chinook (Table 1; see, e.g., Consumer Reports 2006, Cline 2012, Muñoz-Colmenero et al. 2017). Although data are limited and estimates uncertain, median mislabeling rates for products labeled as Pacific salmon or a Pacific salmon species range from 0 to 33 percent, with Atlantic Salmon the most common substitute (Appendix, Table A1).

Salmon aquaculture production has increased rapidly since 1985 and now drastically outpaces wild catches (Figure 1). In the United States, Atlantic Salmon imports have increased dramatically as well (Figure 2). Almost half of Atlantic Salmon imports come from Chile, followed by Canada and Norway (Figure 3). Global production of Atlantic Salmon is more than a magnitude greater than wild Pacific salmon species, and US imports are four times greater. This discrepancy provides an enabling condition for seafood mislabeling.

Although we do not directly estimate quantities of mislabeled products consumed, production and trade data plus prior mislabeling studies provide insights into potential magnitudes. For example, current evidence suggests the mislabeling rate for Chinook Salmon is likely higher than the rates for Coho or Sockeye Salmon (Table 1). However, United States Sockeye Salmon production was about 25 times greater than Chinook Salmon in 2016. Thus, while mislabeling rates considered alone might suggest an anti-mislabeling program focus on Chinook Salmon, when they are combined with production data, it is less clear which salmon species has a higher volume of Atlantic Salmon mislabeled as the expected product (Sockeye or Chinook) on the market.

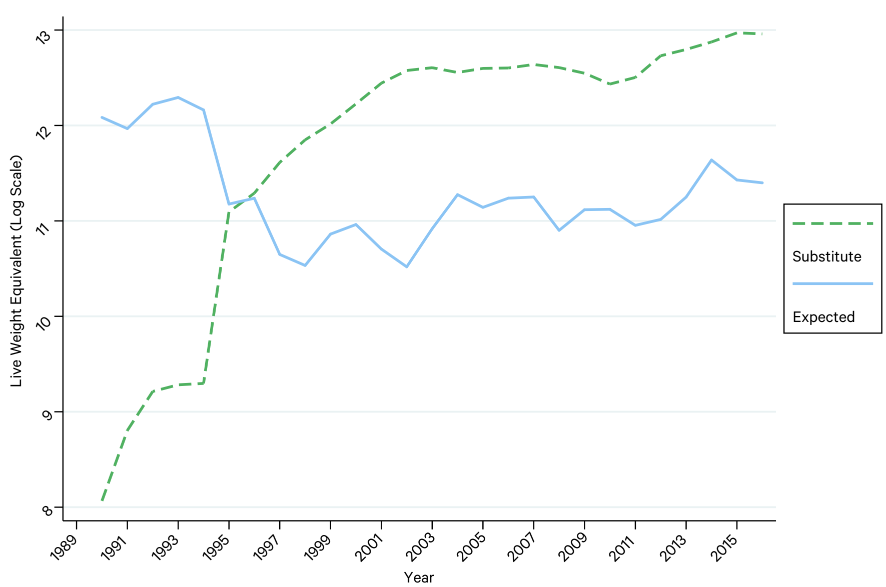
When we incorporate data on the origin and production method of seafood products, we can begin to shed light on the potential environmental costs of seafood mislabeling. Damage from salmon aquaculture varies by country and can include antibiotic and other chemical uses, coastal nutrient pollution, and harms to local salmon populations, such as the spread of parasites like sea lice (Ford and Myers 2008; Burridge et al. 2010; Milewski 2001). For example, antibiotic use in salmon aquaculture can differ greatly across Chile, Norway, and Canada (Miranda et al. 2018). Although changing industry best practices are leading to overall reductions in antibiotics and other chemical uses (Henriksson et al. 2015), the potential effects of salmon mislabeling would likely differ based on the country and time period in which the Atlantic Salmon was produced. Mislabeling studies focused on salmon have yet to determine the provenance of substitute Atlantic Salmon (e.g., Chile or Norway); however, this may be possible with forensic methods complementary to DNA, such as detection of stable isotopes and trace elements (Ortea and Gallardo 2015). Import data can also provide insights into scoping potential environmental costs of salmon mislabeling. When farmed salmon imports are mislabeled as wild-caught Pacific salmon, customers are denied the opportunity to support sustainable wild fisheries, such as Alaska's sustainable Pacific salmon fisheries (Jaffry et al. 2004; Verbeke et al. 2007). But whether salmon mislabeling is precipitating any additional environmental costs and socioeconomic harms on the Pacific salmon industry remains unclear.

Figure 1. Global production of salmon, 1985–2015



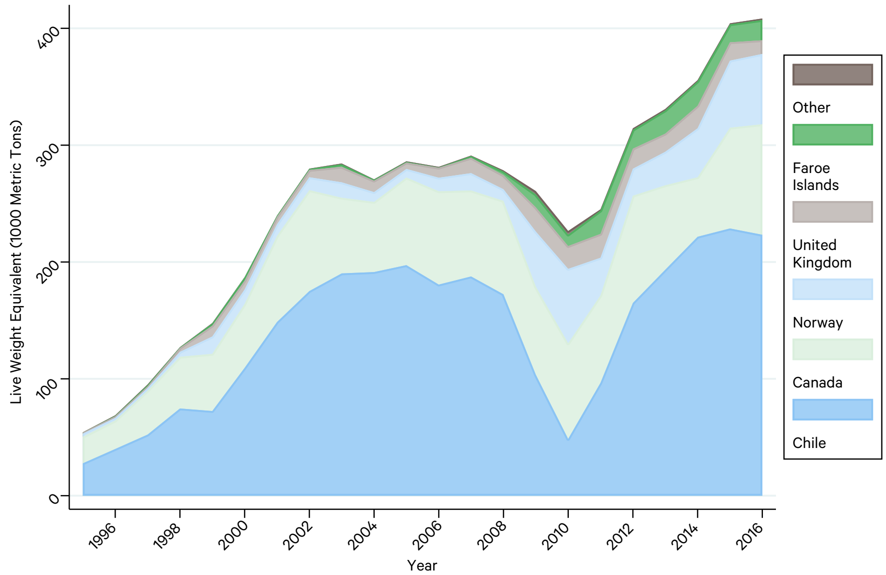
Source: FAO's FishstatJ database (FAO 2018a).
Note: This figure includes production of Atlantic, Chinook, Coho, and Sockeye Salmon.

Figure 2. Apparent US consumption of farm-raised Atlantic Salmon (substitute) and wild-caught Pacific salmon (expected), 1990–2016



Source: Import and export data, NOAA (2018b); production data, FAO's FishStatJ database (FAO 2018a), and annual landings data (NOAA 2018a).
Note: Landed weight is calculated based on FAO conversion factors (FAO N.d.). Chinook, Coho, and Sockeye Salmon are the expected species.

Figure 3. US imports of farm-raised Atlantic Salmon, by country of origin, 1995–2016



Note: Landed weight is calculated based on FAO conversion factors (FAO N.d.)

Table 1. Results from US-based mislabeling studies testing three species of Pacific salmon: Chinook (*Oncorhynchus tshawytscha*), Coho (*O. kisutch*), and Sockeye (*O. nerka*)[5]

	Pacific Salmon Products			
Measure	**Pacific (or wild)**	**Chinook**	**Sockeye**	**Coho**
Number of studies	9	6	6	5
Minimum study rate	0%	0%	0%	0%
Maximum study rate	100%	50%	18%	0%
Mean study rate (standard deviation)	48% (40%)	19% (21%)	3% (7%)	0%
Median study rate	33%	15%	0%	0%
Mode study rate	100%	0%	0%	0%
Simple pooled mean rate	29%	20%	3%	0%

Sources: see Appendix.

Box 1. A framework for estimating the total amount of mislabeled seafood consumed

With data on the mislabeling rate and the total production and import of expected species, the quantity of substitute on the market mislabeled as expected (M_{SE}) can be estimated. We label apparent consumption C_E and C_S (for expected and substitutes, respectively) and mislabeling rate R, defined as follows:

$$R= M_{SE}/(M_{EE}+ M_{SE}) ,$$

where M_{EE} represents the expected on the market labeled as the expected. The total product on the market is equal to the sum of the expected product labeled as the expected (M_{EE}) and the expected product labeled as the substitute (M_{ES}). We assume there is little incentive to label the expected species considered here as the substitute and therefore assume M_{ES} is approximately zero. As a result, M_{EE} is approximately equal to C_E. Therefore, when we substitute C_E for M_{EE} and solve for M_{SE},[6] we find

$$M_{SE}= (R/(1-R))*C_E , R<1.$$

3.2 Atlantic Cod

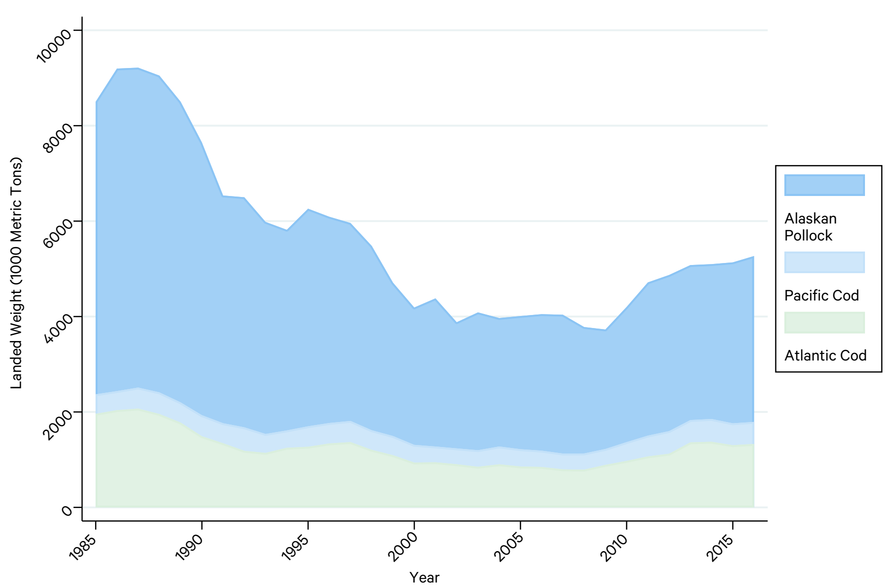
As with salmon, we can use trade and production data to gain a better understanding of the potential scale and effects of mislabeled Atlantic Cod. Cod, a group of wild-caught fish from the Gadidae family, has long been a commercially important fish popular with US consumers (Cheng and Capps 1988). Overall, there are fewer studies in the US on cod than on salmon, but Pacific Cod and Alaska Pollock have been identified as substitutes (Appendix, Table A2). Whether Atlantic Cod is mislabeled more or less often than Chinook Salmon is unclear.

Global production of Atlantic Cod is much lower than that of the two known substitutes, Alaska Pollock and Pacific Cod (Figures 4). Overall production of Atlantic Cod and substitutes has fluctuated over time and is down from its peak, at about half the total recorded in the late 1980s (Figure 4). Substitute production is more than double that of Atlantic Cod (Figure 4). Available US ex-vessel price data suggest that, at least at the landings along the supply chain, Atlantic Cod is the most valuable of the three species (NOAA Fisheries 2016). The decline in global production of Atlantic Cod since the 1980s (Figure 4) may create the enabling conditions for fraud.

Like the world market, the US market for Atlantic Cod and substitutes is dominated by identified substitutes, based on the available production and trade data. The quantity of Atlantic Cod consumed in the United States relative to its substitutes is small: the total 2016 apparent consumption of Atlantic Cod amounted to just 6 percent of the combined US consumption of Atlantic Cod, Pacific Cod, and Alaska Pollock. Apparent consumption of the expected species, Atlantic Cod, has fallen since the late 1980s (Figure 5). By comparison, the apparent consumption of the two substitute species, though variable, has stayed fairly level since 1990.

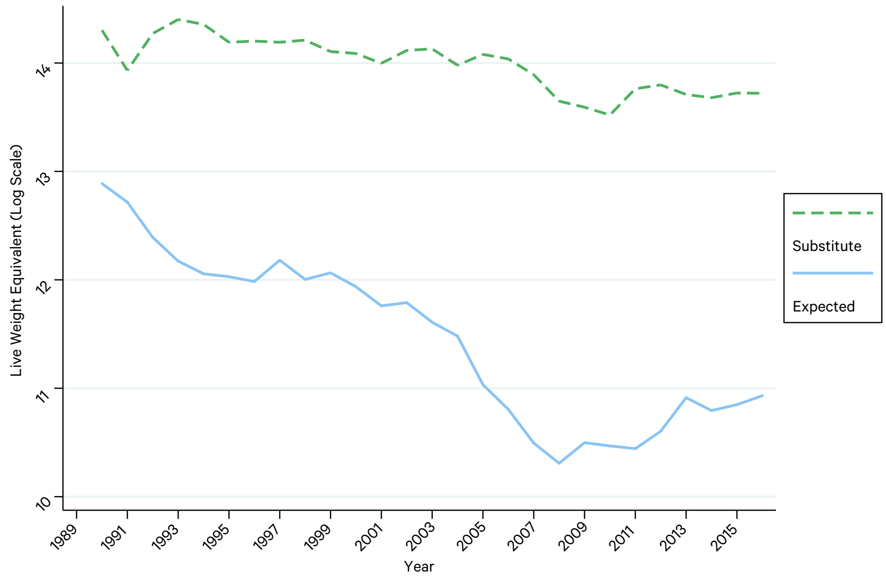
What we know about Atlantic Cod mislabeling provides a contrasting example to Pacific salmon, raising a number of informed hypotheses. First, despite similar mislabeling rates to Chinook, the amount of consumed mislabeled Atlantic Cod could be higher than Chinook Salmon because of the large potential differences in apparent US consumption between the two species: the sum of imports plus production of Atlantic Cod, minus exports, is about 11 times that of Chinook Salmon. Second, though fraudulent, mislabeled seafood sold as Atlantic Cod may not always lead to (potential) biological damage to the substitute species. Some Atlantic Cod stocks have declined (NOAA Fisheries 2017), but Pacific Cod stocks are considered healthier (Barbeaux et al. 2017; Thompson 2017). Alaska Pollock is also considered well-managed. The East Bering Sea stock reached new highs, according to the 2017 assessment (Ianelli et al. 2017). The Gulf of Alaska stock has shown variability in recent years but is expected to increase in 2018 (Dorn et al. 2017). Main Alaska Pollock fisheries from which the United States imports products have followed similar trends over time (see, e.g., Mori and Hiyama 2014; DFO 2018).

Figure 4. Global production of Atlantic Cod and substitute species, 1985–2016



Source: FAO's FishstatJ database (FAO 2018a).

Figure 5. Logged US apparent consumption[7] of Atlantic Cod and substitutes, 1990–2016



Source: NOAA (2018b)
Note: Landed weight calculated based on FAO conversion factors (FAO N.d.). Pacific Cod and Alaska Pollock are included in the figure as substitute species.

Table 2. Results from US-based mislabeling studies testing products labeled Atlantic Cod (*Gadus morhua*)[8]

Measure	Atlantic Cod
Number of studies	5
Minimum study rate	0%
Maximum study rate	100%
Mean study rate (standard deviation)	35% (40%)
Median study rate	33%
Mode study rate	0%
Simple pooled mean rate	23%

Sources: see Appendix.

Conclusions and Further Research

Because of the globalized nature and complexity of seafood markets (Gephart and Pace 2015), seafood mislabeling likely has highly variable and context-specific consequences. Unraveling the causes and effects of seafood mislabeling is a challenging problem that will require novel approaches with multiple types of data. Without these advances and a more rigorous analytical approach, our understanding of seafood mislabeling will be largely limited to idiosyncratic studies, and our ability to inform the design of policies and programs to reduce the problem will be constrained.

Although research on seafood mislabeling has grown over the past decade, most studies have focused on either forensic methodologies for testing fish in markets and restaurants or efforts to find seafood mislabeling in a specific geography. Though important, current data are necessarily incomplete and can be misleading, since they cannot describe the larger scope and potential consequences of seafood mislabeling. Our goal is to provide a framework for calculating an estimate of the total amount of mislabeled fish on the market by integrating mislabeling rates with import and production data. This is a step toward understanding the economic, health, and ecological harms of seafood mislabeling at the national level.

For now, researchers seeking to implement our proposed framework to infer consumption of mislabeled seafood will be stymied by the poor quality of consumption and mislabeling data. Lack of taxonomic detail in trade data currently limits full integration with mislabeling data for many species (Cawthorn and Mariani 2017). Other constraints arise from the paucity of studies and samples, as well as incomplete data reporting and lack of attention to sampling design (Pardo et al. 2016). The former is problematic because estimates of uncertainty are rarely reported (despite often being large), and the latter raises the potential for unmeasurable bias. Therefore, the potential of coupling production and trade data with mislabeling studies awaits more coordinated and targeted research. We call on researchers and advocacy organizations addressing seafood fraud issues to collaborate and agree on common research methodologies and data collection practices to facilitate a more effective national response to a natural resources management and law enforcement problem with unknown but possibly serious economic, ecological, and health consequences.

Notes

1 We adopt taxonomic and common names from the **Species Names** section of "A Guide to AFS Publications Style" by the American Fisheries Society (**www.fisheries.org**).

2 The calculations are subject to some caveats and uncertainty, which may be most pronounced for products that are exported for processing and reimported and/or have passed through multiple countries on the way to the United States.

3 One exception could be if there is zero production but products in the marketplace carry the label—for example, Atlantic Salmon labeled as Chinook in the Chinook off-season, when production is zero.

4 The majority of the global supply of Atlantic Salmon comes from aquaculture, whereas the majority of the global supply of Pacific salmon comes from wild-capture fisheries. In 2016, wild-caught Atlantic Salmon was less than 1 percent of global production, and farmed Pacific salmon (Chinook, Coho, Chum) was about 29 percent of global Pacific salmon production (FAO 2018a). See Appendix for more detail.

5 Since wild-caught salmon is commonly sold in the United States as "Pacific salmon," we also present results with this product as the expected species. The 14 studies vary in their data collection and detail (see Appendix). All mislabeling rate estimates are highly uncertain, with the standard deviation similar to the mean. The mean is highly sensitive to skewed data, which is common with mislabeling data. The simple pooled mean (across studies) is unreliable because it does not have an estimate of variance and problems demonstrated with simply pooling data across studies arise (Bravata and Olkin 2001). Thus, the median (i.e., the middle value) and the mode (i.e., the most frequent value) are also reported; they are often better measures of central tendency. In practice, the assumption that M_{EE} is approximately equal to C_E is sensitive to the point in the supply chain where mislabeling occurs and should be explored further in future work."

6 M_{SE} cannot be identified when R equals 1, which occurs when all product on the market is mislabeled.

7 NOAA Fisheries trade data aggregate groups of products, such as cod, in a manner that does not allow for analysis at the level of Pacific Cod versus Atlantic Cod versus Alaska Pollock (NOAA 2018b). To estimate the tons of Atlantic Cod and substitute species imported from each country, we combine the trade data with country species production percentages calculated from the United Nations Food and Agriculture Organization data (FAO 2018a). For each country and year, we first calculate the percentage of total production attributable to each type of cod (Atlantic versus Pacific). We then apply these percentages to the aggregated trade data for cod from the same country and year, producing estimates of the total tons of Atlantic Cod and Pacific Cod that were imported and exported. The same process is used to estimate tons of Alaska Pollock imported and exported.

8 Because of the limited number of studies and their limited amount of sampling, results are highly variable. Consequently, mislabeling rate estimates are highly uncertain, with the standard deviation greater than the mean. The mean is highly sensitive to skewed data, which is common with mislabeling data. Furthermore, the simple pooled mean (across studies) is unreliable because it does not have an estimate of variance and problems demonstrated with simply pooling data across studies arise (Bravata and Olkin 2001). Thus, the median (i.e., the middle value) and the mode (i.e., the most frequent value) are also reported, which are often better measures of central tendency. See Appendix for more detail.

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Appendix: Mislabeling Rate Data Sources

Table A1. US-based mislabeling studies, Pacific salmon

Study	Description	Pacific ("wild")	Chinook	Sockeye	Coho	Salmonidae
Burros 2005	*New York Times* report that sampled wild fresh salmon at locations in New York City. Species-level information was not reported. Atlantic Salmon was only substitute.	7 (8)				7 (8)
Cline 2012	Peer-reviewed study that collected samples from western Washington sold as wild Pacific salmon. Atlantic Salmon was only substitute.	11 (99)				11 (99)
Consumer Reports 2006	*Consumer Reports* report that sampled wild and farmed labeled salmon from several states at three time periods over two years. Species-level information was not reported. Atlantic Salmon was only substitute.	13 (50)				13 (50)
Consumer Reports 2011	*Consumer Reports* report. Included 28 Pacific salmon samples and species-level information. Four samples were mislabeled using other Pacific salmon species at the substitute. In all cases Coho Salmon was substitute.		2 (8)	2 (11)	0 (9)	4 (28)

Khasker et al. 2015	Peer-reviewed study that included samples labeled as Atlantic Salmon, Pacific salmon, and Rainbow Trout. One sample was mislabeled: Atlantic Salmon labeled Pacific salmon.	1 (10)				1 (52)
Muñoz-Colmenero et al. 2017	Peer-reviewed study from Spain and United States. US-based samples included salmon labeled as Pacific salmon and Chinook Salmon. One Chinook Salmon was mislabeled as Chum Salmon.	0 (6)	1 (24)			1 (30)
Shokralla et al. 2015	Peer-reviewed study from USA that included 8 samples belonging to Salmonidae. One sample labeled Wild Alaskan Salmon was mislabeled as Atlantic Salmon.	1 (1)	0 (1)	0 (1)	0 (1)	1 (8)
Stader 2015	Report by BonafID from St. Louis metropolitan area that included 17 salmon samples identified as Atlantic Salmon, Chinook Salmon, Chum Salmon, Sockeye Salmon, and pacific salmon. Two Pacific salmon samples were mislabeled; however; substitutes were not reported by name.	2 (6)	0 (1)	0 (5)		2 (17)
Warner 2011	Report by Oceana from Boston that included 28 salmon samples of Coho, Sockeye, and Atlantic Salmon. None were mislabeled.			0 (24)	0 (2)	0 (28)*

Warner et al. 2012a	Report by Oceana from New York City that included 56 salmon samples. Total sample sizes by product or label were not reported. Substitutes included Sockeye Salmon, Atlantic Salmon, and Rainbow Trout.	6	3	1	1	11 (56)*
Warner et al. 2012b	Report by Oceana from South Florida that included 16 salmon samples. Total sample sizes by product or label were reported. Atlantic Salmon was substitute in all cases.	2 (2)	1 (2)	0 (4)	0 (1)	3 (16)*
Warner et al. 2012c	Report by Oceana from Los Angeles that included 20 salmon samples. Total sample sizes by product or label were not reported. Two Sockeye Salmon samples were mislabeled as Atlantic and Chum Salmon.			2		2 (20)*
Warner et al. 2013*	Report by Oceana that pooled 14 studies (including above four) from 16 cities. Total sample sizes by product or label were not reported. Atlantic Salmon was most common substitute.	11	8	5	3	28 (348)
Warner et al. 2015	Report by Oceana focused on salmon from four cities and surrounding areas. Data were pooled from Warner et al. (2013); only additional information is reported here. Total sample sizes for product or label were reported. Atlantic Salmon was most common substitute.	27 (41)	7 (19)	0 (17)	0 (2)	

Number of studies	9	6	6	5	10
Minimum study rate	0%	0%	0%	0%	2%
Maximum study rate	100%	50%	18%	0%	88%
Mean study rate (standard deviation)	48% (40%)	19% (21%)	3% (7%)	0%	21% (28%)
Median study rate	33%	15%	0%	0%	12%
Mode study rate	100%	0%	0%	0%	n/a
Simple pooled mean rate	29%	20%	3%	0%	100%

*Family-level data for four studies are included with Warner et al. 2013 for summary statistics.

Note: Results are presented from US-based mislabeling studies testing three species of Pacific salmon: Chinook (Oncorhynchus tshawytscha), Coho (O. kisutch), and Sockeye (O. nerka). Since wild-caught salmon is commonly labeled Pacific salmon in the United States, we also present results from mislabeling studies with this product as the expected species. The most common substitute in salmon mislabeling is Atlantic Salmon. The 14 studies vary in their data collection and detail. Eight of the nine studies that reported the total number of expected Pacific salmon samples identified mislabeling. Fewer data are available for salmon mislabeling at the species level. All mislabeling rate estimates are highly uncertain, with the standard deviation similar to the mean. The mean is highly sensitive to skewed data, which is common with mislabeling data. Thus, the median (i.e., the middle value) and the mode (i.e., the most frequent value) are often better measures of central tendency. The simple pooled mean (across studies) is unreliable because it does not have an estimate of variance and the problems demonstrated with simply pooling data across studies (Bravata and Olkin 2001). Data are shown for three labeled products and at the taxonomic family level for the respective studies (number mislabeled and number of total samples).

Table A2. US-based mislabeling studies, Atlantic Cod

Study	Description	Atlantic Cod	Gadidae
FDA 2013	Report by Department of Health and Human Services. Samples collected randomly from US wholesale distribution chain from 14 states. Included 104 samples of expected Gadidae.	0 (12)	0 (104)
Khaksar et al. 2013	Peer-reviewed study that collected samples from New York, Texas, and California. Included 9 samples of expected Gadidae.	0 (4)	0 (9)
Stader 2015	Report by BonafID that collected samples from St. Louis metropolitan area. Included 9 samples of expected Gadidae. Substitutes not reported by name.	1 (1)	1 (9)
Warner et al. 2012	Report by Oceana that collected samples from New York City. Included 16 samples of expected Gadidae. Two Atlantic Cod samples were Pacific Cod and White Hake. Total sample sizes for Atlantic Cod not reported.	2	4 (16)*
Warner 2011	Report by Oceana that collected samples from Boston. Included 30 samples of expected Atlantic or Pacific Cod. Mislabeled Atlantic Cod samples were Pacific Cod, all from two locations.	6 (18)	8 (30)*
Warner et al. 2013	Report by Oceana that pooled 14 studies (including above 2) from 16 cities. Included 116 cod samples. Total sample sizes by product or label were not reported. Atlantic Cod labeled as Pacific Cod was most common type of cod mislabeling.	14	32 (116)
Wong and Hanner 2008	Peer-reviewed study that collected samples from northeastern United States and Canada. Included 8 US-based samples of expected Gadidae. Two Atlantic Cod samples were mislabeled Alaska Pollock.	2 (5)	2 (8)
Number of studies		5	5

Minimum study rate	0%	0%
Maximum study rate	100%	28%
Mean study rate (standard deviation)	35% (40%)	13% (13%)
Median study rate	33%	11%
Mode study rate	0%	0%
Simple pooled mean rate	23%	14%

Family-level data for four studies (*) are included are included with Warner et al. 2013 for summary statistics.

Note: The seven studies vary in their data collection and detail. Of the five studies that report the total number of expected Atlantic Cod samples, three have uncovered mislabeling. Yet this includes only nine of a total of 40 samples. In general, the limited number of studies and limited sampling yield highly variable results. Consequently, mislabeling rate estimates are highly uncertain, with the standard deviation greater than the mean. The most common Atlantic Cod substitutes are Pacific Cod and Atlantic pollock (n > 1 sample; G. macrocephalus and Pollachius pollachius). The mean is highly sensitive to skewed data, which is common with mislabeling data. Thus, the median (i.e., the middle value) and the mode (i.e., the most frequent value) are often better measures of central tendency. The simple pooled mean (across studies) is unreliable because it does not have an estimate of variance and the problems demonstrated with simply pooling data across studies (Bravata and Olkin 2001). Data are shown for Atlantic Cod mislabeling and at the taxonomic family level for the respective studies (number mislabeled and number of total samples).