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Exploring the causes of seafood fraud: A meta-analysis on mislabeling and price

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ABSTRACT

Seafood mislabeling is receiving increased attention by civil society, and programs and policies to address it are being implemented widely. Yet, evidence for the causes of mislabeling are largely limited to anecdotes and untested hypotheses. Mislabeling is commonly assumed to be motivated by the desire to label a lesser value product as a higher value one. Using price data from mislabeling studies, Δ_{mislabel} is estimated (i.e., the difference between the price of a labeled seafood product and its substitute when it was not mislabeled) and a meta-analysis is conducted to evaluate the evidence for an overall *mislabeling for profit* driver for seafood fraud. Evidence is lacking; rather, Δ_{mislabel} is highly variable. Country nor location in the supply chain do not account for the observed heterogeneity. The Δ_{mislabel} of substitute species, however, provides insights. Some species, such a sturgeon caviar, Atlantic Salmon, and Yellowfin Tuna have a positive Δ_{mislabel}, and may have the sufficient characteristics to motivate *mislabeling for profit*. Atlantic Bluefin Tuna and Patagonian Toothfish have a negative Δ_{mislabel}, which could represent an incentive to mislabel in order to facilitate market access for illegally-landed seafood. Most species have price differentials close to zero—suggesting other incentives may be influencing seafood mislabeling. Less than 10% of studies report price information; doing so more often could provide insights into the motivations for fraud. The causes of mislabeling appear to be diverse and context dependent, as opposed to being driven primarily by one incentive.

1. Introduction

With the advent of accessible tools for food forensics [1], seafood fraud is receiving increased attention by governments, academics, and civi society [2–4]. Over 100 studies investigating seafood mislabeling have been conducted in dozens of countries. In sum, tens of thousands of samples have been tested covering hundreds of species [5,6]. While its potential impacts on policies, markets, and ecosystems are concerning, the causes and consequences of seafood mislabeling remain elusive. The current evidence for the causes of mislabeling, for example, are largely limited to anecdotal observations and untested hypotheses.

Understanding the causes of seafood mislabeling is a critical step to explore the consequences of seafood fraud, as well as to design solutions to reduce it. This is particularly important as existing national policies are being revised and new ones implemented [7,8]. In the United States, for example, a new seafood import monitoring program was recently implemented focused on reducing seafood fraud and illegal, unregulated and unreported (IUU) fishing. It is being rolled out in stages, with the first stage covering sixteen groups of products that were deemed priorities [9]. Yet, the program is controversial due to the potential costs and complexities involved in implementing a traceability program. Some even claim that it could violate legal obligations under the World Trade Organization [10]. Insights into why seafood mislabeling is occurring can help elucidate the incentives for seafood fraud, which can be used to inform policies and programs.

Seafood mislabeling is commonly assumed to be primarily motivated by the desire to label a lesser value product as a higher value one [4,6,11–13]. Economic theory predicts that information asymmetry in seafood products (i.e., sellers have more information about the true quality than buyers) can motivate mislabeling [12]. While intentional mislabeling of lower-value product for more expensive one has been documented [14–16], how widespread this incentive is has not been rigorously evaluated. Alternative drivers for seafood mislabeling are plausible [6,17]. This includes more complex incentives that are

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ultimately connected to profit, such as regulation avoidance (e.g., tariffs) and market access. But, seafood mislabeling could also result from factors unrelated to profit, such as confusing and weak regulations on product labels, mixed fisheries of similar species, and informal supply chains [18,19]. Yet, information on causes and motivations for seafood mislabeling are currently limited to observations on case-by-case basis. This study evaluates the current evidence for a simple *mislabeling for profit* driver for seafood fraud: a lower-value product masquerading as a higher-value one. Using price data from mislabeling studies, differences are explored in the labeled price of a seafood item and the estimated price of its real identity. This price differential provides some evidence for the different incentives for seafood mislabeling. In this study, a meta-analysis is conducted on mislabeling and price, and the results are discussed within the broader contexts of seafood fraud and designing cost-effective policies and programs to reduce it.

2. Methods and materials

A systematic literature review was conducted using the Web of Science to compile all published literature on seafood fraud up through December 2017. A total of 331 publications were identified related to seafood fraud (See Supplementary materials for details). A review was also conducted for reports and articles on mislabeling that did not undergo a formal peer-review process. An additional 69 publications were identified related to seafood mislabeling. Each publication was screened for cost data on seafood mislabeling, which resulted in only 24 publications. For studies with primary data and using a seafood sample tested for mislabeling as the replicate, the following information was compiled and coded when possible: 1) content of the label, 2) genus reported, 3) species reported, 4) the product form (e.g., whole, filet), 4) the location in the supply chain (e.g., restaurant, grocery store), 5) country where the sample was collected, 6) year collected, and 7) the true identity (i.e., genus and species) of the sample (See Supplementary materials for details). Fishbase and Sealifebase were used as taxonomic authorities and for common names reported here [20,21].

Of the limited mislabeling studies that reported information on prices, data were presented in several ways. Some studies reported the price of each seafood sample, while others reported averages or ranges for a particular seafood product. For each seafood sample, the difference between the price of the labeled item and its substitute when it was not mislabeled was estimated ($\Delta_{\text{mislabel}} = P_{\text{label}} - P_{\text{substitute}}$). The price of a seafood sample was recorded as reported by the source (P_{label}). In some cases, the cost of a substitute species when it was not mislabeled was also reported ($P_{\text{substitute}}$). In cases when it was not, the entire price dataset of the particular study was used to estimate the cost of a substitute seafood product. This was done by taking the average price of the substitute when it was not mislabeled in the same form (e.g., filet) and from the same location in the supply chain (e.g., restaurant). The following is a hypothetical example: a study tests five samples of Pacific salmon (*Oncorrhynchus* spp.) and five samples of Atlantic Salmon (*Salmo salar*) from ten restaurants for mislabeling. None of the Atlantic Salmon were mislabeled but three samples labeled Pacific salmon were actually Atlantic Salmon. The study reported the price paid for each salmon sample (P_{label}). The price of the substitute ($P_{\text{substitute}}$) is estimated by taking the average price of the five Atlantic Salmon samples that were not mislabeled. In order to standardize the price data across studies, all price data was converted to 2017 euros (€) using year-specific exchange and inflation rates [22,23]. Due to differences in price reporting across studies, Δ_{mislabel} estimates necessarily differ in their precision and accuracy. In cases when only averages are reported for P_{label} and $P_{\text{substitute}}$, estimates of variability at the study level are underestimates (see Table 1).

Meta-analysis is a powerful tool to aggregate, contrast, and synthesize findings from the literature on a particular topic [24]. It is the most appropriate tool to evaluate the evidence for the simplest and most commonly cited incentive for seafood mislabeling: labeling an item as another to increase profit. If prevalent, one would expect a clear signal in the prices of mislabeled seafood (i.e., $\Delta_{\text{mislabel}} > 0$). A meta-analysis requires a set of effect size estimates with their corresponding sampling variance. In this case, the effect size estimates are for an individual group (i.e., there is no control group): the standardized mean difference in price for each study ($\Delta_{\text{mislabel}} = P_{\text{label}} - P_{\text{substitute}}$), along with the corresponding standard deviation and sample size.

Seafood mislabeling studies are not exactly identical in their methods nor the characteristics of the samples tested, and those differences may introduce variability (i.e., heterogeneity) among any true effect in Δ_{mislabel}. Thus, a random-effects model is used to model that heterogeneity [25]. The model starts with $i = 1,\ldots,k$ independent effect size estimates, each estimating the true effect size. The model assumes that,

$$y_i = \theta_i + e_i, \tag{1}$$

where y_i denotes the observed effect in the i-th study, θ_i is the corresponding (unknown) true effect, e_i is the sampling error, and $e_i \sim N(0, v_i)$. The random-effects model is represented by

$$\theta_i = \mu + u_i, \tag{2}$$

where $u_i \sim N(0, \tau^2)$. The goal of the meta-analysis is to estimate μ, the average true effect, and τ^2, the amount of heterogeneity among the true effects. A restricted maximum-likelihood estimator is used to estimate the residual heterogeneity (τ^2) [26]. A mixed-effects model is useful in order to include a moderator that may account for at least part of the heterogeneity in the true effects [25]. In particular, to complement the random-effects model, a mixed-effects model is used to test if the country or supply chain location where the seafood was sampled explains any of the observed heterogeneity.

Since the statistical models assume the effect sizes are normally distributed, multiple tests were conducted to assess normality and the presence of outliers. First, Shapiro-Wilk's and Anderson-Darling normality tests were conducted. Second, model performance was evaluated with a suite of case deletion and residual diagnostics to identify any studies that strongly deviate (i.e., outliers) [27]. Before and after removing any potential outliers from the dataset, model assumptions were also assessed with normal quantile plots [28]. Lastly, the effect size was estimated using permutation tests as a complementary approach to the maximum-likelihood estimator [29,30]. All analysis were conducted in the statistical language R and adopted an α-level of 0.05 [31]. The meta-analysis and associated analysis were conducted using the R package *metafor* [27]. See Supplementary materials for additional information.

3. Results and discussion

Relatively few mislabeling studies reported prices data: Δ_{mislabel} was estimated from 16 studies [Table 1; 15,17,32,33–45]. We identified an additional eight studies that had some price information but were excluded from the analysis because it was not possible to extract usable data (i.e., Δ_{mislabel}) [14,16,46–51]. The resulting price dataset covered nine countries: Brazil, Canada, China, France, Greece, Italy, South Africa, Spain, and United States. Since prices were often not reported for all seafood tested for mislabeling, the sample size of Δ_{mislabel} was less than the total number of seafood samples: ranging from 7 to 90 per study, with a median of 15 (Table 1). In total, Δ_{mislabel} was estimated for 46 products tested for mislabeling; however, 80% consisted $<$ 10 total samples (Table SM1). One study was excluded from the statistical models because a measure of variance could not be estimated [33; Table 1]. A second study, investigating caviar mislabeling, was highly influential in the model [15]. When this study was excluded, the data met normality assumptions using multiple tests and diagnostics (See Supplementary materials and Fig. SM1).

We failed to find evidence of an overall *mislabeling for profit* effect. The estimated true effect size was not significantly different than zero

Table 1
Data included in a meta-analysis on the price differential of mislabeled seafood. The difference in price ($\Delta_{mislabel} = P_{label} - P_{substitute}$) was calculated from mislabeled seafood samples from the studies below. Often only a subset (n) of samples in each study had sufficient information to estimate a price differential. Price data varied depending on the source and, thus, was calculated several ways. Two sources were excluded from statistical analyses. See Table SM1 for additional information.

Study	Price Data	n
Sources included in statistical analyses		
Ardura et al. 2010	Average price reported from official government statistics for expected and substitute products.	23
Barbuto et al. 2010	Single price reported for expected and substitute products.	34
Benard-Capelle et al. 2015	Price per sample reported, along with form and supply chain location. Substitute price was estimated by the average price of the product when it was not mislabeled, matching form and location.	10
Burros 2005	Price reported per sample. A range was reported for the substitute product. The midpoint of the range was used.	7
Carvalho et al. 2011	Single price reported for some expected and substitute products for two different forms (i.e., filets and whole fish).	16
Cawthorn & Hoffman 2017	Price per sample reported, along with form and additional information. Substitute price was estimated by the average price of the product when it was not mislabeled.	15
Garcia-Vaszquez et al. 2011	Average market prices reported for each product in different forms (i.e., whole fish and filets/slices). In two cases, whole fish price was used as proxy for the labeled and substitute products.	8
Gordoa et al. 2017	Price per sample reported. Substitute price was estimated by the average price of the product when it was not mislabeled.	90
Hanner et al. 2011	Price per sample reported. Substitute price was estimated by the average price of the product when it was not mislabeled. In eight cases, the average price across all forms was used to estimate the substitute price.	11
Lowenstein et al. 2009	Price per sample reported. Substitute price was estimated by the average price of the product from same location type when it was not mislabeled.	17
Munoz-Colmenero et al. 2016	Average price was reported from a national and international source, with the former preferred. Only the price differential is reported for mislabeled species.	14
Munoz-Colmenero et al. 2015	Average market prices are reported.	30
Wang & Hsieh 2016	Average prices are reported. Price for "fish" was used to estimate price for *Pangasianodon hypophthalmus*, as this species was the focus of the study,	15
Xiong et al. 2016	Price per sample reported. Substitute price was estimated by the average price of the product from same location type when it was not mislabeled. Substitute price for *Dissostichus mawsoni* was estimated from the average price of the label "toothfish" when it was not mislabeled. Labels that included *Dissostichus* or toothfish were not considered mislabeled when the sample was identified as *Dissostichus* spp.	28
Sources excluded from statistical analyses		
Consumer Reports 2006	Average prices reported. Study was for a single species and was excluded from statistical models because there was no estimate of variability.	13
Doukakis et al. 2012	Price range reported for each product. The midpoint was used. Not included in the model because it was an extreme outlier.	7

(Fig. 1; Table 2). Permutation tests produced the same results (See Supplementary materials). As important, model results suggests that the true effects are heterogeneous (Table 2). Almost all of the heterogeneity can be attributed to variability in effect size as opposed to sampling variance (I^2, Table 2). These results suggest that effect size ($\Delta_{mislabel}$) is highly variable across studies, suggesting that multiple incentives may be motivating seafood mislabeling as opposed to primarily one driver (Fig. 1). Identifying factors underlying the heterogeneity is challenging with the current evidence because mislabeling studies tend to sample across multiple seafood products, forms, and supply chain locations—often with little attention to probability sampling. However, there is no evidence to suggest that country accounts for any of the heterogeneity in the observed effect. The results of the mixed-effects model using country where seafood was sampled (or pooling across European Union countries) as a moderator showed no effect ($QM = 0.036$, $p = 0.849$ and $QM = 0.005$, $p = 0.942$, Table SM2). While food labeling and traceability regulations differ across countries [e.g., European Union, China, United States; 7, 52], country does not influence the observed heterogeneity in $\Delta_{mislabel}$ across studies. This is perhaps not surprising given one might expect that mislabeling rates

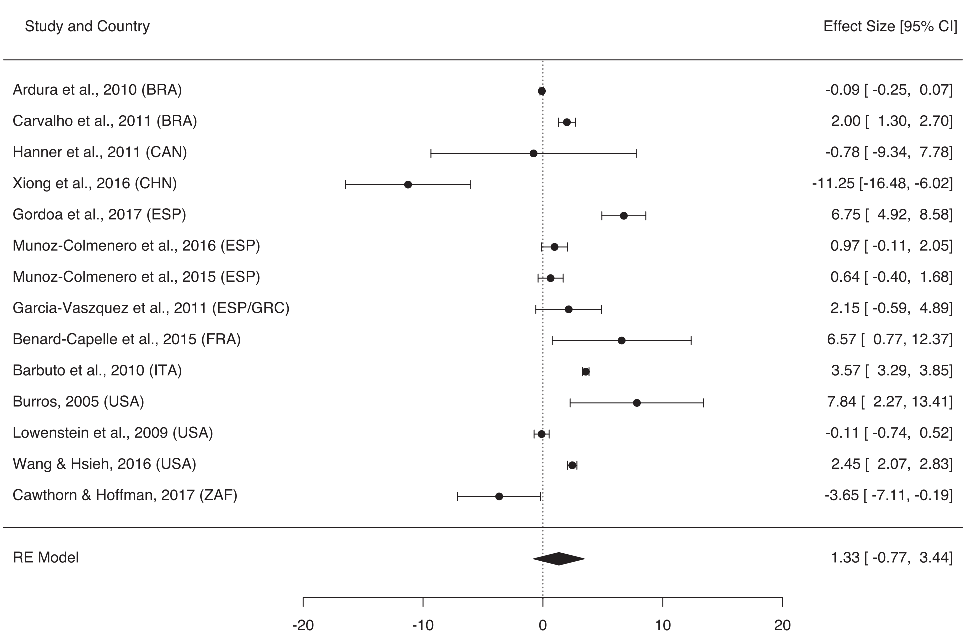

Fig. 1. Forest plot of effect sizes [95% CI] for each study included in the meta-analysis random-effects (RE) model. The predicted mean effect size (i.e. price differential of mislabeled seafood) is 1.33 and is not significantly different than zero (see Table 2). Results of the model suggest that almost all of the observed heterogeneity can be attributed to variability in effect sizes as opposed to sampling variance. Countries where studies took place are shown.

Table 2
Results of a random-effects model assessing the price differential of mislabeled seafood across 14 studies. The effect was the average price differential (2017 € 1.33) between a labeled seafood item (P_{label}) and the estimated price of its true identity ($P_{substitute}$). The average true effect size (*μ*) is not significantly different from zero and effect sizes are highly variable across studies.

Parameter	Estimate	95% CI	p-value
Average true effect size (μ)	1.33	− 4.21	0.21
Estimated amount of total heterogeneity (τ^2)	3.7	6.56–53.43	< 0.001
Percentage of the total variability in the effect size estimates that is due to heterogeneity among the true effects (I^2)	99.38%	98.72–99.84	
The ratio of the total amount of variability (heterogeneity plus sampling variance) to the amount of sampling variance (H^2)	162.13	78.21–629.81	

may differ across regulatory regimes but not necessarily the $\Delta_{mislabel}$ or any underlying incentives.

One plausible factor that could account for the observed variability in a price effect is the location in the supply chain where the sample was collected. For example, restauranteurs may have, on average, different motivations for mislabeling compared to fishmongers or seafood buyers for retail outlets. Unfortunately, there is insufficient replication across studies to evaluate these factors using a mixed-effects model. Pooling across the limited number of studies, however, there is little evidence to suggest any differences in $\Delta_{mislabel}$ across the supply chain, with all estimates including zero within one standard deviation (Fig. 2). We were not able to estimate $\Delta_{mislabel}$ for any samples that were collected at the wholesale level.

Another factor that could account for the variability in $\Delta_{mislabel}$ is the species or product involved in mislabeling. Seafood mislabeling necessarily involves two species: the *expected* species (e.g., the species that the seafood is purported to be based on a label) and the *substitute*—the true identity of the mislabeled product. Insufficient replication across studies prohibits any statistical modeling and limits inferences. The average price differential (and variability) by species, however, does provide some insights into mislabeling. For example, the $\Delta_{mislabel}$ of substitute species ranges from + €25 to -€12 (Fig. 3). While further research is needed, we hypothesize the observed species differences in $\Delta_{mislabel}$ are signs of different causes (i.e., incentives) for seafood mislabeling.

Sturgeon caviar has by far the greatest price differential of substitute species (€25; Fig. 3). While other causes have been suspected to motivate sturgeon mislabeling which also interact with any economic

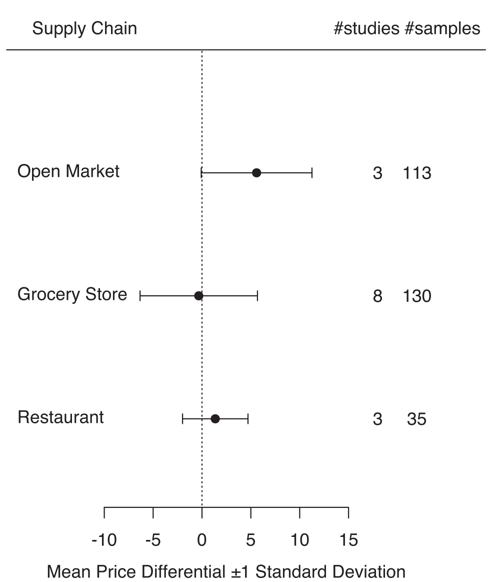

Fig. 2. Mean price differential and variance pooled across studies for seafood samples at different locations in the supply chain. Number of studies and samples are shown. Inferences are limited since locations consists of only 3–8 studies and data is pooled across studies. See Supplementary materials for definitions of supply chain locations.

motivation (e.g., scarcity), profit is the most common suspected driver of mislabeling for this group [15,53]. For example, Beluga caviar *(Huso huso*) captures a higher price and is often mislabeled by cheaper alternatives, which can increase profit margins by five-fold [15,53–57]. Yellowfin Tuna also captures a substantial profit (€10) when used as a substitute for Atlantic Bluefin and Bigeye Tuna [17,34,40]. In Spain, for example, Yellowfin Tuna, with an average price of ~€13 kg^{-1}, doubled its market price when it was sold as bluefin tuna [17]. Similarly, Atlantic Salmon labeled as Pacific salmon captures an average profit of €9 [32,33,39]. Both tuna and salmon enjoy high demand and are easily substitutable, either as sushi or filets [58]. For example, all three tuna species mentioned above are used for *shashimi* products, with bluefin the most valuable and scarce [58]. In the United States and Canada, where Pacific and Atlantic salmon are both common in the market, mislabeling has been documented in multiple geographies, with reported mislabeling rates varying widely [14,32,33,59–62].[2] While Pacific salmon prices vary significantly across species and time [63], reported mislabeling often involves expensive Pacific salmon (e.g., Chinook Salmon, *O. tshawytscha*) being substituted by cheaper farmed Atlantic or other wild Pacific salmon species [14,33,62]. The substitutability of these species coupled with high demand may provide a strong incentive for *mislabeling for profit*. Further, at least in some US geographies, seafood consumers have a preference for wild over farmed salmon [64]. In certain geographies, tuna and salmon species, along with caviar, likely have sufficient characteristics to commonly motivate the labeling of a lesser valued species for a higher valued one (e.g., demand, substitutability, price, scarcity in time or space). This is supported by relatively high reported mislabeling rates for these three products [5,17,34,39,53,55,61,65–67]. For example in the United States, where several mislabeling studies targeting Pacific salmon species have been conducted, study-level mean mislabeling rates for the higher-value Chinook Salmon are higher than lower-value species such as Coho and Sockeye Salmon (*O. kisutch, O. nerka*) [68].

On the other end of the spectrum, two substitute species have average $\Delta_{mislabel}$ and standard deviations that are negative and do not include zero: Atlantic Bluefin Tuna (-€6) and Patagonian Toothfish (-€13; Fig. 3). In one of the largest studies conducted in the European Union, Gordoa and colleagues documented Atlantic Bluefin Tuna being sold as Yellowfin and Bigeye Tuna with a minimum loss of €13 kg^{-1} [17]. Referring to it as *reverse substitution*, the authors hypothesized this type of mislabeling was a means to facilitate the commercialization of illegally-landed Atlantic Bluefin Tuna. Reverse substitution has also been documented at-sea. In 2017, for example, a fishing vessel was cited for mislabeling 100 t of illegally-landed Southern Bluefin Tuna (*Thunnus maccoyii*) as the less valuable Bigeye Tuna [69]. While prices are variable [44], our $\Delta_{mislabel}$ estimate for Patagonian Toothfish is also negative, raising the possibility of reverse substitution in China. In this case, both Patagonian and Antarctic Toothfish were substituted for

[2] The majority of the global supply Atlantic Salmon comes from aquaculture, while the majority of the global supply of Pacific salmon comes from wild capture fisheries. Wild-captured Atlantic Salmon was < 1% of 2016 global production. Farmed Pacific salmon (Chinook, Coho, Chum) was ~16% of global Pacific salmon production in 2016. Source: FAO.

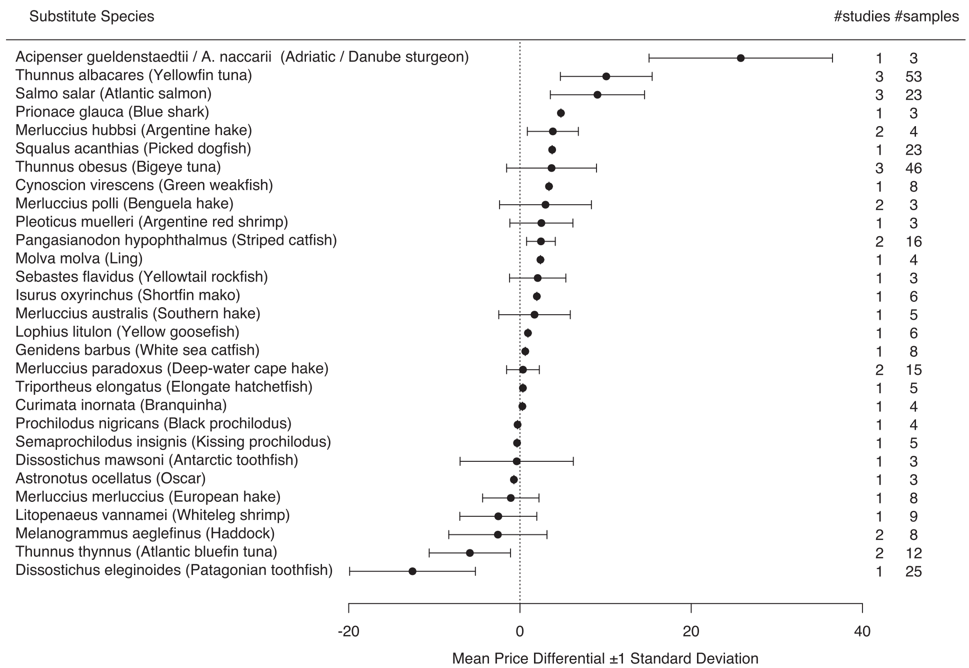

Fig. 3. Mean price differential and variance pooled across studies for substitute species involved in seafood mislabeling. Species with ≥ 3 samples are included. Number of studies and samples are shown. All species consist of < 3 studies and many consists of a single study, limiting any inferences.

Sablefish (*Anoplopoma fimbria*), a high-value and popular species in China [44]. Mislabeling of toothfish has been documented in the United States and Canada; however, in the majority of cases it was considered mislabeled due to the use of unacceptable market names or Antarctic Toothfish being a substitute for Patagonian Toothfish [39,70–72]. While illegal harvesting of toothfish in the southern oceans has decreased since its peak in the 1990s, it is still a major concern [73–75]. China is a destination for illegal toothfish: one estimate suggests that toothfish imports are double the official statistics due to smuggling, driven by an increase in demand [76]. While more research is needed on the role of toothfish substitution and price dynamics, reverse substitution is an intriguing type of seafood fraud because it suggests some actors may be motivated to mislabel in order to gain market access for illegal seafood. How prevalent it is remains to be seen. Like other potential connections between IUU fishing and seafood mislabeling that have been hypothesized (e.g., stock depletion, undersized or over-quota landings, and distortions in catch statistics) [77–79], little empirical evidence exist to access their prevalence or explore the details of those connections.

Most substitute species have price differentials and standard deviations that include zero—suggesting that other incentives are influencing seafood mislabeling (Fig. 3.). Anecdotal evidence exist for several potential drivers of seafood mislabeling. For example, it could be motivated by a desire to avoid regulation. While striped catfish (*Pangasianodon hypophthalmus*) had a small positive Δ_{mislabel} (€2), it provides an intriguing hypothesis for mislabeling to avoid regulation. After a 40% anti-dumping tariff on US imports from Vietnam in 2003, there appears to be an increase in the number of prosecutions for mislabeling of the species [80–84]. A case settled in 2009, for example, involved the illegal import of 4500 t and $12 million in avoided duties, which represents ~12% of the imported volume that year [85,86]. Under some circumstances, mislabeling could be driven by the need for the appearance of constant supply (e.g., restaurant menus) in face of increase fluctuations and decline in fisheries landings [87]. Unintentional mislabeling could be common: confusing seafood naming practices and policies are commonplace [88–90]. Accidental mislabeling could also occur given the informal nature of many seafood supply chains and the presence of mixed fisheries with similar species [18,19,41]. While alternative incentives to *mislabeling for profit* have been hypothesized, including those that are ultimately tied to profit and those that are not, evidence for their prevalence is limited to series of anecdotal accounts. More research on developing frameworks and signatures of the different causes of seafood mislabeling is critical step in order to be able to inform targeted policies and programs to reduce it. Doing so will require the collection of additional types of data alongside mislabeling rates, which have been the primary focus of mislabeling studies [68].

Due to the lack of price data and replication of studies, the observed results and patterns viewed through the lens of estimating Δ_{mislabel} raise evidence-based hypotheses as opposed to definitively answering any questions about the incentives for seafood mislabeling. Seafood mislabeling studies rarely present price data: less than 10% of studies do so. Further, the meta-analysis results are less robust than they could be since Δ_{mislabel} was estimated using averages in some cases. Inferences are further limited due to the sampling protocol of mislabeling studies: most sample seafood opportunistically without taking into account sampling design or effort [3,68]. Nonetheless, our results suggest that the causes of mislabeling are diverse and context dependent, as opposed to being driven primarily by one incentive. Given the sheer volumes involved, complex supply chains, and global nature of seafood, reducing seafood fraud is a wicked problem. Designing solutions to reduce it will likely require intricate systems-level knowledge. Price data can usually be collected easily and cheaply, and more attention to doing so could provide much needed insights in the motivations for seafood fraud.

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Declaration of interest statement

None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2018.11.022.

References

[1] R.S. Rasmussen, M.T. Morrissey, Application of DNA-based methods to identify fish and seafood substitution on the commercial market, Compr. Rev. Food Sci. Food Saf. 8 (2) (2009) 118–154.

[2] NOAA Fisheries, Federal agencies announce proposal creating U.S. seafood traceability program ⟨http://www.fisheries.noaa.gov/mediacenter/2016/02_February/04_02_proposed_seafood_traceability.html⟩; 2016.

[3] M.Á. Pardo, E. Jiménez, B. Pérez-Villarreal, Misdescription incidents in seafood sector, Food Control 62 (2016) 277–283.

[4] K. Warner, P. Mustain, B. Lowell, S. Geren, S. Talmage, Deceptive Dishes: seafood Swaps Found Worldwide, Oceana, Washington DC, 2016.

[5] R.E. Golden, K. Warner, The global reach of Seagood Fraud: A Current Review of the Literature, Oceana, 2014, ⟨http://usa.oceana.org/publications/reports/global-reach-seafood-fraud-current-review-literature⟩.

[6] A.M. Naaum, K. Warner, S. Mariani, R.H. Hanner, C.D. Carolin, Seafood Mislabeling Incidence and Impacts, Seafood Authenticity and Traceability, Elsevier, 2016, pp. 3–26.

[7] S. Charlebois, B. Sterling, S. Haratifar, S.K. Naing, Comparison of global food traceability regulations and requirements, Compr. Rev. Food Sci. Food Saf. 13 (5) (2014) 1104–1123.

[8] P. D'Amico, A. Armani, D. Gianfaldoni, A. Guidi, New provisions for the labelling of fishery and aquaculture products: difficulties in the implementation of regulation (EU) n. 1379/2013, Mar. Policy 71 (2016) 147–156.

[9] Department of Commerce, Magnuson-Stevens Fishery Conservation and Management Act; Seafood Import Monitoring Program, Federal Register, 2016, pp. 88975–88998.

[10] Southern Shrimp Alliance, National Ocean Council Committee Designates Shrimp as an At-Risk Species, ⟨http://www.shrimpalliance.com/national-ocean-council-committee-designates-shrimp-as-an-at-risk-species/⟩, 2015.

[11] Oceana, Too cheap to be true. Seafood fraud in Brussels, Oceana Europe, ⟨https://eu.oceana.org/sites/default/files/421/oceana_factsheet_seafood_fraud_brussels_eng.pdf⟩, 2015.

[12] A.I. Ugochukwu, J.E. Hobbs, P.W. Phillips, R. Gray, An economic analysis of private incentives to adopt DNA barcoding technology for fish species authentication in Canada, Genome 58 (12) (2015) 559–567.

[13] J. Fraser, Seafood industry lagging in traceability efforts, Seafoodsource (2018), ⟨https://www.seafoodsource.com/features/seafood-industry-lagging-in-traceability-efforts⟩.

[14] E. Cline, Marketplace substitution of Atlantic salmon for Pacific salmon in Washington State detected by DNA barcoding, Food Res. Int. 45 (1) (2012) 388–393.

[15] P. Doukakis, E.K. Pikitch, A. Rothschild, R. DeSalle, G. Amato, S.-O. Kolokotronis, Testing the effectiveness of an international conservation agreement: marketplace forensics and CITES caviar trade regulation, PLoS One 7 (7) (2012) e40907.

[16] K. Kappel, U. Schröder, Substitution of high-priced fish with low-priced species: adulteration of common sole in German restaurants, Food Control 59 (2016) 478–486.

[17] A. Gordoa, G. Carreras, N. Sanz, J. Viñas, Tuna species substitution in the Spanish commercial chain: a knock-on effect, PLoS One 12 (1) (2017) e0170809.

[18] S.P. Iglésias, L. Toulhoat, D.Y. Sellos, Taxonomic confusion and market mislabelling of threatened skates: important consequences for their conservation status, Aquat. Conserv.: Mar. Freshw. Ecosyst. 20 (3) (2010) 319–333.

[19] V. Crego-Prieto, D. Campo, J. Perez, J.L. Martinez, E. Garcia-Vazquez, A. Roca, Inaccurate labelling detected at landings and markets: the case of European megrims, Fish. Res. 129 (2012) 106–109.

[20] R. Froese, D. Pauly, Fishbase., ⟨www.fishbase.org⟩, version (02/2018), World Wide Web electronic publication, 2018.

[21] M.L.D. Palomares, D. Pauly, SeaLifeBase. Version (02/2018), World Wide Web electronic publication, 2018, ⟨www.sealifebase.org⟩.

[22] Alioth Finance, Euro Inflation Calculator, Alioth Finance, ⟨http://www.in2013dollars.com/Euro-inflation⟩, 2018.

[23] OFX, Exchange rates, OFX Group, ⟨https://www.ofx.com/⟩, 2018.

[24] I. Olkin, Meta-analysis: reconciling the results of independent studies, Stat. Med. 14 (5-7) (1995) 457–472.

[25] S. Raudenbush, Analyzing effect sizes: random effects models, in: H. Cooper, L. Hedges, J. Valentine (Eds.), The Handbook of Research Synthesis and Meta-Analysis, Russell Sage Foundation, New York, 2009, pp. 295–315.

[26] W. Viechtbauer, Bias and efficiency of meta-analytic variance estimators in the random-effects model, J. Educ. Behav. Stat. 30 (3) (2005) 261–293.

[27] W. Viechtbauer, Conducting meta-analyses in R with the metafor package, J. Stat. Softw. 36 (3) (2010) 1–48.

[28] M.C. Wang, B.J. Bushman, Using the normal quantile plot to explore meta-analytic data sets, Psychol. Methods 3 (1) (1998) 46.

[29] D.A. Follmann, M.A. Proschan, Valid inference in random effects meta-analysis, Biometrics 55 (3) (1999) 732–737.

[30] J. Higgins, S.G. Thompson, Controlling the risk of spurious findings from meta-regression, Stat. Med. 23 (11) (2004) 1663–1682.

[31] R Development Core Team, R: a Language and Environment for Statistical Computing, The R Foundation for Statistical Computing, Vienna, Austria, 2017⟨http://www.R-project.org⟩.

[32] M. Burros, Stores Say Wild Salmon, but Tests Say Farm Bred, New York Times, 2005.

[33] Consumer Reports, The salmon scam. Wild often isn't, Consumer Reports August (2006) 15.

[34] J.H. Lowenstein, G. Amato, S.-O. Kolokotronis, The real maccoyii: identifying tuna sushi with DNA barcodes-contrasting characteristic attributes and genetic distances, PLoS One 4 (11) (2009) e7866.

[35] A. Ardura, I.G. Pola, I. Ginuino, V. Gomes, E. Garcia-Vazquez, Application of barcoding to Amazonian commercial fish labelling, Food Res. Int. 43 (5) (2010) 1549–1552.

[36] M. Barbuto, A. Galimberti, E. Ferri, M. Labra, R. Malandra, P. Galli, M. Casiraghi, DNA barcoding reveals fraudulent substitutions in shark seafood products: the Italian case of "palombo"(Mustelus spp.), Food Res. Int. 43 (1) (2010) 376–381.

[37] D.C. Carvalho, D.A. Neto, B.S. Brasil, D.A. Oliveira, DNA barcoding unveils a high rate of mislabeling in a commercial freshwater catfish from Brazil, Mitochondrial DNA 22 (sup1) (2011) 97–105.

[38] E. Garcia-Vazquez, J. Perez, J.L. Martinez, A.F. PARDINas, B. Lopez, N. Karaiskou, M.F. Casa, G. Machado-Schiaffino, A. Triantafyllidis, High level of mislabeling in Spanish and Greek hake markets suggests the fraudulent introduction of African species, J. Agric. Food Chem. 59 (2) (2011) 475–480.

[39] R. Hanner, S. Becker, N.V. Ivanova, D. Steinke, FISH-BOL and seafood identification: geographically dispersed case studies reveal systemic market substitution across Canada, Mitochondrial DNA 22 (sup1) (2011) 106–122.

[40] J. Bénard-Capelle, V. Guillonneau, C. Nouvian, N. Fournier, K. Le Loët, A. Dettai, Fish mislabelling in France: substitution rates and retail types, PeerJ 2 (2015) e714.

[41] M. Muñoz-Colmenero, M. Klett-Mingo, E. Díaz, O. Blanco, J.L. Martínez, E. Garcia-Vazquez, Evolution of hake mislabeling niches in commercial markets, Food Control 54 (2015) 267–274.

[42] M. Muñoz-Colmenero, O. Blanco, V. Arias, J.L. Martinez, E. Garcia-Vazquez, DNA authentication of fish products reveals mislabeling associated with seafood processing, Fisheries 41 (3) (2016) 128–138.

[43] D. Wang, Y.-H.P. Hsieh, The use of imported pangasius fish in local restaurants, Food Control 65 (2016) 136–142.

[44] X. Xiong, L. Guardone, M.J. Cornax, L. Tinacci, A. Guidi, D. Gianfaldoni, A. Armani, DNA barcoding reveals substitution of Sablefish (Anoplopoma fimbria) with Patagonian and Antarctic Toothfish (Dissostichus eleginoides and Dissostichus mawsoni) in online market in China: how mislabeling opens door to IUU fishing, Food Control 70 (2016) 380–391.

[45] D.-M. Cawthorn, L.C. Hoffman, Deceit with decapods? Evaluating labelling accuracy of crustacean products in South Africa, Food Control 73 (2017) 741–753.

[46] Y.H.P. Hsieh, Species substitution of restaurant fish entrees, J. Food Qual. 21 (1) (1998) 1–11.

[47] S. Nolhgran, T. Tomalin, You order grouper; what do you get? Tampa Bay Times (2006).

[48] C.E. Cox, C.D. Jones, J.P. Wares, K.D. Castillo, M.D. McField, J.F. Bruno, Genetic testing reveals some mislabeling but general compliance with a ban on herbivorous fish harvesting in Belize, Conserv. Lett. 6 (2) (2013) 132–140.

[49] H.A. Cunha, V.M. da Silva, T.E. Santos, S.M. Moreira, N.A. do Carmo, A.M. Solé-Cava, When you get what you haven't paid for: molecular identification of "Douradinha" fish fillets can help end the illegal use of river dolphins as bait in Brazil, J. Hered. 106 (S1) (2015) 565–572.

[50] C.C. Stawitz, M.C. Siple, S.H. Munsch, Q. Lee, S. Derby, Financial and ecological implications of global seafood mislabeling, Conserv. Lett. 10 (2017) 681–689.

[51] J. Wen, L. Tinacci, P. Acutis, M. Riina, Y. Xu, L. Zeng, X. Ying, Z. Chen, L. Guardone, D. Chen, An insight into the Chinese traditional seafood market: species characterization of cephalopod products by DNA barcoding and phylogenetic analysis using COI and 16SrRNA genes, Food Control 82 (2017) 333–342.

[52] J. Hofherr, J. Martinsohn, D. Cawthorn, B. Rasco, A.M. Naaum, Regulatory Frameworks for Seafood Authenticity and Traceability, Seafood Authenticity and Traceability, Elsevier, 2016, pp. 47–82.

[53] V.J. Birstein, P. Doukakis, R. DeSalle, Molecular phylogeny of Acipenserinae and black caviar species identification, J. Appl. Ichthyol. 15 (4-5) (1999) 12–16.

[54] A. Cohen, Sturgeon poaching and black market caviar: a case study, Environ. Biol. Fishes 48 (1–4) (1997) 423–426.

[55] V.J. Birstein, P. Doukakis, B. Sorkin, R. DeSalle, Population Aggregation Analysis of Three Caviar-Producing Species of Sturgeons and Implications for the Species Identification of Black Caviar, Conserv. Biol. 12 (4) (1998) 766–775.

[56] S.R. Fain, D.J. Straughan, B.C. Hamlin, R.M. Hoesch, J.P. LeMay, Forensic genetic identification of sturgeon caviars traveling in world trade, Conserv. Genet. 14 (4) (2013) 855–874.

[57] A. Ludwig, D. Lieckfeldt, J. Jahrl, Mislabeled and counterfeit sturgeon caviar from Bulgaria and Romania, J. Appl. Ichthyol. 31 (4) (2015) 587–591.

[58] S. Bose, A. McIlgorm, Substitutability among species in the Japanese tuna market: a cointegration analysis, Mar. Resour. Econ. 11 (3) (1996) 143–155.

[59] E.H.-K. Wong, R.H. Hanner, DNA barcoding detects market substitution in North American seafood, Food Res. Int. 41 (8) (2008) 828–837.

[60] R.S. Rasmussen Hellberg, A.M. Naaum, S.M. Handy, R.H. Hanner, J.R. Deeds, H.F. Yancy, M.T. Morrissey, Interlaboratory evaluation of a real-time multiplex polymerase chain reaction method for identification of salmon and trout species in commercial products, J. Agric. Food Chem. 59 (3) (2011) 876–884.

[61] K. Warner, P. Mustain, C. Carolin, C. Disla, R. Golden-Kroner, B. Lowell, M. Hirshfield, Oceana Reveals Mislabeling of America's Favorite Fish: Salmon, Oceana, Washington DC, 2015.

[62] M. Muñoz-Colmenero, F. Juanes, E. Dopico, J.L. Martinez, E. Garcia-Vazquez,

Economy matters: a study of mislabeling in salmon products from two regions, Alaska and Canada (Northwest of America) and Asturias (Northwest of Spain), Fish. Res. 195 (2017) 180–185.
[63] G. Knapp, C. Roheim, J.L. Anderson, The Great Salmon Run: Competition Between Wild and Farmed Salmon, TRAFFIC North America and the World Wildlife, Washington DC, 2007.
[64] C.A. Roheim, P.O. Sudhakaran, C.A. Durham, Certification of shrimp and salmon for best aquaculture practices: Assessing consumer preferences in Rhode Island, Aquac. Econ. Manag. 16 (3) (2012) 266–286.
[65] B.A. Maralit, R.D. Aguila, M.F.H. Ventolero, S.K.L. Perez, D.A. Willette, M.D. Santos, Detection of mislabeled commercial fishery by-products in the Philippines using DNA barcodes and its implications to food traceability and safety, Food Control 33 (1) (2013) 119–125.
[66] S. Mariani, A.M. Griffiths, A. Velasco, K. Kappel, M. Jérôme, R.I. Perez-Martin, U. Schröder, V. Verrez-Bagnis, H. Silva, S.G. Vandamme, Low mislabeling rates indicate marked improvements in European seafood market operations, Front. Ecol. Environ. 13 (10) (2015) 536–540.
[67] C.-H. Chang, H.-Y. Lin, Q. Ren, Y.-S. Lin, K.-T. Shao, DNA barcode identification of fish products in Taiwan: government-commissioned authentication cases, Food Control 66 (2016) 38–43.
[68] K. Kroetz, C.J. Donlan, C.E. Cole, J.A. Gephart, P. Lee, Examining Seafood Fraud Through the Lens of Production and Trade: How Much Mislabeled Seafood do Consumers Buy? Resources for the Future Report, Washington DC, 2018.
[69] Newshub, Chinese fishing company fined $825K over misreported catch, Newshub (2017), 〈http://www.newshub.co.nz/home/money/2017/06/chinese-fishing-company-fined-825k-over-misreported-catch.html〉.
[70] P.B. Marko, H.A. Nance, K.D. Guynn, Genetic detection of mislabeled fish from a certified sustainable fishery, Curr. Biol. 21 (16) (2011) R621–R622.
[71] K. Warner, W. Timme, B. Lowell, M. Hirshfield, Oceana Study Reveals Seafood Fraud Nationwide, Oceana, Washington DC, 2013.
[72] D.B. Stern, E.C. Nallar, J. Rathod, K.A. Crandall, DNA Barcoding analysis of seafood accuracy in Washington, DC restaurants, PeerJ 5 (2017) e3234.
[73] H. Österblom, Ö. Bodin, Global cooperation among diverse organizations to reduce illegal fishing in the Southern Ocean, Conserv. Biol. 26 (4) (2012) 638–648.
[74] H. Osterblom, O. Bodin, U. Rashid Sumaila, A.J. Press, Reducing illegal fishing in the Southern ocean: a global effort, Solutions 4 (5) (2015) 72–79.
[75] CCAMLR, Illegal, unreported and unregulated (IUU) fishing, Commission for the Conservation of Antarctic Marine Living Resources, 〈https://www.ccamlr.org/en/compliance/illegal-unreported-and-unregulated-iuu-fishing〉, 2018.
[76] A. Zhong, China's Antarctic Toothfish Market is Bustling But Smuggling Remains a Problem, Seafoodnew.com 〈http://chinaseafoodexpo.com/2017/12/06/chinas-antarctic-toothfish-market-bustling-smuggling-remains-problem/〉, 2017.
[77] J.L. Jacquet, D. Pauly, Trade secrets: renaming and mislabeling of seafood, Mar. Policy 32 (3) (2008) 309–318.
[78] S.J. Helyar, Ha.D. Lloyd, M. de Bruyn, J. Leake, N. Bennett, G.R. Carvalho, Fish product mislabeling: failings of traceability in the production chain and implications for illegal, unreported and unregulated (IUU) fishing, PLoS One 9 (6) (2014) e98691.
[79] D.D. Miller, U.R. Sumaila, I.U.U. Fishing, and Impact on the Seafood Industry, Seafood Authenticity and Traceability, Elsevier, 2016, pp. 83–95.
[80] Environmental Crimes Section Monthly Bulletin, United States v. James L. Stovall, III., et al., No. 1:08-CR-00032 (M.D. Ga.), Department of Justice, 〈https://www.justice.gov/sites/default/files/enrd/legacy/2015/04/13/LPS-190677-v1-ECS_Bulletin_2009_07_Block.PDF〉, 2009.
[81] Environmental Crimes Section Monthly Bulletin, United States v. Thomas George, No. 2:10-CR-00029 (D.N.J.), Department of Justice, 〈https://www.justice.gov/sites/default/files/enrd/legacy/2015/04/13/August_2010.pdf〉, 2010.
[82] Department of Justice, Seafood wholesaler sentenced for false labeling of fish, Department of Justice, 〈https://www.justice.gov/archive/usao/ma/news/2011/May/KATZsentPR.html〉, 2011.
[83] Environmental Crimes Section Monthly Bulletin, United States v. Karen Blyth et al., No. 1:10-CR-00011 (S.D. Ala.), Department of Justice, 〈https://www.justice.gov/sites/default/files/enrd/legacy/2015/04/13/LPS-190653-v1-ECS_Bulletin_2011_02_Block_508.pdf〉, 2011.
[84] Department of Justice, California Seafood Corporation Sentenced to Pay $1 Million for False Labeling of Seafood Products, Department of Justice, 〈https://www.justice.gov/opa/pr/california-seafood-corporation-sentenced-pay-1-million-false-labeling-seafood-products〉, 2012.
[85] Department of Justice, President of company that illegally imported catfish sentenced to more than five years in federal prison, US Department of Justice, 〈https://www.justice.gov/opa/pr/president-company-illegally-imported-catfish-sentenced-more-five-years-federal-prison〉, 2009.
[86] NMFS, Foreign Trade Database, National Marine Fisheries Service, 〈http://www.st.nmfs.noaa.gov/commercial-fisheries/foreign-trade/〉, 2017.
[87] D.D. Miller, M. Clarke, S. Mariani, Mismatch between fish landings and market trends: a western European case study, Fish. Res. 121 (2012) 104–114.
[88] R. Smithers, Supermarkets criticised for 'poor and condusing' fish labeling, Guardian (2011), 〈https://www.theguardian.com/environment/2011/may/05/supermarkets-fish-labelling-criticised〉.
[89] L. Towers, US seafood naming rules: do they provide real guidance for the seafood insdustry, Fish. Site (2013), 〈https://thefishsite.com/articles/us-seafood-naming-rules-do-they-provide-real-guidance-for-the-seafood-industry〉.
[90] J. Barendse, J. Francis, Towards a standard nomenclature for seafood species to promote more sustainable seafood trade in South Africa, Mar. Policy 53 (2015) 180–187.