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A meta-analysis of seafood species mislabeling in the United States

Sarah Ahles [a], Christina A. Mireles DeWitt [b], Rosalee S. Hellberg [a,*]

[a] Chapman University, Schmid College of Science and Technology, Food Science Program, One University Drive, Orange, CA, 92866, USA
[b] OSU Seafood Research & Education Center, Department of Food Science and Technology, Oregon State University, Astoria, OR, 97103, USA

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ABSTRACT

Seafood is vulnerable to mislabeling due to complex global supply chains, varying prices, and the similar appearance of species. While numerous studies have been published on seafood mislabeling, the focus is often on species known to be commonly substituted. Therefore, the overall mislabeling rates of seafood sold in the U.S. remain unknown, especially for the most consumed species. The objective of the current study was to compile the results of seafood mislabeling studies into a single resource to provide informative statistics on U.S. seafood mislabeling. A meta-analysis was conducted on U.S. seafood mislabeling studies that tested commercial samples of bony fish (Osteichthyes) and shellfish from 2010 to 2023. A total of 35 studies, including 4179 samples from 32 U.S. states, were analyzed. The overall mislabeling rate was 39.1%, with the majority (60.9%) of samples correctly labeled. Species substitution was observed in 26.2% of samples, followed by unacceptable market names (17.1%) and conflicting market names (1.1%). The sum of the rates for individual mislabeling categories is greater than the overall rate because some samples were assigned to multiple categories. The top 10 consumed seafoods reported by the National Fisheries Institute for 2021 had a mislabeling rate of 31.0%, compared to 53.0% for the most frequently investigated species. The species substitution rate for the top 10 consumed seafoods was 13.9%, compared to 42.5% for frequently investigated species. The results of this investigation provide comprehensive information on seafood mislabeling in the U.S., with the potential to influence policy decisions and inform outreach efforts.

1. Introduction

Seafood is one of the most-traded food commodities worldwide, with fisheries and aquaculture production reaching a record 214 million tonnes and international trade valued at USD 151 billion in 2020 (FAO, 2022). The U.S. is the top importer of seafood, followed by China, Japan, Spain, and France (FAO, 2022). Total U.S. per capita seafood consumption was 9.3 kg in 2021, equivalent to an increase of 15% since 2011 (NOAA, 2024b). U.S. commercial and recreational fisheries supported nearly 2.3 million jobs and generated USD 321 billion in sales in 2022 (NOAA, 2024a). The U.S. Food and Drug Administration (FDA) *Seafood List*, which provides standardized seafood labeling guidance to industry, includes commercial market names for over 2000 seafood species (FDA, 2024). However, the majority of U.S. seafood consumption (76%) is limited to 10 species categories (in descending order, based on 2021 data): shrimp, salmon, canned tuna, tilapia, Alaska pollock, pangasius, cod, crab, catfish, and clams (NFI, 2024).

Seafood is highly susceptible to mislabeling due to increasing demand, complex global supply chains, similar appearance of species, and wide price variation (Silva, Hellberg, & Hanner, 2021). Species mislabeling includes species substitution and the use of unacceptable or misleading market names. Species substitution constitutes adulteration (21 U.S.C. § 342) and misbranding (21 U.S.C. § 343) and occurs when one species is misrepresented as another species. Intentional substitution usually involves the replacement of a high-quality species, such as red snapper (*Lutjanus campechanus*), with less expensive species, such as tilapia (*Oreochromis* spp.) (Warner, Timme, Lowell, & Hirshfield, 2013). The use of an unacceptable market name refers to labeling a species with an unapproved commercial name per the FDA *Seafood List* (FDA, 2024). Unacceptable market names may mislead consumers by misrepresenting the true identity of the species, which introduces health risks and may render the product misbranded (FDA, 2023). Conflicting market names, in which a product is labeled with the names of two or more species (e.g., "rockfish red snapper"), are also problematic in the seafood industry (Kitch, Tabb, Marquis, & Hellberg, 2023; Liou, Banda, Isaacs, & Hellberg, 2020). While intentional mislabeling for economic gain is

* Corresponding author. Chapman University, One University Drive Orange, CA, 92866, USA.
E-mail address: hellberg@chapman.edu (R.S. Hellberg).

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considered fraud, it is important to note that species mislabeling may also be unintentional due to the similar appearance of species or a lack of knowledge regarding acceptable market names (Kitch et al., 2023).

In addition to economic losses, numerous negative consequences are associated with seafood mislabeling (Silva et al., 2021). A significant concern is the potential risk to public health due to exposure to allergens or toxins in certain seafood species (Fry, 2012; Silva et al., 2021). For example, prior reports of seafood mislabeling have included illness from tetrodotoxin through the substitution of monkfish with pufferfish (Cohen et al., 2009); undeclared presence of shellfish allergens due to the substitution of fish with shellfish (Kitch et al., 2023); exposure to gempylotoxin through the substitution of tuna with escolar (Warner, Mustain, Lowell, Geren, & Talmage, 2016); and potential exposure to elevated mercury levels due to the substitution of low-mercury fish for higher-mercury species (Liou et al., 2020). Seafood mislabeling may also compromise the effectiveness of certification programs used by consumers to choose environmentally sustainable seafood (Willette et al., 2017). Furthermore, mislabeling can potentially undermine religious practices when a non-kosher fish (e.g., *Pangasius* spp.) is substituted for a kosher fish (e.g., Pacific cod; Warner, Timme, & Lowell, 2012).

Increased scrutiny of seafood mislabeling has informed investigative and regulatory efforts over the past 20 years, such as the U.S. Seafood Import Monitoring Program (SIMP), which established recordkeeping and reporting requirements for 1100 species categorized in 13 species groups (NOAA, 2024c). Numerous seafood mislabeling studies have been conducted in the U.S., focusing on different fish categories, geographic areas, and product types (for example, Cline, 2012; Khaksar et al., 2015; Kitch et al., 2023; Korzik et al., 2020; Liou et al., 2020; Logan, Alter, Haupt, Tomalty, & Palumbi, 2008; Lowenstein, Amato, & Kolokotronis, 2009; Peterson, McBride, Jhita, & Hellberg, 2021; Rasmussen Hellberg et al., 2011; Roungchun, Tabb, & Hellberg, 2022; Spencer et al., 2020; Wallstrom, Morris, Carlson, & Marko, 2020; Warner, Timme, & Lowell, 2012; Warner, Timme, Lowell, & Hirshfield, 2012; Warner et al., 2013; Warner, Timme, Lowell, & Stiles, 2012; Willette et al., 2017). While some of these studies have reported relatively high mislabeling rates of 63–91% (Kitch et al., 2023; Spencer et al., 2020), others have reported relatively low mislabeling rates of 5–21% (Cline, 2012; Khaksar et al., 2015; Peterson et al., 2021; Rasmussen Hellberg et al., 2011; Roungchun et al., 2022; Wallstrom et al., 2020). In some instances, researchers focused on species and/or retail categories known to be commonly substituted (Logan et al., 2008; Spencer et al., 2020; Warner, Mustain, et al., 2015), resulting in elevated species mislabeling rates. The wide range of seafood mislabeling rates reported in the literature and the focus on commonly substituted species highlight the inaccuracy of extrapolating results from singular mislabeling studies to all U.S. seafood. Furthermore, many studies focus on lesser-consumed species, leading to a gap in knowledge regarding the mislabeling rates for the most commonly consumed species.

Several review articles have compiled rates of seafood mislabeling across multiple studies (Blanco-Fernandez, Garcia-Vazquez, & Machado-Schiaffino, 2021; Giusti, Malloggi, Tinacci, Nucera, & Armani, 2023; Golden & Warner, 2014; Kroetz, Donlan, Cole, Gephart, & Lee, 2018; Leahy, 2021; Luque & Donlan, 2019; Naaum, Warner, Mariani, Hanner, & Carolin, 2016; Pardo, Jiménez, & Pérez-Villarreal, 2016; Warner et al., 2016), with overall mislabeling rates of 13–58%. However, there is a need for research focused solely on compiling information on U.S. seafood mislabeling rates. Additionally, there is a lack of comprehensive data on the mislabeling rates among the most-consumed species in the U.S. Therefore, the objective of the current study was to consolidate the results of U.S. seafood mislabeling studies into a single comprehensive resource and address a critical knowledge gap in understanding how the mislabeling rates of the most frequently investigated species differ from those most commonly consumed. Combining seafood mislabeling data into a single resource is critical in providing accurate, industry-wide statistics on U.S. retail seafood. Lastly, the compilation of U.S. seafood mislabeling data may provide support for a targeted focus on the species that are most vulnerable to mislabeling rather than the application of broad policies to all seafood species.

2. Materials and methods

2.1. Data collection

Three databases (Google, Google Scholar, and Web of Science) were searched to retrieve U.S. seafood market studies published by peer-reviewed journals, government agencies, and non-governmental organizations (Giusti et al., 2023; Luque & Donlan, 2019). The following search terms were utilized: "mislabel* OR fraud OR species substitution OR unacceptable market name OR misdescri* OR species authentication AND seafood OR fish OR shellfish AND United States OR U.S. OR USA OR America OR North America." Relevancy was assessed by the title and abstract content. The references sections of relevant articles and the "cited by" function on Google Scholar were utilized to gather additional relevant studies (Giusti et al., 2023). The search was concluded in June 2024.

2.2. Inclusion criteria and data organization

For inclusion in the meta-analysis, the studies must have obtained seafood samples from the U.S. commercial market between 2010 and 2023. This time frame was selected because updates made to the FDA *Seafood List* are available dating back to 2010. Access to these updates was essential to accurately assess the labeling status for commercial samples based on the version of the FDA *Seafood List* available at the time of sample collection. The minimum requirements for inclusion of an individual fish or shellfish sample from a given study were the label or menu name and genetic identity. The use of these inclusion criteria allowed for a direct comparison of the rates of species substitution, unacceptable market names, and conflicting market names across a single dataset. If the reported data was insufficient, correspondence with authors was attempted to acquire the supplementary data. Correspondence was also initiated to clarify additional sampling information (e.g., date, geographic location, retail setting, and/or product form). Mislabeling determinations for each sample were carried out as described in section 2.4 (additional details provided in Appendix A). All recorded sample information was considered in the mislabeling assessment. Samples were assigned to species categories based on their taxonomic classification and/or market name grouping on the FDA *Seafood List* (see Appendix B for details). The data points were organized into a Microsoft Excel file with the following information included for each sample (if available): state where the sample was collected, retail setting, product form, species category (based on label declaration), mislabeling determination (i.e., species substitution, unacceptable market name, and/or conflicting market name), and reference (Table S1).

2.3. Data filters

Data filters were applied to reduce bias and inaccuracies in the mislabeling determinations discussed in section 2.4. Samples that could not be identified to the genus or species level based on the genetic testing results were excluded. Samples that were genetically identified as a species not found on the FDA *Seafood List* were excluded unless they met one or more of the following criteria: (1) there was a regulatory definition associated with the declared species, (2) the label or menu declaration included a common name found on the FDA *Seafood List*, or (3) the World Register of Marine Species (https://www.marinespecies.org/aphia.php?p=search) listed a synonym of the scientific name that was found on the FDA *Seafood List*. The addition of the identified species to the FDA *Seafood List* in the same year of sample collection (as determined by the FDA *Seafood List* updates and additions; https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-seafood-list-fdas-guide-determine-acceptable-seafood-n ames) warranted exclusion unless the date of sample collection occurred after its addition to the FDA *Seafood List*. This study was focused on bony fish (Osteichthyes) and shellfish; therefore, elasmobranchs (e.g., sharks, skates, rays, and sawfish) were excluded. Samples with incomplete or unclear labeling data that could not be clarified after three attempts to contact authors were excluded from the analysis as it was not possible to assess the mislabeling status accurately.

2.4. Mislabeling determinations

Instances of mislabeling were assigned to one or more of the following categories: species substitution, unacceptable market name, or conflicting market name. A detailed guide for the mislabeling category determinations and exceptions used in this study is provided in Appendix A. The version of the FDA *Seafood List* available at the time of sample collection was used as the basis for mislabeling determinations. A sample was considered mislabeled based on species substitution if the declared species did not match the genetic identity. A sample was considered to have an unacceptable market name if it was labeled with a market name that was inconsistent with the FDA *Seafood List* or if the market name included a misleading geographic descriptor or production method (e.g., farmed or wild). A sample was determined to have a conflicting market name if conflicting species names, geographic origins, and/or production methods were declared across the recorded product information. The mislabeling rate equation [(total number of mislabeled samples/total samples) * 100] was applied to generate mislabeling rates by species category, state, retail setting, product form, mislabeling category, and overall. Separate species mislabeling rates were calculated for the top 10 consumed seafoods in the U.S. reported by the National Fisheries Institute based on 2021 consumption data (NFI, 2024) and the most frequently investigated species (i.e., species categories representing $\geq$3.0% of total samples, not including the top 10 consumed seafoods). Red snapper samples were categorized separately from other snapper species due to their historically high mislabeling rate (Isaacs & Hellberg, 2020; Spencer et al., 2020).

2.5. Statistical analysis

The mislabeling rates within each of the following groupings were compared using the Chi-squared test with a significance value of $p < 0.05$: top 10 U.S. seafoods consumed, most frequently investigated species categories, product forms, frequently investigated U.S. states ($\geq$3.0% of total samples), and retail settings. Significant results were subject to the test of equality of proportions with a significance value of $p < 0.05$, using the Bonferroni correction for multiple comparisons. Categories with <55 samples were excluded from the statistical analysis due to their relatively small sample size. All statistical tests were conducted in R Studio version 2024.04.2 + 764 (R Core Team, 2022).

3. Results and discussion

3.1. Sample collection

A total of 4179 samples (i.e., data points) collected from 2010 to 2023 were gathered from 35 studies across 32 U.S. states (Table S1). Most of the studies were peer-reviewed journal articles (n = 26), followed by reports published by non-governmental organizations (n = 8) and governmental organizations (n = 1). In comparison, a meta-analysis of seafood mislabeling in the Italian market examined 3576 samples from 51 peer-reviewed studies published from 2005 to 2022 (Giusti et al., 2023) and a global analysis conducted by Pardo et al. (2016) examined 4500 samples from 51 peer-reviewed articles published from 2010 to 2015. On the other hand, a global seafood mislabeling meta-analysis conducted by Luque and Donlan (2019) included a much larger sample size (n = 27,314) obtained from 141 studies (17 peer-reviewed and 24 from other sources) published through 2017.

3.2. Overall mislabeling rates

Out of the 4179 samples analyzed in this study, 39.1% were associated with at least one form of mislabeling. Specifically, species substitution was observed in 26.2% of samples, unacceptable market names were observed in 17.1% of samples, and conflicting market names were observed in 1.1% of samples. The sum of the individual mislabeling categories is greater than the overall mislabeling rate because some samples exhibited multiple types of mislabeling. The most sampled species category was salmon (21.1% of samples), followed by tuna (10.8%), red snapper (8.2%), shrimp (7.1%), halibut (6.7%), and cod (5.9%). This study is the first quantitative review of seafood mislabeling to include an analysis of conflicting and unacceptable market names based on the FDA *Seafood List*, revealing relatively lower mislabeling rates compared to species substitution. The rate of species substitution (26.2%) is within the range of global mislabeling rates (19–36%) reported in previous quantitative reviews (Giusti et al., 2023; Golden & Warner, 2014; Leahy, 2021; Luque & Donlan, 2019; Naaum et al., 2016; Pardo et al., 2016; Warner et al., 2016).

3.3. Mislabeling rates based on species category

3.3.1. Mislabeling rates for top 10 seafoods consumed in the U.S.

While the top 10 seafood categories represented 76% of total U.S. consumption in 2021 (NFI, 2024), they only constituted 42.9% of samples analyzed in this study. This highlights how mislabeling studies often target species vulnerable to substitution (Logan et al., 2008; Spencer et al., 2020; Warner, Mustain, et al., 2015), leading to an underrepresentation of the top 10 seafoods consumed in the U.S. The overall mislabeling rate for the top 10 consumed seafoods combined was 31.0%, with species substitution observed in 13.9% of samples, unacceptable market names observed in 20.8% of samples, and conflicting market names observed in 0.9% of samples (Fig. 1). The rate of unacceptable market names was significantly higher ($p < 0.05$) than the species substitution rate, according to the test of equality of proportions. This suggests that the top 10 consumed seafoods are predominantly mislabeled due to the use of market names that are inconsistent with the FDA *Seafood List*, as opposed to being substituted with a different species than anticipated. There are several reasons why manufacturers or retailers may choose to use an unacceptable market name, including a desire to increase the appeal of a product for marketing purposes, a lack of awareness regarding the FDA *Seafood List*, or a desire to intentionally mislead consumers regarding the true identity of the species. While the use of an acceptable market name is not a legally enforceable responsibility unless it is associated with specific regulatory or statutory requirements, the use of names that are false or misleading may lead to a food being deemed misbranded under section 403(a)(1) of the Federal Food, Drug, and Cosmetic Act (FDA, 2023).

The overall mislabeling rates among the top 10 consumed seafoods represented by > 10 samples per category were highest for crab (76.3%), followed by salmon (37.3%), cod (26.4%), pangasius (26.1%), shrimp (25.8%), canned tuna (17.2%), catfish (5.7%) and tilapia (0%; Fig. 1). There was minimal data available on clam (n = 2) and Alaska pollock (n = 2). Additionally, the sample sizes for tilapia (n = 50) and pangasius (n = 23) fell below the threshold of $\geq$55 samples per category for statistical analysis. Among the categories evaluated statistically, crab was mislabeled at a significantly higher rate ($p < 0.05$) than the other top 10 seafoods, and catfish was mislabeled at a significantly lower rate than shrimp, salmon, cod, and crab, according to the test of equality of proportions with the Bonferroni correction. There were no significant differences ($p > 0.05$) in the overall mislabeling rates for shrimp, canned tuna, and cod. An examination of the reasoning for the mislabeling trends observed can be found below within the discussion of species substitution and unacceptable market names.

As shown in Fig. 1, the species substitution rate for the top 10 consumed seafoods represented by > 10 samples per category was

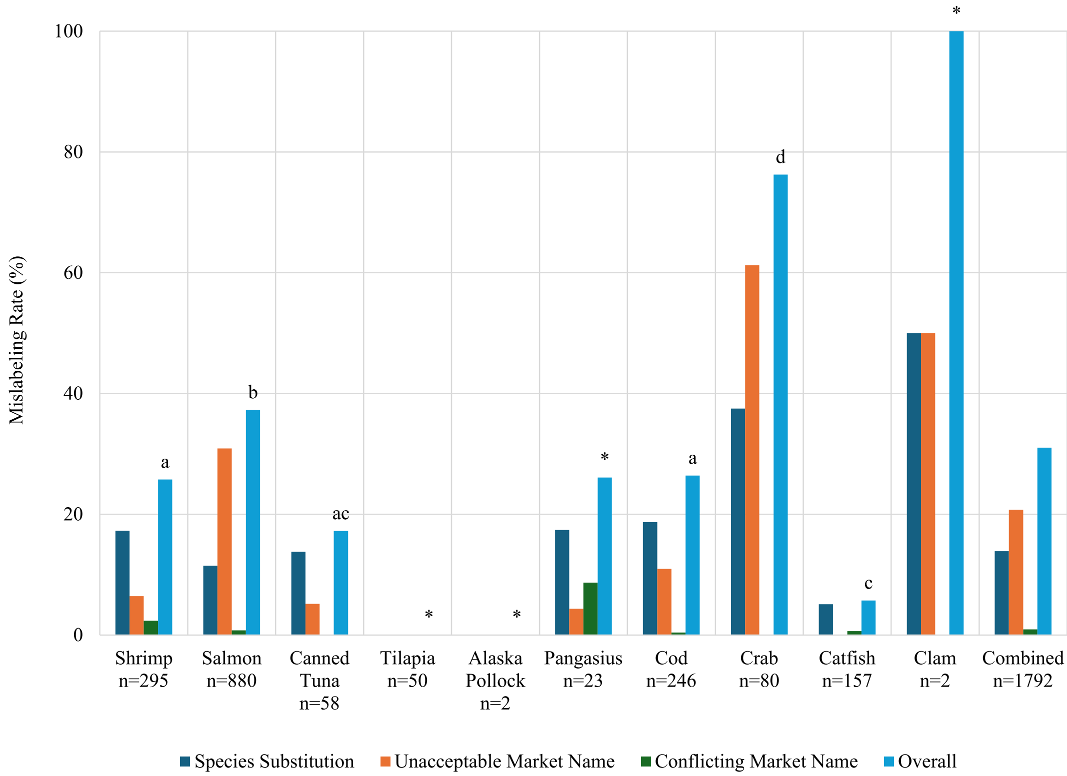

Fig. 1. Mislabeling rates for the top 10 consumed seafoods in the U.S. according to 2021 consumption data (NFI, 2024), including the total number (n) of samples analyzed per category. Note: Significant differences among the overall mislabeling rates are indicated by different lowercase letters based on the test of equality of proportions with the Bonferroni correction ($p < 0.05$). *Mislabeling rates for categories with <55 samples were not analyzed statistically.

highest in crab (37.5%), followed by cod (18.7%), pangasius (17.4%), shrimp (17.3%), canned tuna (13.8%), salmon (11.5%), and catfish (5.1%). Species substitution was not observed in any samples of Alaska pollock or tilapia. Alaska pollock and tilapia are relatively low-value species (NOAA, 2024b), making them less likely to be mislabeled as another species (Luque & Donlan, 2019). Instead, tilapia is often detected as a substitute for higher-value species, such as red snapper (Luque & Donlan, 2019). Crab is especially vulnerable to species substitution due to the range of values associated with different crab species on the commercial market (NOAA, 2024b) combined with varying supply and demand of certain species (DOJ, 2019; Warner, Lowell, et al., 2015). For example, a series of U.S. Department of Justice (DOJ) court cases revealed that a shortage of domestic blue crab (*Callinectes sapidus*) beginning in 2010 led two seafood processors to substitute the product with foreign crab meat and falsely label it to continue to fill orders (DOJ, 2019, 2020). Salmon is similarly vulnerable to species substitution due to the range of species on the commercial market with varying prices, as well as heightened demand for wild-caught species (Garcia et al., 2024). The species substitution rate determined for salmon in the current study (11.5%) is similar to the global rate (13%) reported previously (Pardo et al., 2016). In contrast, the species substitution rate for pangasius samples in the current study (17.4%) is higher than that reported for Pangasiidae globally (8%; Luque & Donlan, 2019), while the species substitution rate for catfish in the current study (5.1%) is lower than that reported for Ictaluridae globally (12%; Luque & Donlan, 2019). The low mislabeling rate observed for catfish is likely associated with the relatively low value of these species (NOAA, 2024b) combined with a mandatory continuous U.S. Department of Agriculture (USDA) inspection program for Siluriformes (Bosko, Foley, & Hellberg, 2018; FSIS, 2015). Although the inspection program also applies to pangasius, the mislabeling rate for pangasius determined in this study was only based on 23 samples, indicating a need for further research on this species category.

The rate of unacceptable market names for the top 10 consumed seafoods represented by > 10 samples per category was highest for crab (61.3%), followed by salmon (30.9%), cod (11.0%), shrimp (6.4%), canned tuna (5.2%), and pangasius (4.3%; Fig. 1). Alaska pollock, catfish, and tilapia did not have any incidences of unacceptable market names. The relatively high rates of unacceptable market names observed for crab and salmon were largely due to the generic labeling of many samples as "crab" and "salmon." The FDA *Seafood List* calls for greater specificity in the labeling of crab and salmon species; for example, the acceptable market names for *Salmo salar* and *Callinectes sapidus* are Atlantic salmon and blue crab, respectively (FDA, 2024). On the other hand, numerous Ictaluridae species share the acceptable market name of "catfish" on the FDA *Seafood List* (FDA, 2024), which likely led to the high compliance in acceptable market names observed for catfish.

Pangasius showed the highest rate (8.7%) of conflicting market names among the top 10 consumed seafoods, followed by shrimp (2.4%), salmon (0.8%), catfish (0.6%), and cod (0.4%); the remaining categories had rates of 0%. The two instances of conflicting market names observed for pangasius involved a sample labeled as "swai basa" and a sample labeled as "red fish basa," both of which include the names of two species within a single market name (Liou et al., 2020).

3.3.2. Mislabeling rates for frequently investigated species

The most frequently investigated species categories, excluding the top 10 consumed seafoods, were: tuna (9.4% of samples, excluding canned/retort), red snapper (8.2% of samples), halibut (6.7% of samples), other snapper (4.4% of samples), sole (4.4% of samples), amberjack (3.4% of samples), and eel (3.3% of samples; Fig. 2). When combined, the frequently investigated categories represented 39.7% of total samples and had an overall mislabeling rate of 53.0%. This rate was significantly higher ($p < 0.05$) than the overall mislabeling rate for the top 10 consumed seafoods (31.0%), according to the test of equality of proportions. Among the frequently investigated species, the highest

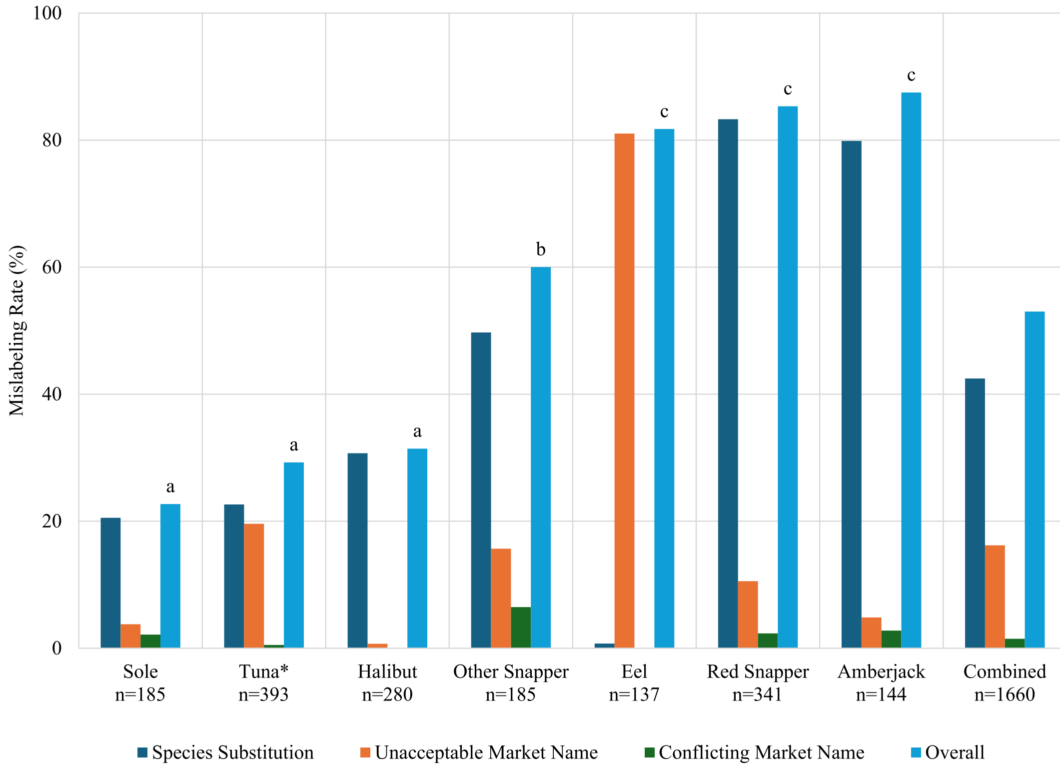

Fig. 2. Mislabeling rates for the most frequently investigated species categories (n ≥ 3.0% of samples), including the total number (n) of samples analyzed per category. Note: Significant differences among the overall mislabeling rates are indicated by different lowercase letters based on the test of equality of proportions with the Bonferroni correction ($p < 0.05$). *Excluding canned/retort tuna.

overall mislabeling rate was observed in amberjack (87.5%), followed by red snapper (85.3%), eel (81.8%), other snapper (60.0%), halibut (31.4%), tuna (29.3%), and sole (22.7%; Fig. 2). The mislabeling rates for amberjack, red snapper, and eel were significantly higher ($p < 0.05$) than those for the other categories of frequently investigated species, according to the test of equality of proportions with the Bonferroni correction (Fig. 2). In comparison, the mislabeling rates for halibut, tuna, and sole were significantly lower ($p < 0.05$) than those for the other species categories.

The most frequently investigated species categories had a combined species substitution rate of 42.5% (Fig. 2). This rate was significantly higher ($p < 0.05$) than the species substitution rate for the top 10 consumed seafoods (13.9%), according to the test of equality of proportions. This result was expected, as seafood market studies with a targeted focus on species vulnerable to substitution typically observe relatively higher substitution rates (Spencer et al., 2020; Warner, Roberts, Mustain, Lowell, & Swain, 2019; Willette et al., 2017). The highest substitution rate among the most frequently investigated species was observed for red snapper (83.3%), followed by amberjack (79.9%), other snapper (49.7%), halibut (30.7%), tuna (22.6%), sole (20.5%) and eel (0.7%; Fig. 2). Similarly, Naaum et al. (2016) reported that snapper, halibut, and tuna were among the most mislabeled types of seafood in the U.S. Previous quantitative reviews conducted globally have also found red snapper to be the most substituted species, with rates of 70–81% (Golden & Warner, 2014; Luque & Donlan, 2019). Red snapper is a historically overfished species that is highly susceptible to substitution due to its high market value and limited supply (Isaacs & Hellberg, 2020). It is often substituted with lower-value species such as tilapia, rockfish, and other snapper species. On the other hand, species substitution associated with amberjack was predominantly due to the substitution of yellowtail (*Seriola lalandi*) with buri (*Seriola quinqueradiata*). This form of substitution has been reported in numerous studies and is thought to be due to challenges in foreign name translation rather than intentional fraud (Kitch et al., 2023; Warner et al., 2013).

The rate of unacceptable market names for the most frequently investigated species combined was 16.2% (Fig. 2). This rate was significantly lower ($p < 0.05$) than the rate of unacceptable market names for the top 10 consumed seafood categories (20.8%), according to the test of equality of proportions. This difference is likely attributed to the generic labeling of salmon using unacceptable market names weighted by its large sample size (n = 880). The highest rate of unacceptable names among the most frequently investigated species categories was observed for eel (81.0%), followed by tuna (19.6%), other snapper (15.7%), red snapper (10.6%), amberjack (4.9%), sole (3.8%), and halibut (0.7%). Most of the eel samples (97.1%) were from a single study (Ely et al., 2023), in which 82 of 134 samples were marketed simply as "unagi" (the Japanese translation of "eel"), which is not considered an acceptable market name according to the FDA *Seafood List* (FDA, 2024). Additionally, many of the eel samples (78.1%) were in the form of sushi/sashimi products, which are frequently associated with mislabeling (discussed in section 3.4). Tuna was often marketed using names absent from the FDA *Seafood List*, such as "ahi" (without mention of "tuna") or "white tuna," a market name reserved for canned tuna products according to 21 C.F.R. § 161.90 (Warner et al., 2013).

The combined rate of conflicting market names for the most frequently investigated species was 1.5%, led by other snapper (6.5%), amberjack (2.8%), red snapper (2.3%), sole (2.2%), and tuna (0.5%; Fig. 2). There were no conflicting market names for eel and halibut samples. Examples of conflicting market names observed for snappers include the labeling of products as snapper/pollock (Underwood, 2018), madai/snapper or madai/red snapper (Warner et al., 2013), and red snapper/rockfish (Liou et al., 2020). When comparing the top 10 consumed seafoods to the most frequently investigated species, the rate of conflicting market names was not significantly different ($p > 0.05$), according to the test of equality of proportions.

3.4. Mislabeling rates separated by product form

The highest overall mislabeling rate based on product form was observed for the sushi/sashimi category (67.5%), followed by the “other” category (i.e., ceviche, poke, raw, roe, and seared; 54.7%), cooked (45.9%), unspecified (38.2%), smoked (29.4%), fresh/frozen (27.4%), dried/jerky (21.6%), and canned/retort samples (16.5%; Fig. 3). The overall mislabeling rates for the sushi/sashimi and “other” categories were significantly higher ($p < 0.05$) than the rates for the canned/retort and fresh/frozen categories, according to the test of equality of proportions with the Bonferroni correction. Conversely, the overall mislabeling rates for the “other,” cooked, and unspecified categories were statistically similar (Fig. 3). Fresh/frozen seafood was the most sampled product form (51.2% of samples), followed by cooked (18.3%), sushi/sashimi (18.0%), unspecified (5.8%), “other” (3.1%; i.e., ceviche, poke, raw, roe, and seared), canned/retort (2.0%), dried/jerky (1.2%), and smoked (0.4%). The sample sizes for the dried/jerky (n = 51) and smoked (n = 17) categories fell below the threshold of ≥55 samples per category for statistical analysis.

The highest species substitution rate was observed for sushi/sashimi samples (45.0%), followed by cooked (32.4%), “other” (25.8%), unspecified (21.6%), fresh/frozen (18.9%), canned/retort (11.8%), smoked (11.8%), and dried/jerky samples (9.8%; Fig. 3). Among sushi/sashimi species categories representing ≥3.0% of samples, the highest substitution rates were observed in halibut (100%), red snapper (96.8%), other snapper (92.0%), and amberjack (82.0%; Table S1). The high substitution rate for halibut sushi/sashimi is recognized as a persistent problem in the seafood industry and often involves the mislabeling of flounder species as halibut (Kitch et al., 2023). This form of mislabeling can introduce health risks when olive flounder (*Paralichthys olivaceus*) is substituted for halibut due to the occurrence of the myxosporean parasite, *Kudoa septempunctata*, in olive flounder (Kitch et al., 2023; Willette et al., 2017). As previously discussed, red snapper is highly vulnerable to substitution due to its high value and limited supply (Isaacs & Hellberg, 2020). The red snapper sushi/sashimi substitution rate reported in the current study (96.8%) is consistent with the 100% substitution rate for red snapper in U.S. sushi restaurants reported by Khaksar et al. (2015). The majority (79.9%) of amberjack sushi/sashimi samples were labeled as “yellowtail” but identified as buri. As mentioned above, the substitution of buri for yellowtail is thought to be due to challenges in foreign name translation rather than intentional fraud (Kitch et al., 2023; Warner et al., 2013). Interestingly, cooked samples showed a two-fold higher substitution rate in the current study (32.4%) as compared to the rate reported by Giusti et al. (2023) for cooked/pre-cooked samples (14.9%) in Italy, while the substitution of fresh/frozen samples was lower in the current study (18.9%) as compared to the rate reported for Italian seafood (29.2%). Most cooked samples in the current study (93.7%) were collected from restaurants, which were associated with a higher incidence of mislabeling overall (discussed in section 3.6). The increased rate of mislabeling found for cooked samples in the current study is consistent with previous findings reporting increased rates of seafood mislabeling as the degree of processing increases (Muñoz-Colmenero, Blanco, Arias, Martinez, & Garcia-Vazquez, 2016). However, this trend was not observed across all product categories; for example, canned/retort samples showed consistently low rates of mislabeling compared to fresh/frozen samples (Fig. 3).

The rate of unacceptable market names was highest in the “other” product category (38.3%), followed by the sushi/sashimi (29.6%), smoked (23.5%), cooked (20.8%), unspecified (17.8%), dried/jerky (11.8%), fresh/frozen (10.5%), and canned/retort (7.1%) categories (Fig. 3). The high rate of unacceptable market names for the “other” product category can be explained by the predominance (53.1%) of ceviche and poke products, which are frequently labeled using generic terms such as “fish” or “salmon” (Kitch et al., 2023). The relatively high sushi/sashimi mislabeling rates can be partially attributed to sushi

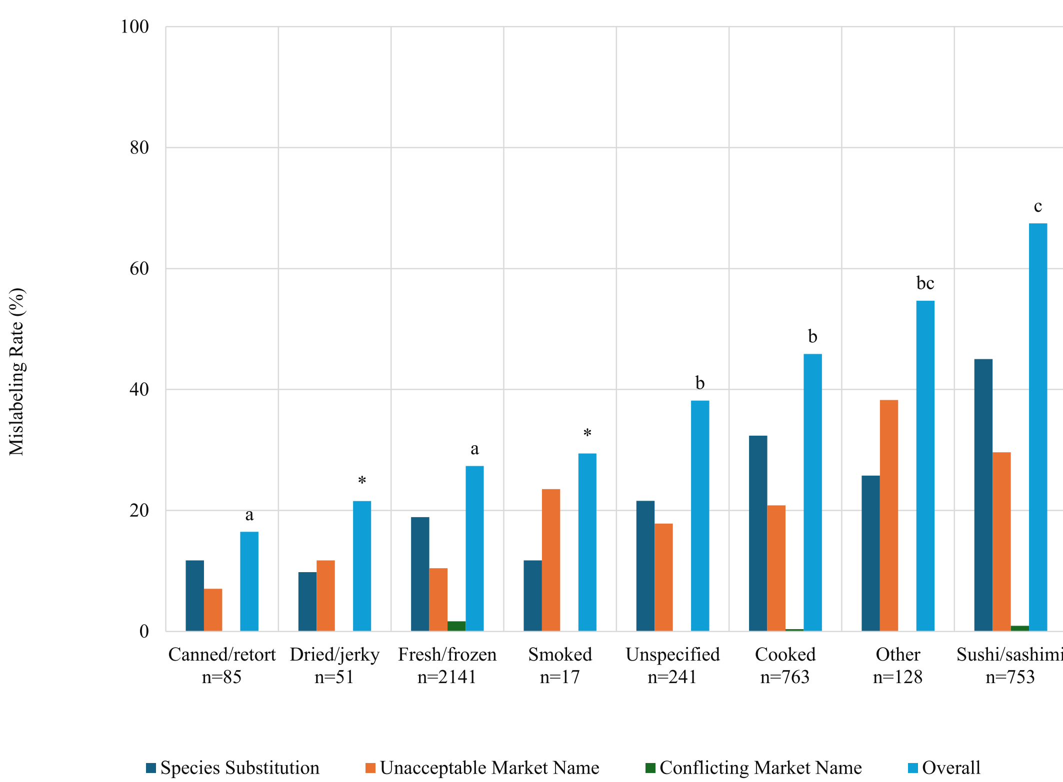

Fig. 3. Mislabeling rates separated by product forms, including the total number (n) of samples analyzed per category. Note: Significant differences among the overall mislabeling rates are indicated by different lowercase letters based on the test of equality of proportions with the Bonferroni correction ($p < 0.05$). *Mislabeling rates for categories with <55 samples were not analyzed statistically.

naming conventions, which are not always in agreement with the acceptable market names on the FDA *Seafood List* (Kitch et al., 2023). For example, 76.6% of eel sushi/sashimi samples were marketed using names inconsistent with the FDA *Seafood List* (e.g., "unagi") and 25.7% of tuna sushi/sashimi samples had unacceptable market names, including use of the term "white tuna" (discussed in section 3.3.2). The rate of conflicting market names was highest in the fresh/frozen category (1.7%), followed by sushi/sashimi (0.9%) and cooked (0.4%) categories. Conflicting market names were not observed in the remaining product categories.

3.5. Mislabeling rates for the most frequently investigated U.S. States

Mislabeling was observed on at least one occasion in 27 of the 32 states represented in this study, as well as in Washington, D.C. (Table S1). The five states with no mislabeling observed (i.e., Maine, New Hampshire, New Jersey, Rhode Island, and West Virginia) were associated with low sample sizes (<10 samples per state), indicating a need for additional research in these regions. Sampling efforts were concentrated in California (36.4% of samples), New York (12.5%), Washington (5.8%), Florida (5.4%), Washington D.C. (4.9%), North Carolina (3.4%), and Illinois (3.1%). When comparing the most frequently investigated U.S. states (i.e., ≥3.0% of samples; Fig. 4), North Carolina had a significantly higher ($p < 0.05$) overall mislabeling rate (52.4%) compared to California (37.8%) and Washington State (24.7%), according to the test of equality of proportions with the Bonferroni correction. The overall mislabeling rates for Illinois (46.9%), New York (44.1%), Washington, D.C. (43.4%), Florida (41.5%), and California (37.8%) were statistically similar ($p > 0.05$) to each other. In comparison, a previous nationwide study reported mislabeling rates similar to those in the current study for cities in Florida (38%), New York (39%), Northern California (38%), and Washington State (18%; Warner et al., 2013). Conversely, the mislabeling rates reported by Warner et al. (2013) for Illinois (32%) and Washington, D.C. (26%) were relatively low compared to those observed in the current study (46.9% and 43.4%, respectively). It is important to point out that the mislabeling rates calculated for each state in the current study are largely influenced by the studies included in this meta-analysis that were conducted in these regions. For example, studies that targeted species highly vulnerable to mislabeling resulted in higher rates of mislabeling reported for that region. Therefore, a relatively high mislabeling rate reported for a given state does not necessarily mean that seafood in that state is more frequently mislabeled.

The species substitution rate among the most frequently investigated U.S. states was highest in North Carolina (46.9%), followed by Illinois (35.9%), New York (32.1%), Washington, D.C. (31.2%), California (25.5%), Florida (23.2%), and Washington State (18.1%; Fig. 4). The high rate of species substitution in North Carolina is likely due to the high proportion of samples labeled as "local" shrimp (40.6%) and red snapper (38.5%), species known to be vulnerable to mislabeling (Korzik et al., 2020; Spencer & Bruno, 2019; Spencer et al., 2020). For example, one study conducted on shrimp in North Carolina found that one-third of samples labeled as "local" shrimp were actually whiteleg shrimp (*Litopenaeus vannamei*), a predominantly imported and globally farmed species (Korzik et al., 2020). Another study conducted in North Carolina that was focused on red snapper reported a 90.7% mislabeling rate (Spencer et al., 2020). The majority of samples associated with Illinois and New York were from market surveys conducted by the non-profit organization Oceana (Warner et al., 2013, 2014; Warner, Mustain, et al., 2015; Warner, Roberts, et al., 2019; Warner, Timme, & Lowell, 2012), which reported substitution in a variety of seafood categories, including red snapper, salmon, shrimp, and tuna. For example, 94% of tuna samples purchased as part of a survey conducted in New York City, NY, were sushi samples labeled as "white tuna" but identified as escolar (Warner, Timme, & Lowell, 2012).

The rate of unacceptable market names was highest in New York (22.7%), followed by Washington, D.C. (22.4%), Florida (22.3%), Illinois (18.0%), California (14.5%), Washington State (7.8%), and North

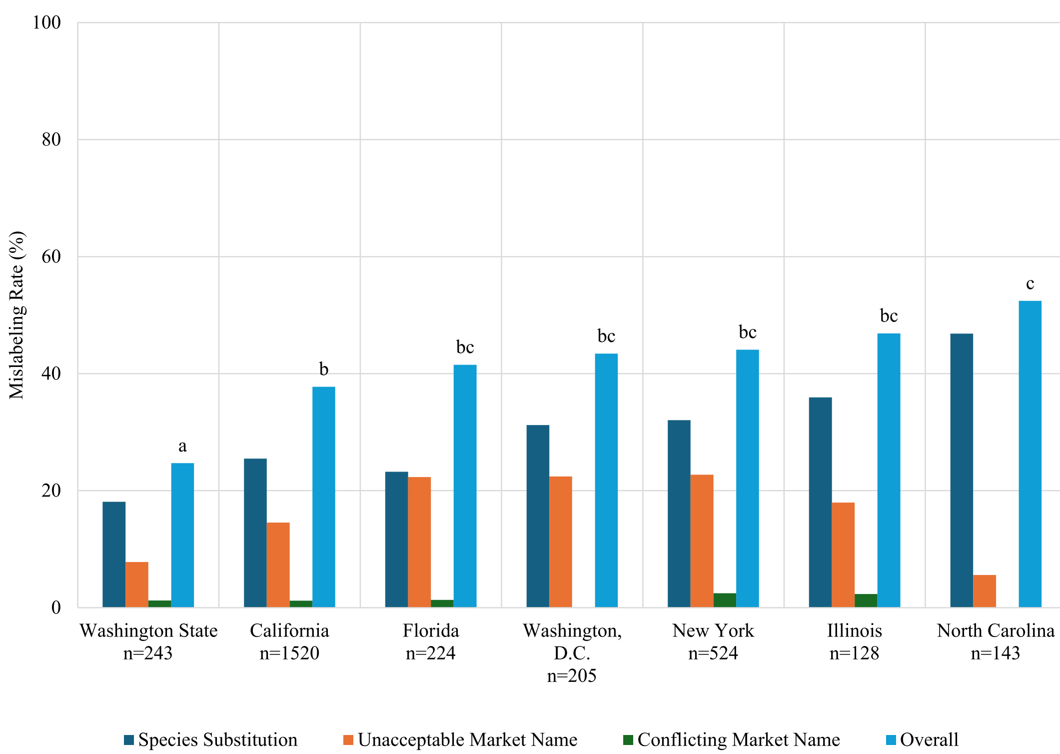

Fig. 4. Mislabeling rates for the most frequently investigated states (n ≥ 3.0% of samples) including the total number (n) of samples analyzed per category. Note: Significant differences among the overall mislabeling rates are indicated by different lowercase letters based on the test of equality of proportions with the Bonferroni correction ($p < 0.05$).

Carolina (5.6%). As mentioned above, the majority of samples associated with New York were from market surveys conducted by Oceana (Warner et al., 2014; Warner, Mustain, et al., 2015; Warner, Roberts, et al., 2019; Warner, Timme, & Lowell, 2012), in which unacceptable market names were observed for seafood categories such as eel, salmon, snapper, and tuna (Table S1). Similarly, the majority of samples associated with Washington, D.C., were from market surveys conducted by Oceana (Warner et al., 2013, 2014; Warner, Lowell, et al., 2015, 2019; Warner, Mustain, et al., 2015; Warner, Roberts, et al., 2019), with unacceptable market names observed for seafood categories such as crab, salmon, and tuna (Table S1). The rate of conflicting market names was highest in New York (2.5%), followed by Illinois (2.3%), Florida (1.3%), Washington State (1.2%), and California (1.2%). No conflicting market names were recorded in North Carolina or Washington, D.C.

3.6. Mislabeling rates by retail setting

The overall mislabeling rate was highest in restaurants (55.4%), followed by "other" retailers (i.e., farmers' markets, fishmongers, food trucks, and unspecified markets; 52.7%), seafood markets (42.6%), online retailers (31.5%), and grocery stores (26.2%; Fig. 5). The overall mislabeling rates for restaurants, "other" retailers, and seafood markets were significantly higher ($p < 0.05$) than that for grocery stores, according to the test of equality of proportions with the Bonferroni correction (Fig. 5). Additionally, the overall mislabeling rate for seafood markets was significantly higher ($p < 0.05$) than that for grocery stores but statistically similar ($p > 0.05$) to the rates for restaurants, "other" retailers, and online retailers (31.5%). Grocery stores were the most sampled retail type (52.0%), followed by restaurants (41.4%), online retailers (3.0%), seafood markets (2.2%), and other retailers (1.3%).

The high rate of mislabeling in restaurants may be explained by the inclusion of sushi venues within this category, as sushi/sashimi samples were among the most mislabeled product forms (discussed in section 3.4). Noncompliance in the "other" category may be explained by the unconventional nature of the retail settings or the predominance of snapper/red snapper samples (70.9% of samples). The relatively low incidence of mislabeling in grocery stores is influenced by the high proportion (89.1%) of fresh/frozen samples in this retail category, which observed lower overall mislabeling than the other product forms (discussed in section 3.4). Similarly, Warner et al. (2013) also found that the highest incidences of mislabeling across the U.S. were observed in sushi venues (74%) and restaurants (38%), followed by grocery stores (18%). Further, Warner, Roberts, et al. (2019) found that the mislabeling rate for small markets, including seafood markets, was double that of large-chain grocery stores.

The species substitution rate in the current study was highest in seafood markets (41.5%), followed by restaurants (37.5%), "other" retailers (36.4%), online retailers (26.8%), and grocery stores (16.2%; Fig. 5). Similarly, Liou et al. (2020) reported a relatively low rate of species substitution (13%) for various species sold in California grocery stores, while Luque and Donlan (2019) reported a substitution rate of 22% for seafood from grocery stores globally. The species substitution rate observed for restaurants in the current study (37.5%) is relatively high compared to the global species substitution rate for restaurants (27%) reported by Luque and Donlan (2019). Of the 48.6% of restaurants in the current study classified as sushi restaurants, the substitution rate was approximately 42.9% (Table S1). This is nearly three times greater than the substitution rate (16.3%) reported by Khaksar et al. (2015) for seafood from sushi restaurants in California, New York, and Texas. The difference in substitution rates is likely influenced by studies in the meta-analysis that targeted species vulnerable to mislabeling at sushi restaurants.

The rate of unacceptable market names was highest in restaurants (24.9%), followed by "other" retailers (23.6%), grocery stores (12.2%), and online retailers (3.9%; Fig. 5). There were no incidences of unacceptable market names for seafood markets. The high rate of

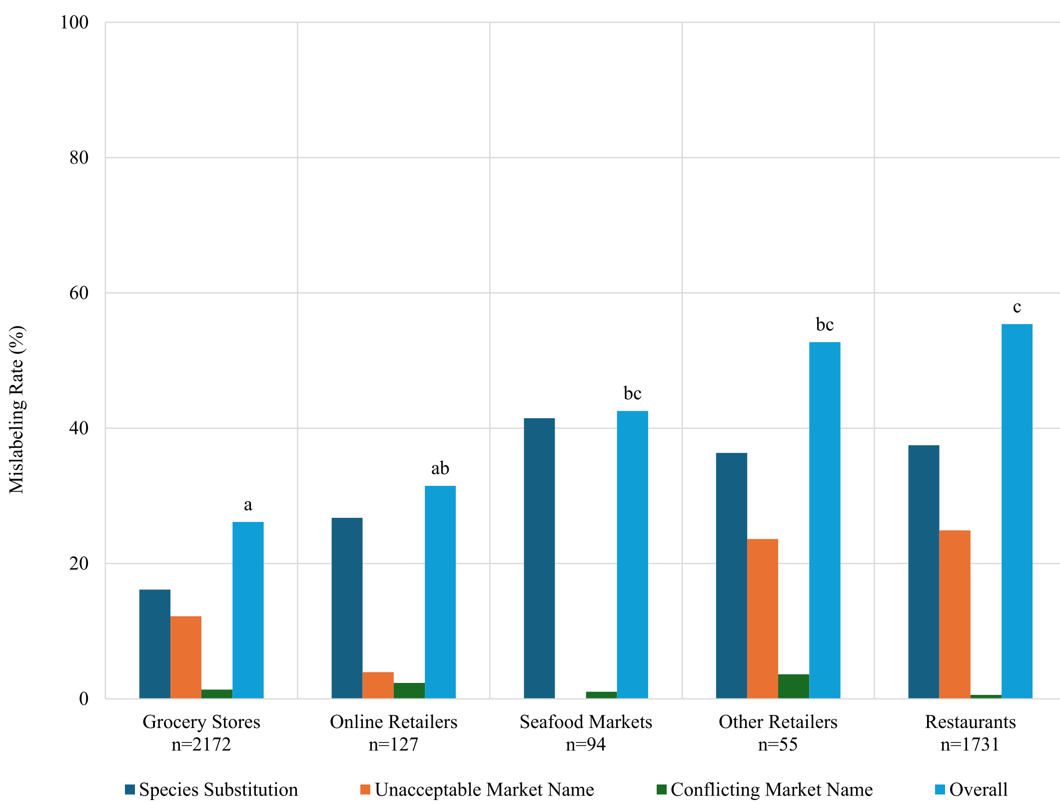

Fig. 5. Mislabeling rates separated by retail setting, including the total number (n) of seafood samples analyzed per category. Note: Significant differences among the overall mislabeling rates are indicated by different lowercase letters based on the test of equality of proportions with the Bonferroni correction ($p < 0.05$).

unacceptable market names at restaurants may be partially attributed to the use of sushi naming conventions (discussed in section 3.4) at sushi restaurants. The relatively low rate of unacceptable market names for seafood sold at grocery stores (12.2%) is similar to the rate reported by Liou et al. (2020) for Southern California grocery stores (9%). The rate of conflicting market names was highest in "other" retailers (3.6%), followed by online retailers (2.4%), grocery stores (1.4%), seafood markets (1.1%), and restaurants (0.6%). The use of conflicting market names at seafood markets and grocery stores is partly due to discrepancies between the species or geographic origins displayed on the label and placard information, as previously reported (Liou et al., 2020).

4. Conclusions

This study provides the first comprehensive analysis of the mislabeling incidence for U.S. retail seafood with specific information on species substitution, unacceptable market names, and conflicting market names. It is also the first study to examine the mislabeling rates for the top 10 consumed seafoods in the U.S. compared to the most frequently investigated seafoods. The findings of this study demonstrated that the top 10 consumed seafoods reported by the National Fisheries Institute based on 2021 consumption data exhibit lower overall mislabeling and substitution rates than the most frequently investigated species. However, additional data on mislabeling trends for clam, pangasius, and pollock samples is needed. Mislabeling among the top 10 consumed seafoods was mainly due to unacceptable market names, suggesting a need for outreach and education to improve compliance with the FDA *Seafood List*. Alternatively, species substitution was the predominant form of mislabeling among the most frequently investigated species. Relatively high mislabeling rates were observed for unconventional retailers, restaurants, and sushi/sashimi samples, revealing target areas for future investigations and compliance efforts. Future studies should adopt standard language for the various types of seafood mislabeling (i.e., species substitution, unacceptable market name, and conflicting market name) to allow for direct interpretation of data across studies. Verbal declarations should be considered separately from labeling/menu declarations due to the varying levels of expertise and information provided to staff and other retail personnel. Additionally, researchers should provide all supplemental data in their publications, including the declared name verbatim, product form, and country of origin.

CRediT authorship contribution statement

Sarah Ahles: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christina A. Mireles DeWitt:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Rosalee S. Hellberg:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodcont.2024.111110.

Appendix A. Mislabeling Definitions

A.1 Mislabeling Determinations

All samples were assessed for mislabeling at the time of sample collection per the archived FDA *Seafood List* updates and additions (https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-seafood-list-fdas-guide-determine-acceptable-seafood-names). The mislabeling categories were not exclusive, meaning that a sample could be classified under more than one category if applicable.

A.1 Species Substitution

Seafood samples that were identified as a different species than the species or species group declared on the label were determined to be substituted. Common names for species were determined based on the FDA *Seafood List*, and species groupings were determined using SeaLifeBase (https://www.sealifebase.ca/), FishBase (https://fishbase.mnhn.fr/search.php), and/or the FDA *Seafood List*. Highly processed samples (e.g., retort) with additional species detected other than the declared species were assigned the species substitution designation.

A.2 Unacceptable Market Names

Seafood samples that were labeled with market names inconsistent with the FDA *Seafood List* were determined to have an unacceptable market name. Samples were determined to have an unacceptable market name if a false or misleading geographic descriptor was used as part of the market name or if the indicated production method (e.g., farmed or wild) was false or misleading. FishBase and SeaLifeBase were used to assess the validity of geographic descriptors and production methods, with supplementary sources of information consulted as needed. Geographic terms inserted within a common name or other acceptable market name (e.g., blue Mexican shrimp instead of blue shrimp) led to the designation of an unacceptable market name, regardless of validity (FDA, personal communication, May 8, 2023).

Seafood samples with typos of up to two characters in the genetic identity or market name were not considered mislabeled; however, in cases where excusing a typo would result in species substitution, an unacceptable market name was assigned (e.g., "stripped jack" identified as white trevally (*Pseudocaranx dentex*)). In cases where a label listed conflicting species names with typo(s), conflicting and unacceptable market names were assigned (e.g., "blue snapper pollack" identified as pollock (*Pollachius virens*)). Samples marketed in a foreign language only were considered to have an unacceptable market name; however, in the case where an English name recognized by the FDA *Seafood List* supplemented a foreign language market name, the sample was not considered mislabeled.

A.3 Conflicting Market Names

Seafood samples that contained conflicting species designations or conflicting geographic descriptors/production methods across product information (e.g., the placard and label) were considered to have conflicting market names. For example, a sample described as "yellowtail" on the label and as "albacore tuna" on the placard would be considered to have a conflicting market name. Likewise, a product described as "farmed" on the label and as "wild" on the placard would be considered to have a conflicting market name. Reference to multiple species within a single market name (e.g., "yellowtail albacore tuna") was also considered to be a conflicting market name.

A.4 Special Cases

1. Samples labeled as wild salmon that were identified as Atlantic salmon (*Salmo salar*) were considered substituted due to the scarceness of commercially available wild Atlantic salmon (Tom & Olin, 2010; Warner, Lowell, et al., 2015).
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2. Shrimp samples labeled as "local" or "wild" with a geographic descriptor were considered substituted if (1) the identified species was not associated with the declared region and (2) a different species of wild shrimp was associated with the declared region (e.g., "local North Carolina shrimp" identified as whiteleg shrimp (*Litopenaeus vannamei*)).
3. Crab samples with "Maryland," "MD," or "Chesapeake Bay" within the market name or the "True Blue" label (https://marylandsbest.maryland.gov/true-blue-maryland-crab-meat/) indicated blue crab (*Callinectes sapidus*) and were considered substituted if identified as other species not local to the region (e.g., *Portunus* spp. from the Indo-Pacific; Warner, Lowell, et al., 2015).
   Warner, K., Lowell, B., Disla, C., Ortenzi, K., Savitz, J., & Hirshfield, M. (2015). *Oceana Reveals Mislabeling of Iconic Chesapeake Blue Crab*. Oceana. Retrieved 06/28/2024 from https://usa.oceana.org/wp-content/uploads/sites/4/crab_testing_report_final_3.27.15.pdf

Appendix B. Data Organization

B.1 Species Category

Assignment to a species category was carried out based on the FDA *Seafood List* and FishBase/SeaLifeBase. The following online resources were used to interpret foreign market names: Hawaii Seafood (https://www.hawaii-seafood.org/wild-hawaii-fish/), Jisho (a Japanese-English dictionary; https://jisho.org/), and UC Merced Fish Dictionary (http://sail.ucmerced.edu/Fish_dictionary.pdf). Samples marketed in a foreign language were translated and assigned to their respective species categories; however, samples without translations available across the three online translation resources were assigned to the "unspecified" category. Those labeled as "white fish" were also placed in the "unspecified" category.

B.2 Product Form

Samples were categorized as one of the following product forms: fresh/frozen, sushi/sashimi, cooked, smoked, canned/retort, dried/jerky, unspecified, and "other" (i.e., ceviche/poke/raw/roe/seared). The "fresh/frozen" product category included uncooked, not ready-to-eat (NRTE) seafood obtained from grocery stores, seafood markets, fishmongers, farmers' markets, unspecified markets, and online retailers. The "fresh/frozen portions" subcategory was reserved for cuts of fish, such as "fillets" and "steaks," while the "fresh/frozen whole" subcategory was reserved for whole fish (Table S1). The "sushi/sashimi" product category contained samples with the qualifying words "sushi," "sashimi," "nigiri," or "roll" (with the exception of lobster roll sandwiches). The "cooked" product category was assigned to samples that were described as "broiled," "sauteed," "steamed," "grilled," or any other method that indicated a cooked product. The "canned/retort" product category contained samples from cans, jars, pouches, and other forms of retort processing. Samples from grocery stores or seafood markets described as "burgers" without any other qualifying descriptors were categorized under the "unspecified" category. All other samples with ambiguous or unspecified product forms were categorized in the "unspecified" category.

B.3 Retail Setting

The retail settings were recorded as reported in the datasets provided with each study and consisted of the following categories: restaurants, grocery stores, seafood markets, online retailers, "other" retailers (i.e., farmers' markets, fishmongers, food trucks, and unspecified markets), and unspecified retailers. In cases where the retail categories for each sample were not provided, the name of the retailer (if available) was searched on Google Maps™ (Mountain View, CA) to determine the retail setting.

Data availability

I have shared the data as a supplementary file.

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