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[Article]

Effect of Trawling and Habitat on Mercury Concentration in Juvenile Red Snapper from the Northern Gulf of Mexico

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Abstract.—We evaluated mercury (Hg) contamination in juvenile red snapper *Lutjanus campechanus* (<250 mm total length) as an indicator of Hg pollution on the northern Gulf of Mexico (GOM) continental shelf. Specifically, we examined the effects of fish size, commercial shrimp trawling, and habitat type on total Hg concentrations and stable nitrogen isotope ratios ($\delta^{15}N$; a proxy for trophic position) in red snapper. Red snapper Hg concentrations and $\delta^{15}N$ values were positively and significantly correlated with fish size. In addition, red snapper collected over trawled habitats had significantly higher Hg concentrations and $\delta^{15}N$ values than did red snapper collected from similar, nontrawled habitats. Red snapper also exhibited habitat-specific differences in Hg concentrations and $\delta^{15}N$ values, but differences were size dependent and generally small. Our study suggests that the Hg concentrations of juvenile red snapper in the northern GOM are elevated in areas where commercial shrimp trawling occurs, possibly due to increases in both red snapper trophic position and bioavailable Hg in trawled areas. Additional studies are needed to determine whether Hg concentrations are elevated in fish from trawled areas in other marine ecosystems.

Mercury (Hg) is a toxic heavy metal that accumulates in food webs and has increased in the environment primarily because of anthropogenic activities (NRC 2000; Pacyna and Pacyna 2005). Coal burning releases inorganic Hg into the atmosphere, where it resides until it is deposited onto the earth's surface (Jackson 1997). In marine ecosystems, sulfate-reducing bacteria (SRB) associated with sediments convert inorganic Hg, the most common form in the environment, to highly toxic methylmercury (MeHg; Morel et al. 1998; Ullrich et al. 2001; Mason and Gill 2005). Production of MeHg is related to factors that influence geochemical conditions and microbial activity in the sediment, such as redox conditions, sediment grain size, organic matter content, and density of infaunal burrows (Bloom et al. 1999; Mason and Lawrence 1999; Hammerschmidt and Fitzgerald 2004; Benoit et al. 2006). Organisms at the base of the food web, such as phytoplankton, absorb MeHg directly from the water (Miles et al. 2001). Consumers, including fish, are exposed to MeHg primarily through the diet (Hall et al. 1997; Tsui and Wang 2004), and fish with high trophic positions have elevated concentrations of MeHg (Wiener et al. 2003).

The primary source of MeHg in humans is consumption of Hg-contaminated fish (NRC 2000), and MeHg has negative effects on human health (NRC 2000; Clarkson 2002). Despite the fact that the majority of fish consumed by humans are marine (Munthe et al. 2007), most studies investigating factors that affect MeHg contamination in fish have focused on freshwater lakes (Wiener et al. 2003; Munthe et al. 2007). Understanding the factors that regulate MeHg contamination in marine fish is critical, because many commercial and recreational fish species have MeHg concentrations at or above the recommended levels for safe consumption (NRC 2000; USEPA 2006).

Coastal marine ecosystems like the Gulf of Mexico (GOM) continental shelf are subject to large-scale anthropogenic sediment disturbance from commercial shrimp trawling. Similar to other anthropogenic activities that disturb the sediment (e.g., dredging), commercial shrimp trawling may enhance MeHg production by altering geochemical conditions and microbial activity in the sediment (Bloom and Lasorsa 1999; Eggleton and Thomas 2004). In addition to

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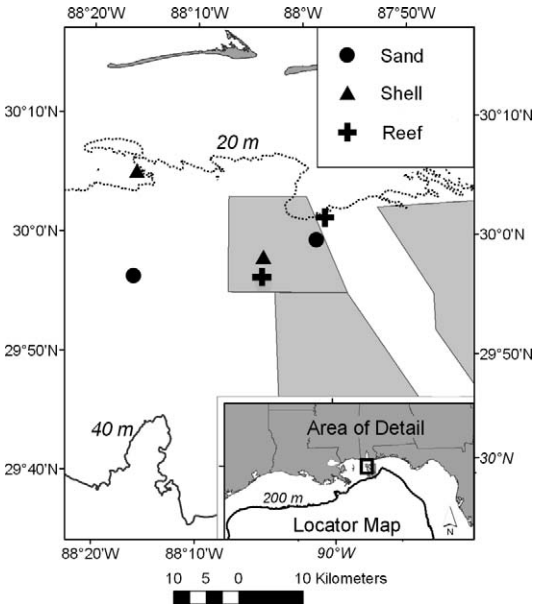

FIGURE 1.—Study region on the northern Gulf of Mexico continental shelf, where the effect of trawling on mercury concentrations and stable isotope ratios in juvenile red snapper was examined. The 20-, 40-, and 200-m (map inset) depth contours are shown; the 200-m contour represents the shelf edge. Sampling sites (sand, shell, and reef habitat types) are represented by symbols, and the artificial reef permit area (de facto nontrawled subregion) is indicated by shading.

affecting MeHg production, trawling may affect MeHg concentrations in fish by altering food web structure (Thrush and Dayton 2002).

Coastal marine ecosystems also exhibit large spatial variability in habitat types (Thrush and Dayton 2002). The northern GOM continental shelf is largely dominated by mud and sand habitat (Kennicutt et al. 1995) and also contains natural hard-bottom habitats in the form of reef banks, ledges, and shell rubble ridges that exist on the shallow (<40 m) inner shelf (Schroeder et al. 1988; Dufrene 2005). Methylmercury production and fish contamination may differ with respect to habitat because the redox conditions, organic content, and invertebrate communities within sediments differ among habitats (Dufrene 2005; Wells et al. 2008c).

Habitat use by red snapper *Lutjanus campechanus* has been well studied on the northern GOM continental shelf. Juvenile red snapper (defined here as age-0 or age-1 sexually immature fish < 250 mm total length [TL]; Woods et al. 2007) primarily use sand, shell rubble, and low-relief microhabitats (e.g., rubble patches, debris; Workman and Foster 1994; Szedlmayer and Howe 1997; Patterson et al. 2005). Because juvenile red snapper exhibit habitat and site fidelity (Workman et al. 2002) and are low-level consumers (Wells et al. 2008b), their Hg concentrations can be used to indicate MeHg bioavailability in habitats where they reside (Lindqvist et al. 1991; Bank et al. 2007).

In this study, we evaluated Hg concentrations in juvenile red snapper as an indicator of Hg pollution in marine fish inhabiting the northern GOM continental shelf. Specifically, we wanted to determine whether Hg concentrations in juvenile red snapper were related to commercial shrimp trawling presence and habitat type. We also examined stable nitrogen isotope ratios ($\delta^{15}N$; a proxy for trophic position) in juvenile red snapper to determine whether differences in trophic position could explain possible differences in Hg concentrations among study sites.

Methods

Study site.—Red snapper were collected from a northern GOM continental shelf region consisting of two subregions (Figure 1). The first subregion was an area of open shelf that was exposed to commercial shrimp trawling. Wells et al. (2008c) divided commercial shrimp trawling effort (J. Nance, National Oceanic and Atmospheric Administration [NOAA], National Marine Fisheries Service [NMFS], Galveston, Texas, personal communication) by bottom surface area (Patella 1975) and conservatively estimated that trawling effort in this subregion was sufficient to disturb the entire seafloor at least once per year. Electronic logbook data from shrimp fishing vessels indicate that some locations in the subregion are targeted with much-greater frequency (NRC 2002). The second subregion was an extensive (>3,000-km^2) artificial reef permit area that was directly adjacent to the subregion exposed to trawling (Figure 1). The artificial reef permit area served as a de facto nontrawled area, because shrimp vessels voluntarily avoid it due to the possibility of losing their nets by snagging them on reef structures (Link 1997; NRC 2002). As such, the presence of the artificial reef permit area provided a unique opportunity to evaluate the effect of trawling on Hg concentrations in fish. We assumed that no or limited trawling occurred in the artificial reef permit area, but there is some uncertainty surrounding this assumption. Trawler entry into the artificial reef permit area is possible because no regulations or enforcing mechanisms are currently in place to exclude shrimp vessels from the area. Distributional shrimp trawl effort data indicate that extensive trawling effort occurs outside the artificial reef permit area, while little to no effort occurs within this area (NRC 2002). In addition, Link (1997) calculated that the addition of the artificial reef permit

area annexed the largest portion of untrawlable bottom to the northern GOM inner shelf. A second assumption in this study was that the presence of artificial reefs did not affect Hg concentrations or feeding patterns ($\delta^{15}N$) of red snapper. This is supported by a preliminary survey indicating that Hg concentrations did not differ between red snapper collected from natural reefs and those collected from artificial reefs (M.M.C., personal observation). In addition, two studies found that reef-associated organisms made up a small percentage of the diets of red snapper associated with artificial and natural reefs (McCawley et al. 2006; Wells et al. 2008b). To minimize any potential effect of artificial reefs, we selected study areas in which sonar surveys indicated an absence of artificial reefs (Dufrene 2005).

Within each subregion, we collected fish from three habitat types: sand with interspersed mud, shell rubble ridges, and high-relief (>2-m) natural reefs (Figure 1). Seabed characterization within each subregion was performed with digital side-scan sonar and was ground-truthed with box core sediment analysis during previous studies (Dufrene 2005; Patterson et al. 2005). Similar habitat types inside and outside the artificial reef permit area contained sediment with similar grain size, organic content, and calcium carbonate content. Habitat types exhibited limited variation in mean depth. Mean depths for trawled habitats were 30 m for sand habitat, 18 m for shell habitat, and 24 m for reef habitat; depths for non-trawled habitats were 25 m for sand habitat, 26 m for shell habitat, and 29 m for reef habitat.

Field sampling.—Red snapper were collected during three sampling cruises in May, August, and October 2004. Within each habitat × trawl combination, we randomly selected three fish sampling sites (total of 18 sampling sites in the study) that were separated by 1–5 km. The 18 sampling sites were fixed for the duration of the study, and each site was sampled during each cruise. All sampling was performed during daylight hours (from 30 min after sunrise to 30 min before sunset).

Red snapper were collected with otter trawls. Trawl gear included a single net (width = 12.8 m; mesh size of body = 4 cm; mesh size of cod-end lining = 0.7 cm) towed at approximately 4.6 km/h for 10 min/sample. Trawls were towed along the edges of the reef habitats to avoid damaging immobile fauna (i.e., sponges, corals) or hanging the net. Trawling is an effective method of collecting juvenile red snapper (Wells et al. 2008a); unlike commercial shrimp trawling, our collections were one-time disturbance events that affected a limited area. We were also able to use otter trawls in the artificial reef permit area, because we first conducted a side-scan sonar survey to ensure that the area was free of hangs. Otter trawls primarily capture juveniles, and use of additional sampling gears that target adults was beyond the scope of this study.

After collections were made, red snapper were transported to the laboratory and stored at −80°C. In the laboratory, the total length (TL) of each fish was measured to the nearest millimeter. Red snapper epaxial muscle tissue was dissected from the left side and dried in a drying oven (Yamato, Orangeburg, New York; Model DX 600) at 60°C for 24 h or until the sample reached a constant weight; the tissue was then homogenized with a ball-mill grinder (Dentsply International, York, Pennsylvania). Ground muscle tissue was stored in clean glass scintillation vials until Hg or $\delta^{15}N$ analysis was performed.

Mercury analysis.—Total Hg was used as a proxy for MeHg, because 97% of total Hg in red snapper tissue is in the form of MeHg (Bank et al. 2007). Total Hg analysis was performed with a direct Hg analyzer (Milestone, Inc., Monroe, Connecticut; DMA-80) that uses thermal decomposition, gold amalgamation, and atomic absorption spectrometry (USEPA 1998). A calibration curve was generated using three reference materials from the Institute for National Measurement Standards (National Research Council of Canada): MESS-3 (marine sediment: certified value = 91 ± 9 ng of total Hg/g of dry weight [mean ± 95% confidence interval]), PACS-2 (marine sediment: certified value = 3,040 ± 200 ng/g), and DORM-2 (muscle of spiny dogfish *Squalus acanthias*: certified value = 4,640 ± 260 ng/g). Quality assurance included reference samples, duplicate samples, and blanks. Reference samples (MESS-3 or TORT-2, hepatopancreas of the American lobster *Homarus americanus*) were analyzed every 10 samples, and the mean percent recovery was 103 ± 4% (mean ± SD; range = 96–111%; $n = 21$). Duplicate samples were analyzed every 20 samples, and the mean relative percent difference was 1.19 ± 1.06% (range = 0.05–1.45%; $n = 9$). Blanks (empty quartz sample boats) were analyzed every 20 samples, and the mean Hg content was 0.06 ± 0.05 ng (range = 0.01–0.19 ng; $n = 10$).

Stable isotope analysis.—The $\delta^{15}N$ in red snapper was used as a proxy for red snapper trophic position (Bank et al. 2007). Stable nitrogen isotopes are used differentially in cellular processes, resulting in a predictable increase in the heavy isotope (^{15}N) relative to the light isotope (^{14}N) with each increase in trophic level (≈3–4‰; Minagawa and Wada 1984; Peterson and Fry 1987).

Ground muscle tissue (4–5 mg) was placed in a tin boat with 10 mg of precombusted vanadium pentoxide (V_2O_5). The N isotopic composition of red snapper muscle tissue was determined with a Finnigan MAT

DeltaPlus continuous-flow stable isotope mass spectrometer (Thermo Fisher Scientific, Inc., Waltham, Massachusetts) attached to a Carlo Erba elemental analyzer (CE Elantech, Lakewood, New Jersey) at Louisiana State University (Fry 2007). Nitrogen isotopic values are reported relative to atmospheric N_2 using the standard equation:

$$\delta_{\text{sample}}(‰) = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1,000,$$

where R represents the ^{15}N:^{14}N ratio.

Data analysis.—Linear models were used to relate red snapper Hg concentrations or $\delta^{15}N$ values to TL ($n = 125$). The number of juveniles (from all habitat × trawl combinations) included in analyses was 52 from May sampling, 40 from August sampling, and 33 from October sampling. Two-factor analysis of covariance (ANCOVA) fixed-effects models were used to test for the effects of habitat and trawling on red snapper Hg concentration or $\delta^{15}N$, and fish TL was included as the covariate. A posteriori differences among means were detected with Tukey's honestly significant difference test (Day and Quinn 1998). To determine whether differences in Hg concentrations between trawled and nontrawled subregions could be explained by $\delta^{15}N$ values, we used a two-factor ANCOVA with habitat and trawling as fixed factors and $\delta^{15}N$ values and TL as the covariates (Baron and Kenny 1986).

We used an ANCOVA design because TL is correlated with Hg concentrations in red snapper (Bank et al. 2007) and because TL differed between treatment groups in this study. In ANCOVA models, regression analysis is used to remove the covariate's effect from the unexplained variability in the response variable. The final ANCOVA tests the difference between treatment means (Hg or $\delta^{15}N$) adjusted for the effect of the covariate (Quinn and Keough 2002). Linearity was tested for each ANCOVA model; full ANCOVA models were first examined with all factors, covariates, and covariate × factor interactions included. Nonsignificant interaction terms ($P > 0.05$) were then removed from the models, and only the reduced models were used for statistical interpretations.

The homogeneous variance assumption was examined with residual plots, and normality was examined using a probability plot of the residuals versus the expected values. Two outliers exceeded the traditional interquartile range (IQR) test. The IQR test is used to identify extreme outliers and was calculated by use of the inner- and outer-fence method (Ott 1993; Brant 1990). The two outliers were deleted from the data set to meet assumptions of homogeneous variance and normality, but results were not affected by removal of these outliers. All analyses were performed using the Statistical Analysis System (SAS Institute 2006) and a significance level of 0.05.

Results

Juvenile red snapper from all sites had a mean (±SE) Hg concentration of 148.3 ± 4.8 ng/g of dry weight and a mean $\delta^{15}N$ value of 13.6 ± 0.1‰. For samples pooled from all locations, Hg concentrations and $\delta^{15}N$ values were positively and significantly correlated with TL (Figure 2; $\text{Hg} = 13.77 + 0.94\text{TL}$, $R^2 = 0.76$, $P < 0.001$; $\delta^{15}\text{N} = 13.04 + 0.01\text{TL}$, $R^2 = 0.25$, $P < 0.001$). A significant positive correlation was also observed between Hg concentration and $\delta^{15}N$ (Figure 3; $\log_{10}\text{Hg} = -3.09 + [0.39 \times \delta^{15}\text{N}]$, $R^2 = 0.46$, $P < 0.001$).

Red snapper that were collected over trawled habitats had a significantly higher Hg concentrations (least-squares mean = 150.9 ± 4.4 ng/g) than fish that were collected from nontrawled habitats (132.2 ± 3.7 ng/g; Figure 4a; Table 1). In general, Hg concentrations in red snapper collected from a given habitat type were higher for fish sampled in the trawled subregion than for those sampled in the nontrawled subregion (Figure 5; Table 2); post hoc comparisons indicated a significant difference between fish from trawled and nontrawled shell-type habitats ($P = 0.007$). We detected a significant habitat effect and habitat × TL interaction effect on Hg concentrations in red snapper (Table 1). The significant interaction indicates that the effect of habitat type on red snapper Hg concentrations is dependent on TL (Figure 4b). For the smallest size-classes of red snapper, Hg values were highest in fish collected from sand habitat, intermediate in fish from shell habitat, and lowest in fish from reef habitat. However, for the largest size-classes, the order was reversed (i.e., Hg values were in descending order for reef, shell, and sand habitats).

Red snapper collected from trawled habitats had a significantly higher $\delta^{15}N$ value (least-squares mean = 13.8 ± 0.1‰) than those collected from nontrawled habitats (13.5 ± 0.1‰; Figure 6a; Table 1). Similar to the results for Hg concentrations, the red snapper $\delta^{15}N$ value within a given habitat type was higher for the trawled region than for the nontrawled region, and post hoc comparisons indicated a significant difference between fish from trawled and nontrawled shell habitats ($P < 0.001$; Figure 5; Table 2). The habitat effect and habitat × TL interaction effect on $\delta^{15}N$ values were significant (Table 1). The significant interaction indicates that the effect of habitat on red snapper $\delta^{15}N$ depends on TL (Figure 6b). For the smallest size-classes of red snapper, $\delta^{15}N$ values were highest in fish collected from reef habitat, intermediate in fish from sand habitat, and lowest in fish from shell

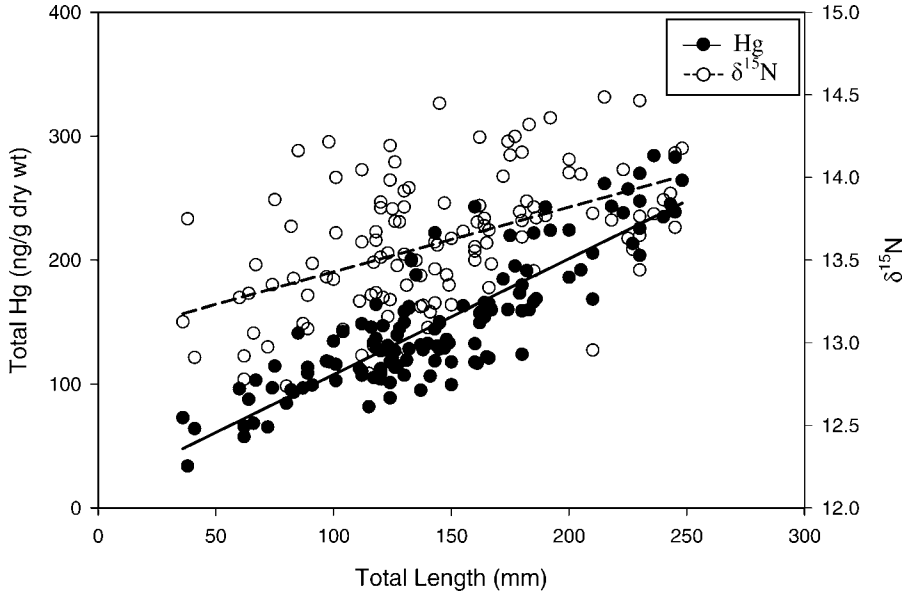

FIGURE 2.—Relationship between total mercury (Hg) concentration (ng/g of dry weight) or stable nitrogen isotope ratio ($\delta^{15}N$; ‰) and total length (mm) of juvenile red snapper collected from all three habitat types (sand, shell, and natural reef) of the northern Gulf of Mexico continental shelf in 2004.

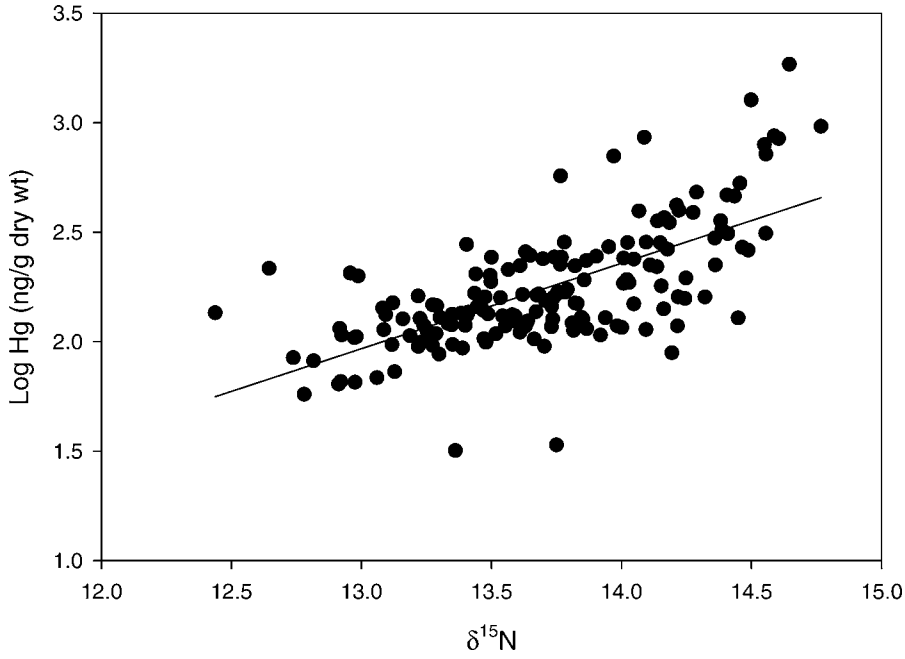

FIGURE 3.—Relationship between $\log_{10}$(total mercury [Hg] concentration) (ng/g of dry weight) and stable nitrogen isotope ratio ($\delta^{15}N$; ‰) of juvenile red snapper collected from all three habitat types (sand, shell, and natural reef) of the northern Gulf of Mexico continental shelf in 2004.

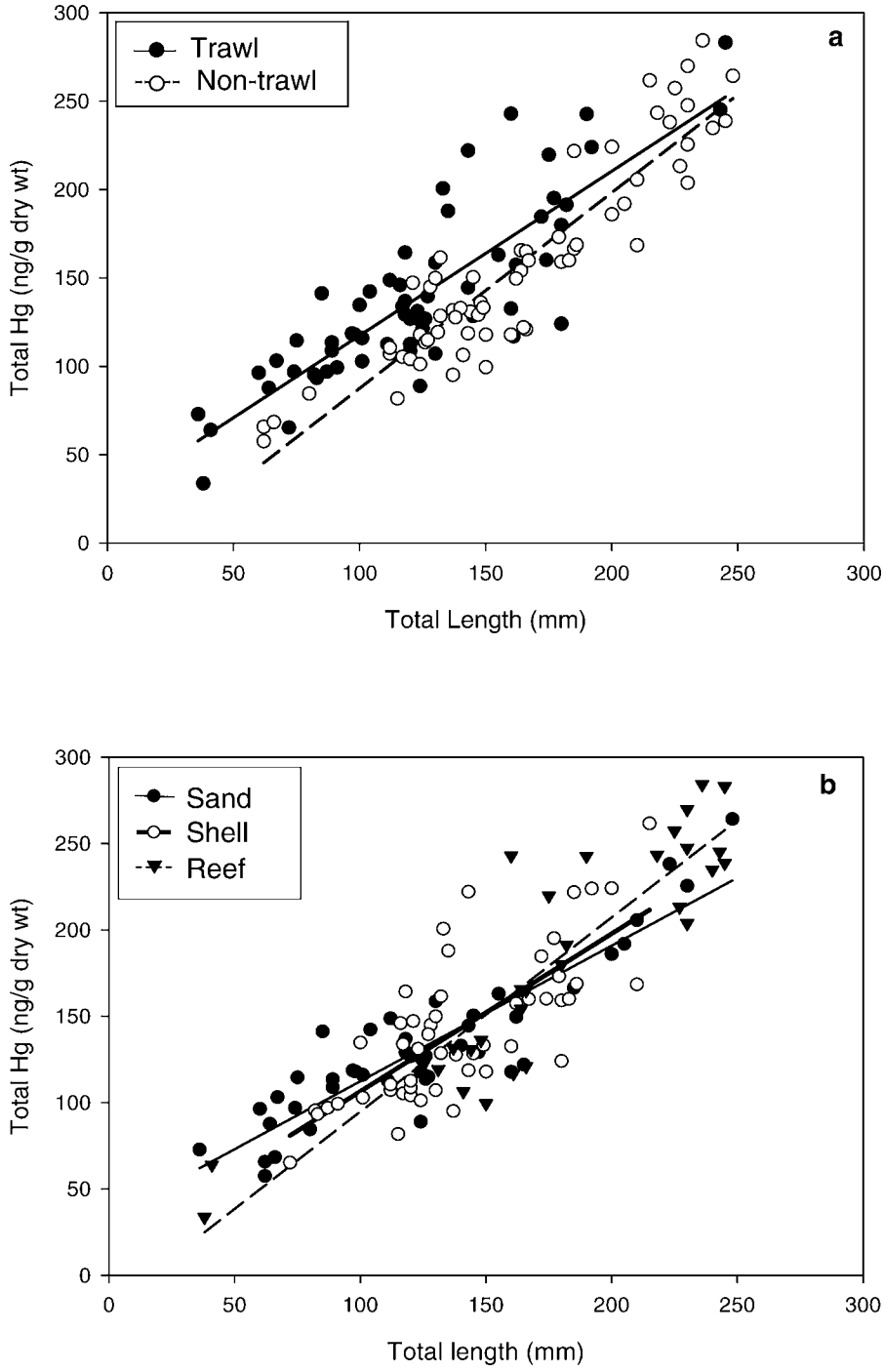

FIGURE 4.—Relationship between total mercury (Hg) concentration (ng/g of dry weight) and total length (mm) of juvenile red snapper collected in 2004 from **(a)** trawled and nontrawled subregions and **(b)** sand, shell, and natural-reef habitat types of the northern Gulf of Mexico continental shelf.

habitat. The order of $\delta^{15}N$ values among habitats was reversed for the largest size-classes.

Because Hg concentrations were positively related to $\delta^{15}N$ and because $\delta^{15}N$ was elevated in trawled areas, $\delta^{15}N$ may have acted as a mediating variable (Baron and Kenny 1986). A mediating variable is one that represents the generative mechanism through which the focal independent variable (i.e., trawling) is able to influence the dependent variable of interest (i.e., Hg; Baron and Kenny 1986). To determine whether $\delta^{15}N$ was a mediating variable for the effect of trawling on Hg concentrations, we used the approach recommended by Baron and Kenny (1986) and regressed Hg on both trawling and $\delta^{15}N$ values. The model also included habitat and TL. The effect of $\delta^{15}N$ value was not significant ($F = 0.11$; df = 1, 119; $P = 0.74$), but we found a significant main effect of trawling ($F = 18.3$; df = 1, 119; $P < 0.001$) on Hg concentrations when all other variables were included in the model. This result indicated that $\delta^{15}N$ was not a mediating variable; it could only have been considered a mediating variable if trawling had produced no effect on Hg concentrations when $\delta^{15}N$ values were controlled (Baron and Kenny 1986).

TABLE 1.—Results of reduced analysis of covariance models investigating the effects of habitat type (sand, shell, and reef), presence of trawling, and fish total length (TL; mm) on the total mercury (Hg) concentration (ng/g of dry weight) and stable nitrogen isotope ratio ($\delta^{15}N$; ‰) in juvenile red snapper collected in 2004 from the northern Gulf of Mexico continental shelf.

Dependent variable	Significant factors	df (factor, model error)	*F*	*P*
Hg	Trawling	1, 118	21.1	<0.001
	Habitat type	2, 118	4.99	0.008
	Total Length (TL)	1, 118	406	<0.001
	Habitat type × TL	2, 118	3.76	0.026
$\delta^{15}N$ value	Trawling	1, 118	34.5	<0.001
	Habitat type	2, 118	6.51	0.002
	TL	1, 118	77.3	<0.001
	Habitat type × TL	2, 118	8.95	<0.001

Discussion

The Hg concentrations in red snapper muscle tissue increased with fish TL. Previous studies have repeatedly found a positive correlation between Hg concentrations and fish size (McClain et al. 2006; Cai et al. 2007). Because fish increase in both age and trophic position as they grow, it is difficult to discern whether the increase in Hg observed in this study resulted from biomagnification or from time-related bioaccumulation. Nevertheless, the significant relationship between $\delta^{15}N$ and TL indicates that trophic position also increases with size; thus, biomagnification is a possible explanation for the observed increase in Hg with increasing TL.

The Hg concentrations in juvenile red snapper were elevated in areas of the northern GOM continental shelf where shrimp trawling occurred. To our knowledge, this is the first study to document a positive relationship between the presence of trawling and fish Hg concentration. This study adds to a growing body of evidence that anthropogenic disturbance of sediments leads to increased contaminant concentrations in marine organisms (Eggleton and Thomas 2004). Our study was limited to one nontrawled subregion because of the limited availability of additional nontrawled regions in the northern GOM. The lack of replication limits our ability to generalize results from this study to the entire GOM shelf or to other marine ecosystems. Future studies should compare fish Hg concentrations between trawled and nontrawled areas of other marine ecosystems to determine whether the relation between trawling and elevated Hg concentrations is generalizable.

The Hg concentrations may have been higher in trawled areas because physical disturbance of the sediments led to an increase in MeHg production and availability. Trawling mixes sediment from the anoxic zone into surface water (Thrush and Dayton 2002), possibly resulting in the release of sediment- and porewater-associated MeHg and increasing its availability for incorporation into the food web (Eggleton and Thomas 2004). In addition, sediment mixing due to trawling causes translocation of organic carbon to the anoxic zone (Thrush and Dayton 2002) and may have stimulated the MeHg-producing SRB (Fitzgerald and Lamborg 2003). Bloom and Lasorsa (1999) examined MeHg concentrations in the water column above dredge spoil and found that both mechanisms probably contributed to elevated Hg concentrations. In one of the only studies to examine Hg concentrations in biota after anthropogenic sediment disturbance, Bellas et al. (2007) hypothesized that Hg in caged filter-feeding mussels was elevated after dredging due to mobilization of bioavailable Hg to the water column. Studies are needed to determine whether MeHg concentrations are higher in the sediment and water column of trawled GOM areas than in nontrawled areas.

An alternative but not mutually exclusive hypothesis for explaining the elevated Hg concentrations observed in red snapper from trawled areas is an increase in fish trophic position associated with sediment disturbance (i.e., trophic position acting as a mediator variable). Trophic position is positively correlated with Hg concentrations in fish (Cabana and Rasmussen 1994; Cai et al. 2007; this study), and we detected an enhancement of both trophic position (i.e., elevated $\delta^{15}N$) and Hg concentrations in red snapper collected

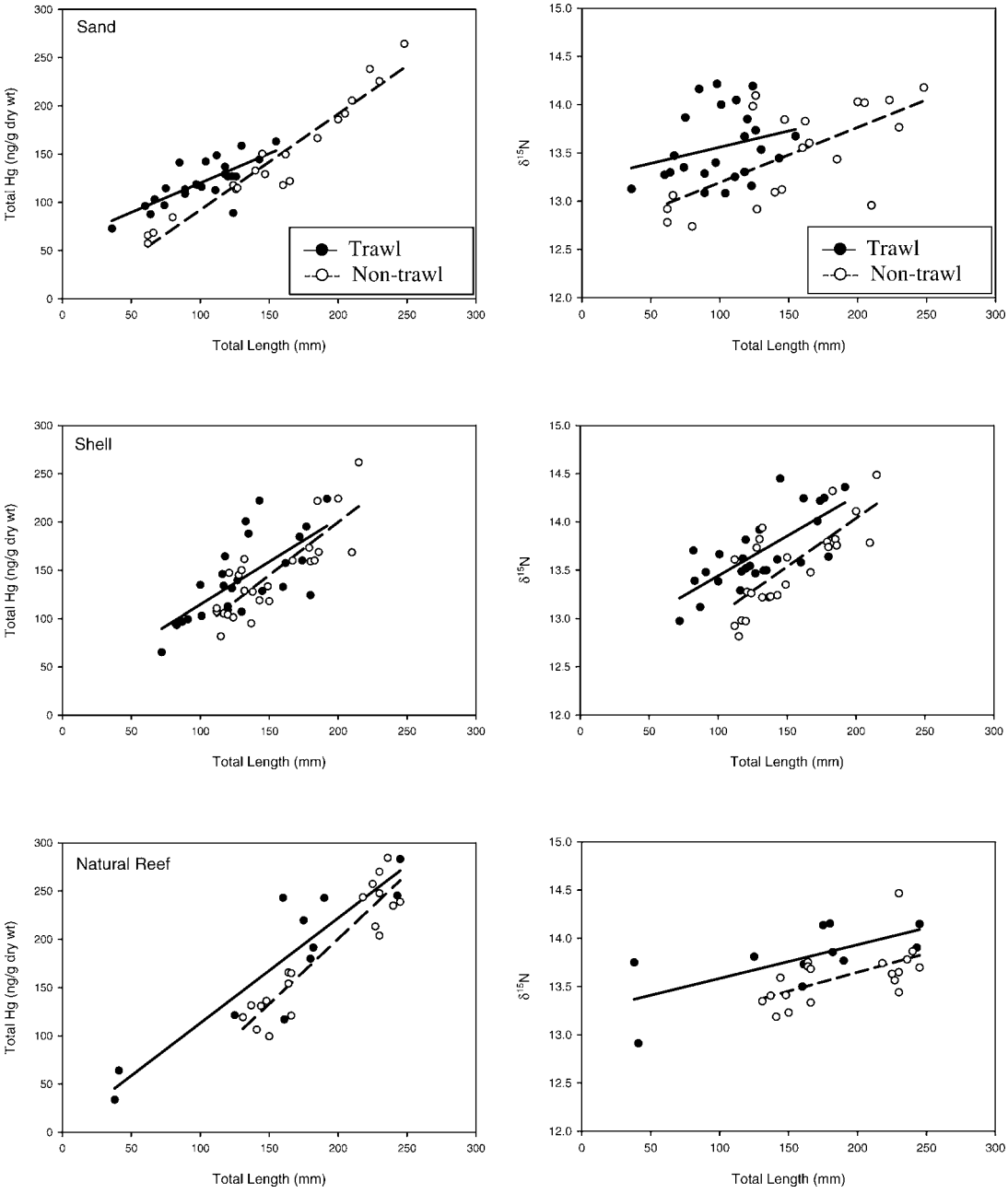

FIGURE 5.—Relationship between total mercury (Hg) concentration (ng/g of dry weight) or stable nitrogen isotope ratio ($\delta^{15}N$; ‰) and total length (mm) of juvenile red snapper collected in 2004 from the sand, shell, and natural-reef habitat types within trawled and nontrawled subregions of the northern Gulf of Mexico continental shelf.

from trawled habitats. The enriched $\delta^{15}N$ in fish from trawled areas may be attributed to an increase in the opportunity for red snapper to prey upon benthic organisms that have been injured or killed by trawling. Kenchington et al. (2005) found that changes in the diets of demersal fishes were caused by prey availability alterations brought about by trawling disturbances. It was demonstrated that large fish predators rapidly moved into recently trawled areas to feed and take advantage of the increase in foraging opportunities (Wassenberg and Hill 1987; Kaiser and Spencer 1994). In the GOM, a similar phenomenon

was observed wherein bottlenose dolphins *Tursiops truncates* preyed on fishes that were exiting trawl openings (University of Georgia Marine Extension Service and NMFS Harvesting Branch 2003). To test the hypothesis that elevated Hg concentrations in fish from trawled areas were related to trophic position, we used Baron and Kenny's (1986) approach for identifying mediator variables. We found that $\delta^{15}N$ values did not have a significant effect on Hg concentrations, which indicates that enhanced $\delta^{15}N$ in trawled areas was not responsible for the elevated Hg concentrations in fish from these areas. Therefore, we hypothesize that differences in MeHg bioavailability between trawled and nontrawled subregions were responsible for differences in Hg concentrations.

A key assumption of our interpretation of red snapper $\delta^{15}N$ values is that the $\delta^{15}N$ values near the base of the food web for a given habitat type are similar between trawled and nontrawled subregions. Our contention that an increase in $\delta^{15}N$ values represents an increase in juvenile red snapper trophic position and our hypothesis that red snapper diet shifted in trawled areas are supported by gut content data (Wells et al. 2008b). Wells et al. (2008b) found that juvenile red snapper in trawled areas had higher percentages of fish and mysid shrimp in their guts than did red snapper captured from nontrawled areas. More studies are needed to determine (1) how red snapper trophic position is affected by trawling and (2) the relative contributions of an increase in trophic position and sediment disturbance to elevated Hg concentrations in juvenile red snapper.

We interpret our results to mean that the presence of commercial shrimp trawling was the primary factor responsible for differences in red snapper Hg concentrations and $\delta^{15}N$ values between trawled and nontrawled subregions for a given habitat type. Factors other than trawling and habitat type, such as depth differences among study sites, may have affected our results. However, this is unlikely because although Hg concentrations and $\delta^{15}N$ values were consistently higher for samples from the trawled subregion, depth differences between trawled and nontrawled habitat types were not consistent. The depth of sand habitat was greater in the trawled subregion than in the nontrawled subregion, but the depths of shell and reef habitats were greater in the nontrawled subregion than in the trawled subregion. Moreover, mean depth differences between trawled and nontrawled subregions for a given habitat type were minimal (range of means = 5–8 m).

Habitat-specific differences in Hg concentrations of juvenile red snapper were size dependent and generally weak. The lack of a strong habitat-specific pattern in red snapper Hg concentrations is surprising, because

TABLE 2.—Least-squares means (±SE) of total mercury (Hg) concentration (ng/g dry weight) and stable nitrogen isotope ratio ($\delta^{15}N$; ‰) in juvenile red snapper collected from sand, shell, and reef habitat types within trawled and nontrawled subregions of the northern Gulf of Mexico continental shelf in 2004 (significant post hoc differences: $^*P < 0.05$).

Habitat type	Subregion	*n*	Hg	$\delta^{15}N$
Sand	Trawled	24	148.2 ± 8.7	13.7 ± 0.1
Sand	Nontrawled	20	137.7 ± 5.4	13.5 ± 0.1
Shell	Trawled	26	162.5 ± 5.1*	13.8 ± 0.1*
Shell	Nontrawled	25	137.2 ± 4.9*	13.5 ± 0.1*
Natural reef	Trawled	11	141.9 ± 8.4	13.8 ± 0.1
Natural reef	Nontrawled	19	121.7 ± 8.2	13.4 ± 0.1

MeHg production in marine ecosystems is a function of sediment characteristics like grain size and organic carbon content (Mason and Lawrence 1999; Hammerschmidt and Fitzgerald 2004, 2006; Hung and Chmura 2006). Seabed characterization of our study sites identified differences in grain size, organic carbon content, and carbonate content among sand, shell, and reef habitats (Dufrene 2005); all of these factors could affect MeHg production. Despite differences in sediment characteristics, we found no consistent differences in red snapper Hg concentrations among habitats. However, caution should be used in generalizing our results to other nearshore marine habitats. Due to limited replication in this study, we do not know whether the habitat effect on Hg concentrations in juvenile red snapper is absent throughout the GOM or only absent at the sites we examined.

Results from this study suggest that the presence of commercial shrimp trawling does not increase juvenile red snapper Hg concentrations to levels that would cause a public health concern; this finding is not surprising considering the small size of fish examined in this study. However, our study demonstrates that Hg concentrations are elevated in juvenile red snapper from northern GOM continental shelf areas where commercial shrimp trawling occurs. Given the intense fishing effort throughout the northern GOM shelf and the ability of Hg to bioaccumulate and biomagnify, more research focusing on Hg dynamics of recreationally and commercially important species is needed.

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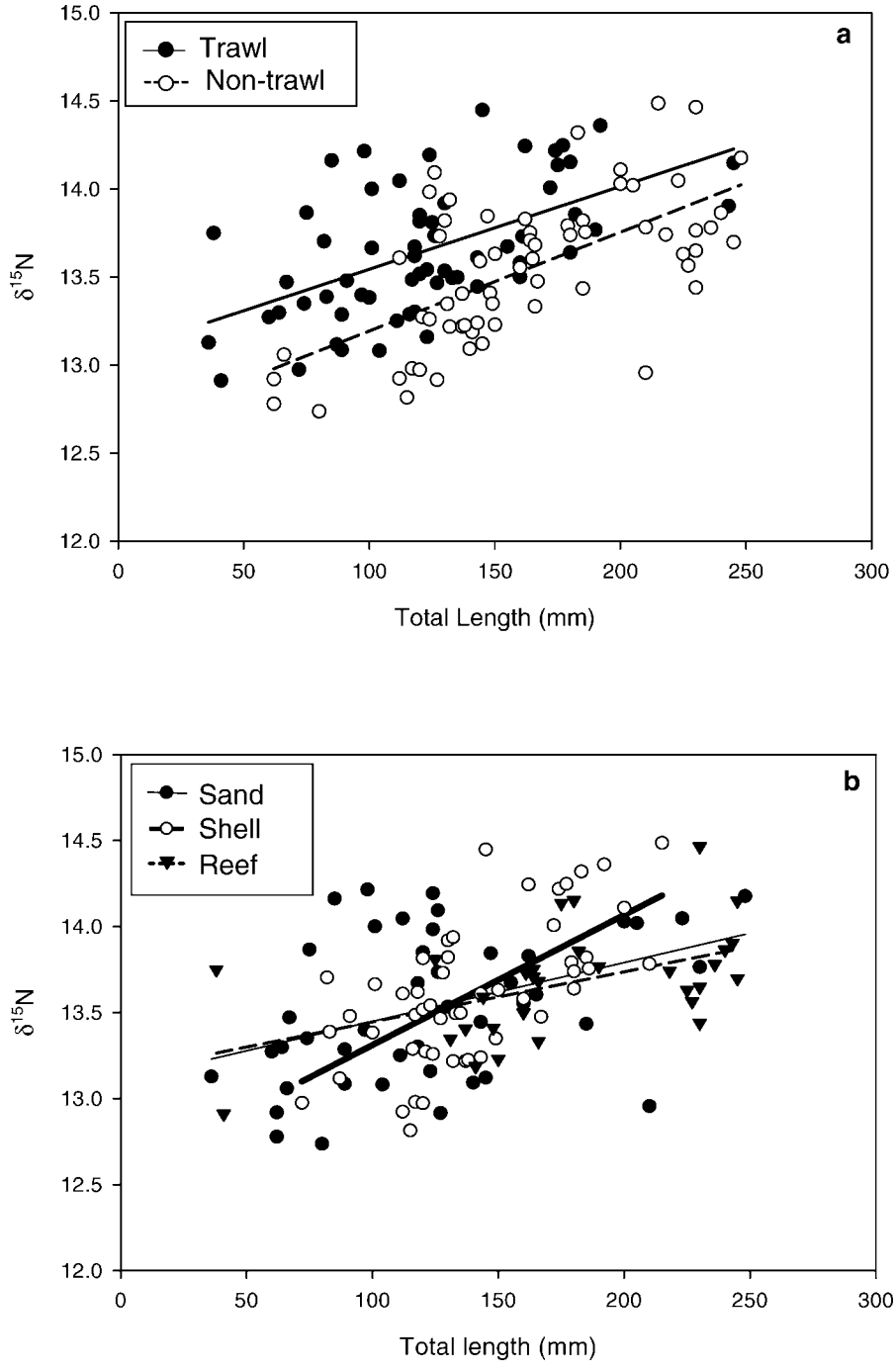

FIGURE 6.—Relationship between stable nitrogen isotope ratio ($\delta^{15}N$; ‰) and total length (mm) of juvenile red snapper collected in 2004 from **(a)** trawled and nontrawled subregions and **(b)** sand, shell, and natural-reef habitat types of the northern Gulf of Mexico continental shelf.

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