

**Abstract**—We examined the effect of habitat and shrimp trawl bycatch on the density, size, growth, and mortality of inshore lizardfish (*Synodus foetens*), a nonexploited species that is among the most widespread and abundant benthic fishes in the north central Gulf of Mexico. Results of quarterly trawl sampling conducted from spring 2004 through spring 2005 revealed that inshore lizardfish are most abundant on sand habitat, but larger fish are more common on shell rubble habitat. There was no significant difference in fish density between habitats exposed to shrimp trawling on the open shelf versus those habitats within a permitted artificial reef zone that served as a *de facto* no-trawl area; this finding indicates that either inshore lizardfish experienced minimal effects from trawling or, more likely, that fish moved between trawled and non-trawled habitats. Exploitation ratio (bycatch mortality/total mortality) estimates derived from catch curve analysis ranged from 0.43 inside the artificial reef zone to 0.55 outside the reef zone, thus indicating that inshore lizardfish are subject to significant fishing mortality in the north central Gulf of Mexico despite the lack of a directed fishery for the species. We infer from this result that effects of shrimp trawl bycatch may be significant at the population level for nonexploited species and that a broader ecosystem-scale examination of bycatch effects is warranted.

Manuscript submitted 7 November 2007.  
Manuscript accepted 23 June 2008.  
Fish. Bull. 106:417–426 (2008),

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## Habitat and bycatch effects on population parameters of inshore lizardfish (*Synodus foetens*) in the north central Gulf of Mexico

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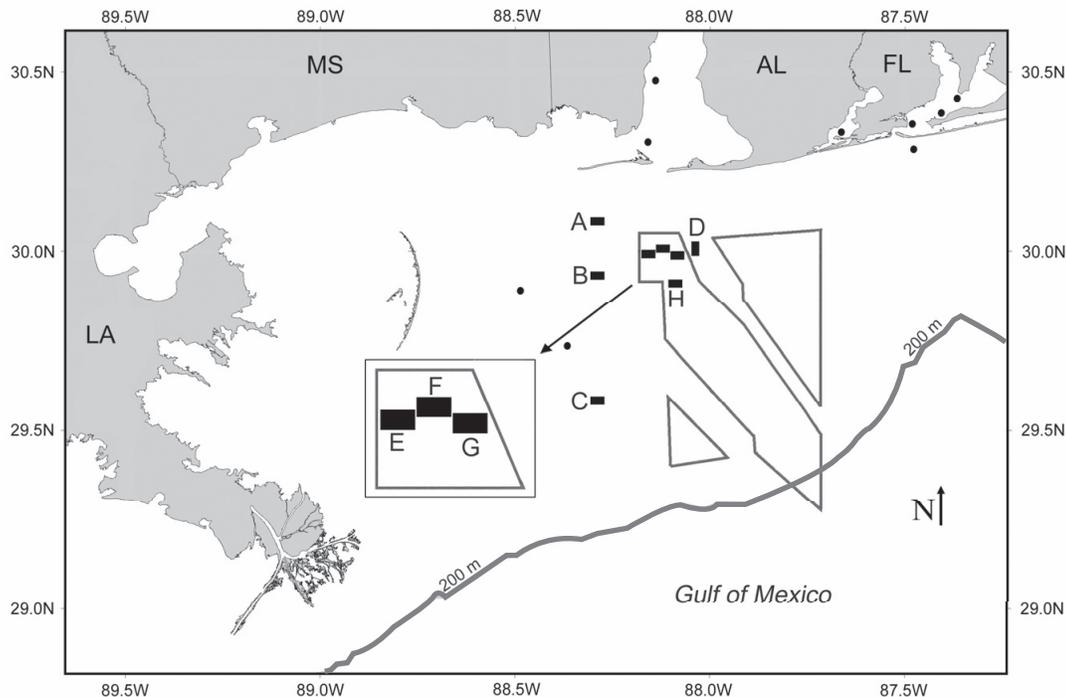
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Habitat degradation and bycatch of adult or younger life-stage individuals of nontargeted species are among the greatest ecosystem effects of fishing (Hall et al., 2000; Pauly et al., 2002, 2003; Thrush and Dayton, 2002). In fact, bycatch of nontargeted species or life stages may pose an even greater threat to marine ecosystem health than direct the harvest of targeted species (Crowder and Murawski, 1998; Baum et al., 2003; Harrington et al., 2005). Therefore, biologists, conservation groups, and fisheries agencies have called for a transition away from single species management to a more holistic ecosystem-based fisheries management (EBFM) approach (Zabel et al., 2003; Francis et al., 2007; Marasco et al., 2007). A single-species approach traditionally has been applied to estimate maximum sustainable yield (MSY) and to subsequently set total allowable catch (TAC) for most fisheries, but that approach does not account for or mitigate against direct and indirect ecosystem effects of fishing.

The shortcomings of single species management are evident when considering management of the penaeid shrimp trawl fishery in the northern Gulf of Mexico (GOM). That fishery has operated near its estimated MSY since the 1950s, averaging approximately  $130 \times 10^6$  lbs/yr in total land-

ings of brown (*Farfantepenaeus aztecus*), white (*Litopenaeus setiferus*), and pink (*Farfantepenaeus duorarum*) shrimps, but greater than  $1 \times 10^9$  lbs/yr of bycatch have also been associated with those landings (Diamond, 2004; Ortiz et al., 2000; Strelcheck and Hood, 2007). Although that level of bycatch is clearly substantial, its effects on fishes at the population level have been studied for only a few commercially important fishes (Diamond et al., 2000; Porch, 2007). Perhaps a more comprehensive approach would be to analyze the effects of bycatch on the community (e.g., Wells, 2007), as well as to examine species-specific effects for nonexploited but ecologically important fishes.

Inshore lizardfish (*Synodus foetens*) is an ideal model species for examining the effects of shrimp trawl bycatch on the population demographics and dynamics of an ecologically but not commercially important species. Inshore lizardfish are ubiquitous on the northern GOM shelf and are among the ten most frequently encountered benthic fishes in trawl samples there (Wells, 2007). The ecological importance of inshore lizardfish has been assumed to be significant given their abundance on the shelf and carnivorous habits (Garcia-Abad et al., 1999); however, relatively little is known about their population ecology in the



**Figure 1**

Map of areas sampled for inshore lizardfish (*Synodus foetens*) in the northern Gulf of Mexico from spring 2004 through spring 2005. Large polygons on the shelf indicate artificial reef zones. Habitats inside the artificial reef zones served as *de facto* no trawl areas. Habitats A and F are predominantly sand; habitats B and E are low relief (1–2 m) shell rubble; habitats C and G are high relief (2–3 m) shell habitat; and habitats D and H are reef habitats. Filled circles indicate sites where inshore lizardfish were sampled opportunistically for otolith marginal condition and age analyses. The 200-m isobath is shown to indicate the shelf edge.

northern GOM. As part of a broader study examining the effects of habitat type and shrimp trawl bycatch on demersal and benthic fishes in the north central GOM, the objectives of the work presented here were to examine inshore lizardfish life history and ecology and to estimate potential impacts of shrimp trawl bycatch on them. Specifically, we estimated the effect of habitat type and shrimp trawl bycatch on inshore lizardfish density, size, age, and mortality in various habitats on the north central GOM continental shelf.

### Materials and methods

Inshore lizardfish were sampled within four habitat types in the north central GOM: sand, low-relief shell rubble (low shell), high-relief shell rubble (high shell), and reef. Habitats were mapped with sidescan sonar and groundtruthed with boxcores and benthic grab samplers during previous studies (Schroeder et al., 1988; Dufrene, 2005; Strelcheck et al., 2005). Dufrene (2005) characterized shell rubble habitats as ridges standing 1–m (low-relief) or 2–3 m (high-relief) above the surrounding seabed and extending up to 200 m across. Boxcore sediment samples revealed that ridges are composed of

>50% calcium carbonate ( $\text{CaCO}_3$ ), and shell fragments from both marine and estuarine taxa, the latter of which come from lower sea levels that date from the Holocene Epoch. Reef sites were characterized by Schroeder et al. (1988) as reef-like outcrops of rock rubble and shell hash supporting a diverse epifaunal assemblage. Each of the four study habitat types was found on both the open shelf and within an artificial reef zone (AR zone) off Alabama (Fig. 1). Shrimp trawling is prevalent on the open shelf, but the AR zone functions as a *de facto* no trawl area (NRC, 2002, Fig. B.9 in that report). Therefore, by sampling inside and outside the AR zone the effect of shrimp trawl bycatch on inshore lizardfish population parameters could be tested.

Inshore lizardfish were sampled quarterly from May 2004 to April 2005 in the habitats described above using a bottom trawl rigged and fished according to the Southeastern Monitoring and Assessment Program's (SEAMAP) trawling protocol, except that trawl samples were not taken during winter and spring 2005 in the high shell habitat outside the AR zone because of weather constraints. The sampling gear was a 12.8-m, four-seam semiballoon otter trawl rigged with 2.4-m  $\times$  1-m doors, a 54.9-m bridle, a tickler chain set 1.1 m shorter than the footrope, and a codend with 4-cm

mesh. The sole deviation from SEAMAP protocol was the inclusion of a 0.7-cm mesh bag within the codend to retain small fish. Three replicate tows were made in each habitat type inside and outside the AR zone during quarterly sampling. Before trawl sampling, a hydrographic cast was made at each station with a Seabird 19plus CTD (Sea-Bird Electronics Inc., Bellevue, WA) to measure temperature, salinity, and dissolved oxygen. Then, trawling was conducted at 4.6 km/h for approximately 10 minutes. Up to ten fish were randomly sampled from each trawl sample and immediately frozen in ziploc bags and brought to the laboratory for processing. Individuals were thawed, weighed to the 0.1 g, measured to the nearest mm total length (TL), and their sex was determined by macroscopic examination of gonads. Both sagittal otoliths were then extracted for age analysis as detailed below.

Additional fish were opportunistically sampled with trawls approximately monthly from the north central GOM (Fig. 1). In the laboratory, sampled individuals were measured, weighed, and their sex determined as above. Their sagittae then were extracted and stored. The purpose of opportunistic collections was to provide monthly samples to identify the timing of otolith opaque zone formation by means of marginal condition analysis, but those samples were also included in age and growth analyses.

Inshore lizardfish density was estimated as the number of individuals caught divided by the area swept by the trawl. Trawl width under tow was estimated as 0.8 × 12.8 m, which was based on National Marine Fisheries Service (NMFS) unpublished data of towing conditions for their standard trawl survey gear. Distance towed was estimated with GPS coordinates recorded while the trawl was on the seafloor. Analysis of variance (ANOVA; 5 × 4 × 2 factorial design) allowed us to test sampling quarter, habitat, and exposure to trawling effects, as well as their interactions, on inshore lizardfish density and size. All statistical analyses were computed with SAS (SAS Institute Inc., Cary, NC). Density values were transformed by taking the natural log of (*density* + 1) and size was log-transformed to meet parametric assumptions of normality and heteroscedasticity. Analysis of variance test statistics (*F*-tests) were computed for both density and fish size with type-III sums of squares despite the two missing cells (i.e., no high shell data outside the AR zone for either winter or spring 2005) in the factorial design noted above. However, additional ANOVAs were also computed after removing all high shell habitat data to confirm results from the unbalanced models computed with the full data set.

One sagitta from each fish was used to determine age. Otoliths were set in epoxy and a 0.5-mm transverse section including the core was cut with a Buehler (Buehler Ltd., Lake Bluff, IL) Isomet saw fitted with a diamond blade. Each section was mounted on a glass slide with thermoplastic cement, sanded with 3200 grit wet-or-dry sand paper, and polished with an alumina powder slurry on a felt polishing cloth. Marginal condition analysis

was performed to verify that opaque zones formed annually in adults (Beckman et al., 1990). Opaque zones were then counted to determine age. Otolith thin sections were read with a compound microscope with both reflected and transmitted light. Two different readers counted opaque zones in each sample; readers counted opaque zones independently without knowledge of fish size or the other reader's age estimate to ensure that no bias occurred during process. If counts for a given otolith differed, the otolith was read a second time by both readers. Average percent error (APE) was computed to assess precision between readers (Campana, 2001). Length-at-age was plotted and then least-squares fits of the nonlinear von Bertalanffy growth curve were computed to estimate inshore lizardfish growth for males, females, and both sexes jointly:

$$L_t = L_\infty (1 - e^{-K(t-t_0)}), \quad (1)$$

where  $L_t$  = estimated length at age  $t$ ;  
 $L_\infty$  = asymptotic length;  
 $K$  = growth coefficient;  
 $t$  = age in years; and  
 $t_0$  = hypothetical age at zero length.

A likelihood ratio test was computed to test whether sex-specific growth functions were significantly different from one another (Kimura, 1980).

Three independent estimates of natural mortality ( $M$ ) were computed based on maximum observed longevity according to the methods of Royce (1972), Hoenig (1983), and Pauly (1980):

$$M = 4.6/(t_{max}) \text{ (Royce, 1972),} \quad (2)$$

$$\ln(M) = 1.44 - 0.982 \ln(t_{max}) \text{ (Hoenig, 1983),} \quad (3)$$

$$\ln(M) = -0.0152 - 0.279 \ln(L_\infty) + 0.6543 \ln(K) + 0.463 \ln(T) \text{ (Pauly, 1980),} \quad (4)$$

where  $M$  = natural mortality/yr;  
 $t_{max}$  = the oldest aged fish in sample; and  
 $T$  = mean temperature °C.

Total instantaneous annual mortality ( $Z$ ) was estimated with catch curve analysis (Ricker, 1975). Bycatch mortality ( $F_b$ ) was computed by subtraction:

$$F_b = Z - M \quad (5)$$

where  $F_b$  = instantaneous annual fishing (bycatch) mortality;  
 $Z$  = instantaneous annual total mortality; and  
 $M$  = instantaneous annual natural mortality.

The difference in total mortality between habitats exposed to trawling versus nontrawled habitats was tested with analysis of covariance (ANCOVA) test for equal slopes. Exploitation ratio ( $E$ ) was estimated as the ratio of  $F_b/Z$  (Ricker, 1975).

**Table 1**

Mean environmental parameters measured in habitats sampled for inshore lizardfish, *Synodus foetens*, in the northern Gulf of Mexico during 2004 and 2005 sampling. Habitat C (high relief shell rubble outside the artificial reef zone) was not sampled in winter or spring 2005. Descriptions and locations of habitat types are provided in Figure 1.

Quarter	Sampling dates	Habitat	Depth (m)	Temperature (°C)	Salinity (psu)	Dissolved oxygen (mg/L)
Spring 2004	16 May 04	A	17.3	22.2	34.2	7.0
	16 May 04	B	30.3	19.9	35.2	6.5
	19 May 04	C	39.6	19.5	35.7	6.3
	18 May 04	D	19.0	24.4	34.6	6.9
	17 May 04	E	29.0	20.6	35.2	7.3
	18 May 04	F	27.3	20.7	35.1	7.1
	18 May 04	G	24.0	21.1	35.0	7.5
	17 May 04	H	28.0	20.6	35.2	7.3
Summer 2004	3 Aug 04	A	18.0	23.5	36.0	3.3
	3 Aug 04	B	30.6	22.9	36.4	4.2
	4 Aug 04	C	37.2	20.7	36.4	5.0
	5 Aug 04	D	19.8	24.0	36.0	4.6
	4 Aug 04	E	28.8	22.6	36.1	3.4
	4 Aug 04	F	28.0	22.9	36.1	3.6
	5-Aug 04	G	23.0	22.3	36.2	1.8
	4 Aug 04	H	30.7	22.5	36.1	2.9
Fall 2004	29 Oct 04	A	17.7	26.0	35.5	3.9
	27 Oct 04	B	30.7	23.1	36.3	4.9
	26 Oct 04	C	37.4	28.1	36.2	5.8
	28 Oct 04	D	18.3	26.0	35.3	5.4
	27 Oct 04	E	28.8	27.0	36.3	5.7
	28 Oct 04	F	26.5	26.7	36.3	5.2
	28 Oct 04	G	27.5	25.8	35.8	4.7
	27 Oct 04	H	29.0	26.5	36.3	5.2
Winter 2005	27 Jan 05	A	18.0	20.1	35.6	5.9
	25 Jan 05	B	30.8	20.1	35.6	5.9
	26 Jan 05	D	19.0	18.1	34.5	6.7
	25 Jan 05	E	29.0	20.6	35.7	5.9
	26 Jan 05	F	26.5	20.8	35.7	5.9
	26 Jan 05	G	23.5	19.3	35.2	6.4
	25 Jan 05	H	31.5	19.8	35.5	6.3
	Spring 2005	27 Apr 05	A	18.0	20.2	36.3
27 Apr 05		B	31.0	20.2	36.3	3.7
28 Apr 05		D	18.6	20.3	35.5	3.9
28 Apr 05		E	29.5	20.5	36.0	4.0
27 Apr 05		F	27.0	20.2	36.3	3.7
28 Apr 05		G	24.0	20.4	35.9	3.6
28 Apr 05		H	31.0	20.6	36.0	4.1

## Results

All habitat types were sampled each quarter, with the exception noted above that high shell habitat outside the artificial reef zone was not sampled during winter and spring 2005. Hydrographic parameters generally were consistent among sampled habitats within sampling quarters. Water depth of trawl samples ranged from a mean of 18 m for sand habitat outside the AR zone to

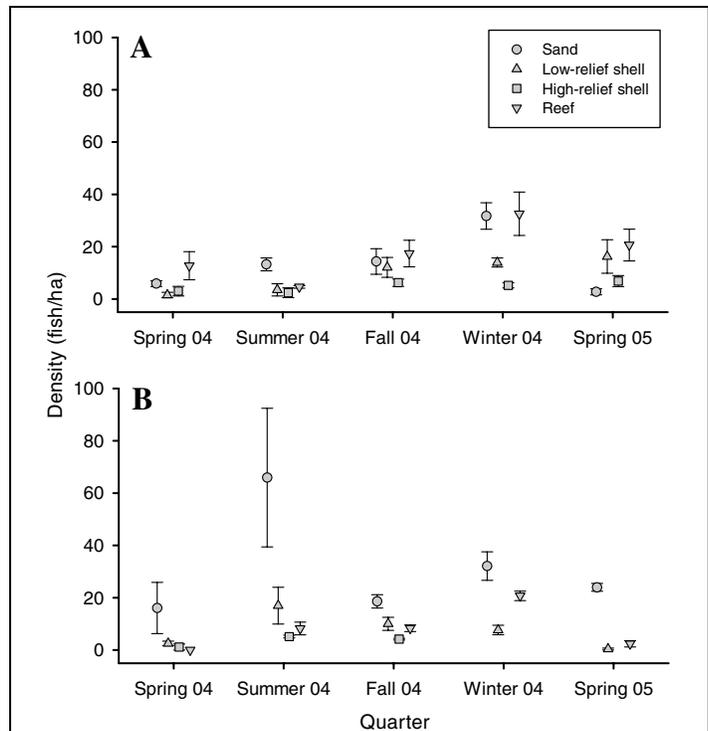
38 m for high shell habitat outside the AR zone (Table 1). Temperature ranged from 19° to 26°C among quarters (mean=22.1°C), and salinity ranged between 35 and 36 psu. Dissolved oxygen fluctuated by season and was lowest during summer months.

A total of 1239 inshore lizardfish were caught in trawl samples in study habitats; 749 of those fish were randomly sampled and brought to the laboratory for further analysis. An additional 221 fish were sampled

opportunistically in various locations to enhance sample sizes and the temporal coverage for otolith marginal condition analysis and aging (Fig 1). Within study habitats, inshore lizardfish appeared in 91% of all trawl samples. Fish density was significantly different among sampling quarters and habitats (ANOVA,  $P < 0.001$  for both), but not between trawled and untrawled habitats (ANOVA,  $P = 0.2754$ ; Fig. 2). However, interpretation of the main effects on density is complicated because of significant first-order interactions between sampling quarter and trawl effects (ANOVA,  $P < 0.001$ ) and habitat and trawling effects (ANOVA,  $P < 0.001$ ); there was no difference in significance for main effects or interactions between tests computed with or without the high shell habitat data. Inshore lizardfish were more abundant in sand habitat (mean density  $\pm$  standard error [SE]=22.5 [ $\pm 4.0$ ] fish/ha) than in the other three habitats (mean density  $< 13$  fish/ha), but the level of difference was driven by two sand habitat samples taken outside the AR zone in summer 2004 that yielded the highest estimated densities (105 and 65 fish/ha, respectively). Among study habitats not exposed to trawling, inshore lizardfish densities were similarly high for sand and high shell habitats (Fig. 2A).

Inshore lizardfish caught during quarterly sampling ranged in TL from 49–404 mm (Fig. 3A), whereas opportunistically sampled fish ranged in TL from 76 to 472 mm (Fig. 3B). Fish length was significantly different among sampling quarters (ANOVA,  $P < 0.001$ ), habitats (ANOVA,  $P < 0.001$ ), and levels of the trawling effect (ANOVA,  $P = 0.006$ ; Fig. 3). However, interactions between sampling quarter and habitat (ANOVA,  $P < 0.001$ ) and habitat and the trawl effect (ANOVA,  $P < 0.001$ ) complicated interpretation of the main effects; there was no difference in significance for the main effects, or their interactions on fish size between tests computed with and without the high shell habitat data. Overall, mean ( $\pm$ SE) fish size was smaller in habitats exposed to trawling (230.7 [ $\pm 3.2$ ] mm TL) than in habitats sampled within the AR zone (242.9 [ $\pm 2.2$ ] mm TL). However, high shell habitat outside the AR zone sampled in spring 2004 had the largest mean ( $\pm$ SE) size (320.0 [ $\pm 44.4$ ] mm TL) among all factor level combinations, although only three fish were captured in that habitat in spring 2004. Fish size was smallest (mean TL  $\pm$ SE=204.7 [ $\pm 4.6$ ] mm) during summer 2004 among all habitats. That trend was most pronounced in sand habitat both inside and outside the AR zone where high densities (Fig. 2) of mostly small fish (Fig. 4) were encountered.

Of the 970 otoliths prepared for age estimation (749 from quarterly sampling and 221 opportunistically sampled), age could be determined for 967. Marginal condition analysis demonstrated that otolith opaque zones generally began forming in November and continued to do so until February (Fig. 5). All samples were at least one year of age. The oldest fish sampled was a 424-mm-



**Figure 2**

Mean ( $\pm$ standard error) density (fish/ha) of inshore lizardfish (*Synodus foetens*) sampled from spring 2004 through spring 2005 in study habitats in the northern Gulf of Mexico for (A) areas inside the artificial reef zone that were not subjected to trawling and (B) areas outside the artificial reef zone that were subjected to trawling.

TL 9-year-old female that was sampled in June 2006 onboard during the SEAMAP trawl survey. Of the fish sampled within study areas, the oldest was 8 years and nearly half of all fish were 3-year-olds. Reader agreement was judged to be good with an APE of 5.94%.

Von Bertalanffy growth functions were not significantly different between sexes (likelihood ratio  $\chi^2$ -test,  $P = 0.998$ ); thus size-at-age data were modeled jointly between sexes. The resultant growth equation was  $L_t = 290.8(1 - e^{-0.486(t-0.204)})$  (nonlinear regression,  $P < 0.001$ ;  $r^2$  (coefficient of determination? If so, lower-case)=0.22) (Fig. 6). Estimates of  $M$  based on an observed  $t_{max}$  of 9 yr were 0.51/yr, 0.49/yr, and 0.53/yr from the methods of Royce (1972), Hoenig (1983), and Pauly (1980), respectively. Before conducting catch curve analysis, the age distribution of the aged fish ( $n = 749$ ) sampled in our study habitats was expanded to the samples collected that were not aged ( $n = 490$ ). This was accomplished by computing habitat- and sampling quarter-specific age distributions and by assigning age by means of a random number table for fish collected that were not aged. Then, catch curve analysis was computed for ages 3 yr and older because those were the fully recruited ages (Fig. 7). Total mortality of inshore lizardfish sampled within the AR zone was  $Z = 0.93/y$

(linear regression,  $P < 0.001$ ,  $r^2 = 0.993$ ); estimated total mortality outside the AR zone was  $Z = 1.10/\text{yr}$  (linear regression,  $P < 0.001$ ,  $r^2 = 0.971$ ). Therefore, fish outside the AR zone were exposed to higher  $Z$  than those inside, but the slopes were not significantly different between the two catch curves (ANCOVA test for equal slopes,  $P = 0.232$ ). By subtraction,  $F_b$  estimates ranged from 0.40 to 0.44/y inside the AR zone and 0.57 to 0.61/y outside the AR zone. Resultant  $E$  estimates ranged from 0.43 to 0.47 for fish sampled inside the AR zone and 0.52 to 0.55 for fish outside the AR zone.

## Discussion

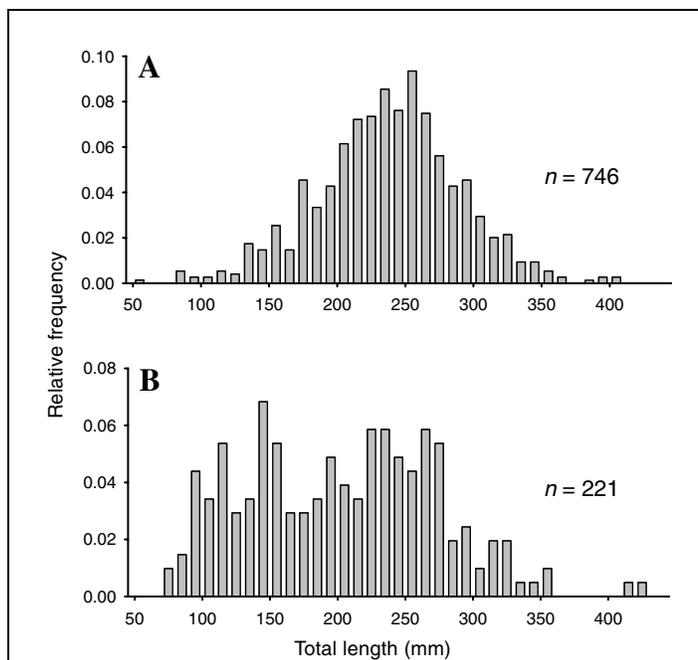
Inshore lizardfish were nearly ubiquitous throughout study areas. Fish abundance was greater in summer, especially for smaller individuals, possibly indicating that recruitment to study habitats from estuarine and inshore habitats occurred in summer. Small inshore lizardfish begin recruiting from estuaries to Campeche Bay in the southern GOM in June and continued to do so until October (Garcia-Abad et al., 1999). A similar pattern was observed in the present study where both size and inshore lizardfish age were lowest in summer. Overall, catch-at-age data indicated that inshore lizardfish did not fully recruit to the study sites until age three, but the mean age of fish sampled in summer was

slightly less than 3 yr. Fish size, as well as age, was greatest in high shell habitat, but density was lowest there. Cruz-Escalona et al. (2005) reported that adult inshore lizardfish in the southern GOM preferred sand habitat, and our data indicated a similar trend in the northern GOM. However, smaller fish may avoid more complex habitats, such as shell rubble ridges, because of the presence of predators or increased competition for food.

Fish were larger, on average, inside the AR zone, but fish density was not significantly different inside and outside the AR zone, which may have resulted from the movement of inshore lizardfish among trawled and untrawled habitats. No direct observations of inshore lizardfish movement were made in this study, but individuals are known to move 10s of km as they recruit to adult habitats on the shelf from inshore estuarine nursery habitats (Cruz-Escalona et al., 2005). Other lizardfishes also move significant (10s to 100s of km) distances (Sweatman, 1984; Golani, 1993). Furthermore, experimental closure of areas to bottom trawling in Australia's northern prawn fishery did not yield significant differences in lizardfish density between areas open to trawling and those closed to trawling because fish moved into trawled areas after trawling occurred, thus restoring high densities there (Stobutzki et al., 2003). Therefore, the lack of differences observed in inshore lizardfish density in areas exposed to trawling and those not exposed to trawling during the present study may have resulted from fish moving between trawled and untrawled areas.

Marginal conditional analysis confirmed that the timing of opaque zone formation in inshore lizardfish otoliths is similar to a range of demersal (e.g., black drum [*Pogonias cromis*] and red snapper [*Lutjanus campechanus*] and benthic (e.g., southern flounder [*Paralichthys lethostigma*]) fishes in the northern GOM (Beckman et al., 1990; Patterson et al., 2001; Fischer and Thompson, 2004) and that annual opaque zones are laid down from November to February. Based on counts of annuli, the maximum longevity observed for inshore lizardfish (9 years) was similar to the maximum longevity reported for other synodontid species. For example, Yoneda et al. (2002) reported that a *Saurida* species from the East China Sea lived to 11 years and Thresher et al. (1986) aged a *Saurida* species from the northwestern Australian shelf to be 7 years.

The low regression coefficient ( $r^2 = 0.22$ ) of the von Bertalanffy growth function computed with size-at-age data reflects the substantial variability in inshore lizardfish size-at-age. Hood and Johnson (1999) reported vermilion snapper (*Rhomboplites aurorubens*) displayed similar variability in size-at-age in the GOM. They indicated vermilion snapper were difficult to age, but their high reader agreement indicated that the observed variability in size-at-age was not an artifact of inaccurate aging. Similarly, we infer



**Figure 3**

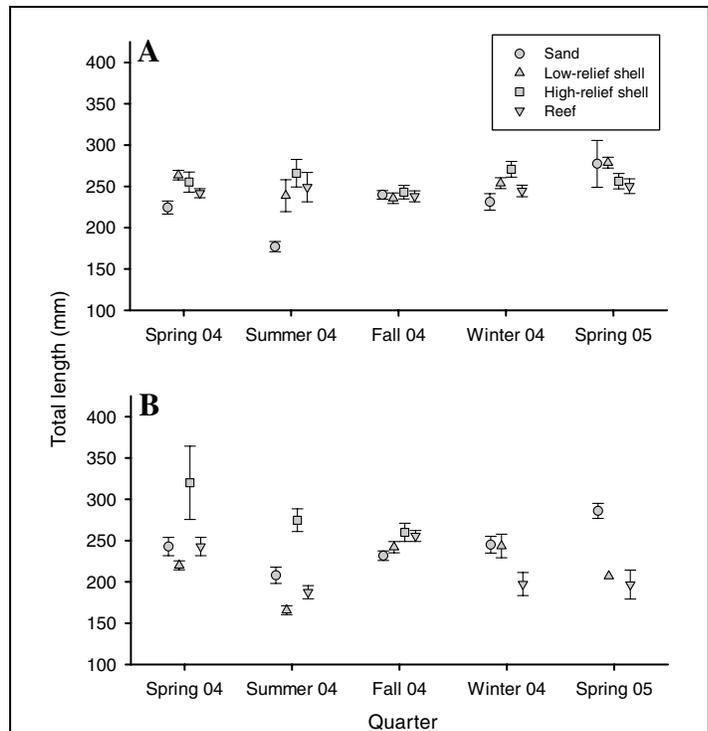
Frequency histograms of total length (mm) distributions of inshore lizardfish (*Synodus foetens*) collected within (A) study habitats and (B) for fish sampled opportunistically in the north central Gulf of Mexico during spring 2004 through spring 2005. Sample sizes ( $n$ ) are shown for each histogram.

the variability in size-at-age reported for inshore lizardfish is representative of the variability in the population given the high APE computed between reader age estimates.

Results from catch curve analysis and calculations of  $F_b$  appear to indicate that shrimp trawl bycatch mortality was substantial for inshore lizardfish. However, that interpretation depends on the assumption that the sampling gear has a logistic selectivity-at-age function for inshore lizardfish, and that there was no other source of fishing mortality beyond that of shrimp trawl bycatch. If the selectivity-at-age function was domed shaped, for example, then some of the decline in numbers of larger, older fish in our sample would have been due to older fish not being fully selected by the gear; however, our interpretation was that the observed decline, beyond that due to  $M$ , was caused by considerable bycatch mortality. Experiments could be designed to estimate the selectivity function of our sampling gear for inshore lizardfish, but no data currently exist to evaluate selectivity. However, given the small size of even the largest inshore lizardfish sampled in relation to the size of the sampling trawl, it seems reasonably safe to assume that a logistic selectivity function existed. Furthermore, it seems unlikely that other sources of fishing mortality, beyond shrimp trawl bycatch, are substantial for inshore lizardfish in the north central GOM. Inshore lizardfish are not targeted by recreational fishermen in the region and we have no knowledge of them being captured in commercial or recreational hook-and-line fisheries as bycatch.

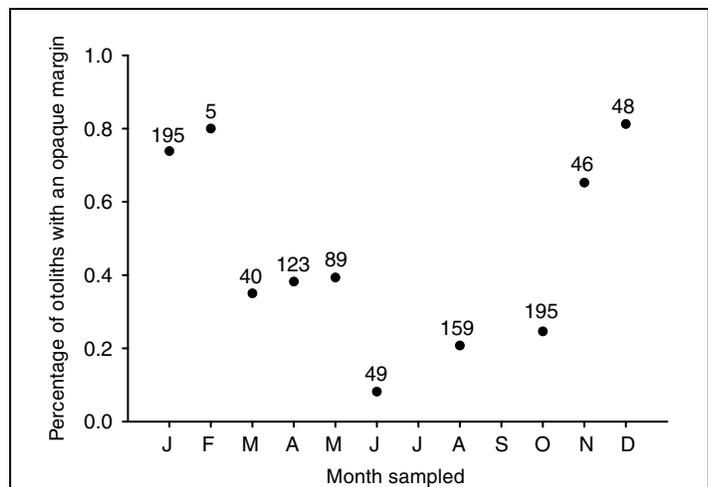
The difference in  $Z$ , hence  $F_b$ , was not statistically significant between fish sampled inside and those sampled outside the AR zone. Nonetheless, a difference of  $Z=0.17/\text{yr}$  clearly is biologically meaningful. The lack of a larger difference may indicate that either the assumption that no trawling occurs inside the reef zone was false, or that inshore lizardfish moved between habitats inside and outside the AR zone. Results of electronic tracking of shrimp trawler GPS coordinates indicate some shrimping effort may occur inside the AR zone (NRC, 2002, Fig. B.9 in that report). However, shrimping effort was shown to be orders of magnitude greater outside than inside the AR zone. Therefore, the lack of difference in  $Z$ , hence  $F_b$ , between habitats inside and outside the AR zone most likely was caused by movement of inshore lizardfish into and out of the AR zone.

Exploitation ratios computed for inshore lizardfish appear to indicate that the species is heavily fished in the northern GOM despite the lack of a directed fishery for it. A general rule of thumb is that an  $E$  approaching 0.5 indicates that a fished population is fully exploited, whereas a ratio greater than 0.5 indicates heavy fishing pressure



**Figure 4**

Mean ( $\pm$ standard error) total length (mm) of inshore lizardfish (*Synodus foetens*) sampled from spring 2004 through spring 2005 from study habitats in the northern Gulf of Mexico for (A) areas inside the artificial reef zone that were not subjected to trawling and (B) areas outside the artificial reef zone that were subjected to trawling.



**Figure 5**

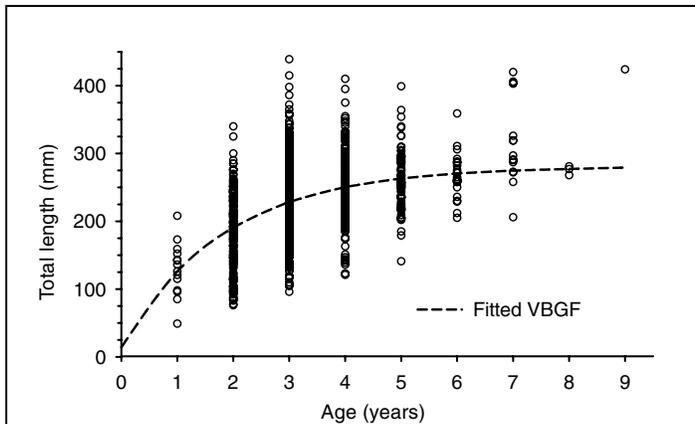
Results from marginal condition analysis of otolith transverse thin sections of inshore lizardfish (*Synodus foetens*). Data plotted indicate the mean number of otolith samples for a given month that had opaque rather than translucent margins. Monthly sample sizes are indicated on the figure.

that could lead to overexploitation (Gulland, 1977). Pauly et al. (2001) demonstrated that ecosystem effects, as measured by declines in the mean trophic level of landings, were apparent at exploitation ratios ( $E$ ) of 0.4 and were substantial at ratios of 0.6. Silvestre and Garces (2004) estimated  $E$ ,  $E_{max}$  (exploitation rate associated with maximum yield per recruit), and  $E_{0.1}$  (a biological reference point analogous to  $F_{0.1}$ ) for 25 fish populations exploited in trawl fisheries in coastal

waters of Brunei Darussalam. Fishes were similar in size to inshore lizardfish {mean  $L_{\infty}$  (standard deviation [SD])=262 mm [143]} but their  $M$  estimates were much greater (mean  $M$  [SD]=1.61/yr [0.48]). Mean (SD) estimates of  $E_{max}$  and  $E_{0.1}$  among the species were 0.54 (0.04) and 0.36 (0.03), respectively. Our estimates of  $E_b$  for inshore lizardfish approach the mean  $E_{max}$  level estimated by Silvestre and Garces (2004) and exceed their mean  $E_{0.1}$  reference point. Therefore, inshore lizardfish exploitation rates estimated in our study would indicate that the species is fully exploited despite there being no directed fishery for the species. If other non-exploited fishes have similarly high  $F_b$  rates as inshore lizardfish, then simulations conducted by Pauly et al. (2001) would indicate that substantial trophic effects of trawl bycatch may exist in the ecosystem.

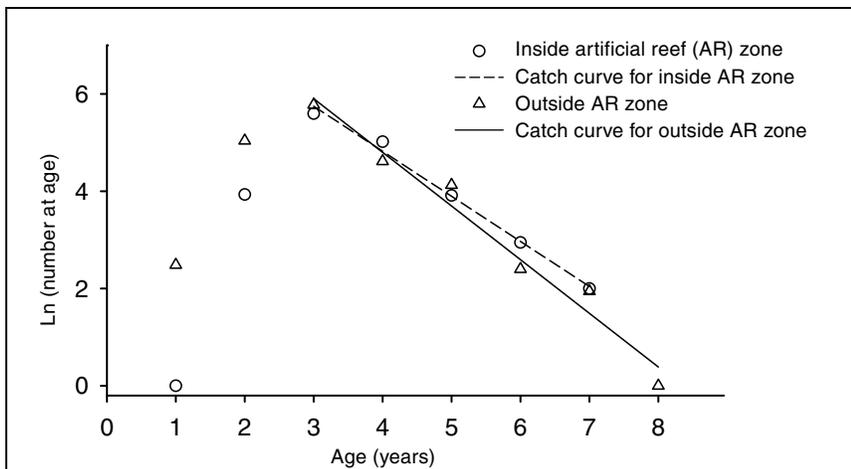
Although it is likely that demersal or benthic fishes other than inshore lizardfish have suffered similarly high  $F_b$  due to shrimp trawling in the north central GOM, the only other species that have been examined quantitatively (Atlantic croaker [*Micropogonias undulatus*] and red snapper) are also heavily exploited by directed fisheries. Bycatch rates for shrimp trawls have had significant effects on those two species at the population level (Diamond et al., 2000; Porch, 2007; Wells et al., in press), but distinguishing bycatch effects from those caused by the directed fisheries can be problematic. Furthermore, shrimp trawl fisheries have had significant effects on the ecosystem beyond that of bycatch of nontargeted species at various life stages (Thrush and Dayton, 2002; Gray et al., 2006).

In the northern GOM the investigation of bycatch has been centered around the overfished status of red snapper because of the economic importance of that species (Strelcheck and Hood, 2007). Results from this study demonstrate that nonexploited but ecologically important species, such as inshore lizardfish, may be significantly impacted by shrimp trawl bycatch. Results presented here demonstrate that effects of shrimp trawl bycatch may be significant at the population level for nonexploited species and indicate that a broader, ecosystem-scale examination of bycatch effects is needed (Diamond, 2004; Wells et al., in press). If species other than inshore lizardfish show similar direct effects on their populations, or if habitat degradation is causing indirect effects on populations and communities, a new approach to management of the shrimp fishery may be warranted.



**Figure 6**

Von Bertalanffy growth function (VBGF) fitted to size-at-age data for inshore lizardfish (*Synodus foetens*), namely all fish ( $n=967$ ) sampled from spring 2004 through spring 2005 in study habitats in the northern Gulf of Mexico, as well as those sampled opportunistically. Resultant VBGF fitted to all data:  $L_t = 290.8(1 - e^{-0.486(t-0.204)})$ , where  $L_t$  = length at age  $t$ .



**Figure 7**

Catch curves computed for inshore lizardfish (*Synodus foetens*) sampled inside (open circles,  $\circ$ ) and outside (open triangles,  $\Delta$ ) outside the artificial reef zone in the north central Gulf of Mexico from spring 2004 through spring 2005. Plotted lines are linear regressions of  $\ln(\text{number})$  versus  $\text{age}$  for the fully recruited ages: inside the artificial reef zone  $\ln(\text{catch}) = (-0.94/\text{yr})\text{age} + 8.18$ ; outside the artificial reef zone  $\ln(\text{catch}) = (-1.02/\text{yr})\text{age} + 8.31$ .

**Acknowledgments**

Funding for this project was provided by National Sea Grant (grant number NA16RG2249). We thank the National Oceanic and Atmospheric Administration-National Marine Fisheries Service Pascagoula, MS Laboratory for providing field assistance, equipment, and boat time aboard the RV *Caretta*. Field support and expertise provided by D. Hopper, K. Falana, and D. Saksa was invaluable for the success of this project. We also thank D. Wells, E. Berris, K. Boswell, M. McDonough, and M. Miller for sampling assistance and Y. Allen for preparing the study site map. An earlier draft of the manuscript was improved by comments provided by Chris Legault and two anonymous reviewers.

**Literature cited**

Baum, J. K., R. A. Myers, D. G. Kehler, B. Worm, S. J. Harley, and P. A. Doherty.  
 2003. Collapse and conservation of shark populations in the northwest Atlantic. *Science* 299:389–392.

Beckman, D. W., A. L. Stanley, J. H. Render, and C. A. Wilson.  
 1990. Age and growth of black drum in Louisiana waters of the Gulf of Mexico. *Trans. Am. Fish. Soc.* 119:537–544.

Campana, S. E.  
 2001. Accuracy, precision, and quality control in age determination, including a review of the use and abuse of age validation methods. *J. Fish Biol.* 59:197–242.

Crowder, L. B., and S. A. Murawski.  
 1998. Fisheries bycatch: Implications for management. *Fisheries* 23:8–17.

Cruz-Escalona, V. H., M. S. Peterson, L. Campos-Davilla, and M. Zetina-Regon.  
 2005. Feeding habits and trophic morphology of inshore lizardfish (*Synodus foetens*) on the central continental shelf off Veracruz, Gulf of Mexico. *J. Appl. Ichthyol.* 21:525–530.

Diamond, S. L.  
 2004. Bycatch quotas in the Gulf of Mexico shrimp trawl fishery: can they work? *Rev. Fish Biol. Fish.* 14: 207–237.

Diamond, S. L., L. G. Cowell, and L. B. Crowder.  
 2000. Population effects of shrimp trawl bycatch on Atlantic croaker. *Can. J. Fish. Aquat. Sci.* 57:2010–2021.

Dufrene, T. A.  
 2005. Geological variability and holocene sedimentary record on the northern Gulf of Mexico inner to mid-continental shelf. M.S. thesis, 100 p. Louisiana State Univ., Baton Rouge, LA.

Fischer, A. J., and B. A. Thompson.  
 2004. The age and growth of southern flounder, *Paralichthys lethostigma*, from Louisiana estuarine and offshore waters. *Bull. Mar. Sci.* 75:63–77.

Francis, R. C., M. A. Hixon, M. E. Clarke, S. A. Murawski, and S. Ralston.  
 2007. Ten commandments for ecosystem-based fisheries scientists. *Fisheries* 32:318– 233.

Garcia-Abad, M. C., P. Sanchez-Gil, and M. Tapia-Garcia.  
 1999. Distribution, abundance and reproduction of *Synodus foetens* on the continental shelf of the southern Gulf of Mexico. *Thalassas* 15:9–18.

Golani, D.  
 1993. The biology of the Red Sea migrant, *Saurida undosquamis*, in the Mediterranean and comparison with the indigenous confamilial *Synodus saurus* (Teleostei: Synodontidae). *Hydrobiologia* 271:109–117.

Gray, J. S., P. Dayton, S. Thrush, and M. J. Kaiser.  
 2006. On effects of trawling, benthos and sampling design. *Mar. Poll. Bull.* 52:840–843.

Gulland, J. A.  
 1977. Fish population dynamics, 2<sup>nd</sup> ed., 384 p. John Wiley and Sons, New York, NY.

Hall, M. A., D. L. Alverson, and K. I. Metuzals.  
 2000. By-Catch: Problems and solutions. *Mar. Poll. Bull.* 41:204–219.

Harrington, J. M., R. A. Meyers, and A. A. Rosenberg.  
 2005. Wasted fishery resources: discarded by-catch in the USA. *Fish Fish.* 6:350–361.

Hoenig, J. M.  
 1983. Empirical use of longevity data to estimate mortality rates. *Fish. Bull.* 82:898–903

Hood, P. B., and A. K. Johnson.  
 1999. Age, growth, mortality, and reproduction of vermilion snapper, *Rhomboplites aurorubens*, from the eastern Gulf of Mexico. *Fish. Bull.* 97:828–841.

Kimura, D. K.  
 1980. Likelihood methods for the von Bertalanffy growth curve. *Fish. Bull.* 77:765–776.

Marasco, R. J., D. Goodman, C. B. Grimes, P. W. Lawson, A. E. Punt, and T. J. Quinn.  
 2007. Ecosystem-based fisheries management: some practical suggestions. *Can. J. Fish. Aquat. Sci.* 64:928–939.

NRC (National Research Council).  
 2002. Effects of trawling and dredging on seafloor habitat, 136 p. National Academies Press, Washington, D.C.

Ortiz, M., C. M. Legault, and N. M. Ehrhardt.  
 2000. An alternative method for estimating bycatch from the U.S. shrimp trawl fishery in the Gulf of Mexico, 1972–1995. *Fish. Bull.* 98:583–599.

Patterson, W. F., J. H. Cowan Jr., C. A. Wilson, and R. L. Shipp.  
 2001. Age and growth of red snapper, *Lutjanus campechanus*, from an artificial reef area off Alabama in the northern Gulf of Mexico. *Fish. Bull.* 99:617–628.

Pauly, D.  
 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. *J. Cons. Int. Explor. Mer* 39:175–792.

Pauly, D., J. Alder, E. Bennett, V. Christensen, P. Tyedmers, and R. Watson.  
 2003. The future for fisheries. *Science* 302:1359–1362.

Pauly, D., V. Christensen, S. Guenette, T. J. Pitcher, U. R. Sumaila, C. J. Walters, R. Watson, and D. Zeller.  
 2002. Towards sustainability in world fisheries. *Nature* 418:689–695.

Pauly, D., M. L. Palomares, R. Froese, P. Sa-a, M. Vakily, D. Preikshot, and S. Wallace.  
 2001. Fishing down Canadian aquatic food webs. *Can. J. Fish. Aquat. Sci.* 58:51–62.

Porch, C. E.  
 2007. An assessment of the red snapper fishery in the U.S. Gulf of Mexico using a spatially-explicit age-structured model. *In* Red snapper ecology and fisheries in the U.S. Gulf of Mexico (W. F. Patterson, III, J. H.

- Cowan Jr., G. R. Fitzhugh, and D. L. Nieland, eds.), p. 325–351. Am. Fish. Soc., Bethesda, MD.
- Ricker, W. E.  
1975. Computation and interpretation of biological statistics of fish populations, 382 p. Bull. Fish. Res. Board Can. Ottawa, Canada.
- Royce, W. E.  
1972. Introduction to Fishery Science, 351 p. Academic Press, New York, NY.
- Schroeder, W. W., A. W. Shultz, and J. J. Dindo.  
1988. Inner-shelf hardbottom areas, northeastern Gulf of Mexico. Trans. Gulf Coast Assoc. Geol. Soc. 38:535–541.
- Silvestre, G. T., and L. R. Garces.  
2004. Population parameters and exploitation rate of demersal fishes in Brunei Darussalam (1989–1990). Fish. Res. 69:73–90.
- Stobutzki, I., P. Jones, and M. Miller.  
2003. A comparison of fish bycatch communities between areas open and closed to prawn trawling in an Australian tropical fishery. ICES J. Mar. Sci. 60:951–966.
- Strelcheck, A. J., and P. B. Hood.  
2007. Rebuilding red snapper: Recent management activities and future management challenges. In Red snapper ecology and fisheries in the U.S. Gulf of Mexico (W. F. Patterson, III, J. H. Cowan Jr., G. R. Fitzhugh, and D. L. Nieland, eds.), p. 353–363. Am. Fish. Soc., Bethesda, MD.
- Strelcheck, A. J., J. H. Cowan Jr., and A. Shah.  
2005. The influence of reef location on artificial reef fish assemblages in the north-central Gulf of Mexico. Bull. Mar. Sci. 77:425–440.
- Sweatman, H. P. A.  
1984. A field study of the predatory behavior and feeding rate of a piscivorous coral reef fish, the lizardfish *Synodus englemani*. Copeia 1984:187–194.
- Thresher, R. E., K. J. Sainsbury, J. S. Gunn, and A. W. Whitelaw.  
1986. Life history strategies and recent changes in population structure in the lizardfish genus, *Saurida*, on the Australian Northwest Shelf. Copeia 1986:876–885.
- Thrush, S. F., and P. K. Dayton.  
2002. Disturbance to marine benthic habitats by trawling and dredging: Implications for marine biodiversity. Annu. Rev. Ecol. Syst. 33:449–473.
- Wells, R. J. D.  
2007. The effects of trawling and habitat use on red snapper and the associated community. Ph.D. diss., 180 p. Louisiana State Univ., Baton Rouge, LA.
- Wells, R. J. D., J. H. Cowan Jr., W. F. Patterson, III, and C. J. Walters  
In press. Effect of trawling on juvenile red snapper habitat selection and life history parameters. Can. J. Fish. Aquat. Sci.
- Yoneda, M., T. Sakai, M. Tokimura, H. Horikawa, and M. Matsuyama.  
2002. Age and growth of the lizardfish *Saurida* species in the East China Sea using otolith ring marks. Fish. Res. 55:231–238.
- Zabel, R. W., C. J. Harvey, S. L. Katz, T. P. Good, and P. S. Levin.  
2003. Ecologically sustainable yield. Am. Sci. 91:150–157.