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Abstract.—Seasonal habitat suitability index models were developed for juvenile red snapper *Lutjanus campechanus* in the western Gulf of Mexico. Habitat factors considered in the analysis included water temperature, salinity, and dissolved oxygen at the bottom; depth and density of offshore petroleum platforms; and low-relief bottom structures. High-value habitat for juvenile red snapper is characterized by depths between 18 and 64 m, water temperatures of 24–26°C, salinities around 35%, and dissolved oxygen levels of at least 5 mg/L. Density of low-relief structures was not a significant habitat element, and an inverse association was found between juvenile red snapper abundance and the density of offshore platforms. Results of the model analysis suggest that the step-like expansion of the hypoxic area (dissolved oxygen ≤ 2 mg/L) offshore of the mouth of the Mississippi River and west to the Louisiana–Texas border, which first occurred in 1993, has reduced habitat carrying capacity for juvenile red snapper in this region by up to 25%, averaging 19%. This environmental change may limit the level to which overfished Gulf red snapper stocks can be rebuilt to historical levels.

The red snapper *Lutjanus campechanus* is a federally managed species supporting important commercial and recreational fisheries in the Gulf of Mexico (Goodyear 1995). Commercial domestic landings of red snapper from the U.S. Gulf of Mexico were relatively stable at around 2,750 metric tons from 1964 to the mid-1970s (Goodyear 1995). Landings declined to 2,250 metric tons in 1979, recovered to 3,301 tons in 1983, and then declined again. By 1991, landings were on the order of 1,000 metric tons and have since been curtailed by quotas (Goodyear 1995). Management began in 1984 when the Gulf of Mexico Fishery Management Council's (GMFMC's) reef fish fishery management plan became effective. This plan has been variously amended to provide additional protection to the U.S. stock. Because substantial quantities of juvenile red snapper are taken in the shrimp fishery, shrimp trawl bycatch reduction measures have been implemented (U.S. Office of the Federal Register 63:[14 April 1998]:18139–18147).

Management actions since 1990 appear to be having positive effects (Schirripa and Legault 1997). Recruitment, harvest, and size of fish in the harvest are all trending upwards (Rothschild et al. 1997; Schirripa and Legault 1997), suggesting that this overfished stock may be starting to recover. Overfishing, including bycatch in the shrimp fishery, is generally considered the primary impediment to full recovery of red snapper. However, the degree to which habitat changes might have contributed to the initial decline and might limit full recovery to historical levels has not been addressed.

The Magnuson–Stevens Fishery Conservation and Management Act, the 1996 revision and reauthorization of the 1976 Public Law 94–265 (Act), requires that fishery management plans include an identification and description of essential fish habitat (EFH), adverse impacts on EFH (including the effects from fishing), and actions to conserve and enhance EFH. One of the first steps identified in this mandate is to define and map habitat for each major life history stage of a managed species at the highest level of detail allowed by existing data. Four levels of data for identifying EFH are recognized in the Final Rule implementing this pro-

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vision: (1) presence–absence distribution data; (2) habitat-related density data; (3) growth, reproduction, and survival rate within habitats; and (4) production rates by habitat. Level 1 information can be used to identify the geographic range of a species; data at levels 2–4, if available, can be used to identify habitats valued most highly within the geographic range of the species.

Red snapper spawn mainly during June through August in the northern Gulf of Mexico (Render 1995). The early life history comprises a planktonic egg stage (18–27 h; Rabalais et al. 1980; Minton et al. 1983), a larval stage (25–47 d; Leis 1987), and a benthic juvenile stage that occurs after the larvae undergo metamorphosis and settle to the bottom. Size at settlement is about 1.7 cm (Szedlmayer and Conti, in press). Red snapper enter the Gulf shrimp trawl fishery as bycatch when they have grown to about 5 cm total length (TL) (Szedlmayer and Shipp 1994; Goodyear 1995). However, they do not appear fully vulnerable to the trawls used in the fishery and to sample the juvenile life history phase until fall, when they are 10 cm TL or longer (Goodyear 1995; Gallaway et al. 1998). Benthic juveniles are broadly distributed over soft bottoms (Goodyear 1995) and other trawlable bottoms of low relief (vertical scale in centimeters; Szedlmayer and Shipp 1994). They occupy these habitats from the time of settlement in the summer of their first year through the following summer and fall, when they have reached 18–20 cm TL. At these sizes, they begin to recruit to high-profile reefs like petroleum platforms (Gallaway et al. 1981; Stanley 1994; Render 1995). They are fully recruited to high-relief habitat by their second January at ages of about 18 months.

Juvenile red snapper exhibit highest abundance in microhabitats of low relief that range from silted-over patches of rubble to individual items of trash or debris like cans, mesh webbing from lost fishing gear, and plastic bags (e.g., Workman and Foster 1994; Szedlmayer and Conti 1999). A key feature seems to be that large predators (like adult red snapper) are not densely aggregated in the same areas. Most of the habitats where juveniles occur can be sampled by trawling.

In contrast, reef habitats occupied by subadult and adult red snapper are mainly nontrawlable because they have vertical scales in meters (as opposed to centimeters). These habitats range from boulder-sized blocks of carbonate like the South Texas Banks to coral reefs like the Flower Garden Banks to structures like petroleum platforms and sunken ships. Parker et al. (1983) estimated that of 2,780 km^2 of natural high-relief reef habitat occurs within the 18–91-m depth range between Pensacola, Florida, and the Texas–Mexico border. LGL and SAIC (1997) estimated that petroleum platforms provide an additional 12 km^2 of reef habitat.

The benthic juvenile life stage (ages 0 and 1) is the focus of this habitat assessment. Fish are age 0 through December of their first year but are not fully recruited to the trawl gear (which provides the basis of the assessment) until about the following October (Goodyear 1995; Gallaway et al. 1998). In January (about 6 months actual age) juvenile red snapper are, by convention, classified as age-1 fish (Goodyear 1995). Thus, age-0 fish are well represented for only a brief period in October and November, and most data on juveniles are for age-1 fish 6–18 months old as they increase in modal size from about 9 cm TL in January to 18–20 cm in December.

Level 2 information (habitat-related density) is available for age-0 and age-1 red snapper in the western Gulf of Mexico. As will be described below, relative abundance data (catch per unit effort, CPUE) and associated environmental data have been collected by the National Marine Fisheries Service (NMFS) in the western Gulf of Mexico on a consistent regional and seasonal basis since 1985 (Nichols and Pellegrin 1989; Goodyear 1995). The CPUE data, collected by standardized bottom trawling according to a random sampling design, have had adequate quality assurance and review to ensure that the density estimates are comparable among the habitats sampled. These data have been used, in part, to index annual recruitment trends (e.g., Nichols and Pellegrin 1989; Goodyear 1995; Schirripa and Legault 1997) and to estimate shrimp trawl bycatch (Nichols et al. 1987, 1990, 1995; Nichols 1990, 1996; Nichols and Pellegrin 1992; Gallaway et al. 1998).

In this paper, we use these and other data to map habitat utilization patterns of juvenile red snapper. We assumed that CPUE reflects the degree to which geographic areas are used by the fish and that the degree of use reflects or indicates relative habitat value. These premises provide the basis for developing habitat suitability index (HSI) models for juvenile red snapper by methods first developed by the U.S. Department of the Interior (USFWS 1980, 1981, 1982). Previous applications of this approach to marine fish species include HSI models for Gulf menhaden *Brevoortia patronus* (Christmas et al. 1982), southern kingfish *Menticirrhus americanus* (Sikora and Sikora 1982), red drum *Sciaenops ocellata* (Buckley 1984), Atlantic croaker *Micropogonias undulatus* (Diaz and Onuf 1985), southern flounder *Paralichthys lethostigma*, and gulf flounder *P. albigutta* (Enge and Mulholland 1985).

Methods

Spatial estimates of the abundance of juvenile red snapper were based on benthic trawl data gathered for the western Gulf of Mexico by NMFS during 1985–1997 as part of the fall groundfish (Nichols and Pellegrin 1989) and summer Southeast Area Monitoring and Assessment Program (SEAMAP) surveys (Goodyear 1995). For convenience, we will refer to both of these data sets as the SEAMAP data. Year 1985 was the first year that the fall (October–November) component of these studies was expanded geographically to sample the entire region between Pensacola, Florida, and Brownsville, Texas, from 9 to 109 m, as had been sampled in the summer (June–July) SEAMAP surveys beginning in 1982. Before 1985, the fall sampling was restricted to a much smaller region than the summer sampling.

Several vessels have participated in the SEAMAP programs (Goodyear 1995), but we restricted our analysis to the R/V Oregon II rather than attempt to calibrate CPUE among vessels. A standard 12-m shrimp trawl was used throughout all the sampling conducted by NMFS in these surveys. Size data were routinely collected for red snapper in both surveys beginning in 1985. The seasonal surveys differed somewhat in detail until 1987, when minor differences in sampling approaches were reconciled (Goodyear 1995).

Stations were selected according to a stratified random design. The coastline was divided into segments (strata) based on commercial shrimp statistical area boundaries. A station began at the intersection of a depth contour and a randomly chosen offshore location within a stratum. Trawling was conducted perpendicular to the depth contours. Duration of each trawl was set by the distance between the inner and outer depth boundary for each station. Depth was measured by fathometer when the end of the station was reached.

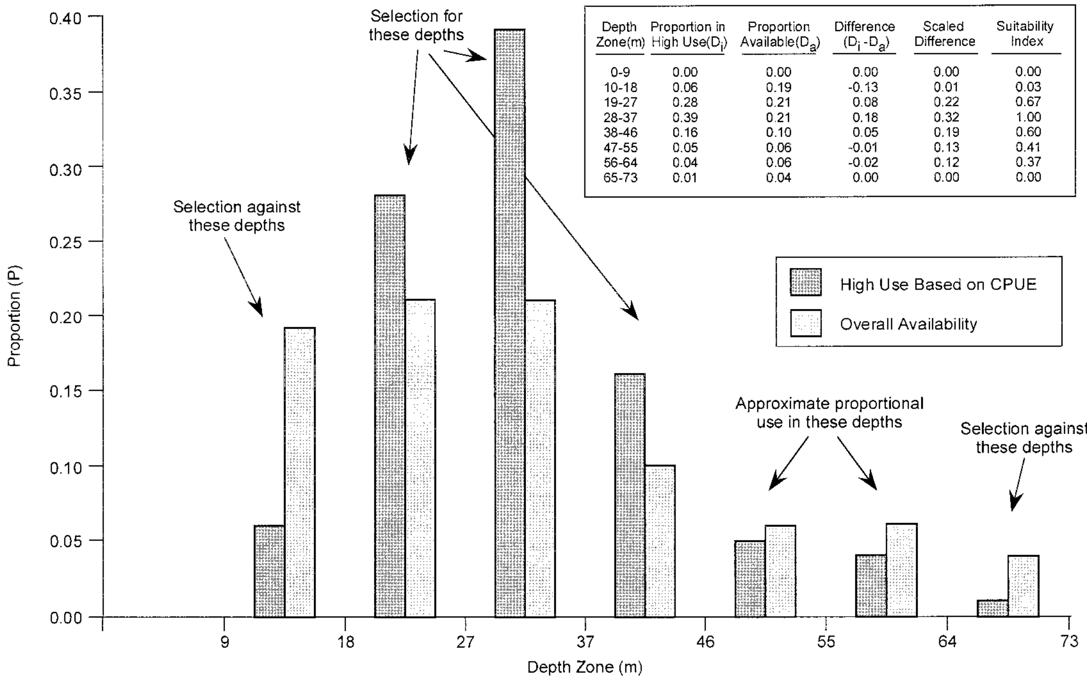
Following examination of the data, we arbitrarily determined that the finest spatial resolution that was practical for evaluating mean annual abundance patterns was a spatial cell of 10′ of latitude by 10′ of longitude. Each of the resulting 560 model cells contains 334 km^2. The total area modeled is on the order of 187,000 km^2. Mean catch per hour trawling (CPUE) with a 12-m-wide trawl was then calculated for each model cell where trawling occurred.

For each of the two seasons, a CPUE was calculated for each SEAMAP tow and the positive values were assigned to catch categories divided into quartiles. All zero CPUE values (45% of the fall and 68% of the summer tows had zero catch of red snapper) were assigned to the lowest catch category. A subset of the SEAMAP data included tows for where a complete suite of depth, temperature, salinity, and dissolved oxygen measurements existed. These were used to develop the relationships between relative abundance (catch categories) and habitat factors.

The habitat factors considered in the models were depth; bottom water temperature, salinity and dissolved oxygen; the density of bottom obstructions of sufficient size to be recorded as a shrimp trawl ''hang'' site as recorded by the Texas A&M Sea Grant Program; and the density of petroleum platforms as recorded by the Minerals Management Service (MMS) and the U.S. Coast Guard (USCG). The first four factors were included in the NMFS survey data that were provided to us in digital format (Scott Nichols and Ken Savastano, NMFS). The environmental measurements used to model the overall area included data obtained by sampling gears other than the standard shrimp trawl. We used all the environmental data collected for the region and period of interest to characterize model cells regardless of the type of sampling being conducted.

Offshore oil and gas platform locations were acquired from MMS and the USCG as noted above. A data set as of 1995 was created from those files, and the number of platforms in each model cell was calculated. Texas A&M Sea Grant provided a file of shrimp trawl net hang locations, which was used to create a hang data set. These data provided an estimate of the density of relatively high-relief bottom obstructions in each model cell. The hang data set only includes data west of 89°30‘W longitude. Habitat values for model cells east of that location were calculated with no hang factor.

Scaled suitability indices (SI) were derived for each of the habitat factors. High-use habitat areas for juvenile red snapper were defined as those for which CPUE values were in the upper two catch categories of the CPUE values for each season. Seasonal suitability index tables were prepared for each factor by comparing the frequency of juvenile red snapper high-use areas in each interval spanning the factor's range (e.g., depth D_i in Figure 1)



Depth Zone(m)	Proportion in High Use(D_i)	Proportion Available(D_a)	Difference (D_i - D_a)	Scaled Difference	Suitability Index
0-9	0.00	0.00	0.00	0.00	0.00
10-18	0.06	0.19	-0.13	0.01	0.03
19-27	0.28	0.21	0.08	0.22	0.67
28-37	0.39	0.21	0.18	0.32	1.00
38-46	0.16	0.10	0.05	0.19	0.60
47-55	0.05	0.06	-0.01	0.13	0.41
56-64	0.04	0.06	-0.02	0.12	0.37
65-73	0.01	0.04	0.00	0.00	0.00

FIGURE 1.—Determination of the juvenile red snapper suitability index (SI) for depth in the western Gulf of Mexico during the fall season. Twenty-one percent of the 560 model cells had depths from 28 to 37 m D_a, whereas 39% of the cells supporting high catch per unit effort (in the two highest quartiles) occurred in the same depth range. Abundance at these depths was thus higher than would be expected based on the overall availability of this depth range in the model region. The normalized value of the scaled difference between use and availability constitutes the suitability index for a particular depth interval.

to the overall availability of that factor interval (D_a). The difference between the two values (e.g., $D_i - D_a$) was calculated. A large positive difference suggested selection for a given factor interval; a large negative value suggested selection against the interval. The difference data were next scaled to positive values and the suitability index was calculated by setting the maximum factor interval value to 1.0 and all other values as the ratio of the scaled index to that maximum value. Factor intervals with high-use occurrence values that were less than 5% of the highest high-use occurrence values, as well as elements that occurred in high-use areas less than 1% of the time, were automatically set to suitability of zero to reduce undue influence from scaling infrequently occurring small values.

Each seasonal model was based on six habitat factors aggregated into three life requisites: water quality; relief at depth; and presence of hypoxic bottom water (dissolved oxygen <2 mg/L; Rabalais et al. 1997). The water quality life requisite was determined by temperature and salinity; the index was calculated as the square root of the product of the two suitability indices. Dissolved oxygen levels were divided into four ranges: 0, 1–2, 3–4, and ≥5 mg/L. Trawlers typically do not capture shrimp or demersal fish in their nets when oxygen levels are in the 0–2 mg/L (hypoxic) range (Leming and Stuntz 1984; Renaud 1986). In general, a dissolved oxygen concentration of at least 5 mg/L will sustain most marine organisms that do not depend on atmospheric oxygen (Stickney 1984).

Relief at depth was determined by depth and the combined effects of platforms and hangs. The index was calculated as one-half of the sum of the depth index and the square root of the product of the hang index and the platform index. For areas east of 89°30W longitude, the calculation was simplified to one-half of the sum of the depth index and the platform index. The HSI for each cell was then calculated as the cube root of the product of the water quality index, the hypoxic bottom index, and the relief at depth index (Figure 2).

Much concern has been expressed over the spa-

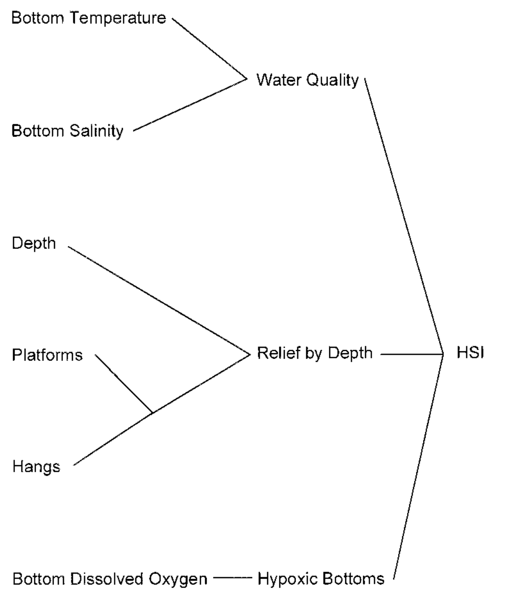


FIGURE 2.—Schematic showing consolidation of habitat variables into three life requisites used to develop habitat suitability index (HSI) models for juvenile red snapper in the western Gulf of Mexico.

tial increase in summer hypoxic bottom waters off Louisiana between the mouth of the Mississippi River and Sabine Lake on the Louisiana–Texas border (e.g., Rabalais et al. 1997). During 1985–1992, the average area of bottom hypoxia was estimated to be 8,000–9,000 km^2 (Rabalais 1988; Rabalais et al. 1991, 1992, 1994). Since 1993, the average size of the hypoxic zone has been 16,000–18,000 km^2 (Rabalais et al. 1997). A summary of the annual distributions as mapped by Rabalais and her colleagues are provided in the Appendix.

We conducted analyses to determine if the NMFS SEAMAP data corroborated the increase in hypoxia as summarized by Rabalais et al. (1997) and to quantify the effects of this increase on juvenile red snapper habitat. Using the SEAMAP data for 1985–1992, we calculated the frequency of model cells having hypoxic bottom waters. The results were summarized by means of spatial subdivisions of 1° of longitude in each direction from the mouth of the Mississippi River. The same analysis was then conducted for 1993–1996. Comparison of the results provided an estimate of the percent increase in hypoxic bottom waters.

To evaluate the effects of this increase, we modeled HSI values for the period 1985–1992 separately from the period 1993–1996. The relationship between juvenile red snapper abundance and the life requisites as described above were applied to the mean dissolved oxygen levels observed in each cell in the model for 1985–1992, and we ran another model for mean dissolved oxygen levels observed during 1993–1996. The results yielded an assessment of the reduction in habitat value that resulted from the observed increase in the hypoxic zone. These data were also summarized for spatial units of 1° longitude. A paired *t*-test was used to determine significant ($P \leq 0.05$) changes in habitat value associated with the post-1992 expansion of the hypoxic zone.

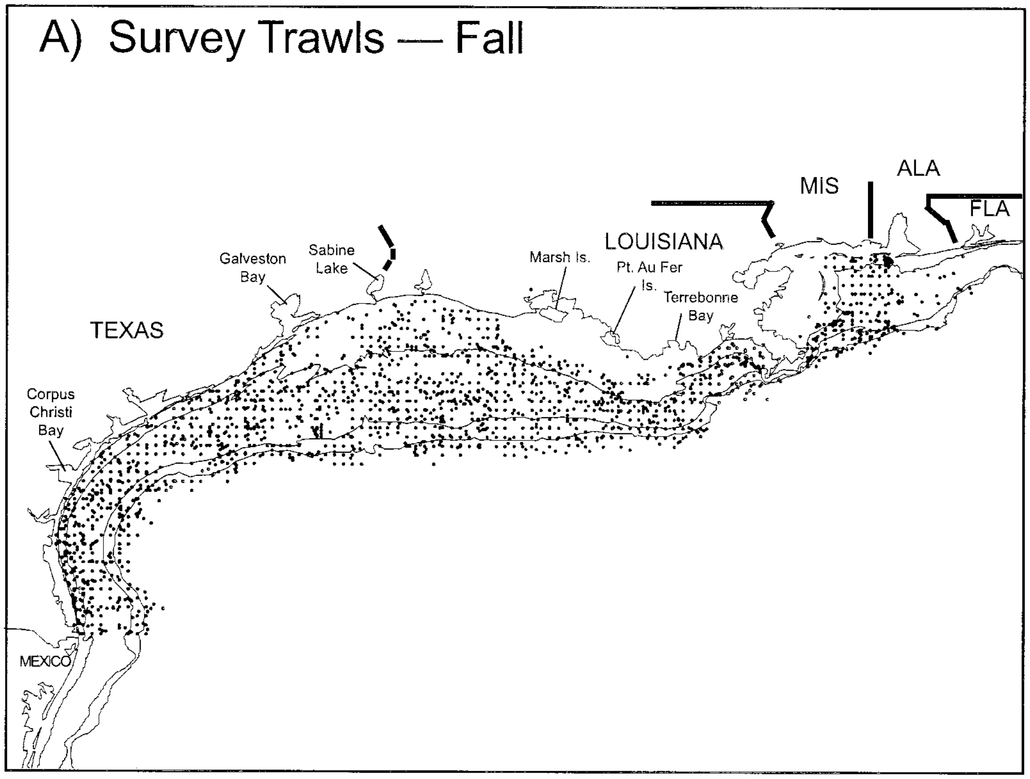
Results and Discussion

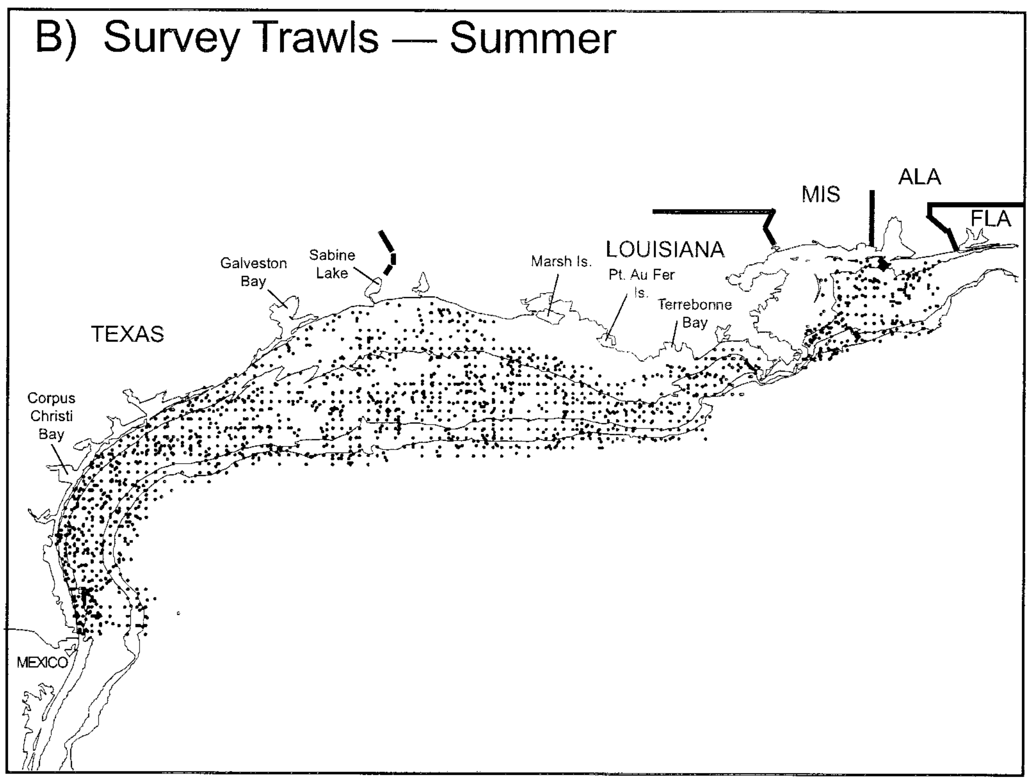
Our database as received from NMFS contains red snapper catch information associated with 2,830 fall and 2,699 summer trawl tows taken in 1985–1997 (Figure 3). Synoptic sets of complete CPUE and environmental data were available for 1,923 fall and 2,120 summer tows. These data were used to characterize relationships between abundance and environmental factors. A larger environmental data set was available to characterize the environment for modeling purposes. There were 5,761 fall and 5,354 summer measurements of bottom water temperature; 4,801 fall and 4,612 summer measurements of bottom water salinity; 3,462 fall and 3,570 summer measurements of bottom water dissolved oxygen; and, 5,761 fall and 5,354 summer determinations of depth. These data are supplemented by location data for over 5,140 offshore oil and gas platforms (including platforms in state as well as federal waters) provided by MMS and the USCG and location data for 12,247 sites where shrimp trawlers have reported hanging their nets on bottom obstructions (high-relief sites).

Suitability Index Values

The distribution of the 1985–1997 seasonal mean values of red snapper CPUE; depth; bottom water temperature, salinity and dissolved oxygen; platform count; and hang or bottom obstruction count are shown for each model cell in the Appendix maps. A summary of the HSI values for each of the environmental factors considered in the model is shown in Figure 4.

Juvenile red snapper SI values for bottom water temperatures were greatest at 26–27°C in fall and 24°C in summer. The GMFMC (1980, 1981) stated that red snapper has a temperature preference between 14°C and 30°C, a lower lethal temperature limit of about 13°C, an upper lethal limit of 33.5°C, and an optimal activity temperature of 18°C. Rivas (1970) observed the highest red snapper abun-


A) Survey Trawls — Fall
MIS
ALA
FLA
LOUISIANA
Galveston Bay
Sabine Lake
Marsh Is.
Pt. Au Fer Is.
Terrebonne Bay
TEXAS
Corpus Christi Bay
MEXICO


B) Survey Trawls — Summer
MIS
ALA
FLA
LOUISIANA
Galveston Bay
Sabine Lake
Marsh Is.
Pt. Au Fer Is.
Terrebonne Bay
TEXAS
Corpus Christi Bay
MEXICO

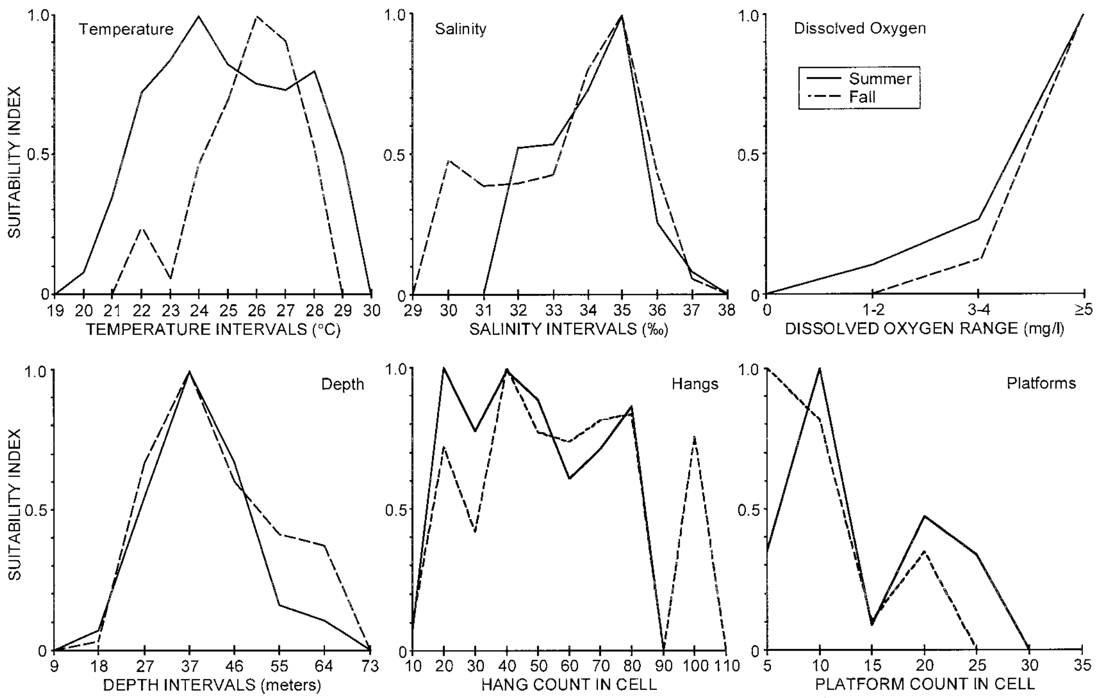


FIGURE 4.—Suitability indices for six environmental factors included in the habitat suitability index models for juvenile red snapper in the western Gulf of Mexico. Summer indices (solid lines) are distinguished from fall indices.

dance in water temperatures of 24.4°C, lowest abundances at 16.7°C, and intermediate abundances at temperatures averaging 20.6°C. Szedlmayer and Shipp (1994) observed maximum abundance of juvenile red snapper off the Alabama coast in July at a temperature of 23.4°C. Based on abundance over the range of observed temperatures, optimum temperatures for juvenile red snapper appears to lie between 24°C and 26°C.

The results of our analysis indicate a maximum salinity SI value of 1.0 for 35‰ in both fall and summer seasons (Figure 4). In fall, juvenile red snapper exhibited moderate SI values for salinities as low as 30‰, but high SI levels were not evidenced until salinity was 34‰ or greater. A similar step increase in SI level was evident between 33‰ and 34‰ for juvenile red snapper in summer. Sharp declines in the SI level was observed for salinities above 35‰ (Figure 4). Mosley (1966) observed that red snapper commonly occur at salinities between 33‰ and 37‰; Szedlmayer and Shipp (1994) reported that maximum abundance corresponded with salinities of 35.0–36.8‰. Huff and Burns (1981) reported that salinities of 60‰ were lethal to 100% of juvenile red snapper in laboratory tests, but that no serious effects were evident at salinities of 45‰. Juvenile red snapper reflect a marine affinity, and high abundance appears to be commonly associated with salinities of 34–35%.

The abundance of juvenile red snapper in summer was typically low in areas having mean dissolved oxygen levels between 0 and 4 mg/L, especially areas where hypoxic conditions were evident (Figure 4). These data indicate that juvenile red snapper require dissolved oxygen levels of 5 mg/L and greater, and that they are adversely affected by levels below 5 mg/L. Szedlmayer and Shipp (1994) observed a trawl CPUE of nearly 800 juvenile red snapper per hour off the coast of Alabama in July 1991, but the catches fell dramatically (less than 25 fish/h from inspection of Figure

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FIGURE 3.—Composite distribution of trawl tows conducted by the western Gulf of Mexico National Marine Fisheries Service during **(A)** fall and **(B)** summer seasons, 1985–1997. The 18-, 54-, and 73-m depth contours are shown for reference.

3 in Szedlmayer and Shipp 1994) in August and October. There was little difference in salinity (35.0–35.‰) or temperature (23.4–24.9°C) among sample dates, but August dissolved oxygen was 0 mg/L from 2 m below the surface to the bottom at 15 m in depth (Szedlmayer and Shipp 1994).

Juvenile red snapper exhibited peak depth SI values for the 28–37-m depth interval and were uncommon at depths less than 18 m in both seasons (Figure 4). The deepest depth interval having an SI value exceeding 0.1 was 64 m. The GMFMC (1981) observed that juveniles were most often collected at depths between 9 and 26 m. Our results suggest that juvenile red snapper habitat lies between 18 and 64 m and that peak abundance occurs at 37 m.

The density of bottom obstructions exhibited little trend with juvenile red snapper abundance, but high-relief SI values were typically higher for areas with 10 or fewer platforms per model cell (Figure 4). Areas of higher platform density may increase exposure of juvenile red snapper to predator aggregations that occur around the base of the platforms (e.g., Sonnier et al. 1976; Gallaway et al. 1981; Stanley 1994; Render 1995). An alternative view is that juvenile red snapper recruit to midwater depths around platform supports, as observed by Gallaway et al. (1981) and Render (1995), and are highly abundant in these regions, but that they are unavailable to bottom trawls there. Another explanation is that the observed relationship is spurious.

Habitat Suitability Indices

Fall collections of red snapper are dominated by age-0 fish that have had about two months of growth from the time of their metamorphosis and settlement to the bottom. In fall, high-value habitat (upper halves of HSI values) for juvenile red snapper was estimated to occur in a broad band across the western Gulf from the Alabama–Florida border to the Texas–Mexico border (Figure 5). The distribution likely extends further south into Mexican waters that are not sampled in U.S. programs. The distribution of upper-half-abundance HSI-value habitat is essentially bounded on the landward side by the 18-m depth contour and on the seaward side by the 54- to 64-m depth contours. The HSI values reflecting the top quartile of the abundance range were scarce around the mouth of the Mississippi River and generally restricted to depths between 18 and 54 m.

In the summer, collections are dominated by age-1 fish approximately 12 calendar months in age. A midshelf band of high-value habitat is evident as it is in fall but with some important differences (Figure 5). First, from the mouth of the Mississippi River to Point Au Fer Island, Louisiana, only five model cells have HSI reflecting the upper half of summer abundance values for juvenile red snapper, and no cells have an HSI value for the top quarter, whereas 27 fall cells in this region had HSI values in the top half of abundance, including two cells in the top quarter. Second, the width of the high-value habitat band was somewhat more constricted in summer than in fall. We believe the fall-to-summer reduction in high-value habitat around the mouth of the Mississippi River is related to an increase in the spatial extent of hypoxic bottom water, as discussed below.

Hypoxic Zone Effects

The percent frequency of modeled cells with hypoxic bottom water in the summers of 1993–1996 increased dramatically in the region between the mouth of the Mississippi River (longitude 89°W) and Sabine Lake (approximately longitude 94°W) relative to 1985–1992 (Figure 6). The area with increased hypoxia did not terminate at the Louisiana–Texas border; increased hypoxia was evident westward to the west end of Galveston Bay, San Luis Pass (Figure 6). These increases in the spatial distribution of hypoxic bottom water conditions resulted in significant (paired *t*-test with $P = 0.05$) reductions in HSI values throughout the region from near the mouth of the river to approximately the west end of Galveston Bay (longitude 95°W) (Figure 6). Over the entire region, habitat value was reduced by an average of 19%, and the maximum observed reduction within a degree of longitude was 25%.

The HSI is not intended to be a predictor of population level, but relative values are considered to be an index of the environment's potential carrying capacity (USFWS 1981). Under the assumption that HSI models index carrying capacity,

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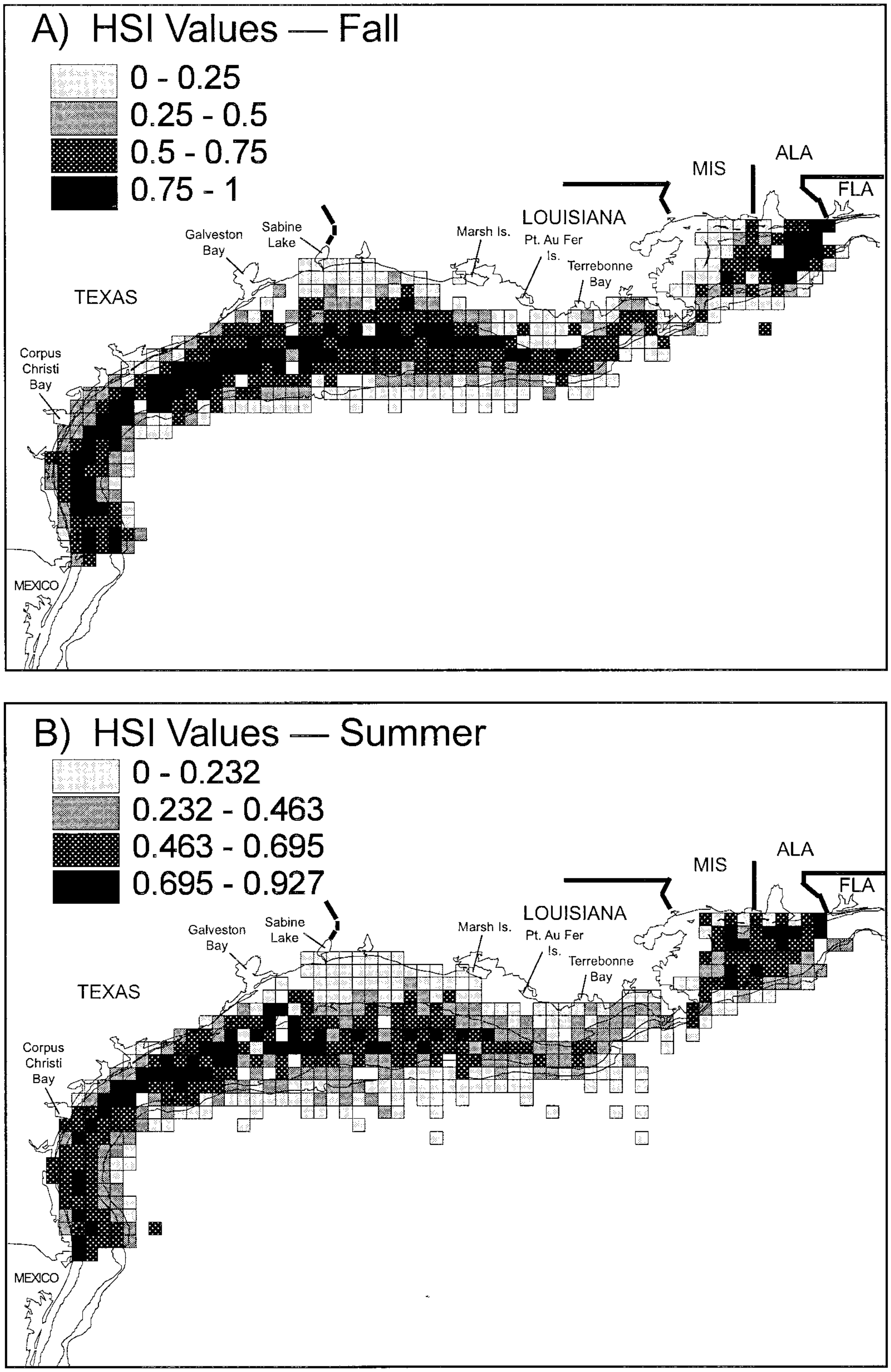
FIGURE 5.—The spatial distribution of habitat suitability index (HSI) values for juvenile red snapper in fall **(A)** and summer **(B)** in the western Gulf of Mexico, based on data from 1985 to 1997. The 18-, 54-, and 73-m depth contours are shown for reference.


A) HSI Values — Fall
0 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
MIS
ALA
FLA
LOUISIANA
Sabine Lake
Galveston Bay
Marsh Is.
Pt. Au Fer Is.
Terrebonne Bay
TEXAS
Corpus Christi Bay
MEXICO
B) HSI Values — Summer
0 - 0.232
0.232 - 0.463
0.463 - 0.695
0.695 - 0.927
MIS
ALA
FLA
LOUISIANA
Sabine Lake
Galveston Bay
Marsh Is.
Pt. Au Fer Is.
Terrebonne Bay
TEXAS
Corpus Christi Bay
MEXICO

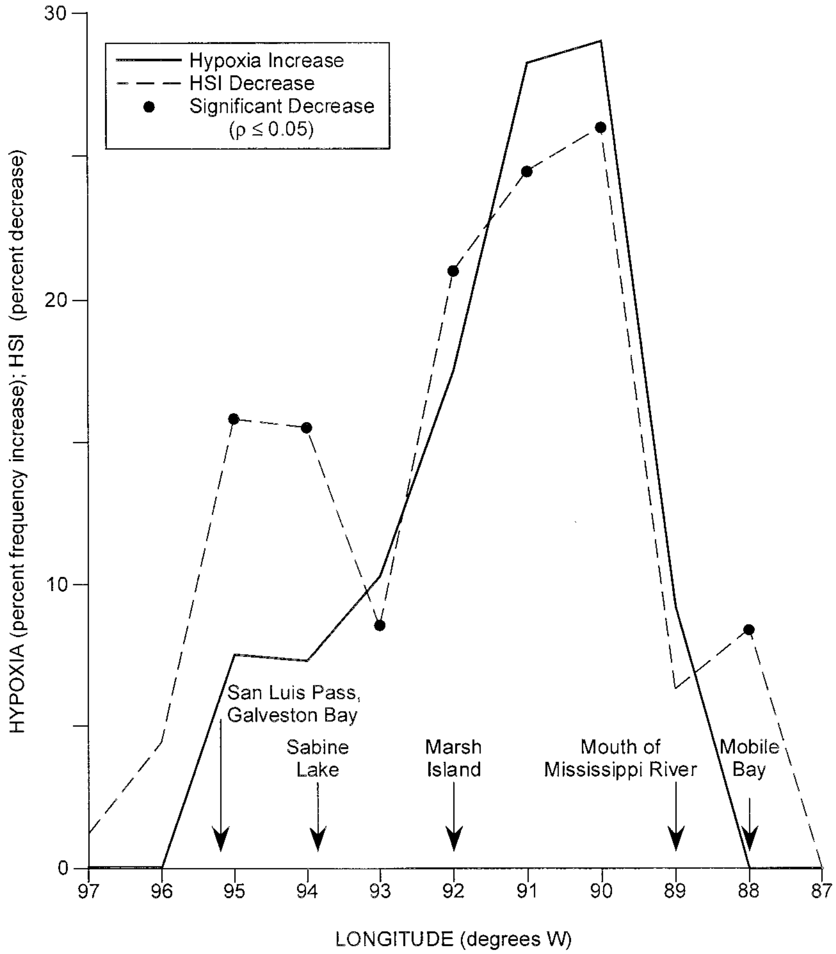


FIGURE 6.—Increase in percent frequency of model western Gulf of Mexico cells having 2 mg/L dissolved oxygen levels or less in summer (hypoxia increase), by degree of longitude, from 1985–1992 to 1993–1996. Corresponding percent decreases in mean habitat suitability indices (HSI) are shown.

a significant reduction (up to 25%) in red snapper habitat carrying capacity has been observed in association with the most recently observed expansion in the size of the hypoxic region occurring in the Gulf of Mexico around the mouth of the Mississippi River. This change, if real, may affect the level to which Gulf red snapper stocks can be rebuilt relative to historical stock levels.

The red snapper is associated with the brown shrimp *Penaeus aztecus* ground assemblage (Chittenden and McEachran 1976; Gallaway 1981), and alternative marine habitat for red snapper is available outside the region directly affected by hypoxic water conditions. Nearshore species dependent on low-salinity conditions characteristic of the white shrimp ground assemblage (e.g., white shrimp *Penaeus setiferus*; Atlantic croaker) have likely undergone much larger reductions in habitat carrying capacity because alternative low-salinity habitats are not extensive outside the hypoxic region. Salinity increases in the offshore direction as well as in nearshore zones to the east and west.

The potential effects of adverse environmental changes have not been, but need to be, taken into account in fishery management plans. This need has been recognized and is presently mandated by the Magnuson–Stevens Fishery Conservation and Management Act. The evident influence of large and increasing hypoxic areas on juvenile red snapper (and associated species) in the western Gulf of Mexico should be recognized.

Acknowledgments

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Appendix: Data Distributions for Red Snapper Surveys

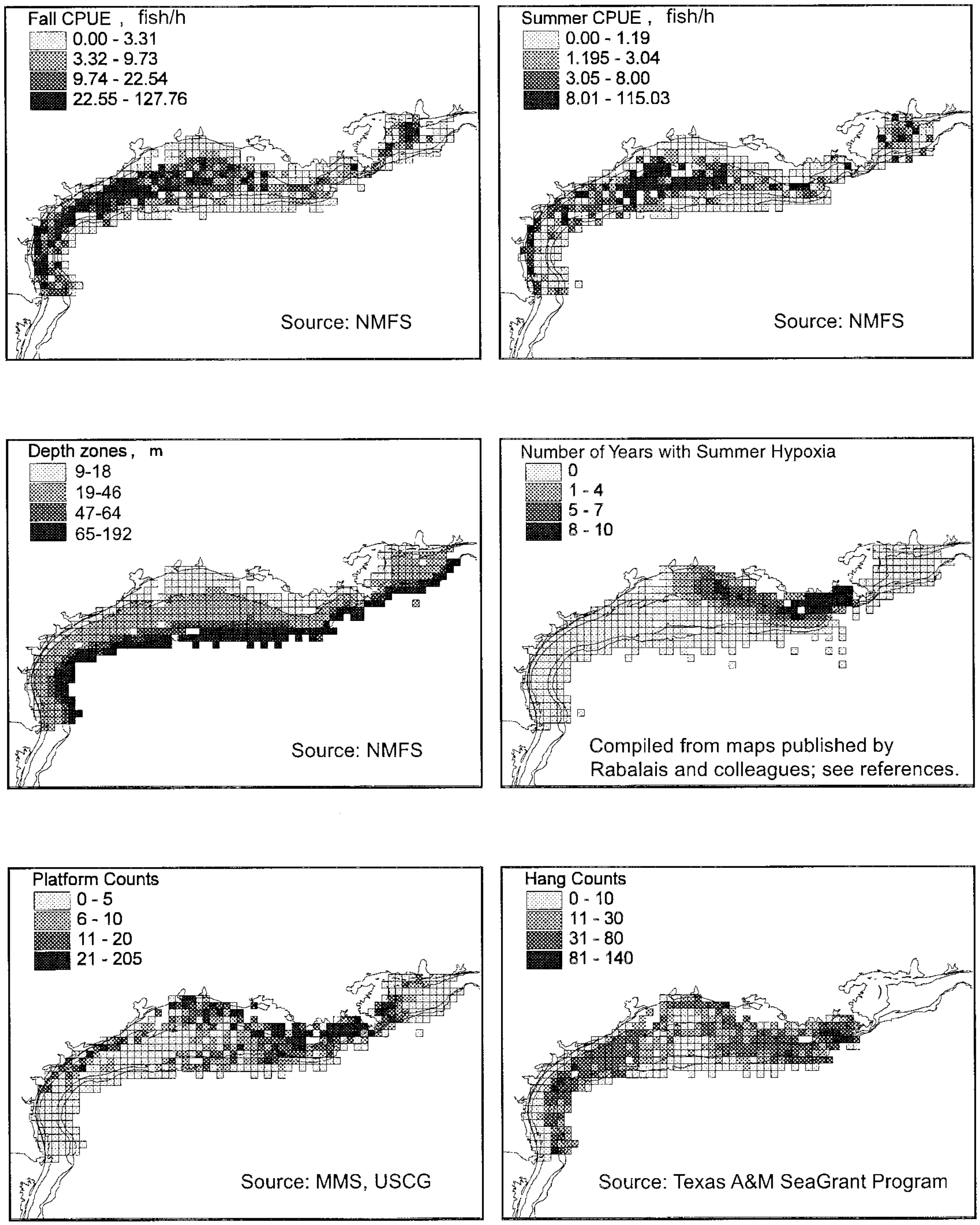

FIGURE A.1.—Quartile abundance indexes for juvenile red snapper in the western Gulf of Mexico, for fall and spring NMFS trawl surveys, and corollary habitat values for 560 model cells. Abbreviations: NMFS = National Marine Fisheries Service; MMS = Minerals Management Service; USCG = U.S. Coast Guard.

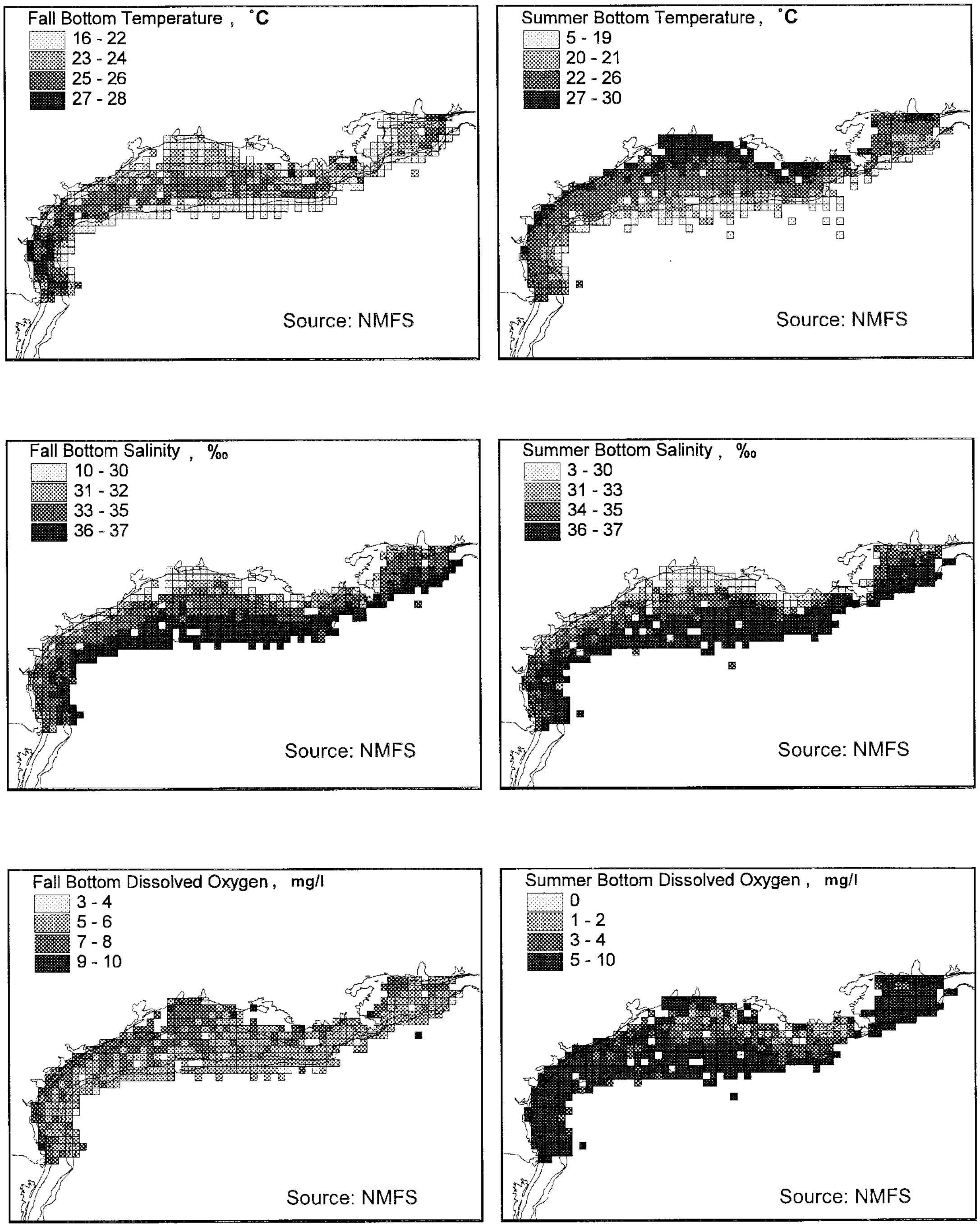

FIGURE A.1.—Continued.