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SUMMARY

1. **PURPOSE.** To provide security and policy review on the document at Tab 1 prior to release to the public.

2. **BACKGROUND.**
 Authors: Joshua M. Courtney, Amy C. Courtney, and Michael W. Courtney
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4. **VIEWS OF OTHERS.** Not applicable.

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Michael W. Courtney
 Michael Courtney, PhD 1 Tabs
 QRC Director/DFRL 1. Nutrient Loading Increases Red Snapper Production in the Gulf of Mexico

Nutrient Loading Increases Red Snapper Production in the Gulf of Mexico

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Abstract

A large, annually recurring region of hypoxia has been identified in the northern Gulf of Mexico and attributed to water stratification and nutrient loading of nitrogen and phosphorus delivered by the Mississippi and Atchafalaya rivers. This nutrient loading increased nearly 300% since 1950, primarily due to increased use of agricultural fertilizers. Over this same time period, the red snapper (*Lutjanus campechanus*) population in the Gulf of Mexico has shifted strongly from being dominated by the eastern Gulf of Mexico to being dominated by the northern and western Gulf of Mexico, with the bulk of the current population in the same regions with significant nutrient loading from the Mississippi and Atchafalaya rivers and in or near areas with development of mid-summer hypoxic zones. The population decline of red snapper in the eastern Gulf is almost certainly attributable to overfishing, but the cause of the population increase in the northern and western Gulf is subject to broad debate, with the impact of artificial reefs (primarily oil platforms which have increased greatly since the 1960s) being the most contentious point. Nutrient loading has been shown to positively impact secondary production of fish in many marine systems. The present paper offers the hypothesis that the increased nutrient loading has contributed significantly to the increased red snapper population in the northern and western Gulf of Mexico.

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Nutrient Loading and Hypoxia in the Gulf of Mexico

Nutrient loads of nitrogen and phosphorus being delivered to the Gulf of Mexico by the Mississippi and Atchafalaya rivers increased markedly in the second half of the 20th century. (Bianchi et al. 2010, Rabalais et al. 2007) The mean annual concentration of nitrate was comparable in 1905-1906 and 1933-1934 when compared with the 1950s. However, the mean annual nitrate concentration tripled from 1955 to 1996 with most of the increase occurring between 1970 and 1983. This increase in nitrate concentration has some contribution from point sources, but is dominated by the increased use of agricultural fertilizers throughout the Mississippi River watershed. The records for phosphorus loading before 1973 are not as reliable. Estimates suggest phosphorus loads have approximately doubled over the same time period, though these estimates are largely based on extrapolation of a regression into the past rather than direct measurements.

There is broad agreement that this nutrient loading is the principal cause of large hypoxic

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zones that occur annually on the Louisiana-Texas shelf in the Gulf of Mexico. Areas of oxygen depleted water at or near the bottom begin to form after the nutrient flux peaks (usually in May), tend to reach a maximum size in July or August, and then dissipate in the fall when water temperatures cool and wind associated with passing cold fronts causes mixing of well oxygenated surface waters and oxygen depleted bottom layers. Mixing caused by tropical storms during the summer can also reduce the size of hypoxic zones. (Bianchi et al. 2010, Rabalais et al. 2007, Rabalais et al. 2002)

In addition to nutrient loading, stratification of the water column on the Louisiana-Texas shelf also contributes to the formation and maintenance of the hypoxic zones. Lower salinity waters from the Mississippi and Atchafalaya rivers are less dense than higher salinity lower layers. Waters higher in the water column also tend to experience more warming which maintains the stratification (warmer water is less dense). The nutrient loading hastens and facilitates the growth of algae and phytoplankton, which, in turn, can also cause a rapid increase in the biomass of zooplankton and nekton. When the phytoplankton and algae die, they sink to the bottom. Likewise, the increased biomass of zooplankton and nekton produce an abundance of feces which also sinks to the bottom. The breakdown of the dead algae, phytoplankton, and feces by aerobic bacteria near the bottom deplete the oxygen near the bottom much faster than it can be replenished by the low rates of mixing with the well-oxygenated surface waters. (Bianchi et al. 2010, Rabalais et al. 2007, Rabalais et al. 2002)

There are many nuances to hypoxia formation, including contributions from carbon loading from Mississippi River water (Rabalais et al. 2002), and the nutrient loading and occasional formation of hypoxic zones in the northern Gulf of Mexico off the coasts of Mississippi and Alabama in years when currents move substantial nutrients eastward from the Mississippi River discharge. (Rabalais et al. 2007) Variations in nutrient loading, fresh water flow from the rivers, and stratification can cause wide variations in the resulting area of hypoxic water. For example, since the regular mapping of the hypoxic zone began in 1985, the hypoxic area has varied from under 5000 km² in 1988 and 2000 to near 20,000 km² in 1999, 2001, 2002, and 2007. (Rabalais et al. 2007)

Nutrient Enrichment and Increased Secondary Production of Marine Systems

Nixon and Buckley (2002) review evidence that secondary production in marine systems tends to be increased by nutrient enrichment. One example is the collapse of the fishery on the Egyptian shelf after the closing of the Aswan dam in 1965. This restricted the deposition of inorganic nutrients by the annual Nile flood; subsequently the fishery collapsed. However, use of inorganic fertilizers and point source discharge of nutrients increased markedly in the Nile delta after that time, and the resulting increase in inorganic nitrogen coincided with a dramatic recovery of the fishery that began in the early to mid 1980s and has continued to the present. Caddy (2000) also discusses the impact of the Aswan dam on the fisheries off the Nile delta and the later rise in production with enriched drainage water in the early to mid 1980s.

A second example discussed by Nixon and Buckley (2002) are Scottish sea loch experiments with fertilization. Though the experiments showed little promise regarding the potential commercial success of estuary fertilization due loss of fish to hypoxia and escape into the open ocean, the experiments demonstrated remarkable increases in benthic fauna (5-6 times

in one of the sea lochs) in spite of heavy feeding from introduced fish. These experiments demonstrated remarkable growth rates of plaice (*Pleuronectes platessa*).

A third example discussed by Nixon and Buckley (2002) is the Baltic Sea which has received increasing amounts of nitrogen and phosphorus from agricultural runoff, urban wastewater, and enriched atmospheric deposition for many decades. Between an early study in 1920-1923 and a later assessment in 1976-1977, the benthic biomass above the halocline was estimated to increase by 2-10 times. Marked decreases in benthic biomass below the halocline over the same interval were attributed to decreases in oxygen due to eutrophication. Nixon and Buckley also describe a historical reconstruction (Thurrow 1997) of biomass and finfish yield in the Baltic Sea showing that both biomass and finfish yield were low in the first half of the 20th century, then increased sharply after about 1950. After considering a number of other possible factors, Thurrow (1997) concluded that nutrient loading and subsequent eutrophication were responsible for the 8-fold increase in fish biomass. In response to some who argued for reduction of nutrient inputs, Thurrow (1997) warned that reduction of nitrogen and phosphorus inputs would "inevitably lead to a lower fish biomass."

Caddy (1993) described a simple conceptual model relating fishery landings to nutrient inputs. There is a positive correlation up to some point above which higher nutrient loadings would cause fishery production to decrease. Caddy speculated that at higher levels of nutrient loadings (above a system dependent threshold) additional nutrients would cause seasonal or permanent bottom anoxia leading to a decline in benthos and benthos-feeding fish. In addition to the examples of production increasing with nutrient load reviewed by Nixon and Buckley (2002), Caddy (2000) describes the increases in production in the northern Mediterranean with increased nutrient load, although some areas (the northern Adriatic) have experienced some years of hypoxia. Oczkowski and Nixon (2007) point out that even though the positive response of fishery production to nutrients has been demonstrated in many cases, (Nixon and Buckley 2002) the dome shaped response predicted by Caddy has not been widely demonstrated in the literature. In a detailed review of available data for nitrogen loadings and fishery production in the Nile delta of Egypt, Oczkowski and Nixon (2007) showed fish landings increased up to a threshold nitrogen loading up to a concentration of approximately 100 μM of dissolved inorganic nitrogen; above this threshold, there was an exponential decrease in landings. Breitberg (2002) also pointed out that high productivity of finfish in nutrient-enriched systems are often greater than losses due to oxygen depletion.

Red Snapper in the Gulf of Mexico

Commercial fishing for red snapper in the Gulf began on a significant scale in the late 1800s. Until 1950, the red snapper harvest in the eastern Gulf dominated the harvest. A number of exploratory trips were made to the western Gulf, including the Louisiana-Texas shelf, but this area was found to be relatively unproductive. From 1950 until the present, the red snapper harvest in the western Gulf has demonstrated an increasing trend, while the production and harvest of the eastern Gulf has steadily declined. (Shipp and Bartone 2009, Gallaway et al., 2009).

In addition to a shift in production from the eastern to the western Gulf, estimates of the sustainable yield in the Gulf have also increased markedly. The highest landings before 1970 were approximately 9 million pounds (mp), and in most years, landings were about 5

mp. (Shipp and Bartone 2009) These yields were not sustainable and led to a collapse of the fishery in the eastern Gulf between 1980 and the early 1990s. However, current model projections of maximum sustainable yield for the Gulf are between 11.3 and 25.4 mp annually, with most of that production dominated by the northern and western Gulf, especially the Louisiana-Texas shelf. (Shipp and Bartone 2009, Cowan et al. 2010)

There is broad agreement that the collapse of the red snapper stocks in the Gulf was due to overfishing. (Shipp and Bartone 2009, Cowan et al., 2010) In contrast, there is lively debate regarding the causes most strongly related to the stock recovery in the western Gulf (the Louisiana-Texas shelf) and in the northern Gulf (off the Alabama coast). The hypothesis that artificial reefs have played an important role finds strong support in the empirical evidence. (Shipp 1999, Shipp and Bartone 2009, Galloway et al. 2009) Red snapper in this area are limited by available habitat which is dominated by sand, silt, and mud bottoms with limited hard bottom or reef which plays a key role at multiple stages of red snapper life history. In 1960, there were only about 351 offshore petroleum platforms in the western and northern Gulf. The number increased to 1520 platforms by 1970 and since 1990 has remained steady at around 4000. Petroleum platforms provide valuable three dimensional artificial reef habitat by extending from the bottom to the surface. Because snapper segregate by depth at petroleum platforms (typically younger fish at shallower depths and older fish deeper), a given area of petroleum platform provides much more habitat than the relatively scarce low relief (most < 1m high) natural reefs in the area. Petroleum platforms support fish densities 10 to 1000 times greater than that of adjacent sand and mud bottoms and also exceed densities of natural hard bottom. In addition, from 1950 to 2009, an estimated 20,000 artificial reef structures have been placed in a 1200 square mile area off the Alabama coast. Though lower relief (< 2m typically) than oil platforms, these reefs were deployed in areas dominated by sandy mud bottoms, having limited natural relief (a few cm), dominated by diminutive fish species. (Shipp and Bartone 2009, Galloway et al. 2009)

The debate often centers around the question of whether these artificial reefs only attract fish or whether they contribute significantly to production. (Cowan et al. 2010) The attraction viewpoint is based heavily on the assumption that red snapper do not recruit heavily to artificial reefs until age 2, thus the artificial reefs are unlikely to relieve a life history bottleneck. (Cowan et al. 2010) In contrast, there is ample evidence that red snapper begin using artificial reefs much earlier in their life history. (Szedlmayer 2011, Shipp and Bartone 2009, Galloway et al. 2009) The attraction viewpoint has also failed to provide compelling evidence for where the increased production of red snapper is coming from if artificial reefs are not contributing significantly. In contrast, the additional support for the production hypothesis is found in correlations of red snapper age with the age of the artificial reef (Syc and Szedlmayer 2012), greater utilization by red snapper of artificial reefs with epibenthic communities (Redman and Szedlmayer 2009), higher site fidelity (Topping and Szedlmayer 2011) than was presumed by Cowan et al. (2010), and density dependent mortality of age 0 fish (Gazey et al. 2008).

Hypothesis

Authors favoring the attraction-only viewpoint of artificial reefs in the Gulf have asserted that high densities of benthic feeding predators will eventually create a feeding halo around the reef and lead to necessary longer foraging distances over soft mud bottoms. (Lindberg et al.

2006, Campbell et al. 2011, Strelcheck et al. 2007) In addition, some authors have viewed the lack of decline in the shallow Gulf shelf biomass as a paradox in light of the seemingly increasing area of the hypoxic zone. (Bianchi et al. 2010) The possibility of the Gulf shelf being on the increasing part of the Caddy curve may not have been considered, even while relating a 4 fold increase in biomass between 2002 and 2010 and citing Caddy (1993). It seems ironic that the areas where biomass has increased 4 fold are portrayed as “dead zones.”

The new hypothesis we offer is that the nutrient loading in the northern and western Gulf of Mexico contributes significantly to the observed increases in red snapper production. The nutrient loading probably has multiple synergistic effects with the vertical reef structures (petroleum platforms), and by increasing biomass and productivity in forage species (red snapper eat almost any available forage) probably put enough forage within relatively short forage distances of most artificial reefs that the halo effect (if it exists at all) is of much less importance than in less productive ecosystems. In a recent study, Daigle (2011) found no halo effect around Louisiana shelf oil platforms that were well populated with red snapper, and no decrease of common red snapper prey items in the areas adjacent to the oil platforms.

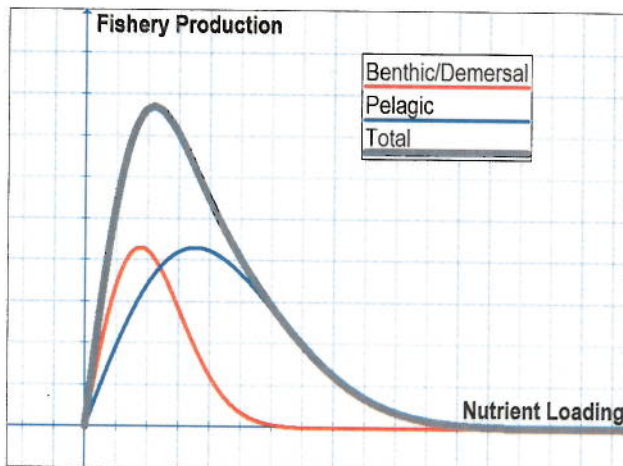


Figure 1: Caddy curve (Caddy 1993, 2000) showing that fishery production likely peaks with some optimal amount of nutrient loading and then sharply declines with higher loading due to eutrophication and hypoxia. Because hypoxia tends to impact bottom waters more strongly, the figure shows conceptual curves for benthic and demersal production separately from pelagic production which is likely to respond positively to greater nutrient loads before a sharp decrease as hypoxia begins to negatively impact the entire water column.

Figure 1 shows a graphical representation of the conceptual Caddy curve. (Caddy 1993, 2000) The basic ideas are intuitive and obvious, even though the details and thresholds will depend on the specific ecosystem. Oczkowski and Nixon (2007) found that Egyptian Nile delta productivity increased at nitrogen concentrations up to 100 μM and then declined. Mississippi River nitrogen concentrations tend to be about 100 μM before dilution with Gulf of Mexico salt water. Given the estimate of a four fold increase in overall biomass on the Louisiana-Texas shelf (Bianchi et al. 2010) and the increase in productivity of red snapper coincident with the increase in nutrient loading, it is certainly reasonable to suggest that red

snapper production is on the rising edge or near the top of the response curve of the species to nutrient loading.

In addition to providing hard substrate for many species near the bottom of the water column, petroleum platforms provide both hard substrate and cover throughout the water column. This enables red snapper to occupy a pelagic role in the food web, in addition to their more commonly accepted demersal role as a reef fish. McCawley (2003) found that even around the relatively low relief (< 2m) artificial reefs off the Alabama coast, red snapper diet included 41% (by weight) of prey items residing in the water column with 55% (by weight) of benthic prey items. The more pelagic role facilitated by petroleum platforms may have the effect of creating a broad, relatively flat near-optimum region in the red snapper production response to increasing nutrient loading as the population is able to shift from benthic to pelagic feeding in years where nutrient loading greatly increase pelagic production or the hypoxic zone depletes benthic resources. de Leiva Monero et al. (2000) found that, averaged across semi-enclosed European seas, pelagic production increased from 0.89 Mt/km² to 2.30 Mt/km² between mesotrophic and eutrophic systems; whereas, demersal production was flat averaging 0.83 Mt/km² for both mesotrophic and eutrophic systems.

It may be fortuitous that most artificial reefs on the Louisiana-Texas shelf are petroleum platforms that extend from bottom to surface providing structure for red snapper habitat at whatever level of the water column happens to be most productive at a given time; whereas, off the coast of Alabama, most of the artificial reefs are relatively low relief. This area of the shelf benefits from some level of nutrient enrichment from the Mississippi river discharge, but since the dominant currents move most of the Mississippi River plume westward, hypoxia in this area is less common.

In addition to the mechanism of increasing available forage for red snapper resident at artificial reefs, there is also the possibility of nutrient loading contributing to red snapper production via other mechanisms:

1. Nutrient loading increases productivity for important forage sources at key life stages.
2. The zone of hypoxia reduces the local population of predators that severely limited production at some life stage bottleneck.
3. At some key life stage, red snapper prey heavily upon forage fleeing from the hypoxic zone or recently deceased forage being moved out of the hypoxic zone by currents.
4. When the hypoxic zone dissipates in the fall, the fauna that quickly populate it provide more abundant forage than the fauna that dominate in the absence of hypoxic events.
5. Nutrient loading increases availability of cover at key life stages where available cover was an important bottleneck.

Discussion: Testability and Broader Applicability

The hypothesis that nutrient loading in the northern and western Gulf contributes significantly to red snapper production is testable and will tend to be supported by the following observations:

1. Correlation of increased red snapper production (or a given life history stage) with nutrient loading. Since nutrient loading varies considerably spatially and temporally, support will be

stronger if the observations are more localized.

2. Correlation of increased red snapper body condition (for example, using the relative condition factor, K_n). Relative condition factor is more sensitive than overall production or growth rates to seasonally or spatially varying factors.

3. The relative importance of hypoxia vs. nutrient loading should be considered. It is expected that nutrient loading in the absence of hypoxia will benefit red snapper more than cases where the same level of local nutrient loading is accompanied by local hypoxia.

4. Observations of nutrient loading leading to increased (probably vegetative) cover and observations of red snapper making use of vegetative cover at a key life history stage.

The principles and mechanisms that may be involved likely have broader applicability for interpreting and perhaps mitigating other eutrophic systems. The hypothesis that a valuable commercial fish species may be able to transition from demersal to pelagic to take advantage of (rather than suffer in) a eutrophic environment may have important analogs in other systems which tend to be dominated by small pelagic fishes once seasonal hypoxia begins (Caddy 2000). The challenge for fisheries managers is to find and determine how to make best use of this possible silver lining in systems strongly impacted by nutrient loading and eutrophication.

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References

Bianchi, T. S., DiMarco, S. F., Cowan, J. H., Hetland, R. D., Chapman, P., Day, J. W., & Allison, M. A. The science of hypoxia in the Northern Gulf of Mexico: a review. *Science of the Total Environment* (2010) 408(7): 1471-1484.

Breitburg, D. Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries and Coasts* (2002) 25(4): 767-781.

Caddy, J. F. Toward a comparative evaluation of human impacts on fishery ecosystems of enclosed and semi-enclosed seas. *Reviews in Fisheries Science* (1993) 1(1):57-95.

Caddy, J. F. Marine catchment basin effects versus impacts of fisheries on semi-enclosed seas. *ICES Journal of Marine Science: Journal du Conseil* (2000) 57(3): 628-640.

Campbell, M. D., Rose, K., Boswell, K., & Cowan, J. (2011). Individual-based modeling of an artificial reef fish community: Effects of habitat quantity and degree of refuge. *Ecological Modelling*, (2011) 222(23): 3895-3909.

Cowan, J. H., Grimes, C. B., Patterson, W. F., *et al.* Red snapper management in the Gulf of Mexico: science-or faith-based? *Reviews in Fish Biology and Fisheries* (2011a) 21(2):187-204.

Cowan Jr, J. H. Red Snapper in the Gulf of Mexico and US South Atlantic: Data, Doubt, and Debate. *Fisheries* (2011b) 36(7):319-331.

Daigle, S. T. *What is the Importance of Oil and Gas Platforms in the Community Structure and Diet of Benthic and Demersal Communities in the Gulf of Mexico?* (Doctoral dissertation, LSU 2011).

de Leiva Moreno, J. I., Agostini, V. N., Caddy, J. F., Carocci, F. Is the pelagic-demersal ratio from fishery landings a useful proxy for nutrient availability? A preliminary data exploration for the semi-enclosed seas around Europe. *ICES Journal of Marine Science: Journal du Conseil*, (2000) 57(4): 1091-1102.

Gallaway, B. J., Szedlmayer, S. T., Gazey, W. J. A life history review for red snapper in the Gulf of Mexico with an evaluation of the importance of offshore petroleum platforms and other artificial reefs. *Reviews in Fisheries Science* (2009) 17(1): 48-67.

Gazey, W. J., Gallaway, B. J., Cole, J. G., Fournier, D. A. Age Composition, Growth, and Density-Dependent Mortality in Juvenile Red Snapper Estimated from Observer Data from the Gulf of Mexico Penaeid Shrimp Fishery. *North American Journal of Fisheries Management*, (2008) 28(6): 1828-1842.

Greene, R. M., Lehrter, J. C., Hagy III, J. D. H. (2009). Multiple regression models for hindcasting and forecasting midsummer hypoxia in the Gulf of Mexico. *Ecological Applications* (2009) 19(5): 1161-1175.

Hanisko, D. S., Lyczkowski-Shultz, J., Ingram, G. W. Indices of larval red snapper occurrence and abundance for use in stock assessment. In W. F. Patterson, J. Cowan, G. R. Fitzhugh, & D. L. Nieland (Eds.), *American Fisheries Society Symposium* (Vol. 60, pp. 285-300). American Fisheries Society, 5410 Grosvenor Ln. Ste. 110 Bethesda MD 20814-2199 USA. 2007.

Lindberg, W. J., Frazer, T. K., Portier, K. M., Vose, F., Loftin, J., Murie, D. J., Hart, M. K. (2006). Density-dependent habitat selection and performance by a large mobile reef fish. *Ecological Applications* (2006) 16(2): 731-746.

McCawley, J. R. Diet and prey demand of red snapper, *Lutjanus campechanus*, on Alabama artificial reefs. (Master's thesis. University of South Alabama, Mobile, Alabama. 2003)

Monk, M. *Identification and Incorporation of Quantitative Indicators of Ecosystem Function into Single-species Fishery Stock Assessment Models and the Associated Biological*

Reference Points (Doctoral dissertation, Virginia Tech 2012).

Nixon, S. W., Buckley, B. A. (2002). "A strikingly rich zone"—Nutrient enrichment and secondary production in coastal marine ecosystems. *Estuaries and Coasts*, (2002) 25(4):782-796.

Rabalais, N. N., Turner, R. E., Wiseman Jr, W. J. Gulf of Mexico Hypoxia, AKA "The Dead Zone". *Annual Review of Ecology and Systematics* (2002) 33:235-263.

Rabalais, N. N., Turner, R. E., Sen Gupta, B. K., Boesch, D. F., Chapman, P., Murrell, M. C. Hypoxia in the northern Gulf of Mexico: Does the science support the plan to reduce, mitigate, and control hypoxia?. *Estuaries and Coasts* (2007) 30(5):753-772.

Redman, R. A., Szedlmayer, S. T. The effects of epibenthic communities on reef fishes in the northern Gulf of Mexico. *Fisheries Management and Ecology*, (2009) 16(5): 360-367.

Shipp, R. L., Bortone, S. A. A perspective of the importance of artificial habitat on the management of red snapper in the Gulf of Mexico. *Reviews in Fisheries Science* (2009) 17(1):41-47.

Strelcheck, A. J., Cowan Jr, J. H., Patterson III, W. F. SEDAR31-RD28. In *American Fisheries Society Symposium* (2007) 60:135-148.

Syc, T. S., Szedlmayer, S. T. (2012). A comparison of size and age of red snapper (*Lutjanus campechanus*) with the age of artificial reefs in the northern Gulf of Mexico. *Fishery Bulletin*, 110(4):, 458-469.

Szedlmayer, S. T. The artificial habitat as an accessory for improving estimates of juvenile reef fish abundance in fishery management. *The use of artificial reefs in fishery management*. (2011) 31-44.

Thurow, F. Estimation of the total fish biomass in the Baltic Sea during the 20th century. *ICES Journal of Marine Science: Journal du Conseil*, (1997) 54(3): 444-461.

Topping, D. T., Szedlmayer, S. T. Home range and movement patterns of red snapper (*Lutjanus campechanus*) on artificial reefs. *Fisheries Research*, (2011) 112(1): 77-84.