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SHORT PAPERS AND NOTES

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POTENTIAL IMPACTS OF EXTREME SALINITY AND SURFACE TEMPERATURE EVENTS ON POPULATION DYNAMICS OF BLACK DRUM, *POGONIAS CROMIS*, IN THE UPPER LAGUNA MADRE, TEXAS.—Black drum, *Pogonias cromis*, are a large bottom feeding sciaenid found mainly inshore from Massachusetts, U.S.A., along the western Atlantic to Argentina (Hoese and Moore, 1998) with a large population in Texas waters. Along the Texas coast, black drum are highly targeted by both recreational and commercial anglers, with the largest portion of the commercial catch coming from the upper Laguna Madre (ULM). This system is also known for having the largest population of black drum along the Texas coast (Pattillo et al., 1997; Martinez-Andrade et al., 2005). Black drum have been reported to make extensive spawning migrations offshore if their locale is near a bay pass (Simmons and Breuer, 1962; Cody et al., 1985); although fish within isolated bays, such as the ULM, may limit such migrations (Osburn and Matlock, 1984). Bumguardner et al. (1996) found that black drum within the ULM system mature at an earlier age (age 2) and have a slower growth rate compared to populations of drum elsewhere. In other bay systems along the Texas coast, maturity generally occurs at age 5 years, similar to black drum from Louisiana, northeast Florida, and Georgia (Music and Pafford, 1984; Murphy and Taylor, 1989; Nieland and Wilson, 1993; Bumguardner et al., 1996).

The ULM is a highly isolated hypersaline bay system located on the south Texas coast with limited access to Gulf of Mexico (GOM) waters due to its separation from the GOM by Padre Island, an extensive barrier island system. While the entirety of the Laguna Madre is known to be hypersaline, the ULM is known for exceptionally high salinities due to low circulation and lack of freshwater inflow (Collier and Hedgpeth, 1950; Tunnell and Judd, 2002). In the ULM, salinities regularly exceed 45 practical salinity units (psu; Tunnell and Judd, 2002). However, prior to the dredging of the Gulf Intracoastal Waterway (GIWW) in the 1940s, the ULM was separated from the lower Laguna Madre by an extensive land bridge and was even more isolated from GOM waters, resulting in much higher salinities than observed today. In addition to hypersalinity, the south Texas coast is periodically subjected to

harsh winter freeze events. Owing to the shallowness of the ULM and surrounding estuaries, such freeze events can result in extensive fish kills (Gunter and Hildebrand, 1951; Moore, 1976; Buskey et al., 1997), which may also locally impact population structure and dynamics of the system. Unique differences in ULM black drum may be developed adaptations to deal with the extreme environmental conditions and the resultant high mortality of this bay system (Bumguardner et al., 1996).

Reproductive adaptations to cope with hypersaline conditions in the ULM have been recorded in other sciaenids, although early maturation due to these conditions has not been reported (Kucera et al., 2002a, 2002b). Others have found that numerous external drivers can influence life history characteristics including age at maturity. Schlosser (1990) found that stream fishes living in more extreme and temporally variable physio-chemical conditions of the upstream environment reached sexual maturity at an earlier age than those living in less extreme downstream conditions. Meffe (1992) found that a population of eastern mosquitofish (*Gambusia holbrooki*) living under thermal stress for 28 years had developed the ability to mature at an earlier age at greater temperatures. Additionally, extensive work has been conducted examining the impacts of fishing pressure on age at maturity among populations (Law, 2000), although the selective impact of fishing pressure may differ from those of extreme environmental conditions as they are highly size selective.

The linkages between hypersalinity, winter freeze events, adult abundance, and black drum recruitment (i.e., juvenile abundance) have not been adequately examined for this system. Therefore, the objectives of this study are to (1) examine the abundance and recruitment patterns of black drum in the ULM compared with other Texas bay systems and (2) determine whether there is a significant relationship between hydrological data (salinity and temperature), adult abundance, and annual recruitment of black drum in the ULM.

Methods.—The ULM consists of multiple minor bay systems including the ULM proper, a primary bay system; Baffin Bay, a secondary bay system; and Alazan Bay, Cayo del Grullo, and Laguna Salada, all tertiary bay systems. For the purposes of this study, Baffin Bay, Alazan Bay, Cayo del

Fig. 1. A map of the upper Laguna Madre (ULM), Texas. For the purposes of this study, Baffin Bay, Alazan Bay, Cayo del Grullo, and Laguna Salada are referred to as Baffin Bay complex (BBC), while the primary bay system is referred to as the ULM proper. The dashed line represents the Gulf Intracoastal Waterway (GIWW).

Grullo, and Laguna Salada will be collectively known as Baffin Bay complex (BBC; Fig. 1).

In order to assess the population dynamics of adult and young-of-the-year black drum on the

Texas coast, data were obtained from Texas Parks and Wildlife Department (TPWD) Marine Resource Monitoring gill net and bag seine surveys, respectively. These surveys were con-

ducted within each of the nine major Texas bay systems (Sabine Lake, Galveston Bay, East Matagorda Bay, Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, upper Laguna Madre, and lower Laguna Madre). Gill net surveys were conducted for 10 wk in the spring and 10 wk in the fall with 45 samples collected per season in each major bay system from 1982 to 2012 (except for East Matagorda Bay where $n = 6$ –20 per season from 1982 to 1984 and $n = 20$ from 1985 to 2012, and Sabine Lake where sampling began in 1986). Catch per unit effort (CPUE) for gill net surveys is given as catches per hour. Bag seine surveys were conducted year round with 10–16 samples collected per month from 1982 to 1991 and 20 samples collected per month from 1992 to 2012 in each major bay systems (except for East Matagorda Bay where sampling began in 1983, $n = 9$ –16 per month from 1983 to 1991 and $n = 12$ per month from 1992 to 2012, and Sabine Lake where sampling began in 1986). CPUE for bag seine surveys is given in catches per hectare.

For both gear types, a stratified random sampling design was used to select appropriate sections of shoreline within each major bay system as part of the TPWD marine resource monitoring program. At each sampling location, surface salinity (psu) and surface temperature (C) were collected. For further descriptions of sampling gear and protocol, see Martinez-Andrade et al. (2005).

Mean annual catch rates were examined from 1982 to 2012 and are given separately for the ULM proper, the BBC, and all other bay systems (hereafter referred to as coastwide). To calculate coastwide catch rates for both gill net and bag seine data, annual bay specific catch rates were weighted based on miles of shoreline in the given bay system as determined by Matlock and Osborn (1982). Only individuals less than 111 mm were included in bag seine catch rates for black drum, as these are considered young-of-the-year (Martinez-Andrade et al., 2005). Catch rates among the ULM proper, the BBC, and coastwide were compared within years using a Friedman rank sum test because normality and variance assumptions were not met for parametric analysis of variance. Mann–Whitney U-tests with a Bonferroni correction of the alpha value were used for post-hoc testing to examine specific differences between sites. Because rank-based statistical procedures are used, the weighting process used to calculate coastwide catch rates does not preclude their comparison with ULM proper and Baffin Bay complex catch rates.

Multiple linear regression was used to assess the relationship between mean black drum

recruitment in the ULM (including both the ULM proper and the BBC; April–Aug. bag seine catch rates used), environmental factors thought to have the largest impact on the fauna of this system [salinity and winter temperature (Dec.–Feb.)], and subsequent abundance of adults. A salinity index was used to take into account raw salinity values and duration of salinity events. This index was calculated as follows:

$$\text{Salinity Index} = \text{Annual mean ULM salinity} \times (\text{Number of uninterrupted hypersaline months} + 1)$$

Here, uninterrupted hypersaline months were defined as consecutive months with a mean salinity greater than 44.1 psu [which is the mean salinity during the sampling period (1982–2012) plus one standard deviation] that occurred in association with that year (i.e., prior to and included in a given calendar year). A 1 mo gap interval was used, which is the allowable period of time that salinity can drop below the predetermined threshold and the hypersalinity event still deemed uninterrupted. These months are not counted as hypersaline months, but the period of time during which they occur is still deemed consecutive. Such methodology has been used in environment-recruitment correlations by Ulanowicz et al. (1982). Minimum monthly winter surface temperature (Dec.–Feb.) was also used as an explanatory variable in the model to take into account abnormally cold winters, which occasionally occur on the south Texas coast. Finally, fall gill net catch rates (Sept.–Nov.) of black drum were used to assess the impact of increased adult populations on subsequent recruitment. Here, a 1 yr lag was applied because spawning generally occurs in early winter (Simmons and Breuer, 1962; Nieland and Wilson, 1993), and thus the recruitment impacted by a given spawning event would be that of the following year. Assumptions of normality were verified by visual examination of plotted residuals and a Shapiro–Wilk normality test on residuals, while assumptions of multicollinearity were verified by visual examination of plotted independent variables. All statistical analyses were done using R (cran.us.r-project.org), and relationships were deemed significant at $\alpha = 0.05$.

Results.—Adult black drum abundance as determined by gill net catch rates was significantly different among sites (Friedman $\chi^2 = 45.7$, $df = 2$, $P < 0.001$). The BBC was found to have significantly greater gill net catch rates than both the ULM proper and coastwide, and the ULM proper catch rates were found to be significantly greater than coastwide (Fig. 2).

Fig. 2. TPWD fishery independent gill net catch rates of black drum as catch per hour within the Baffin Bay complex (solid line), upper Laguna Madre proper (dashed line), and coastwide (excluding entire upper Laguna Madre; dotted line; $\pm$ standard error). Note that standard error is excluded from the plot of coastwide catch rates because of the weighting process used to calculate these values.

Black drum recruitment as determined by bag seine catch rates was significantly different among sites (Friedman $\chi^2 = 39.9$, $df = 2$, $P < 0.001$). The BBC was found to have significantly greater recruitment than both the ULM proper and coastwide. However, ULM proper catch rates were not found to be significantly different from coastwide (Fig. 3a–c).

Mean annual salinity in the ULM during the study period was 37.0 ± 7.1 psu and ranged from 25.0 psu in 1992 to 48.7 psu in 1989. The longest hypersalinity events occurred in association with 1991 (30 mo), 1990 (28 mo), 1989 (18 mo), 2006 (9 mo), and 2012 (9 mo), with the highest salinity index occurring in 1990 (Figs. 4, 5). Minimum winter temperature ranged from 10.2°C in 1990 to 18.7°C in 1998 (Fig. 6). Salinity indices were positively related to recruitment ($t = 4.25$, $df = 1$, 27 , $P = 0.0002$), and minimum winter temperature was negatively related to recruitment ($t = -3.65$, $df = 1$, 27 , $P = 0.001$). Adult abundance showed a strong increase in the early 1990s, and remained high in subsequent years, although showing large amounts of variation. Adult abundance was found to be positively related to recruitment ($t = 3.17$, $df = 1$, 27 , $P = 0.004$). The multiple linear regression relationship is described as follows:

$$\text{Recruitment} = 1031.11 + 108.44 \times (\text{Adult abundance}) + 0.56 \times (\text{Salinity index}) - 81.60 \times (\text{Minimum winter temperature}), (R^2_{\text{adj}} = 0.54, F = 12.97, df = 3, 27, P < 0.0001)$$

Discussion.—Black drum in the ULM, and specifically in the BBC, seem to have the potential for much higher recruitment than elsewhere on the Texas coast, although peaks (years of increased recruitment) occur less often, and the disparity between high and low recruitment years are much greater in this system. This potential for extreme recruitment seems to relate to the unique reproductive biology of the ULM population first observed by Pearson (1928) and Simmons and Breuer (1962) and expanded on by Bumgardner et al. (1996). Early maturation of black drum could result in a higher number of spawning individuals in the population and thus a higher number of recruits, which is supported by the present work. Nonetheless, the variability in recruitment between years cannot be ignored. The two environmental parameters used in the regression model are those thought to have the largest impact on flora and fauna in the ULM. Periods of extended high salinity and periodic winter freezes create an extremely harsh and variable environment and have resulted in events

Fig. 3. TPWD fishery independent bag seine catch rates for black drum as catch per hectare in (a) Baffin Bay complex, (b) upper Laguna Madre proper, and (c) coastwide (excluding entire upper Laguna Madre; $\pm$ standard error). Note the differences in y-axis scale and that standard error is excluded from the plot of coastwide catch rates due to the weighting process used to calculate these values.

Fig. 4. Annual mean surface salinity (solid line) and salinity indices (dashed line) for the upper Laguna Madre (Baffin Bay complex and upper Laguna Madre proper combined). Salinity index calculations take into account both surface salinity and the duration of hypersalinity (44.1 psu) events.

such as harmful algal blooms, fish kills, and physiological impairment of organisms (Gunter and Hildebrand, 1951; Breuer, 1957; Deyoe and Suttle, 1994; Buskey and Hyatt, 1995), which could directly or indirectly impact black drum

recruitment success. Owing to the host of other variables that may also impact recruitment, the regression equation presented here is only intended for use as an exploratory tool, although it does suggest that the highest recruitment

Fig. 5. Monthly mean surface salinity (solid line) for the upper Laguna Madre (Baffin Bay complex and the upper Laguna Madre proper combined). The minimum threshold of hypersalinity (44.1 psu) is shown (dashed line) to highlight the duration of hypersaline events observed in this system and used in the calculation of salinity indices.

Fig. 6. Minimum winter surface temperature (Dec.–Feb.) for the upper Laguna Madre (Baffin Bay complex and upper Laguna Madre proper combined).

occurs under high salinity indices and low winter temperatures. However, the model fit is largely driven by extreme environmental parameters and (presumably) resultant recruitment of a small subset of years (e.g., 1990, 1997, 2001, 2006, 2012). Removal of these extreme years from the data set results in a large decrease in model fit, which suggests that the impacts of these environmental variables on recruitment are only felt under the most extreme conditions.

The sudden increase in abundance of adult black drum from 1992 to 1995 may have been a result of the exceptional 1990 recruitment event. Some of the peak recruitment events that have occurred since 1990 and not associated with extreme salinity and temperature may be more related to the increased adult population and only partially related to environmental factors. Additionally, the potential impact of decreased fishing pressure on the black drum population should be noted, since gill nets were banned in Texas waters in 1988. However, commercial fishing for black drum via trot line has continued, and TPWD data show sharp increases in catch during the early to mid-1990s (Culbertson et al., 2004). This implies that the introduction of these restrictions was probably not the cause of the observed patterns in abundance, and so fishing pressure was not included in the model.

Bumgardner et al. (1996) speculated that the early reproductive maturation of black drum observed in the ULM may be a result of the hypersaline conditions. Early maturation would

result in a greater chance of spawning success given periodic mortality events due to pre-GIWW high salinity events, and other researchers have found similar situations of early maturation under stressful and highly variable conditions (Schlosser, 1990; Meffe, 1992). Prior to the moderation of salinity in the ULM via the GIWW, salinities were reported in excess of 100 psu during drought events, and large fish kills resulting from these events were common (Pearson, 1928; Breuer, 1957). It was most likely under such historic conditions that this reproductive adaptation arose. Since the dredging of the GIWW, salinities rarely exceed 80 psu (TPWD, unpubl. data), and fish kills resulting from high salinity seem to occur less frequently and on a much smaller scale (Gunter, 1967). This suggests that the large population of black drum currently supported by the ULM may be a result of overcompensation in reproductive output (due to early maturation) to counteract periodic mortality events associated with extreme salinity no longer observed.

While the GIWW has been moderating ULM salinities for decades, early maturation is still observed in this system. This would be expected, since selection for later maturation would generally be weak, and thus populations that have trended toward early maturation could remain even after the selection pressure has been removed (Law, 2000). However, the GIWW should serve as a genetic corridor between other “non-early maturing” populations of black

drum along the Texas coast (Anderson and Karel, 2010) introducing such genes into the population. Because early maturation is still evident in the ULM, current salinities may be substantial enough to limit immigration into the bay system (Karel et al. 1996). This suggests a higher salinity tolerance for ULM black drum, although the exact tolerance limits of this population have not been examined.

Observations of black drum in the ULM during high salinity events and their presence in the bay system prior to the dredging of the GIWW (Pearson, 1928; Simmons and Breuer, 1962) suggests that this species may be able to withstand the extreme conditions associated with the ULM better than potential competitors or predators such as spotted seatrout (*Cynoscion nebulosus*) and red drum (*Sciaenops ocellatus*). While adult black drum most likely do not compete with these organisms to any significant extent, juveniles of these species do possess similar feeding strategies (Simmons and Breuer, 1962; Martin, 1979; Dugas, 1986; Peters and McMichael, 1987; McMichael and Peters, 1989; Hettler, 1989). Additionally, many fish species found in the ULM are known to be piscivorous and may opportunistically feed on juvenile black drum. While little work has been done concerning the salinity or temperature tolerance of the species discussed here specific to the hypersaline ULM, tolerance limits reported elsewhere suggest that juvenile and adult black drum may be better suited to deal with the extreme conditions of this bay system (Pattillo et al., 1997). As a result, a loss of such potential competitors and predators during extreme salinity/temperature events due to differential survivorship or tolerance levels could create a sort of hypersalinity or thermal refuge for black drum. This would allow the overcompensation of reproductive output, discussed previously, to then result in extremely high levels of recruitment in the BBC during such years. Additionally, the prevalence of mud bottom habitat and lack of seagrass coverage in the BBC (Tunnell and Judd, 2002) may provide a preferable environment for juvenile black drum and may preclude the presence of seagrass-dependent species such as spotted seatrout in greater numbers (McMichael and Peters, 1989; Pattillo et al., 1997). Nonetheless, until work related to tolerance limits and habitat preferences specific to ULM populations is conducted, it should be stressed that many of these statements are strictly speculative.

The asymptotic pattern of the adult drum population in the BBC suggests that it may have reached a carrying capacity (Fig. 2). Additionally, the large amount of variability between years

at high population levels may further suggest changes in resource availability from year to year, thus limiting this particular population. This was first suggested by Olsen et al. (2014) in light of an emaciation event observed in BBC black drum during the fall of 2012. The unique population dynamics discussed in this report may be at least a partial cause of this event.

Conclusions.—Population dynamics of black drum in the ULM differ from those observed coastwide. Adult black drum are four to six times more abundant in the ULM, and recruitment occurs on a much larger scale here than in other bay systems. This potential for higher recruitment is evidence for early reproductive maturation observed in this population (Bumgardner et al., 1996) and the subsequent large population size resulting from such extreme recruitment. Additionally, variability in recruitment from year to year seems to be at least partially related to high salinity indices and low winter temperature within this system, especially during the most extreme years. Such conditions may result in reduced predation on or reduced interspecific competition with larval/juvenile black drum, resulting in the observed peaks in recruitment, although further work on trophic relationships and salinity tolerance of organisms specific to this bay system is warranted.

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