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Assessing southern flounder (*Paralichthys lethostigma*) long-term population trends in the northern Gulf of Mexico using time series analyses

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ABSTRACT

A long-term fisheries independent data set (1975–2008) was used to assess population trends of juvenile and adult southern flounder (*Paralichthys lethostigma*) along the Texas coast in the northern Gulf of Mexico, USA. The dataset contained a total of 46,784 sites that were sampled with bag seines to monitor small nekton abundance and 22,870 sites that were sampled with gill nets to assess adult fisheries trends. These data were examined for age-specific population trends using generalized least squares and extended with non-parametric bootstrapping to obtain interval estimates of regression parameters (juveniles) and linear regression (adults). These data showed long-term declines in juvenile southern flounder abundance (1.3% per year). For adult southern flounder, rate of decline was much more rapid (2.5% per year). Results suggest that survival of post-juvenile flounder has decreased during the time series. This precipitous decline has prompted increasingly stricter harvest restrictions along the Texas coast. However, these management measures have been insufficient to curb declines.

1. Introduction

Flounder have historically supported an important multi-million dollar commercial and recreational fishery along the Texas coast (Matlock, 1991; VanderKooy, 2000), but declines in this stock have concerned resource managers and led to substantially reduced recreational and commercial catches. While a Fisheries Management Plan (FMP) for the Gulf of Mexico flounder fishery was developed by the Gulf States Marine Fisheries Commission in 2000, a paucity of data prevented a complete Gulf-wide stock assessment for the flounder fishery (VanderKooy, 2000). This fishery is primarily represented by southern flounder (*Paralichthys lethostigma*) and gulf flounder (*Paralichthys albigutta*). In Texas, southern flounder represents over 95 percent of harvested flounder and is one of the top three fish species targeted by anglers (Riechers, 2008). Decreases in harvest (recreational and commercial fishing) suggest that southern flounder may be declining in Texas waters. For example, inshore commercial harvest has declined from 500,000 fish per year between 1985 and 1987 to <100,000 fish in 2007 (Riechers, 2008). Recreational catches have also declined from 200,000 fish in 1987 to <50,000 fish in 2007 (Riechers, 2008). Offshore commercial catch rates have declined from 325,000 fish in 1987 to <50,000 in 2007 (Riechers, 2008). Although harvest catches have declined, long-term population trends for the southern flounder fishery have not been quantitatively examined in Texas.

Due to concern about regional declines, a series of increasing stricter regulations for recreational fishing of southern flounder have been implemented in both directed and shrimp trawl fisheries. Most recently in March 2009, Texas adjusted the bag-limit from a 10-fish to a 5-fish possession law for every month but November (Riechers, 2008). In November (the period when adults migrate offshore to spawn) anglers are limited to a 2 fish possession law. Estimates of by-catch rates in Texas are highly variable, from 925,000 to 9.7 million individual southern flounder per year (VanderKooy, 2000). To reduce by-catch mortality from shrimp trawl by-catch, a limited entry coupled with buy-back program of shrimp vessels was established in 2002 resulting in retirement of 57% of estuary/bait licenses, subsequently reducing flounder catches by at least 40% (Riechers, 2008).

Despite concern about the status of this important fishery, there is little empirical evidence documenting long-term abundance indices in the Gulf of Mexico, preventing effective evaluation of stock status or effectiveness of management actions. Thus, the objective of this study was to use a long-term fisheries independent data set to assess abundance trends of both juvenile (1979–2007) and adult (1975–2008) life-stages of southern flounder throughout the major bay systems off the Texas coast. Specifically, we examined age-specific population trends using generalized least squares with non-parametric bootstrapping to obtain interval estimates of regression parameters (juveniles) and linear regression (adults).

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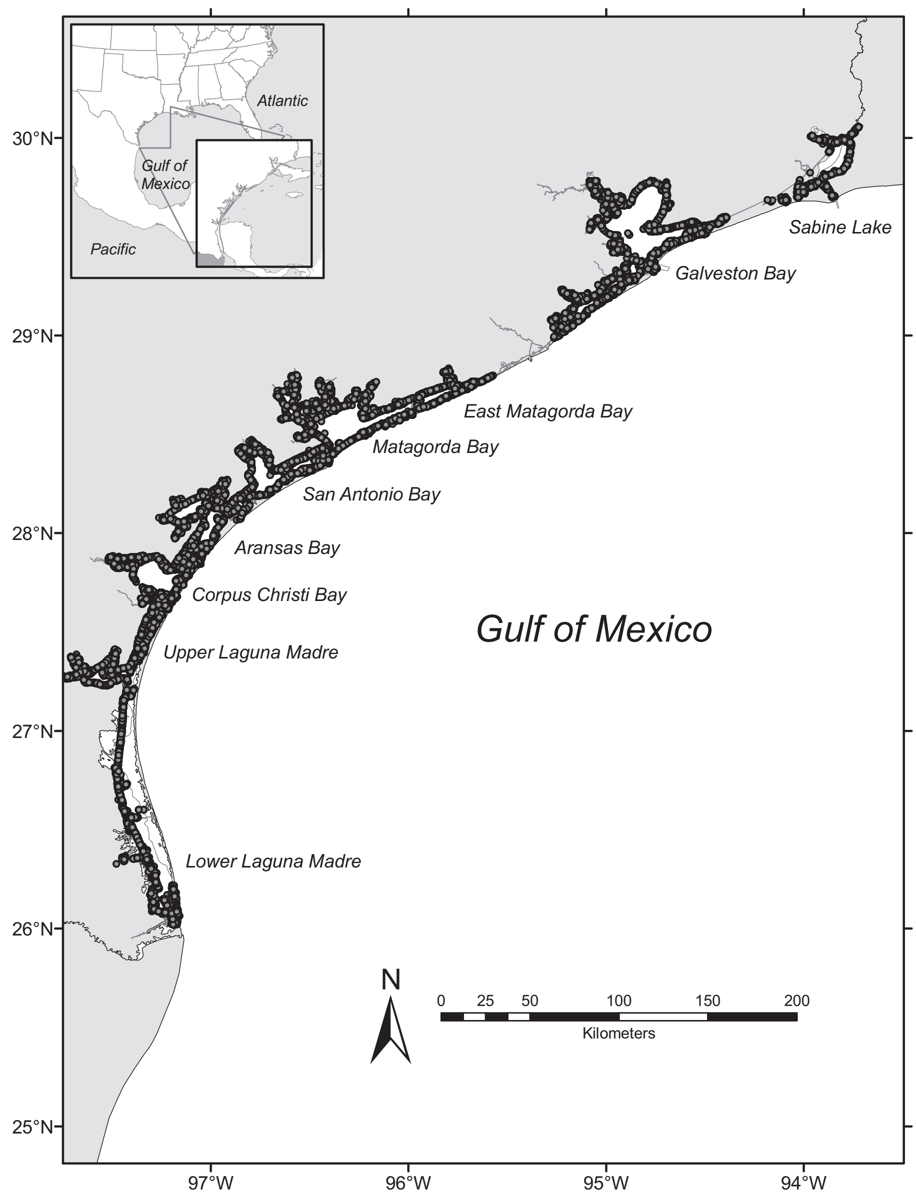

Fig. 1. Total bag seine sampling locations (black circles, n = 46,784) for the TPWD Resource and Sport Harvest Monitoring Program from 1979 to 2007 (each site was sampled once over the course of the study).

2. Materials and methods

2.1. Study area

The study was conducted in nine major bays along the Texas coast, within the northwestern Gulf of Mexico (Fig. 1). The Texas coast is 563 km in length and contains five Barrier Islands that stretch approximately 161 km. There are eight consistently open, federally maintained ship channels that provide pathways for water exchange and animal transport between nearshore bays and the Gulf of Mexico (http://goliath.cbi.tamucc.edu/TexasInletsOnline/TIO%20Main/index.htm). Sample sites were chosen randomly from 1-min latitude and longitude grid cells consisting of a minimum of 15.2 m of shoreline.

2.2. Field collection

Data were collected as part of the Texas Park and Wildlife Department Resource and Sport Harvest Monitoring Program of finfish and shellfish that has occurred since 1977 for juveniles and 1975 for adults in nine bays along the Texas coast (Fig. 1). All sampling followed protocols detailed in the "Marine Resource Monitoring Operations Manual" (Martinez-Andrade et al., 2009). Juvenile southern flounder (<2 years, 11–290 mmTL; Stokes, 1977; Etzold and Christmas, 1979; Stunz et al., 2000) were sampled monthly using a randomized, stratified sampling design along the shoreline of each bay with 18.3 × 1.8-m bag seines. The bag seines used in this study were designed to sample juvenile estuarine fish populations (Martinez-Andrade et al., 2009). While formal gear selection studies were not performed, previous studies on this species have shown this to be an effective gear for sampling juvenile southern flounder (Nañez-James et al., 2009). Bag seines were deployed perpendicular to the shoreline and were carried parallel to the shoreline for 15.2 m. Twenty bag seines were deployed each month in Sabine Lake, Galveston Bay, West Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, Upper Laguna Madre, and Lower Laguna Madre, and 10 bag seines were deployed each month in East Matagorda Bay. Moreover, for each sample (bag

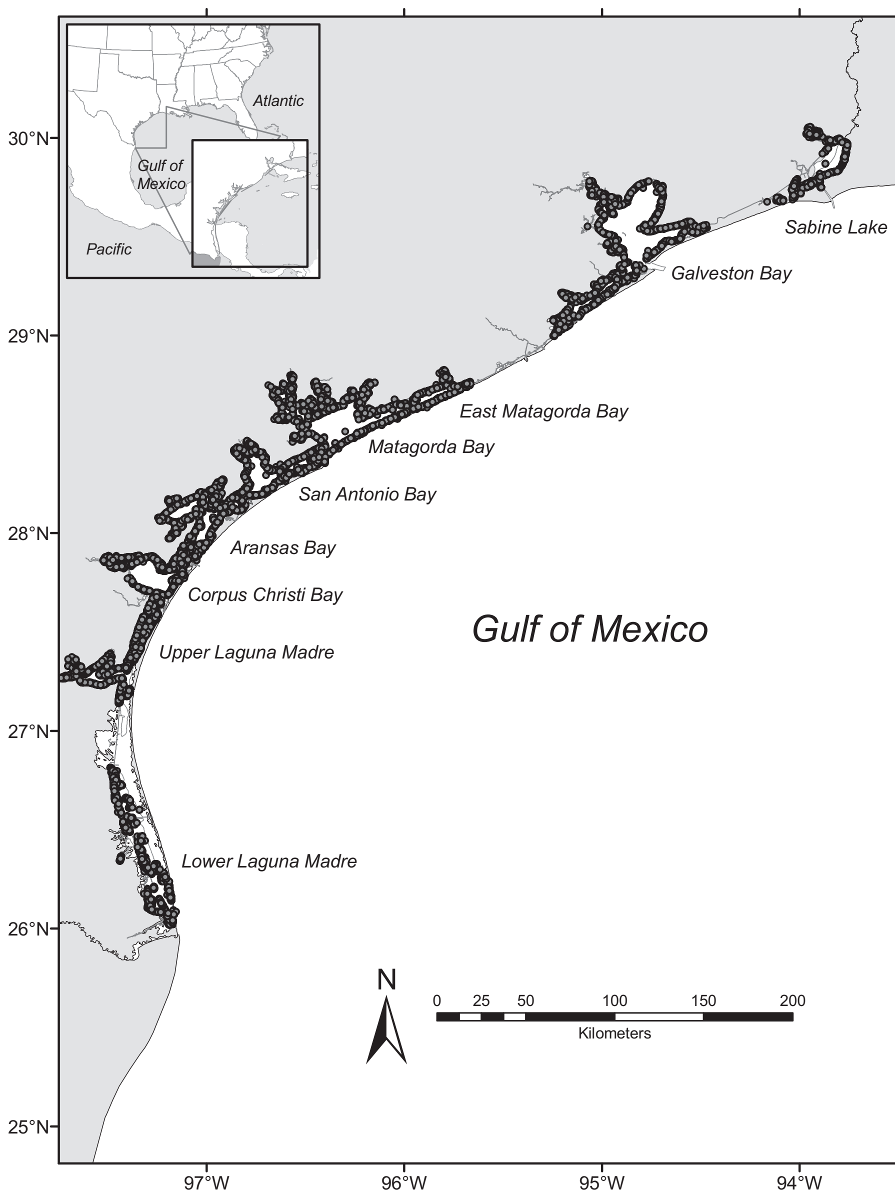

Fig. 2. Total gill net sampling locations (black circles, n = 22,870) for the TPWD Resource and Sport Harvest Monitoring Program from 1975 to 2008 (each site was sampled once over the course of the study).

seine) longitude and latitude coordinates were recorded, and total length (TL) of each fish was measured.

Adult southern flounder (mature at age 1–2) were monitored twice per year (fall and spring) by deploying 183-m gill nets (Martinez-Andrade et al., 2009). Sampling locations (Fig. 2) were selected by dividing each estuary into 5-s gridlets that were chosen randomly without replacement during each sampling period. Each year spring sampling started the second full week of April and fall sampling started the second full week of September. Both sampling periods continued for 10 consecutive weeks. Gill nets were set perpendicular to shore at or near sunset and were retrieved the following day within a few hours of sunrise. At each site, adult southern flounder (≥290 mmTL; Stokes, 1977; Etzold and Christmas, 1979; Stunz et al., 2000) were counted and total length was taken. Ninety nets were deployed yearly (45 seasonally) at Sabine Lake, Galveston Bay, West Matagorda Bay, San Antonio Bay, Aransas Bay, Corpus Christi Bay, Upper Laguna Madre, and Lower Laguna Madre (n = 720 nets a year), and 40 gill nets were deployed yearly (20 seasonally) in East Matagorda Bay (Fig. 2, Martinez-Andrade et al., 2009).

2.3. Time series analyses

All analyses were conducted in R 2.9 (R Development Core Team, 2009) using the following libraries: "TSA" (Chan, 2008), "nlme" (Pinheiro et al., 2009), and "lmtest" (Zeileis and Hothorn, 2002). Prior to analyses, counts of juveniles were standardized to catch per unit effort (CPUE) as the number of fish per hectare (ha) and adult counts were standardized to CPUE as the number of fish per net per hour ($CPUE_{juv}$ = juvenile; $CPUE_a$ = adult). Principal component analysis indicated that there was not a spatial difference among the bays for juveniles and adults. Therefore, all bays were pooled together for both juvenile and adult southern flounder. Mean $CPUE_{juv}$ was calculated on a monthly basis per year and $CPUE_a$ mean was calculated on a yearly basis. Both data sets were tested for assumptions of linear regression using models:

$$1a: \text{Juveniles}: \text{CPUE}_{ij} = \text{Intercept} + Y_i + M_j + \text{Residuals}_{ij}$$

$$2b: \text{Adults}: \text{CPUE}_i = \text{Intercept} + Y_i + \text{Residuals}_i$$

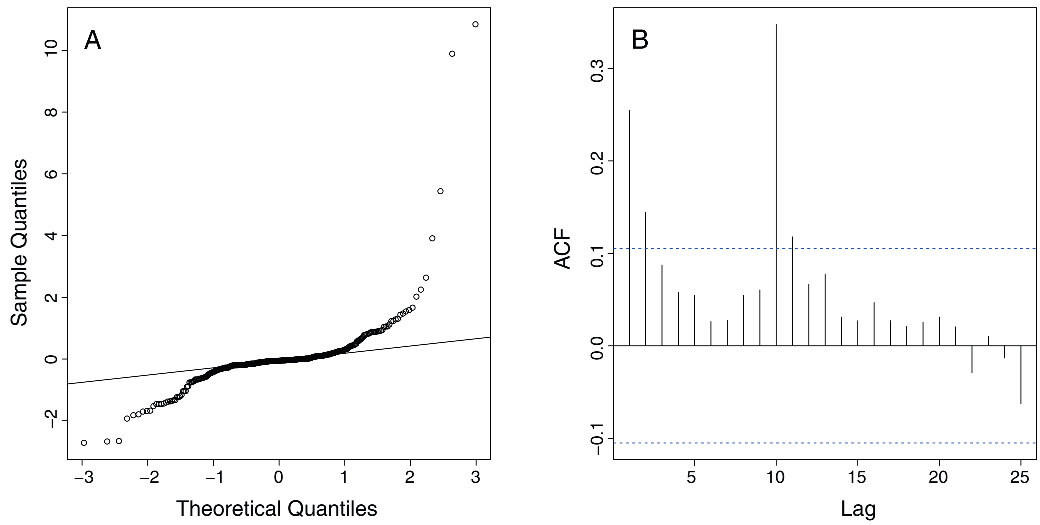

Fig. 3. (A) Quantile plot of the standardized residuals obtained from the juvenile southern flounder regression model (monthly mean $CPUE_{juv} \sim$ Intercept + Year + Month + Residuals) indicating residuals are not normally distributed. (B) Autocorrelation of standardized residuals on a monthly basis. Vertical bars beyond the dashed horizontal lines at approximately 0.1 and −0.1 indicate significant autocorrelation of the residuals at time 1 and 10 months ($p < 0.05$). Lag time of months is on the *X*-axis and the estimated autocorrelation function composes the *Y*-axis.

where $CPUE_{ij}$ equals $CPUE_{juv}$ for year i and month j, $CPUE_i$ equals $CPUE_a$ for year i, Y_i equals the year of collection ($i = 1975, 1976, \ldots, 2008$), and M_j is a factor corresponding to month of collection ($j = 1, 2, \ldots, 12$). Assumptions tested included normality and homogeneity of variance in residuals, independence between variables and linearity between dependent and independent variables (Zuur et al., 2007). The presence of outliers was evaluated graphically with density plots and box plots of the dependent variables, $CPUE_{juv}$ and $CPUE_a$. Normality of residuals was examined using a Quantile–Quantile plot (Fig. 3A), while homogeneity of variance in residuals was examined using a plot of standardized residuals versus fitted CPUE's. Autocorrelation of $CPUE_{juv}$ and $CPUE_a$ was tested by computing sample autocorrelation function of the residuals (Fig. 3B).

Exploratory analysis of juvenile catch data indicated both a large proportion of zeros and outliers. Regression residuals were not normally distributed and contained heterogeneity (Fig. 3A). There was a significant 10-month autocorrelation lag within the juvenile time series (Fig. 3B). To correct for a large proportion of zeros (zeros were included in the model) and heterogeneity of variance, the data were analyzed using generalized least squares (gls) to test the null hypothesis of no difference in mean $CPUE_{juv}$ among months or years:

$$3c: \ CPUE_{ij} \sim \text{Intercept} + Y_i + M_j + CPUE_{i(j-1)} + \text{Residuals}_{ij}$$

where $CPUE_{ij}$, Y_i, and M_j have the same meaning as model 1a, and $CPUE_{i(j-1)}$ equals $CPUE_{juv}$ for the previous month. $CPUE_{i(j-1)}$ was added as a covariate to model 3c to account for autocorrelation within the data set. The residuals were fitted using a varIdent variance structure from the "nlme" library in R, where each month was allowed to have a different variance (Zuur et al., 2007). All months were tested for significance against January, due to January being shown as the first month of recruitment in Texas (King, 1971; Stokes, 1977; Nañez-James et al., 2009). Nonparametric bootstrapping with replacement ($n = 1000$) of the resulting coefficients were used to estimate confidence intervals of the gls model parameters without making assumptions about the population distribution. Confidence intervals at 2.5% and 97.5% were calculated using the bias-corrected accelerated method (Bca). The Bca was chosen to reduce the influence of the outliers on the confidence intervals for Y_i and M_j.

Exploratory analysis conducted on southern flounder $CPUE_a$ indicated that residuals were normally distributed and homogenous, and there was no autocorrelation detected, indicating independence of residuals through time. To test the null hypothesis that the slope of the trend line for adult CPUE over time was not significantly different from zero, a least-squares linear regression was used where:

$$4d: \ CPUE_i \sim \text{Intercept} + Y_i + \text{Residuals}_i$$

where $CPUE_i$ and Y_i have the same meaning as model 2b.

2.4. Comparison of time series

To evaluate the relationship between juvenile and adult time series a lagged regression was conducted using the yearly mean CPUE of adults from 1982 to 2008 and juvenile yearly CPUE from 1979 to 2007. Yearly mean juvenile CPUE was shifted to date back from one year to three years for each yearly mean adult CPUE. Dating back three years was used due to southern flounder reaching adult sizes and maturity around 2 years of age. Akaike's information criterion (AIC) was used to determine the "best" model and an ANOVA was used to determine if there was a significant difference between model 4d and 5e.

$$5e: \ CPUE_i \sim \text{Intercept} + Y_i + FY_j + SY_k + TY_l + \text{Residuals}_{ijkl}$$

where $CPUE_i$ and Y_i have the same meaning as model 2b and FY_j is the yearly mean CPUE for juveniles from the previous year, SY_k is the yearly mean CPUE for juveniles two years back, and TY_l is the yearly mean CPUE for juveniles three years back.

Percent of decline was calculated for both $CPUE_{juv}$ and $CPUE_a$ using the following formula:

$$6f: \ \text{Pct decline} = 1 - \frac{CPUE_{i\,max}}{CPUE_{i\,min}}^{(1/\Delta i)}$$

where $i$max equals the final year in the time series (2007 for the juvenile population and 2008 for the adult population), $i$min equals the first year in the time series (1979 for the juvenile population and 1975 for the adult population), and Δi equals number of years in the time series (juvenile time series = 29 years and adult time series = 33 years). Also, $CPUE_{imax}$ and $CPUE_{imin}$ are the

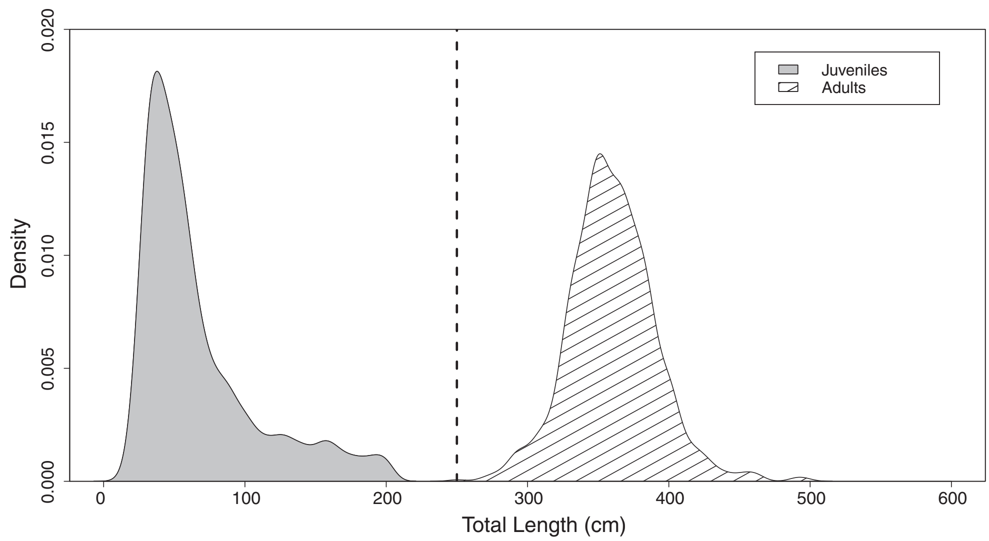

Fig. 4. Density graph of TL of juvenile southern flounder and TL of adult southern flounder. All lengths to the left of the vertical dotted line indicate lengths of juveniles (shaded grey). Mean length = 66.99 mmTL. All lengths to the right of the vertical dotted line indicate lengths of adults (horizontal lines). Mean length = 360.02 mmTL.

predicted mean annual values from the 3c gls model for juvenile population and the 4d linear model (lm) model for the adult population.

3. Results

3.1. Juvenile time series

Over 29 years of monitoring juvenile populations with bag seine sampling (1979 through 2007), 46,784 sites were sampled covering a total of 1460 ha. Juvenile southern flounder were present at 2.33% of the sites ($n = 1088$) with a total of 5712 juvenile southern flounder collected (Fig. 1). The overall arithmetic mean of all of the sampling locations was 0.12 fish/haul. The maximum count of juvenile southern flounder was 85 fish/haul and occurred in Aransas Bay in April 1989.

The total length of southern flounder collected ranged from 11 to 203 mm TL and were considered to be juveniles based on published length at age studies (Stokes, 1977; Etzold and Christmas, 1979; Stunz et al., 2000). Mean length of captured individuals was 66.99 mm TL (Fig. 4). The juvenile patterns over time (1979–2007) showed yearly and monthly variation in recruitment of southern flounder (Fig. 5). December had lowest mean $CPUE_{juv}$ and March had highest (Fig. 5). January, and August through December, had lowest minimum $CPUE_{juv}$ and were consistent over time (Fig. 5). April had highest maximum $CPUE_{juv}$ and November had lowest maximum $CPUE_{juv}$. Moreover, February, March, and April had the three highest mean $CPUE_{juv}$, but those months also had the largest ranges, with April having the largest range. Catch-per-unit-effort ($CPUE_{juv}$) was typically highest in March (21 out of 29 years sampled) (Fig. 5). There were three years, 1982 (March), 1989 (April), and 1990 (February) where $CPUE_{juv}$ was substantially higher than all other years (Fig. 5). Over all years, the minimum monthly mean ranged from 0.0 to 54.6 $CPUE_{juv}$. Maximum monthly mean was 54.63 $CPUE_{juv}$ (occurred April 1989), the overall mean of the monthly means was 4.007 $CPUE_{juv}$, and median was 1.176 $CPUE_{juv}$ (Fig. 5).

A generalized least squares model (gls) indicated that there was a slight but significant decline in yearly $CPUE_{juv}$ from 1979 to 2007 (slope = −0.0117, 95% confidence interval of (−0.022, −0.0007)), which corresponds to a decline of 1.3% per year since 1979 using formula 6f (Table 1). In comparison with the base $CPUE_{juv}$ in January, the $CPUE_{juv}$ was significantly higher in February, March, and April, and significantly lower in October, November, and December. Additionally, standardized residuals from model 3c for each month were evenly distributed (Fig. 6), normally distributed, and the previously significant autocorrelation at 10 months was much reduced.

3.2. Adult time series

A total of 22,870 sites were sampled over the 33-year period (1975–2008). Out of the 22,870 sites adult southern flounder were collected in 40% of the samples ($n = 9188$) with a total of 18,542 adult southern flounder collected. The count of adult southern flounder collected at a sampling location ranged from 0 to 31 (mean = 0.81). The maximum count of adult southern flounder occurred in Upper Laguna Madre in April 1991. For each sampling location a mean length was calculated for all southern flounder collected. Overall, mean length was 360 mmTL and ranged from 250 to 497 mmTL (Fig. 4). The minimum $CPUE_a$ was 0.02 (occurred in 2007) and maximum $CPUE_a$ was 0.103 (occurred in 1980; Fig. 7) with all bays pooled together. There was a highly significant decrease of mean yearly $CPUE_a$ of adult southern flounder ($R^2 = 0.5441$, $F_{1,32} = 38.19$, slope = −0.00148). Overall adult southern flounder have decreased on average by 2.5% per year since 1975 (Fig. 7).

3.3. Juvenile time series versus adult time series

There was no relationship between the juvenile and adult southern flounder time series. Including up to three years of previous yearly mean CPUE of juveniles did not contribute any significance to the adult time series model. The AIC for model 4d was −242.93 and −239.35 for model 5e. Moreover, the comparison ANOVA between the two models indicated no significant difference between model 4d and model 5e ($F_{25,22} = 0.6897$, $p = 0.568$).

To compare relative rates of change in juvenile and adult populations, percentage decline was calculated for $CPUE_{juv}$ from 1979 to 2007 and $CPUE_a$ from 1975 to 2008. Juvenile population indicated an annualized decline of 1.3% $(1 - \left(\frac{3.22}{4.73}\right)^{1/29})$ and the adult population indicated an annualized decline of 2.5% $(1 - \left(\frac{0.037}{0.085}\right)^{1/33})$. Thus, the adult population is declining twice as fast as the juvenile population.

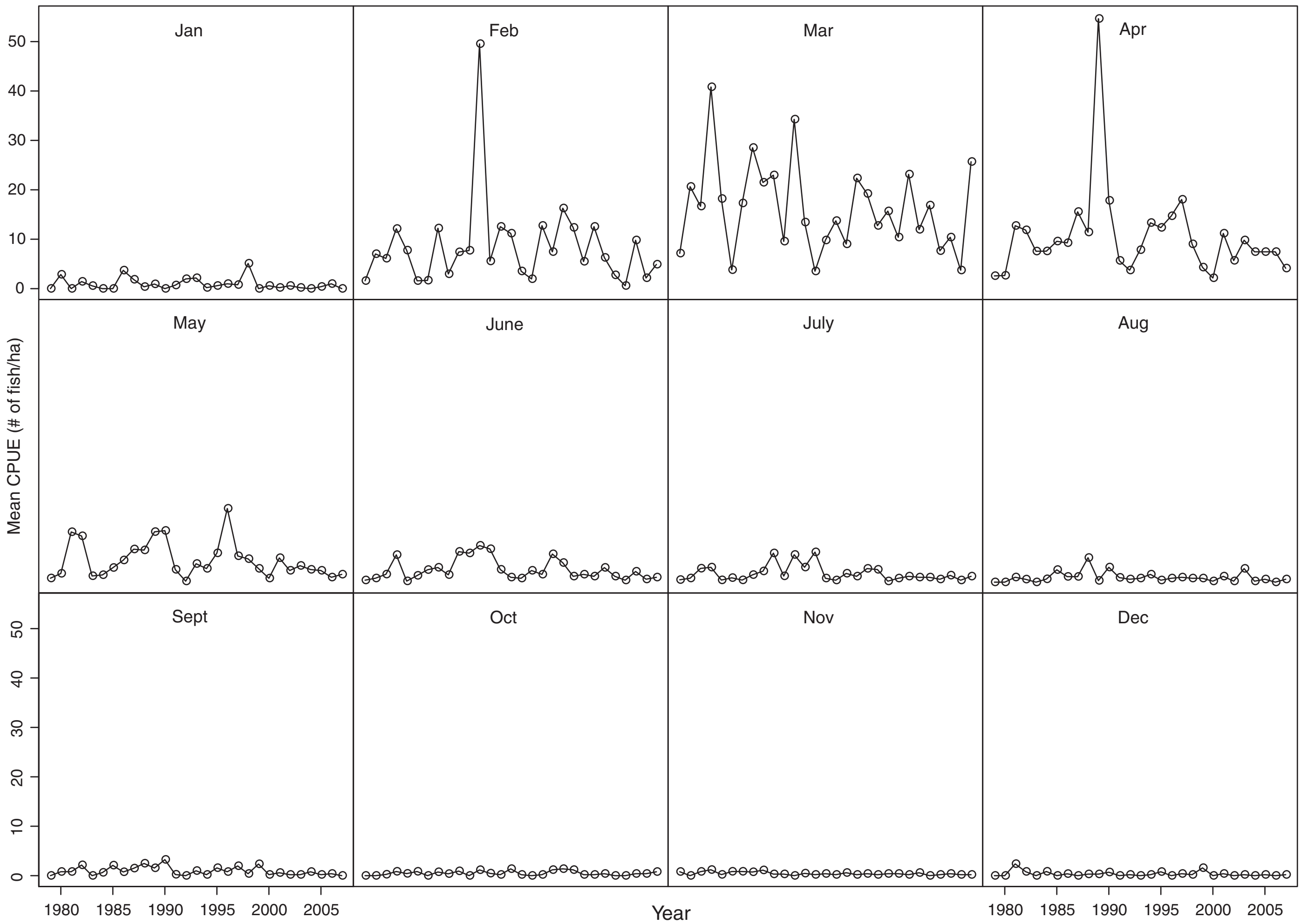

Fig. 5. Mean $CPUE_{juv}$ of juvenile southern flounder by month from 1979 to 2007. In most years, the highest monthly mean $CPUE_{juv}$ occurred in March (72%); for the remaining years, the monthly high occurred in February or April.

4. Discussion

Our results show high monthly recruitment variability of juvenile southern flounder with significant increases in abundance from February to May with a peak in March. Low juvenile abundances in June and subsequent months indicate that the recruitment period ends by May each year. Juveniles present have either moved to different habitats or have grown large enough to avoid the sampling gear. Recruitment of southern flounder has been reported in December (Günter, 1945; King, 1971) although in this study, the abundance of juveniles was significantly lower in both December and January. These results suggest that substantial recruitment begins in February each year. Others have reported high recruitment variability in flatfish populations (Van der Veer et al., 2000). Günter (1945) reported southern flounder recruitment in December and from February to April, whereas Stokes (1977) reported the presence of juveniles starting in January with a peak in February. Simmons and Hoese (1959) stated that recruitment occurred from March to May with a peak in April. Rogers and Herke (1985) and Nanez-James et al. (2009) reported a January to March recruitment period with peaks occurring from February to March. Overall, observed recruitment patterns were consistent with seasonal patterns described previously.

The southern flounder population in Texas is declining and adults are declining two times faster than the juveniles. Catch-per-unit-effort of juveniles decreased only slightly during the 29-year study period (decreasing by 1.3% per year), indicating that the larger decline seen in the adult population may not be due to recruitment limitation and could be the result of over harvesting. A recruitment limited population has been defined as, “a population that is undersaturated as a result of a finite larval supply and could support greater abundance given enhanced recruitment” (Doherty, 1998). Results of the present study indicate that recruitment of southern flounder may not be the primary cause of the adult pop-

Table 1
Summary of results obtained from the generalized least squares model for juvenile southern flounder time series, including confidence intervals obtained from bootstrapping.

	Value	Standard error	*t*-Value	2.50%	97.50%
Intercept	24.25	9.15	2.65	3.58	42.28
Year	−0.01	0.004	−2.56	−0.022	−0.0007
February	7.34	1.68	4.37	4.705	11.081
March	13.09	1.53	8.56	10.032	16.084
April	5.41	1.88	2.88	1.771	9.715
May	0.69	0.68	1.01	−0.674	1.883
June	0.47	0.44	1.05	−0.527	1.359
July	0.22	0.34	0.64	−0.475	0.929
August	−0.37	0.29	−1.25	−0.967	0.158
September	−0.21	0.27	−0.78	−0.781	0.313
October	−0.64	0.25	−2.6	−1.157	−0.192
November	−0.58	0.24	−2.45	−1.072	−0.146
December	−0.65	0.25	−2.58	−1.163	−0.178
Previous month (PM)	0.27	0.03	7.77		

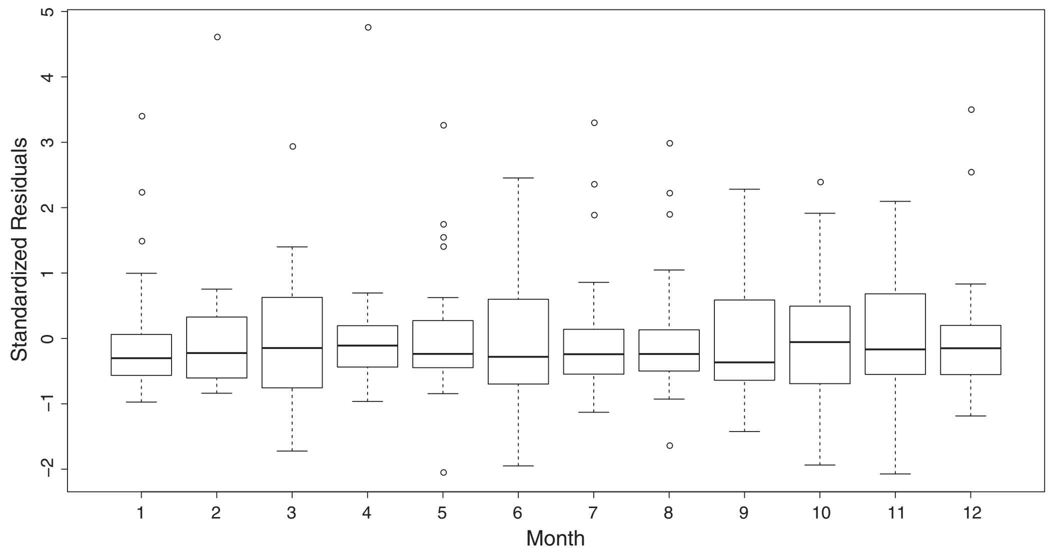

Fig. 6. Boxplots of the residuals per month from the juvenile southern flounder fitted generalized least squares model (3c). Along the *X*-axis, 1 = January, 2 = February, 3 = March, 4 = April, 5 = May, 6 = June, 7 = July, 8 = August, 9 = September, 10 = October, 11 = November, and 12 = December.

ulation decline given that catch rates of juveniles are nearly stable and the rate of decline in adults exceeds what can be explained by the decline in juveniles. The decline in adult southern flounder abundance may be attributed to lower survivorship of adults and late juveniles nearing maturity (sub-adult stage) due to increased fishing and/or natural mortality. Other researchers have shown that survival of juvenile fishes just prior to maturity may be more important for population stability/recovery than young-of-year fish (Gaullucci et al., 2006; Kinney and Simpfendorfer, 2009). Thus, we suggest that management of southern flounder focus on increasing survivorship of one and two year old fish.

The recruitment limitation literature shows that for many marine species recruitment levels can be good predictors of subsequent population size (Hixon, 1998; Armsworth, 2002). However, this was not observed for southern flounder population in Texas as high recruitment levels were observed despite adult declines. For example, this time series encompassed three years with unusually high abundances of juveniles (1982, 1989, and 1990), yet these large abundance peaks were not detected in the adult time series in subsequent years, suggesting density dependent survivorship of juveniles, during periods of peak recruitment. Moreover, there were small peaks in the abundance of adult southern flounder in 1980, 1982, 1985, and 1991 but these peaks were not detected in juvenile population surveys in prior years. Including previous year CPUE of juveniles to the overall adult model was not significantly different than without. These results suggest that abundance trends of juvenile and adult southern flounder were independent, particularly with high mortality rates of post-juvenile flounder that occurred during the time series.

Stunz et al. (2000) demonstrated that a reduced proportion of southern flounder are reaching age of maturity. Both recreational and commercial fishing rates have ranged from 50,000 fish/year to 500,000 fish/year and by-catch rates have been estimated by TPWD at 925,000 fish/year to 9.7 million fish/year, demonstrating that commercial by-catch contributes most to the fishing mortality rate of southern flounder occurr as. Clearly, by-catch rates are well established as major contributors to the decline in fisheries (Jackson et al., 2001; Pauly et al., 2002; Hilborn et al., 2003), and might be a driving force in the decline of adult southern flounder. Regulation and management efforts for southern flounder in Texas have focused on implementing guidelines for recreational and commercial fisheries, yet the population remains in decline.

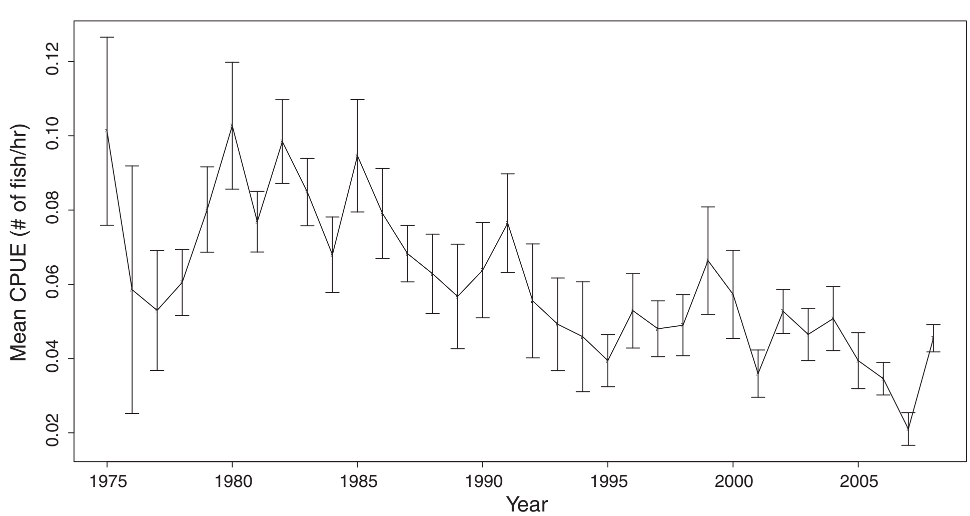

Fig. 7. Adult mean (±SE) $CPUE_a$ from 1975 to 2008. Trend line was determined from the linear regression model ($R^2 = 0.5441$, $F_{1,32} = 38.19$, Slope = −0.0015) indicating a significant decline in the adult southern flounder population.

These continued declines were of major concern for the managing agency prompting increasing regulation of size, bag limits, and seasonal closures beginning in 2009 (Riechers, 2008). Currently, it is too early to assess the population response to these new regulations.

Despite harvest limits on both recreational and commercial fishing, these data show that the southern flounder fishery remains in decline. Results from this study indicate that the southern flounder management program in Texas up to 2008 was not sufficient to maintain southern flounder populations along the Texas coast. We suggest that with continued improvements on recreational and commercial fishing regulations and increased knowledge and management of essential fish habitat for all life-stages of southern flounder may contribute to increased abundances of both juvenile and adult southern flounder.

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