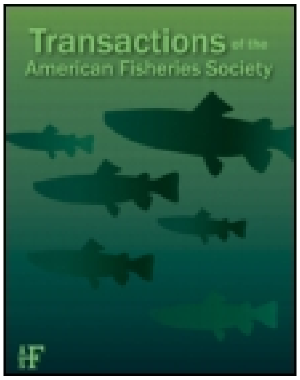

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Developing Fishery-Independent Indices of Larval and Juvenile Gag Abundance in the Southeastern United States

Kyle M. Adamski [a], Jeffrey A. Buckel [a], Kyle W. Shertzer [b], Gretchen Bath Martin [b] & J. Christopher Taylor [c]

[a] Center for Marine Sciences and Technology, Department of Biology, North Carolina State University, 303 College Circle, Morehead City, North Carolina, 28557, USA

[b] National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southeast Fisheries Science Center, Beaufort Laboratory, 101 Pivers Island Road, Beaufort, North Carolina, 28516, USA

[c] National Oceanic and Atmospheric Administration, National Ocean Service, Center for Coastal Fisheries and Habitat Research, 101 Pivers Island Road, Beaufort, North Carolina, 28516, USA

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ARTICLE

Developing Fishery-Independent Indices of Larval and Juvenile Gag Abundance in the Southeastern United States

Kyle M. Adamski* and Jeffrey A. Buckel
Center for Marine Sciences and Technology, Department of Biology, North Carolina State University, 303 College Circle, Morehead City, North Carolina 28557, USA

Kyle W. Shertzer and Gretchen Bath Martin
National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Southeast Fisheries Science Center, Beaufort Laboratory, 101 Pivers Island Road, Beaufort, North Carolina 28516, USA

J. Christopher Taylor
National Oceanic and Atmospheric Administration, National Ocean Service, Center for Coastal Fisheries and Habitat Research, 101 Pivers Island Road, Beaufort, North Carolina 28516, USA

Abstract
We developed an index describing the abundance of gags *Mycteroperca microlepis* at the planktonic postlarval stage, and we assessed the index's potential for use in stock assessment. Data on postlarval gags were collected weekly at the Pivers Island bridge near Beaufort Inlet, North Carolina, during the National Oceanic and Atmospheric Administration's bridgenet program (ichthyoplankton sampling, November–May 1986–2008); additionally, ichthyoplankton were sampled nightly during spring in 2007 and 2008. Catch of juvenile gags was examined in relation to several factors to assist in developing and refining fishery-independent surveys; juveniles were sampled with a small trawl in seagrass beds at 15–20 randomly selected stations near Beaufort Inlet every 2 weeks during June–September 2007 and 2008. Catches of postlarval and juvenile gags were low in both gear types. From 1986 to 2008, weekly concentrations of postlarval gags were highest from mid-April to mid-May, and peak ingress coincided with new moon periods. Juvenile gags were caught throughout the June–September sampling period, and the highest catch per unit effort was observed in July and August. Time of year, percent seagrass coverage, seagrass species, and location inside the estuary influenced juvenile gag catch per unit effort. Growth rates of juvenile gags were rapid (~1.5 mm/d) during summer months and did not differ between years. An annual index of postlarval abundance (adjusted for lunar effects) was developed. The spawning stock biomass from the most recent gag stock assessment was positively correlated with the postlarval abundance index; therefore, this index could be used as a fishery-independent index of spawning stock biomass.

Fishery-independent data can be extremely valuable in the stock assessment process. Monitoring of early life history stages has been used to construct fishery-independent indices of future recruitment in marine fishes (Hanisko et al. 2007; Ingram et al. 2007). A fishery-independent index of abundance is typically considered more reliable than a fishery-dependent index because the former involves consistencies in sampling methodology. A main source of bias with fishery-dependent landings data arises from temporal changes in catchability; this is especially true in reef fisheries, where advances in electronics have improved

*Corresponding author: kmadamski@gmail.com
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the ability of fishers to efficiently target productive locations. Additionally, regulations can limit fishery landings, thus limiting the utility of fishery-dependent data.

Gags *Mycteroperca microlepis* are managed as a single stock in the continental shelf of the Southeast U.S. Continental Shelf Large Marine Ecosystem (SUSLME). The gag is an economically important reef fish that is exploited by recreational and commercial fishers, mainly by means of hook-and-line methods (SEDAR 2006). The most recent stock assessment was completed in 2006 and concluded that the stock was experiencing overfishing but was not overfished (SEDAR 2006). However, if current fishing mortality rates continue, gags probably will become overfished. In reaction to this trend, a reduction in harvest, including a 4-month closure during the gag spawning season, was proposed in 2008 and implemented in 2009 (SAFMC 2009).

The latest gag stock assessment has been criticized because it relied heavily on fishery-dependent data (SEDAR 2006) but did not use a fishery-independent index of abundance. Use of a fishery-independent index of recruits or spawning stock biomass (SSB) would be likely to reduce uncertainty in the assessment. The North Carolina Division of Marine Fisheries (NCDMF 2010) and the South Atlantic Fisheries Management Council (SAFMC 2009) currently cite the need for a fishery-independent index of abundance to improve the gag stock assessment; relative abundance of larvae or juveniles has been used to index current spawning stock size or future year-class strength (Hanisko et al. 2007; Bacheler et al. 2008). Development of fishery-independent sampling methods is particularly relevant with regard to SUSLME snapper and grouper species, for which landings data (the data used in assessments) have decreased due to regulations.

The design of a fishery-independent survey requires consideration of factors that influence catch (Koenig and Coleman 1998). Keener et al. (1988) found that the highest concentrations of planktonic postlarval gags occurred at the surface during night flood tides near estuarine inlets in South Carolina; additionally, they found evidence that the timing of catch was related to putative spawning periodicity. Their findings have not been validated in other locations. Juvenile gags inhabit estuaries during their first summer, typically residing in seagrass beds, oyster reefs, and other structured estuarine habitats (Keener et al. 1988; Ross and Moser 1995; Mullaney and Gale 1996; Koenig and Coleman 1998). Koenig and Coleman (1998) related absolute abundance of juvenile gags in the Gulf of Mexico to several factors, including seagrass characteristics, in an effort to develop an index of abundance. Although juvenile gags have been studied in the SUSLME (Keener et al. 1988; Ross and Moser 1995; Mullaney and Gale 1996), no studies have examined factors influencing juvenile gag catch throughout the summer over a large spatial scale.

There were two primary goals for this study. First, we examined factors that influenced the timing of postlarval gag ingress through Beaufort Inlet, North Carolina; created an index of postlarval abundance from historical ichthyoplankton samples; and compared this index to gag SSB and age-1 abundance. Second, to help refine and develop future fishery-independent surveys, we examined factors that explained variability in juvenile gag catch per unit effort (CPUE) within extensive seagrass beds located in multiple North Carolina sounds.

METHODS

Collection of postlarval gags.—The areas sampled in this study are part of North Carolina's coastal lagoon or sound system, the largest such system in the SUSLME. Ichthyoplankton sampling from the Pivers Island bridge (hereafter referred to as bridgenet sampling; Figure 1) has been conducted since 1986 by the National Oceanic and Atmospheric Administration (NOAA) Beaufort Laboratory. Pivers Island is located in Back Sound, approximately 1.5 km from Beaufort Inlet. From 1986 to 2008, ichthyoplankton were sampled from approximately November to April–May by using a 1- × 2-m^2, fixed, 1-mm-mesh neuston net; there were two exceptions to this general sampling scheme. First, beginning in 2005, sampling occurred throughout the year. Second, from approximately March 2007 to March 2008, a 1-m-diameter ring net with 500-μm mesh was used for weekly sampling while a new bridge was being constructed. For the neuston net and the ring net, four consecutive surface tows were conducted each week; the volume of water filtered for each tow was determined by means of a flowmeter, and the goal was to filter approximately 100 m^3 of water/tow. Plankton nets were used because this gear can effectively sample ingressing postlarval gags (Keener et al. 1988). The number of gags caught in a tow was divided by filtered volume and was then standardized to 1,000 m^3 of water. Sampling was conducted on nighttime flood tides, approximately 2.5 h before high tide as predicted by NOAA (tidesandcurrents.noaa.gov).

To standardize the index for covariates that significantly influenced postlarval catch, intensive sampling was conducted in spring 2007 and spring 2008. In 2007, nightly sampling began on 2 May and continued through 25 June. Because gag catches were zero in nightly samples during June 2007 and weekly samples during June 2005 and 2006, nightly sampling was shifted to take place 1 month earlier in 2008; nightly sampling in 2008 began on 2 April and continued through 29 May. Nightly sampling in 2007 and 2008 was conducted with a 1-m-diameter (500-μm-mesh) ring net, and the methodologies were exactly the same as the weekly sampling methods described above.

Bridgenet data from 1986 to 2008 were analyzed to determine timing and magnitude of gag ingress. Mean nightly gag concentrations (gags/1,000 m^3 of water filtered) were calculated by averaging the concentrations from the four tows. Mean weekly densities were calculated for 1986–2008 by pooling all years and averaging the mean nightly densities for each respective week. Days within each month were categorized into weeks (days 1–7 = week 1; days 8–14 = week 2; days 15–21 = week 3; days 22–28 = week 4; days 29–31 = week 5).

Collection of juvenile gags.—Collections of juvenile gags were made with a 5-m otter trawl (12.7-mm bar mesh in body;

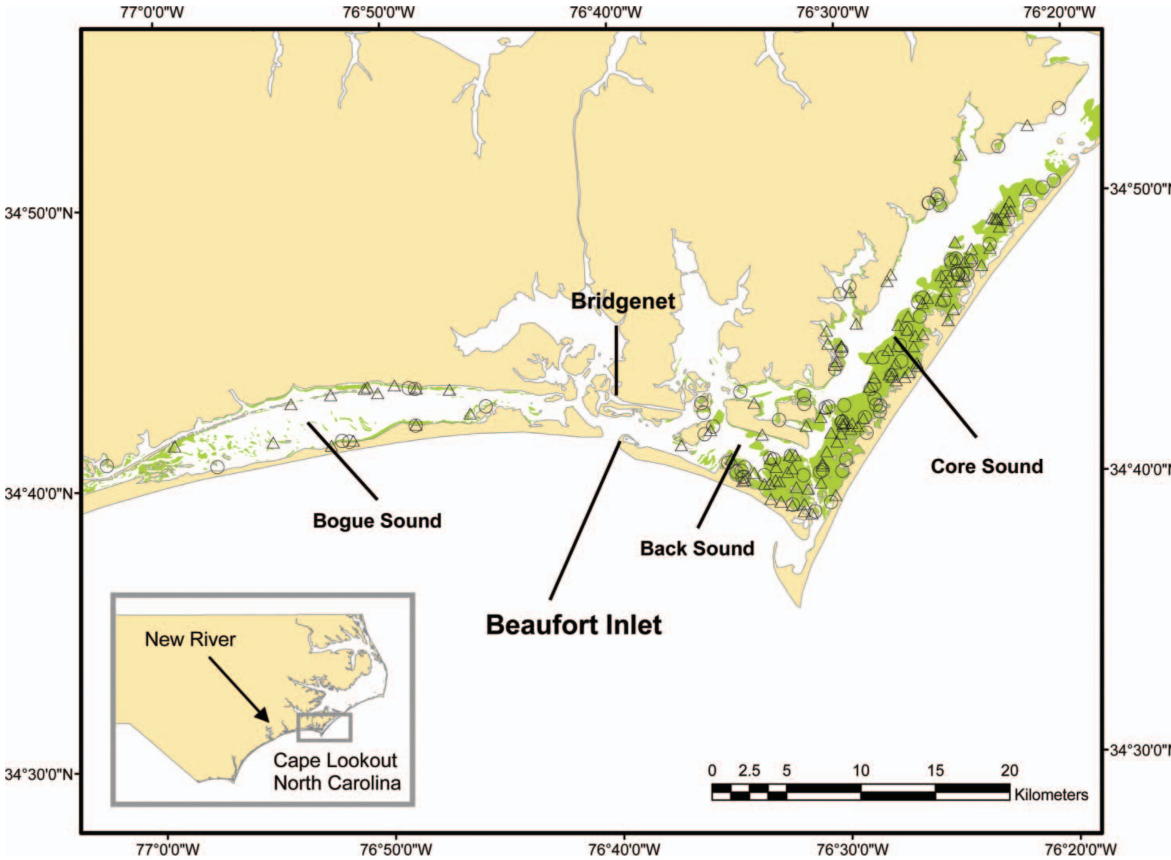

FIGURE 1. The study area at Cape Lookout, North Carolina, where postlarval and juvenile gags were sampled. The Pivers Island bridge (bridgenet sampling platform) is located approximately 1.5 km inside of Beaufort Inlet. Shaded areas within Bogue, Back, and Core sounds represent seagrass beds. Points inside seagrass beds represent randomly generated stations where otter trawl sampling of juveniles was conducted (circles = 2007; triangles = 2008). Inset shows location of the study area within the state. [Figure available online in color.]

3.2-mm bar mesh in bag) within seagrass beds in Bogue, Back, and Core sounds (Figure 1). Sampling was limited to seagrass beds because earlier studies have found that juvenile gags use structured habitat almost exclusively after settlement (Koenig and Coleman 1998; Fitzhugh et al. 2005; Rénan et al. 2006). Sampling for juveniles began in mid-June and continued through mid-September in both 2007 and 2008. From 15 to 20 random sites were sampled every 2 weeks; this number varied because of logistical constraints (e.g., weather or water depth). Random locations were generated within a seagrass spatial layer (seagrass data provided by Scott Chappell, North Carolina Division of Marine Fisheries, Morehead City) by use of Hawth's Analysis Tools (Beyer 2004) in the program ArcGIS; the sample pool included all possible locations within seagrass. Because seagrass beds occur in shallow water (0.5–1.5 m), all trawls were conducted within 1.5 h of high tide. Trawl speeds averaged 3.5 km/h and were 5 min in duration; thus, trawl tracks were approximately 300 m long. At each trawl location, measurements of temperature, dissolved oxygen, and salinity were recorded.

Seagrass assessments were conducted at each trawl location. These assessments consisted of identifying species and quantifying the percent coverage. The two predominant species of seagrass present in North Carolina sounds are eelgrass *Zostera marina* and shoal grass *Halodule wrightii*. Percent coverage was ranked by using the Braun-Blanquet score (scale of 0–5, where 0 = 0% coverage, 1 = 1–5%, 2 = 6–25%, 3 = 26–50%, 4 = 51–75%, and 5 = 76–100%; Wilzbach et al. 2000). Visual estimates of percent coverage were made from the surface over the entire trawl track in 2007 and 2008 (with the exception of the first 15 tows in 2007); this was feasible because of the shallow water. In 2008, the surface visual estimates were compared with those from a 10-quadrat approach, which consisted of throwing a 1-m^2 quadrat approximately every 30 m throughout the trawl track and conducting a snorkel assessment of seagrass coverage. The mean of these 10 quadrat scores was taken as the seagrass coverage for an individual trawl. Because there was a significant positive relationship between the surface visual assessment and the 10-quadrat approach ($r^2 = 0.67$, $P < 0.001$, $n = 54$), surface visual assessments of seagrass coverage were used in all further analyses.

Growth rates of juvenile gags during the summer months (June–September) were estimated by using linear regression to predict total length (mm) from the date of collection; the homogeneity of slopes test was used to compare annual growth rates. Postlarvae and autumn-caught juveniles were not included in this analysis because growth was limited during these times. We used other gear types, including beam trawls, minnow traps, seine nets, and channel nets (see Ross and Moser 1995 for a description of this gear), in an attempt to capture additional juvenile gags for use in growth rate analyses only. Channel-netting was done in collaboration with commercial shrimp fishers in the study region and in an estuary to the south (New River, North Carolina; Figure 1).

Development of a postlarval abundance index.—A delta generalized linear modeling (DGLM) approach (Dick 2004; Maunder and Punt 2004) was used to fit several models to nightly concentrations of gag postlarvae based on April and May catch data; this method was chosen because of the large number of zero-catch observations. The index of abundance from the DGLM method is the product of fitted values from two generalized linear models: (1) a binomial distribution describing variability in the proportion of positive catches (presence–absence) and (2) a second distribution (lognormal in our application) describing variability in positive catches. We included only years that had at least two positive data points. As a result, 13 of the 23 bridgenet sampling years were available for this analysis.

Annual indices of abundance were estimated by adjusting for the influence of significant independent variables with the DGLM function in R software (R Development Core Team 2006). The independent variables considered were year, day, predicted peak tidal height, $\sin(\theta)$, $\sin(2\theta)$, $\cos(\theta)$, and $\cos(2\theta)$ (where θ = lunar day in radians). Lunar days were defined as days from full moon and were based on a 29-d lunar cycle (full moon = 0; new moon = 14.5). The sine and cosine terms are periodic regression terms used to model peaks in ingress during a lunar cycle; deBruyn and Meeuwig (2001) provide details on how these terms relate to lunar cycle.

For a subset of sampling years (1996–2008), observed tide heights were available from NOAA's National Data Buoy Center Station BFTN7 at Pivers Island. Observed tide heights were used to calculate a tide anomaly value (observed tide – predicted tide). The tide anomaly value is used as a proxy for wind, river discharge, and other factors that may cause variation in local tide heights (Ogburn et al. 2009). Tide anomaly and the multiple independent variables listed above were used to model the 1996–2008 data describing postlarval gag ingress.

Models consisting of biologically plausible combinations of these variables were fitted to the 1986–2008 and 1996–2008 postlarval ingress data by use of DGLM. Akaike's information criterion (AIC) values were calculated for the binomial model and the lognormal model (Burnham and Anderson 2002); these scores were added together to produce a total AIC score. Models were ranked from lowest to highest AIC score. The best indices (those with the lowest total AIC score) were compared with the nominal catch rates created by averaging the concentrations (fish/1,000 m^3) of postlarval gags caught during all nights of sampling in April and May of each year.

Refinement of future sampling of juvenile gags.—The DGLM approach was also used to assess the factors that influence trawl-caught juvenile gags in seagrass beds. The dependent variable was the number of gags caught per tow. The independent variables investigated were year, day, Braun-Blanquet score, seagrass species, sound, distance from Beaufort Inlet, and water temperature. Akaike's information criterion was again used for model selection (Burnham and Anderson 2002).

Correlations with other indices of abundance.—The annual index of postlarval gag abundance was compared with other indices of abundance to assess its validity. The postlarval abundance index was compared with estimates of gag SSB and abundance of age-1 recruits from the most recent stock assessment (SEDAR 2006). This stock assessment model was a forward-projection, statistical catch–age formulation. Correlations were examined between (1) gag SSB estimates for year t and the DGLM postlarval index for the same year; (2) SSB for year t and age-1 gag estimates for year $t + 1$; and (3) DGLM postlarval index for year t and age-1 estimates for year $t + 1$.

RESULTS

Postlarval Gag Abundance

From 1986 to 2008, postlarval gags were collected during March–May (Figure 2A). Only three gags were collected in March over the 23-year period. Ingress occurred predominantly in April and May, and the highest catches were observed from week 2 in April through week 4 in May. Postlarval gags were rare; the highest weekly mean density (averaged over all years) was approximately 8 postlarval gags/1,000 m^3 (Figure 2A).

The nightly sampling in 2007 and 2008 better defined the timing of ingress. Ingress occurred over a relatively narrow time frame, and there was interannual variability in the peak ingress period. In total, 26 postlarvae were caught over 43 near-consecutive nights in 2007. During 2007, ingressing postlarvae were only caught in May, and 88% of the annual total was caught during a 7-d period (14–21 May; Figure 2B). In 2008, 15 postlarvae were caught during 56 consecutive nights of sampling in April and May (Figure 2C). There were two periods of ingress during 2008: one in the first half of April ($n = 5$), and the other in the first half of May ($n = 9$).

Although ingress occurred throughout the lunar cycle, most of the positive observations as well as the highest concentrations coincided with the new moon periods in April and May (Figure 3). The two models that provided the best fit to the ingress data (models 1a and 2a in Table 1) contained a periodic regression term ($\cos[\theta]$) indicative of peak ingress around the new moon (lunar day 14; Figure 3). These models had equal support and also included year and day effects. Although model 1a contained a $\sin(2\theta)$ term, this term had little effect on the shape of the model because its coefficient was small (0.096; $\cos[\theta]$

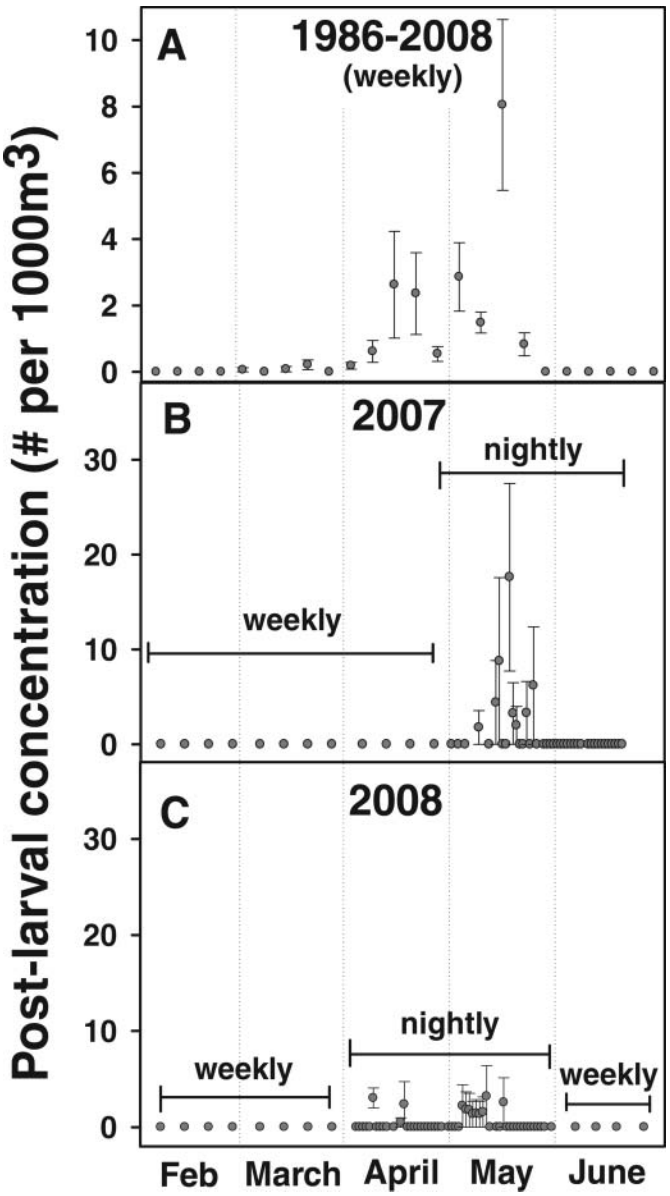

FIGURE 2. Mean (±SE) postlarval gag concentrations (fish/1,000 m^3) based on sampling conducted at the Pivers Island bridgenet site during February–June: **(A)** weekly sampling from 1986 to 2008, **(B)** weekly and nightly sampling in 2007, and **(C)** weekly and nightly sampling in 2008.

coefficient = 0.602; Figure 3). Tide anomaly data were available for 1996–2008. Using this reduced data set, we found no support for tide anomaly as a predictor of postlarval gag ingress (Table 1). The two models that were most supported in this reduced data set (models 1b and 2b in Table 1) were the same as those with the greatest support in the full data set (models 1a and 2a).

The annual abundance of postlarvae captured at the Pivers Island bridge was highly variable (Figure 4). For models 1a and 2a, the DGLM-adjusted mean index and the arithmetic mean index of abundance followed a similar trend (Figure 4). In many

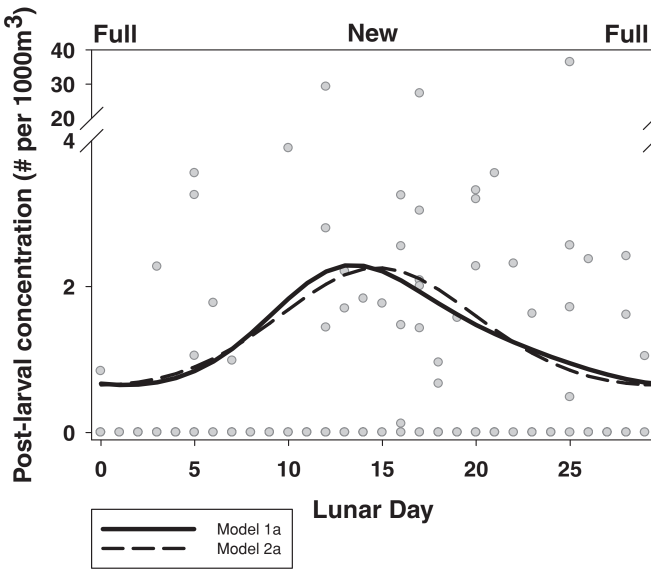

FIGURE 3. Postlarval gag concentrations (fish/1,000 m^3) in April and May 1986–2008 plotted as a function of lunar day. The two models with the most support (models 1a and 2a in Table 1) provided similar fits to the data; peak ingress coincided with the new moon period (i.e., middle of the lunar cycle).

of the years before 2005 (when year-round sampling began), the DGLM indices were adjusted upward of the arithmetic index; this is probably due to reduced sampling in May for those years (Figure 4).

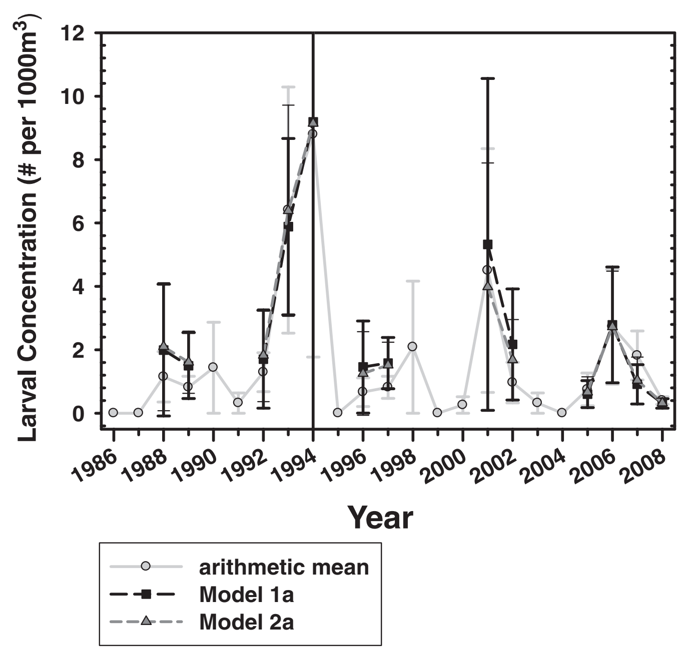

FIGURE 4. Annual postlarval gag concentrations (fish/1,000 m^3; April and May 1986–2008) based on the arithmetic mean and adjusted values (mean ± SE) from delta generalized linear modeling (DGLM) fits (models 1a and 2a in Table 1). The DGLM approach was only used for years that contained at least 2 d of postlarval gag catch.

TABLE 1. List of models fitted to postlarval gag concentrations (Conc) by using the delta generalized linear modeling (DGLM) approach (see Methods) for 1986–2008 (models 1a–13a) and 1996–2008 (models 1b–15b). Models are ranked by total score for Akaike's information criterion (AIC; i.e., total score = sum of AIC scores for the DGLM binomial and lognormal models; ΔAIC = AIC difference between the given model and the best model [i.e., the model with the lowest total AIC]; θ = lunar day value in radians).

Model	Model description	AIC total	ΔAIC
	1986–2008		
1a	Conc = Year + Day + Day^2 + Cos(θ) + Sin(2θ)	431.03	0.00
2a	Conc = Year + Day + Day^2 + Cos(θ)	431.91	0.88
3a	Conc = Year + Day + Day^2 + Predicted tide	438.53	7.50
4a	Conc = Year + Day + Day^2 + Sin(2θ)	441.60	10.57
5a	Conc = Year + Day + Day^2	442.12	11.09
6a	Conc = Year + Day + Day^2 + Sin(θ)	443.79	12.76
7a	Conc = Year + Cos(θ) + Sin(2θ)	444.18	13.15
8a	Conc = Year + Cos(θ)	444.55	13.52
9a	Conc = Year + Day + Day^2 + Cos(2θ)	444.69	13.66
10a	Conc = Year + Cos(θ) + Cos(2θ)	445.09	14.06
11a	Conc = Year + Day + Day^2 + Cos(2θ) + Sin(θ)	446.43	15.40
12a	Conc = Year	452.00	20.97
13a	Conc = Year + Day	452.62	21.59
	1996–2008		
1b	Conc = Year + Day + Day^2 + Cos(θ) + Sin(2θ)	292.63	0.00
2b	Conc = Year + Day + Day^2 + Cos(θ)	296.60	3.97
3b	Conc = Year + Cos(θ) + Sin(2θ)	297.03	4.40
4b	Conc = Year + Cos(θ)	300.03	7.40
5b	Conc = Year + Cos(θ) + Cos(2θ)	302.01	9.38
6b	Conc = Year + Day + Day^2 + Predicted tide	303.70	11.07
7b	Conc = Year + Day + Day^2 + Sin(θ)	309.57	16.94
8b	Conc = Year + Day + Day^2 + Observed tide	310.44	17.81
9b	Conc = Year + Day + Day^2 + Sin(2θ)	311.75	19.12
10b	Conc = Year + Day + Day^2 + Cos(2θ) + Sin(θ)	312.16	19.53
11b	Conc = Year + Day + Day^2	313.31	20.68
12b	Conc = Year	315.26	22.63
13b	Conc = Year + Day + Day^2 + Tide anomaly	315.80	23.17
14b	Conc = Year + Day + Day^2 + Cos(2θ)	316.43	23.80
15b	Conc = Year + Day	318.72	26.09

Juvenile Gag Abundance

Juvenile gags were also rare in trawls. Overall, 56 juveniles were caught in 84 trawls during 2007, and 30 juveniles were caught in 90 trawls during 2008. Year, day, temperature, percent seagrass coverage, seagrass species, and sound (Bogue, Back, and Core sounds) were all important predictors of juvenile gag catch in seagrass beds; the top-three models that contained various combinations of these terms all had essentially equal support (AIC difference between a given model and the best model [i.e., ΔAIC] < 2; Table 2). The CPUE was higher in 2007 than in 2008, and within-year catch often followed the seasonal temperature trend. Additionally, juvenile gag CPUE increased with increasing seagrass coverage (Figure 5A) and was higher in eelgrass beds than in shoal grass beds (Figure 5B). Core Sound had low CPUE in both years, and catches in Back Sound were consistently higher than those in Core Sound (Figure 5C). No damage to seagrass beds was observed in trawl transects.

Rapid growth of juvenile gags began in June and continued through September (Figure 6). This coincides with times of warm temperatures inside the estuary (mean water temperature for June–September was 27.8°C in both 2007 and 2008). Summertime growth rates of gags averaged 1.6 mm/d in 2007 and 1.5 mm/d in 2008 and were not significantly different between years ($F = 0.42$, df = 1, $P = 0.51$). Additionally, there was little variation in growth among individuals within years (2007: $r^2 = 0.88$; 2008: $r^2 = 0.70$); these size data provide strong support for the hypothesis that the influx of gags consists of a single cohort.

Correlations with Other Indices of Abundance

There was a significant positive relationship between SSB and the DGLM postlarval index ($r = 0.72$, $P = 0.03$; Figure 7A).

TABLE 2. List of models fitted to trawl catch of juvenile gags (Gag) by applying the delta generalized linear modeling (DGLM) approach (see Methods) to data from collections made in seagrass beds within Bogue, Back, and Core sounds (BB = Braun-Blanquet coverage class; Spc = seagrass species; BI = distance from Beaufort Inlet; Sound = body of water where collected; Temp = temperature). Models are ranked by total score for Akaike's information criterion (AIC; i.e., total score = sum of AIC scores for the DGLM binomial and lognormal models; ΔAIC = AIC difference between the given model and the best model [i.e., the model with the lowest total AIC]).

Model	Model description	AIC total	ΔAIC
1c	Gag = Year + Day + Day^2 + BB + Sound	274.90	0.00
2c	Gag = Year + Day + Day^2 + BB + Sound + Spc	275.44	0.54
3c	Gag = Year + BB + Sound + Temp + Temp^2	276.74	1.84
4c	Gag = Year + BB + Sound	277.06	2.16
5c	Gag = Year + BB + Spc + Sound + Temp + Temp^2	278.49	3.59
6c	Gag = Year + BB + Spc + Sound	279.62	4.72
7c	Gag = Year + Day + Day^2 + BB + Sound + (Sound × Year)	279.65	4.75
8c	Gag = Year + Day + Day^2 + BB + Sound + Temp + Temp^2	279.84	4.94
9c	Gag = Year + Day + Day^2 + BB + Sound + Spc + BI	282.71	7.81
10c	Gag = Year + Day + Day^2 + BB	284.41	9.51
11c	Gag = Year + Day + Day^2 + BB + BI	285.32	10.42
12c	Gag = Year + BB	286.43	11.53
13c	Gag = Year + BB + Temp + Temp^2	287.19	12.29
14c	Gag = Year + Day + Day^2 + BB + Sound + Spc + BI + Temp + Temp^2	287.88	12.98
15c	Gag = Year + Day + Day^2 + BB + BI + Temp + Temp^2	288.95	14.05
16c	Gag = Year + BB + Spc	289.16	14.26
17c	Gag = Year + Day + Day^2 + Spc	306.46	31.56
18c	Gag = Year + Day + Day^2 + Sound	310.21	35.31
19c	Gag = Year + Spc + Temp + Temp^2	311.02	36.12
20c	Gag = Year + Sound + Temp + Temp^2	311.17	36.27
21c	Gag = Year + Day + Day^2	312.70	37.80
22c	Gag = Year	313.39	38.49
23c	Gag = Year + Day + Day^2 + BI	313.85	38.95
24c	Gag = Year + Day	316.17	41.27
25c	Gag = Year + BI + Temp + Temp^2	317.06	42.16

However, the correlation between gag SSB and age-1 abundance estimates from the stock assessment (SEDAR 2006) was not significantly different from zero ($r = -0.56$, $P = 0.12$; Figure 7B). The correlation between the DGLM postlarval index from year t and the age-1 abundance estimates from year $t + 1$ also did not differ from zero ($r = -0.05$, $P = 0.89$; Figure 7C).

DISCUSSION

Development and Test of the Postlarval Gag Abundance Index

The DGLM postlarval index could be used as a fishery-independent index of SSB in the next gag stock assessment. Hanisko et al. (2007) found that indices of larval and adult red snapper *Lutjanus campechanus* had similar trends in the Gulf of Mexico; a larval index has been used in the stock assessment of Gulf of Mexico red snapper. More years of data throughout a wider range of gag SSB estimates will allow for a better assessment of utility of the postlarval gag abundance index in U.S. Atlantic waters.

Peak ingress of postlarval gags occurred predominantly in April and May near new moons. Peaks in postlarval settlement of other reef fishes have been shown to coincide with new moon periods (Victor 1986; Walsh 1987; Wilson 2001; Watson et al. 2002; Tzeng et al. 2003; Ben-David and Kritzer 2005). In South Carolina, Keener et al. (1988) identified peak ingress of gags as occurring on nighttime flood tides in April and May, and those authors noted that temporal variability in ingress corresponded to temporal patterns in back-calculated hatch dates. Keener et al. (1988) found that most hatch dates coincided with full moon periods and that the mean pelagic larval duration was approximately 43 d. Based on a roughly 29-d lunar cycle, this translates to peak ingress at approximately the new moon period. Strong flood tides and low ambient light associated with new moons might lead to higher catchability of gags by our gear (less chance for active avoidance of gear) or might be ideal for postlarval transport into the estuary and predator avoidance.

The bridgenet program at Pivers Island was designed to target ingressing winter-spawned gag larvae during nighttime flood tides. Before 2005, the inconsistent and low annual catch of gag

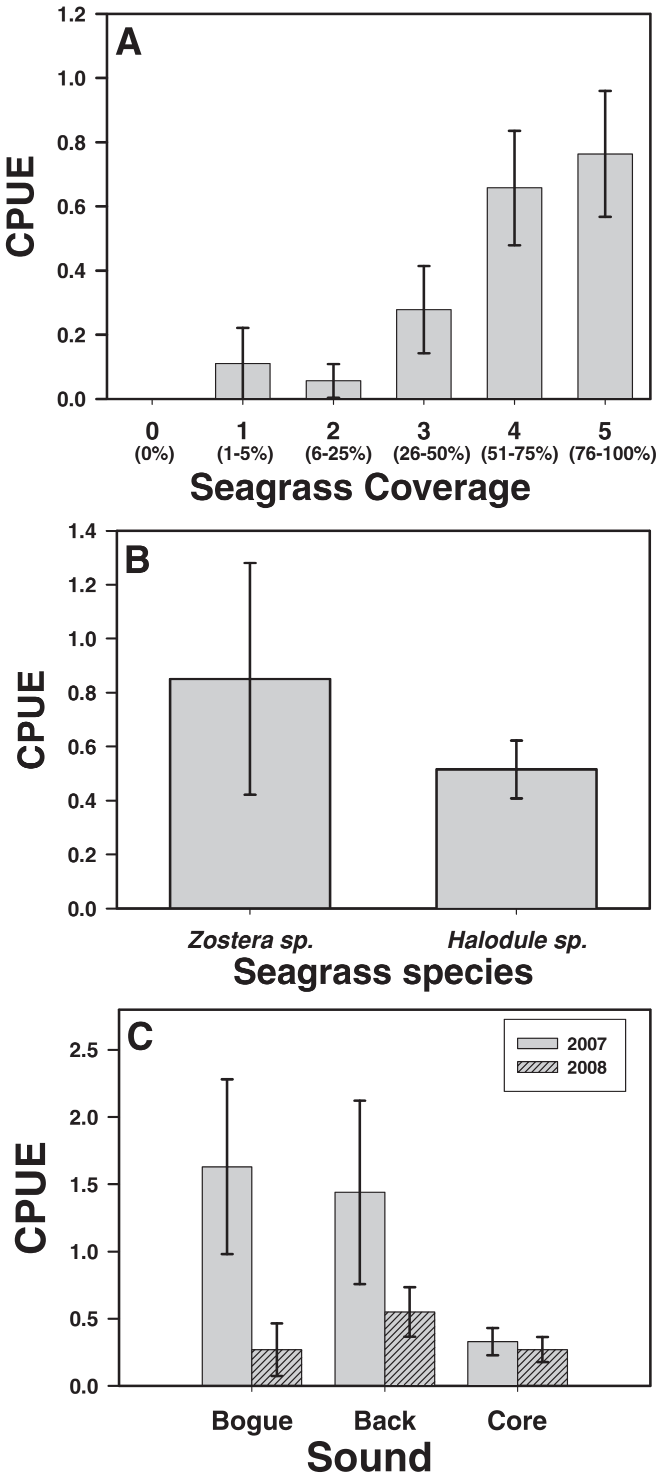

FIGURE 5. Juvenile gag catch per unit effort (CPUE, fish/trawl; mean ± SE) from trawls within seagrass beds near Beaufort Inlet, presented for each **(A)** seagrass coverage class (Braun-Blanquet score = 0–5; percent coverage in parentheses), **(B)** seagrass species (eelgrass *Zostera marina* or shoal grass *Halodule wrightii*), and **(C)** sound where the samples were collected.

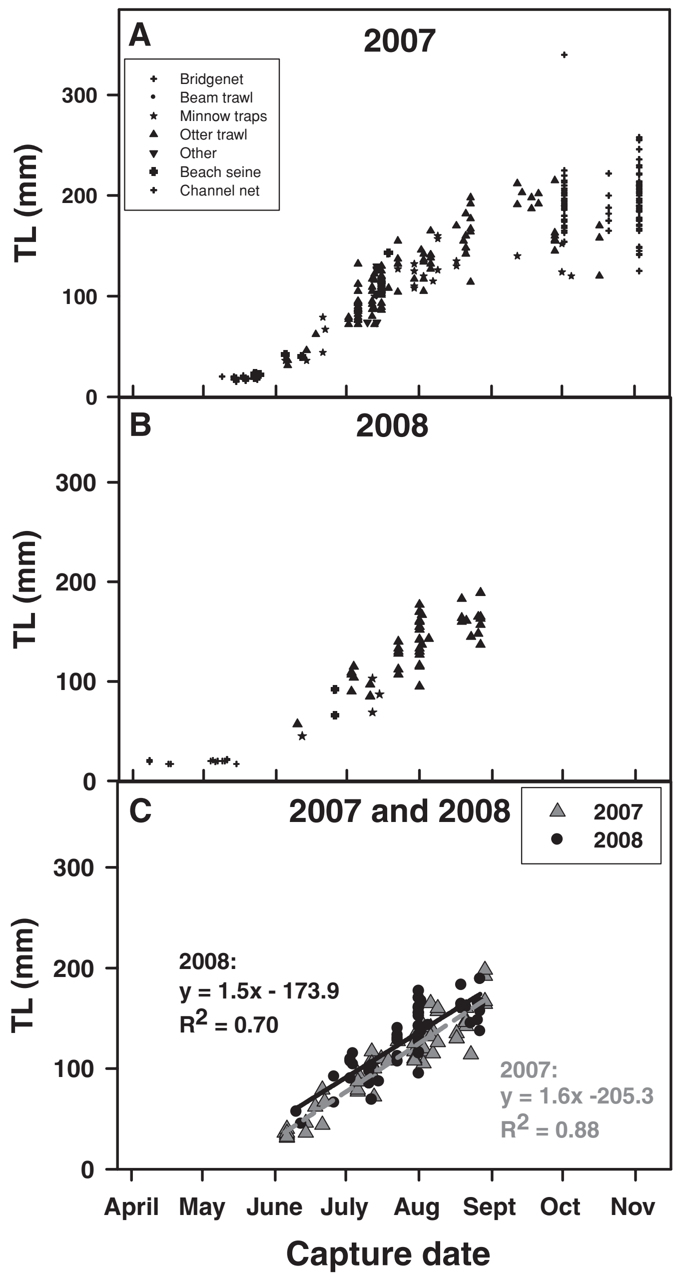

FIGURE 6. Total length (TL; mm) at capture for postlarval and juvenile gags sampled within estuarine waters near Beaufort Inlet during **(A)** 2007 and **(B)** 2008. Gags were collected at ingress (bridgenet sampling; see Methods), during the estuarine phase (captured in trawls, traps, and seines), and during egress (captured in channel nets). **(C)** Linear regression fits to TL versus capture date are presented for the estuarine collection dates common to both 2007 and 2008.

postlarvae at the Pivers Island bridge partly resulted from the use of a sampling protocol designed for winter-spawning fishes (e.g., Atlantic menhaden *Brevoortia tyrannus*); this protocol often missed the critical late-April–May gag ingress period. The DGLM postlarval index values are adjusted for years in which

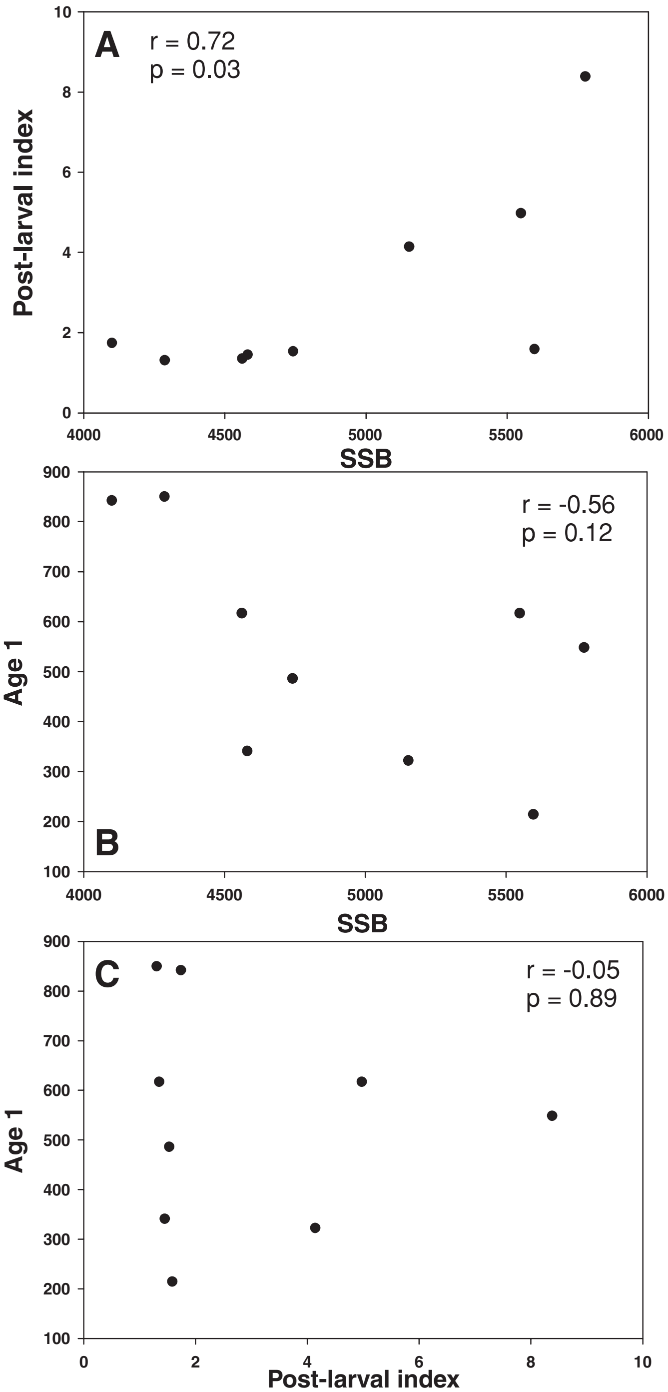

FIGURE 7. Pearson's product-moment correlation (r) analyses between **(A)** delta generalized linear modeling (DGLM)-adjusted postlarval gag index values (present study) and gag spawning stock biomass (SSB; thousands of pounds; from SEDAR 2006), **(B)** age-1 gag index (abundance, thousands of fish; listed as age 0 in SEDAR 2006) and SSB (lagged by 1 year), and **(C)** age-1 gag index and DGLM-adjusted postlarval index values (lagged by 1 year).

sampling did not occur during optimal days of the year or around optimal lunar days. To more effectively index gag postlarvae, sampling should be conducted weekly in both April and May with increased sampling frequency (e.g., nightly) beginning approximately 5 d before and ending approximately 5 d after the new moon.

Refinement of the Index of Juvenile Abundance

Year, day of year, percent seagrass coverage, seagrass species, and sound explained variability in juvenile gag catch. Similarly, Casey et al. (2007) found that year, month, sound, percent seagrass coverage, water depth, and location (shoreline versus shoal) were significant predictors of juvenile gag abundance in southwest Florida estuaries. Thus, habitat use by juvenile gags is similar between Gulf of Mexico and North Carolina estuaries, and this information could be used to stratify existing monitoring programs if the goal is to obtain higher catches of juvenile gags.

Efforts to improve present sampling of juvenile gags appear to be warranted. Fitzhugh et al. (2003) and Johnson and Koenig (2005) described strong and weak year-classes in the age structure of adult gags caught in the Gulf of Mexico and provided evidence that juvenile abundance estimates could be useful in forecasting future year-class strength in the fishery. Below, we detail the responses of juvenile gags to important independent variables.

Catch of juvenile gags was higher in dense seagrass coverage than in sparse coverage and was higher in eelgrass than in shoal grass. These results were similar to Levin and Hay's (2003) findings from mesocosm studies of juvenile gags. Levin and Hay (2003) provided evidence that juvenile gags preferred eelgrass over shoal grass, and they postulated that this preference was attributable to the greater structure provided by eelgrass. Although the same mechanism might be responsible for the pattern observed here, it may simply be a correlation between gag abundance and the phenology of dominant seagrass species: eelgrass dominates early in the summer when gags are abundant, whereas shoal grass is prominent during later summer months when gag catches decline.

Temperature and day of year were important predictors of juvenile gag catch but were confounded. Catch of juveniles in seagrass beds increased throughout the summer, peaked in July or August, and declined thereafter. This trend in relative abundance was consistent with observations made throughout U.S. Atlantic waters (Ross and Moser 1995) and the Gulf of Mexico (Koenig and Coleman 1998; Rénan et al. 2006; Casey et al. 2007). The decline in gag abundance in seagrass beds is believed to be a result of emigration to inshore and offshore hard-bottom habitats. High catches of gags in channel nets during late summer and fall support this theory (Ross and Moser 1995; Rutten 1998; present study).

Juvenile gag settlement size (mean ± SD = 19 ± 1.59 mm total length) showed little variation despite variable ingress dates. After settlement, gags grew rapidly during summer months and displayed low variability in size. The pulsed postlarval ingress period and the low size variability over time suggest that gags recruit to North Carolina waters as a single cohort. This result is consistent with previous results from studies in the Carolinas (Keener et al. 1988; Ross and Moser 1995), which are now confirmed over a larger sampling area. Evidence for a single cohort of gags has also been found in the Gulf of Mexico (Koenig and Coleman 1998; Rénan et al. 2006). This information is important for understanding how catch relates to abundance through changes in catchability (Koenig and Coleman 1998).

Growth slowed in fall because of decreased water temperature or emigration of larger, faster-growing individuals (Ross and Moser 1995). We observed high variability in the size of gags caught in channel nets during fall 2007 (see Figure 6). This variability in size could occur because the channel nets sampled gags that resided in other habitats (e.g., oyster reefs and other hard-bottom substrates) or because many of the gags that were collected by channel nets originated from a different estuary than the fish that were collected by summer trawls. Future investigations into growth rates and eventual size at egress for gags in various habitats (conducted in concert with tagging studies) could provide insight into contributions of each habitat type to adult populations.

Implications

Our work has implications for (1) refinement of sampling programs that target postlarval and juvenile gags and (2) application of postlarval and juvenile indices to the stock assessment and management of SUSLME gags. We first describe the methodological advancements, and we close by discussing the application to stock assessment.

Ichthyoplankton sampling has proven useful for monitoring the SSB or abundance of several species (e.g., Taylor et al. 2009), and it could yet become more useful for the monitoring of gags. The NOAA Beaufort Laboratory's bridgenet program now samples through the end of May; additional nightly sampling around new moons in April and May could result in more accurate and precise annual estimates of gag concentration. Currently, postlarval gags are sampled in South Carolina and Georgia (Marcel Reichert, South Carolina Department of Natural Resources, personal communication; Carolyn Belcher, Georgia Department of Natural Resources, personal communication); collectively, these programs will provide broad spatial coverage across much of the SUSLME.

Channel nets are relatively effective at capturing juvenile gags and should be considered for use in future efforts to index gag abundance. In this study, more than 100 gags were collected in channel nets in just three nights. Ross and Moser (1995) reported catches of more than 250 gags in Bogue Sound during only two nights of sampling. Over a 3-year period (1990–1992), Rutten (1998) collected 2,518 emigrating juvenile gags in channel nets that were fished during August–October in the New River. In contrast, we caught fewer than 125 gags with ichthyoplankton nets and otter trawls combined over two full summers of intense sampling. We agree with Rutten's (1998) argument that juvenile gags caught by channel nets may be a better indicator of future recruitment into the fishery because emigrating juvenile gags have survived the life stages at which most of the mortality is thought to occur. For juvenile sampling, the refinement of an existing bottom-trawl or seine survey might be more appealing to monitoring agencies than designing a new survey that uses unfamiliar channel-net gear, but the trade-offs described above should be considered.

Because of regulations that affect indices derived from fishery-dependent data, there is much interest in developing a fishery-independent index for use in the SUSLME gag stock assessment. The SSB and age-1 abundance estimates (from SEDAR 2006) were not related, implying that factors acting between settlement and age 1 obscure the effects of SSB. The significant positive correlation between gag SSB and the postlarval abundance index is encouraging, as the postlarval index may prove to be a reliable indicator of SSB. We recommend (1) refinement of sampling for postlarval gags in the NOAA Beaufort Laboratory bridgenet program (see above) and (2) consideration of the DGLM postlarval index for use in future stock assessments. The postlarval index created in this study does not appear to be a good predictor of recruitment. It is unknown whether catch of juvenile gags in the estuary will be a good predictor of year-class strength in the U.S. Atlantic fishery, although results for the Gulf of Mexico are encouraging (Fitzhugh et al. 2003; Johnson and Koenig 2005). The use of a combination of gears (i.e., ichthyoplankton net, trawl, and channel net) could allow predictions of current stock size (from postlarvae) and future year-class strength (from juveniles) while also providing further insight into factors that contribute to mortality during early life history stages.

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