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Annual variability in upstream migration of glass eels in a southern USA coastal watershed

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Abstract We investigated the environmental factors that affected temporal variability of eel recruitment and upstream migration in a freshwater coastal river along the southeastern US. Glass eels *Anguilla rostrata* were collected through ichthyoplankton sampling in the lower Roanoke River, North Carolina. Monthly samples were taken from fixed stations from May 2001 through June 2003. There was no evidence of consistent seasonal migration patterns for glass eels in Roanoke River. From May through December in 2001, glass eels were captured only during August. In 2002, glass eels arrived in February and remained in ichthyoplankton samples through October, with the exception of samples from September. Peak catch occurred in March at 4.02 ± 1.2 and declined through June to 0.18 ± 0.07 (#/1,000 m^3). By August, the mean density increased to 0.96 ± 0.82 and to 3.59 ± 2.77 by October. In 2003 from January through June, glass eels were captured only during February and March. Glass eels were routinely collected when river discharge rates were <150 $m^3\ s^{-1}$. River discharge rates >650 $m^{-3}\ s^{-1}$ resulted in no glass eels in our samples. Upstream migration during 2002 was not correlated with water temperature or related to lunar phase. Glass eel freshwater upstream migration was initiated when water temperatures exceeded a threshold range of 10°C to 15°C; however, glass eels continued to migrate when water temperatures approached 30°C. The overall negative effect of river discharge suggests that changes in the water release schedules of upstream hydroelectric facilities during glass eel migration could strongly influence their recruitment success.

Keywords *Anguilla rostrata* · Glass eel · Freshwater migration · River discharge

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Introduction

The declining population of the American eel, *Anguilla rostrata*, is a concern in North America (Meister and Flagg 1997: Haro et al. 2000). Habitat loss and overfishing have been identified as two major causes to declining populations (ASMFC 2000). Since the early 1980s, American eel landings have declined from 1,500 to 400 tonnes (NMFS 2003). Most eels are commercially harvested from estuaries and coastal river systems. New markets and increased demand for juvenile eels in the aquaculture industry have increased fishing effort on the early life stages (Meister and Flagg 1997). Additional factors influencing the sustainability of eel populations include disease, pollution, dam passage, habitat fragmentation, changes in hydrologic regimes and climate change (Castonguay et al. 1994a, b; Beaulaton and Castelnaud 2005). Because of the recent population declines and increasing demand for eels, fisheries managers must have information of stock dynamics to ensure widespread sustainability of the fishery.

The American eel is a catadromous fish with a long and complex life history. They are abundant in estuaries and freshwater along the Atlantic Coast of North America. The natural range extends from southern Greenland to North of South America where they inhabit coastal watersheds (Schmidt 1931; Tesch 2003). American eels spawn in the Sargasso Sea and their larvae are transported by drifting passively into coastal and freshwater systems (Kleckner and McCleave 1985; Williamson 1987; Shiao et al. 2002). Glass eels recruit from the Gulf Stream into Southeastern US estuaries using selective tidal stream transport from November to early May (Helfman et al. 1984; Powles and Warlen 2002; Sullivan et al. 2006). Elvers continue the migration into coastal river systems where they utilize brackish and freshwater habitats and transform into yellow-phase eels (>10TL cm).

There have been numerous studies of the migration of young European eels *A. anguilla* and American eels into estuaries (McCleave and Kleckner 1982; Gascuel 1986; Briand et al. 2003; de Casamajor et al. 2006). All of these studies agree that glass eels migrate into estuaries on flood tides. Additionally, we have a firm understanding about the timing and periodicity of ingress of American glass eels into the US coastal estuarine environments (Powles and Warlen 2002; Sullivan et al. 2006). However, little information exists about the recruitment patterns and timing related to glass eels entering freshwater environments of southeastern US coastal watersheds. We initiated a 27-month study with the overall goal of understanding the seasonal variation and movement patterns of American glass eels entering the freshwater environment. The objective of this study was to examine variation in seasonal patterns in glass eel recruitment and abundance into freshwater. Additionally, we monitored the environmental factors including water temperature, lunar phase and river discharge that may influence upstream migration of glass eels in freshwater.

Study area

The lower Roanoke River watershed in northeastern North Carolina consists of bottomland hardwood forests and cypress swamps. The river depth ranges from 3 to 6 m and can exceed 12 m in areas upriver during high springtime flows or other periods of prolonged high discharge. There is little to no tidal action in Roanoke River and any tidal action is overcome by controlled river flow through reservoir releases for power generation and flood control. From April through July, flow from Roanoke Rapids Dam is controlled between 240 and 167 $m^3 s^{-1}$ to provide adequate flow for successful spawning of striped bass *Morone saxatilis* (Rulifson and Manooch 1990). The dam is 215 river kilometers (rkm) from the river mouth at Albemarle Sound.

The Roanoke River has a diverse ichthyoplankton community. There are several diadromous fish species including moronids (i.e., striped bass, white perch *M. americana*,), alosines (American shad *Alosa sapidissima*, hickory shad *A. mediocris*, alewife *A. pseudoharengus*, blueback herring *A. aestivalis*), Atlantic sturgeon *Acipenser oxyrhynchus*, and American eel. With the exception of Atlantic sturgeon, these species dominate the late winter and spring ichthyoplankton community (Rulifson and Overton 2005).

The Albemarle Sound is approximately 2,770 km^2 with a length of 90 km and an average width of 11 km (Fig. 1; see Haeseker et al. 1996). The average water depth is 4.6 m, and may vary depending on wind direction and lunar tidal fluctuations (Giese et al. 1985; Pietrafesa and Janowitz 1991). The only connection the Albemarle Sound to Atlantic Ocean is via Oregon Inlet. In Albemarle Sound, environmental conditions vary, particularly salinity ranging from 2.0–15.0 psu in the eastern area to 0.0–0.3 psu in the western area approaching the mouth of Roanoke River. Once glass eels enter through Oregon Inlet, they must go through Roanoke or Croatan Sounds before they reach most eastern portion of Albemarle Sound. They must then drift 121 km to reach our sample area, the mouth of Roanoke River.

Methods

We sampled the ichthyofauna in the lower Roanoke River, North Carolina, from May 2001 through June

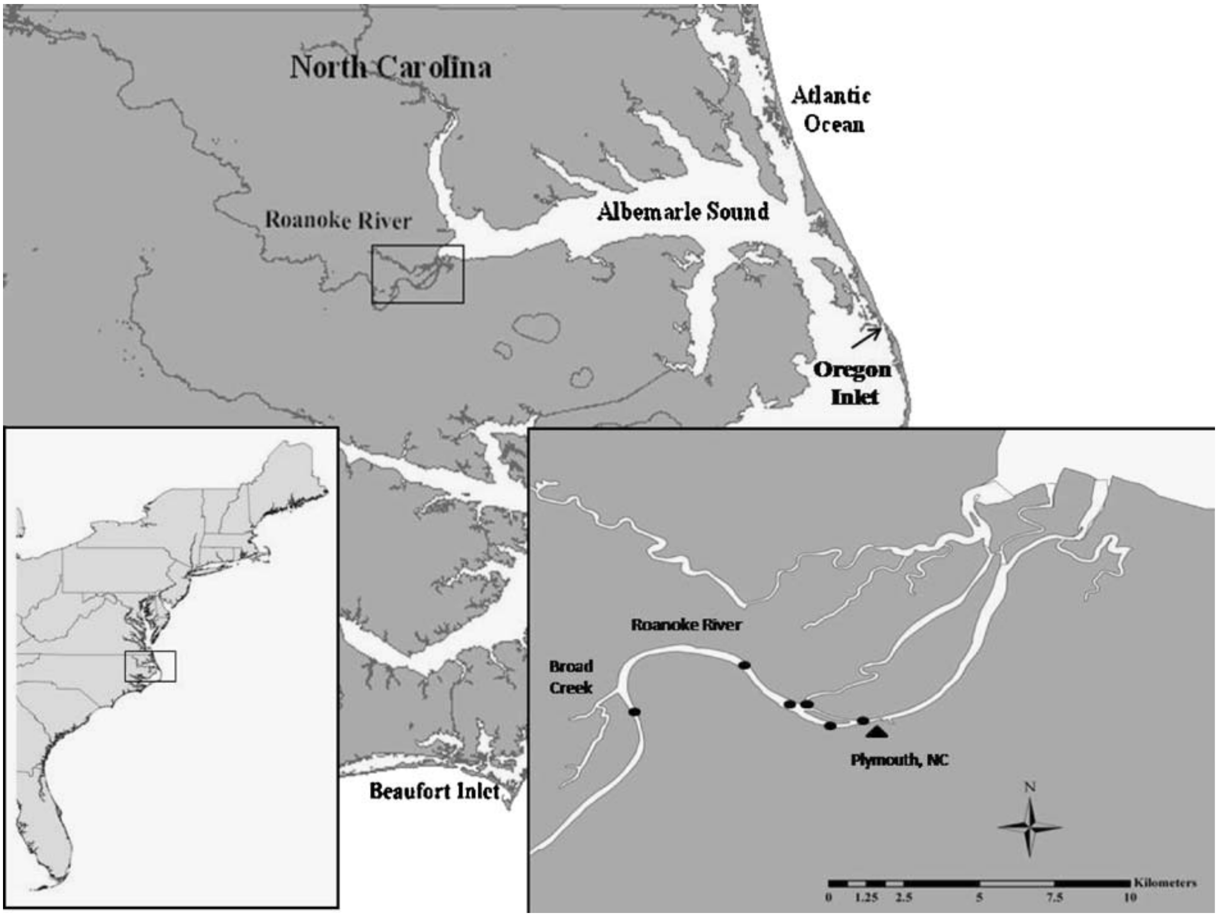

Fig. 1 Map of study area and sampling stations (*closed circles*) in lower Roanoke River, North Carolina

2003 (Fig. 1: River Kilometer 9.6–22.4). Six fixed stations were sampled from pelagic areas in the river channel during the day and at night starting 45 min after sunset. Each station was sampled twice per week from March through July, twice per month in August and September, and once per month during October through February. At each station, water temperature (°C), conductivity (μmhos), and salinity (psu) were measured.

Two types of plankton net configurations were used to collect larvae: (1) paired conical nets towed behind a 6.4-m boat equipped with an inboard engine and (2) paired push nets supported from a mount on the bow of a 4.8-m boat equipped with an outboard engine. The paired conical nets were 0.5 m in diameter constructed of 505-μm nitex mesh with a tail to mouth ratio of 5:1. These nets were towed against the current for 6 minutes obliquely (i.e., raising the nets through the water column during the tow). The paired push nets were 0.5-m square and constructed of 505-μm nitex mesh with a tail to mouth ratio of 5:1. The nets were connected to an aluminum frame mounted on the bow of the boat and the nets could be lowered to sample 0.5 m below the surface. The surface nets were pushed for two minutes against the current to prevent the clogging of the nets with floating debris. At each station, samples from both gear types were collected within 30 minutes of each other. Each net was equipped with a flowmeter mounted inside the mouth of the net to estimate the volume of water filtered. Tow speeds ranged from 0.63 to 4.57 m s^{-1} and volume of water sampled ranged from 14 to 653 m^3. We standardized the catch to density (#/1,000 m^3). The surface pushnets and oblique tows were analyzed together because there was no significant difference in the density of glass eels between the surface push nets and oblique tows (ANOVA; $P > 0.05$). The catch of each sample was preserved in 10% formalin containing Rose bengal dye and the glass eels were separated from debris, counted, and measured. River discharge data were obtained from the Roanoke Rapids Reservoir Dam provided by the US Geological Survey (USGS) water gage 02080500 (36°27′36″ N, 77°38′01″ W).

Statistical analysis

We used density calculated with generalized linear models (GENMOD with LSMEANS; (SAS Institute 2000) with a log-link and a Poisson distribution. We added 0.001 to the density data to avoid problem with zero-capture and log link. We tested the effects ($P < 0.05$) of explanatory variables river discharge, sampling station, lunar phase (full, new) and month in 2002. We only included data during the months in which glass eels were captured. Data from 2001 and 2003 were not statistically tested because only 1 glass eel was captured in 2001 and four glass eels were captured in 2003. We used an analysis of variance (ANOVA) to test for difference in mean river discharge during the sampling period. Pearson Correlation was used to test if glass eel density was correlated to water temperature and river discharge. Data from all years were used in this analysis.

Results

We collected 191 glass eels during the study. Most of the eels were collected in 2002 and the differences in numbers of eels collected among the years were directly related to the lengths of the sampling season. The glass eels collected in our sample ranged in size from 41.1 to 86.1TL mm with a mean of 57.7 ± 1.5 (SE; Fig. 2). The most frequently occurring eel size was 58.0 mm. Glass eels collected in August were significantly larger than eels collected during the other months during 2002 (ANOVA; $df = 7,46$; $P = 0.021$; Fig. 3).

Annual migration patterns and environmental conditions

The seasonal pattern of glass eels migrating into Roanoke River varied among years. From May through December in 2001, only one eel was captured during August (Fig. 4). In 2002, glass eels arrived in February and remained in our samples through October with the exception of September (Fig. 4). Peak mean eel density (#/1,000 m^3 ± SE) in 2002 occurred in March at 0.402 ± 0.124 and declined through June to 0.017 ± 0.001. By August, the mean

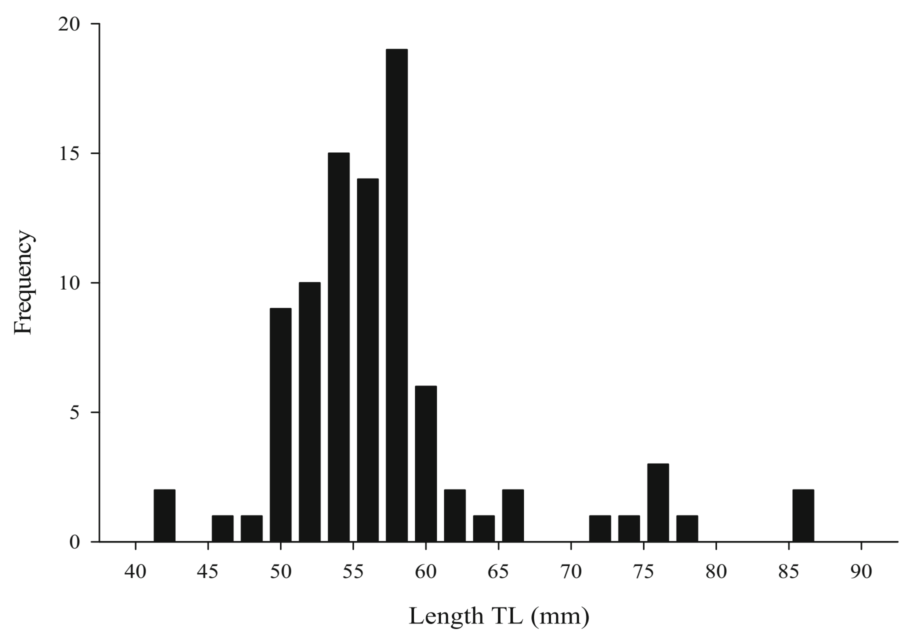

Fig. 2 Length frequency distribution of glass eels collected from the Roanoke River, NC

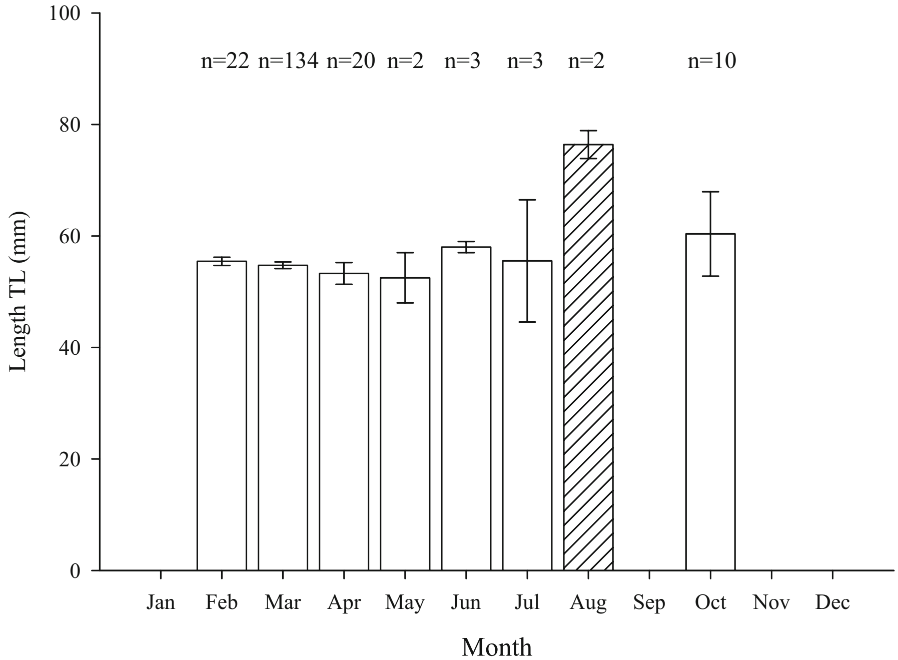

Fig. 3 Mean total length of glass eels (±SE) collected in 2002 in the lower Roanoke River, North Carolina. *Shading differences* indicate statistically significant differences

density increased to 0.095 ± 0.083 and was 0.358 ± 0.277 by October. In 2002, the density of glass eels was significantly affected by sampling month but was not affected by lunar phase (Table 1). Mean density of glass eels was significantly higher in March and October than all other months sampled (Fig. 4). In 2003, eels were captured only during February and March (Fig. 4).

Water temperature patterns were similar from May through December for 2001 and 2002 (Fig. 4). However, the mean monthly water temperature from January through June was warmer in 2002 than 2003. Glass eels were first captured when the water temperatures reached 10.1°C and 5.1°C in 2002 and 2003, respectively. We continued to collect glass eels in 2002 as water temperatures approached 30°C. Glass

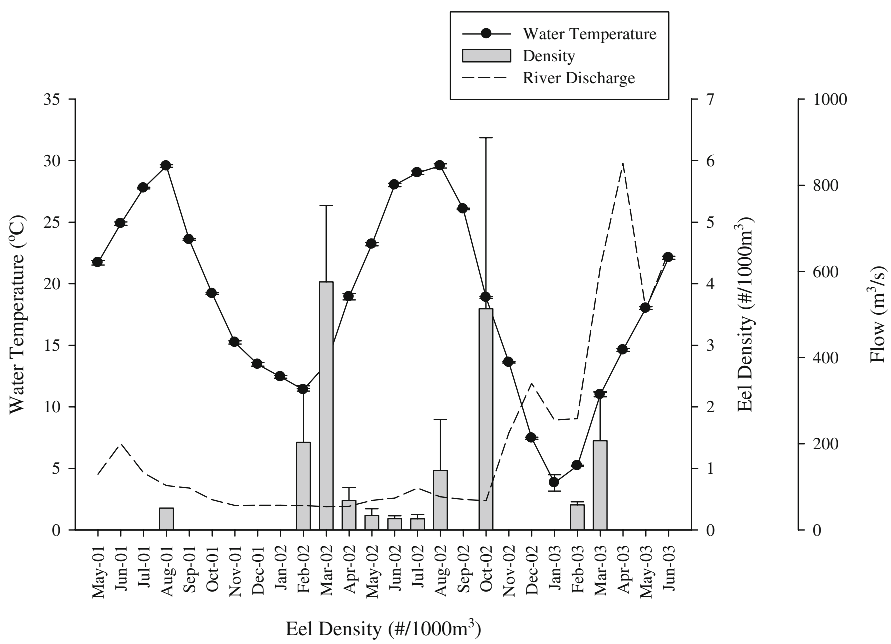

Fig. 4 Glass eel density (#/1,000 m^3±SE), river discharge (m^3 s^{-1}) and water temperature (°C) collected from the Roanoke River, NC from 2001 to 2003

Table 1 Details of the different generalized linear models (GLM) used to model density of glass eels *Anguilla rostrata* in Roanoke River, North Carolina

Effects	*df*	χ^2-value	*p*
Month	7	16.08	0.0244
Lunar phase	1	0.22	0.6358
Sample station	5	9.15	0.1032
River discharge	1	0.62	0.4309

Significance of effects was based on a type III sum of squares.

eel density was not correlated with water temperature (Table 2; Pearson's correlation; $r^2 = 0.152$, $P > 0.05$).

River discharge varied throughout the study. River discharge was significantly higher (ANOVA, $df = 2{,}1092$, $P < 0.0001$) in 2001 (125.5 $m^3\ s^{-1}$) than in 2002 (103.8 $m^3\ s^{-1}$). The mean discharge was 4.4 times higher in 2003 (459.2 $m^3\ s^{-1}$). There was no significant effect of river discharge on glass eel density during 2002 (Table 1). Monthly river discharge was <150 $m^3\ s^{-1}$ in January through October during 2001 and 2002, which represented a period when glass eel densities where the greatest. By November 2002, the river discharge increased to 224.8 $m^3\ s^{-1}$ and steadily increased to 606 $m^3\ s^{-1}$ by March 2003. River discharge reached 800 $m^3\ s^{-1}$ in April, and no glass eels were collected.

Discussion

We expected the seasonal patterns of glass eel recruitment and abundance to be similar for the duration of the study. However, this was not the case and our results show few consistent patterns of monthly glass eel migration in the lower Roanoke River. The migration patterns were distinctly different from 2001–2003. One consistent pattern was that the peak abundance in our study occurred consistently in March in 2002 and 2003. Our results are similar to migration patterns of glass eels at Beaufort Inlet, North Carolina, which is south of Albemarle Sound. Powles and Warlen (2002) sampled ichthyoplankton within 10 km of the nearshore Atlantic Ocean, and showed that the peak abundance of glass eels into the Beaufort Inlet consistently occurred in February and March. Our results also were similar to patterns observed in Altamaha River, Georgia (Helfman et al. 1984). In Nova Scotia peak elver catches occurred from late April to mid-August (Jessop 1998) and in New Jersey estuaries from February to March (Able and Fahay 1998; Sullivan et al. 2006).

Although the peak abundance was similar between years, the period during which glass eels were in the ichthyoplankton was not. Annual glass eel ingress into Beaufort Inlet was consistent from November through May (Powles and Warlen 2002). We did not collect any eels from November through January during our study. In 2002, glass eels appeared in February through October and were absent from November 2002 to February 2003. There are several possible reasons for these patterns observed in our data. Glass eels presumably enter Albemarle Sound through Oregon Inlet. As glass eels migrate through they encounter the discharges of several coastal rivers that drain into Albemarle Sound. It is likely that variations in environmental conditions in Albemarle Sound such as wind direction and freshwater output may influence where and when glass eels migrate.

There was no significant correlation between water temperature and glass eel density. This is consistent with the findings of eels in Rhode Island streams (Sorensen and Bianchini 1986). However, it appears that increasing water temperature stimulated the migration of glass eels in Roanoke River. Water temperature is one of the most important factors influencing migration (Laffaille et al. 2007). The water temperature where peak migrations occurred were different in 2002 (March, 13.4°C) and 2003 (March, 10.9°C). However, temperatures were near the 11°C threshold for glass eels proposed by Helfman et al. (1984) in Georgia and the 12°C threshold proposed by Smith (1955) in New Brunswick and 10–12°C in Nova Scotia (Jessop (2003). Freshwater glass eel migration requires water temperatures to exceed a threshold range of 10°C to 15°C. Water temperature will influence and initiate freshwater eel migration for other Angullid species (White

Table 2 Pearson correlation coefficients *r* between glass eel *Anguilla rostrata* density migrating into the Roanoke River, North Carolina and environmental variables

Variables	1	2	3
Density (eels 1,000 m^{-3})	1.000		
Water temperature (°C)	0.152	1.000	
River discharge ($m^3\ s^{-1}$)	−0.488*	−0.460	1.000

*$P<0.05$

and Knights 1997; Mckinnon and Gooley 1998; August and Hicks 2008).

Glass eels are sensitive to water temperature and are capable of detecting 1°C changes in water temperature (Kim et al. 2002). They become inactive at water temperatures below 5°C (Deelder 1958a). Only in January 2003 did we observe water temperatures below 5°C; there were also no glass eels present in the sample that month. August and Hicks (2008) suggested that water temperatures >22°C inhibited glass eel migration. Our results do not support their findings. In 2002, we collected glass eels even when water temperatures were approaching 30°C (June–September). Likewise glass eels were present in our samples when water temperatures were <10°C (2003 February and March).

In 2002, glass eels were present in our samples from February through October. The mean size of these eels (57.7 ± 0.1 mm TL) showed no seasonal decline in glass eel size in 2002. The mean size of glass eels was consistent throughout the year except during August when they were significantly larger. Other studies have reported a seasonal decline in the size of recruiting glass eels (Tzeng 1985; Jessop 1998; Wang and Tzeng 1998). This is because smaller glass eels respond more slowly to migration stimuli than larger eels (Jellyman and Ryan 1983).

The mean length of glass eels captured in our study was 57.7 mm TL. This estimate was similar to the sizes of glass eels collected from 1989–2004 at Little Egg Inlet, New Jersey (Sullivan et al. 2006). The total lengths of glass eels collected from 2001–2003 at Beaufort Inlet, North Carolina, were on average 2–4TL mm smaller than eels collected in our current study in Roanoke River. There are several possible reasons for greater mean size of glass eels in Roanoke River. Beaufort Inlet is located just southeast of the mouth of the Roanoke River. Glass eels presumably enter into Albemarle Sound through Oregon Inlet (Fig. 1), the only connection Albemarle Sound has to the Atlantic Ocean (Giese et al. 1985). Glass eels must then use flood tides (McCleave and Kleckner 1982) to migrate 121 km through Albemarle Sound to reach our sample area, the mouth of Roanoke River. During migration, they encounter a series of environmental conditions, particularly a salinity gradient of 2.0–15.0 psu as they enter eastern Albemarle Sound to 0.0–0.3 psu as they enter Roanoke River. We did not calculate the transport time of glass eels from Oregon Inlet to Roanoke River but this migration could last from 30 to 40 days (Beaulaton and Castelnaud 2005). However, if glass eels enter Beaufort and Oregon Inlet at the same time and size, the difference in size of glass eels entering Beaufort Inlet and Roanoke River may be because of environmental conditions (water temperature) encountered by glass eels that are favorable to growth as they migrate through Albemarle Sound.

River discharge during our study period was different among years, but we show that river discharge is negatively correlated with eel density. The 2001 and 2002 sampling seasons were characterized by river discharge less than <150 $m^3\ s^{-1}$. However when river discharge was >500 $m^3\ s^{-1}$ no glass eels were collected. Jellyman and Ryan (1983) showed that the largest glass eel migrations coincided with the greatest rainfall and was smallest with the least rainfall. This relationship between abundance and rainfall also was observed in an US east coast estuary (Sullivan et al. 2006). We suggest that river discharges >600 $m^3\ s^{-1}$ likely exceed the optimal suitable conditions for glass eel migration. Typically, high river discharge is associated with increased precipitation, which occurs during the winter months (Schmidt and Luther 2002). Increased terrestrial chemical cues associated with increased river discharge may act as cues for glass eel migration for some *Anguilla* spp. (Sola and Tongiorgi 1996).

The lack of a clear upstream migration pattern into freshwater in our study may be because of the behavioral and physiological changes that glass eels undergo as they enter freshwater areas. As glass eels enter freshwater, they delay further upstream migration and accumulate at the interface. It is possible that they shift behaviorally from migration to settlement. During this stage, glass eels experience ontogenetic changes and the more advanced eels are less inhibited by daylight (Deelder 1958b; Jellyman 1979; Sorensen and Bianchini 1986). Additionally, these more advanced eels become more dispersed and are more concentrated near the shore areas of the river (Jellyman 1979). We did not attempt to stage (after Strubberg 1913) the glass eels collected in our samples. However, 89% of the eels in our sample were incompletely pigmented (<60 TL mm).

We showed that glass eel migration varies annually in Roanoke River. We suggest that migration may be strongly regulated by environmental conditions. Lunar phase had no significant effect on upstream migration patterns. Water temperature was important for initiating eel migration but was not the dominant factor for regulating migration. Because the tidal influence in our study area was minimal, river discharge appeared to be the overriding factor. Water discharge greater than 600 m^3 s^{-1} prohibited the upstream migration of eels. The overall negative effect of river discharge suggests that changes in the water release schedules of upstream hydroelectric facilities during glass eel migration could strongly influence their recruitment success.

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