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Salinity Tolerance of Brown Shrimp *Farfantepenaeus aztecus* as it Relates to Postlarval and Juvenile Survival, Distribution, and Growth in Estuaries

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ABSTRACT: The brown shrimp, *Farfantepenaeus aztecus*, is the major component of the Gulf of Mexico shrimp fishery, and it is critical that we understand its environmental requirements. Brown shrimp spend a large portion of their post-larval (PL) and juvenile life within estuaries distributed along salinity gradients and yet our understanding of the salinity tolerance of various age groups is limited. A series of 48-hr bioassays were conducted in which various ages of *F. aztecus* (PL-10, PL-13, PL-15, PL-17, PL-20, and PL-23) were acclimated from a salinity of 26‰ to 1‰, 2‰, 4‰, 8‰, 12‰, and 26‰ in order to determine their tolerance to these salinities. Finally, PL-80 *F. aztecus* were transferred directly from 25‰ to 2‰, 4‰, and 8‰ waters to study the effects of rapid salinity reductions on juvenile survival. Survival of 10- and 13-day-old PLs was significantly different from the control (26‰) for all salinities tested. Survival of PL-15 shrimp and older was significantly lower than survival of the controls at 1‰ and 2‰ but similar to the control at all other salinities tested. A 4-wk growth trial was conducted with juvenile shrimp at 2‰, 4‰, 8‰, and 12‰. There was no significant difference in survival among treatments, although shrimp maintained at 8‰ and 12‰ grew significantly more than shrimp maintained at 2‰ and 4‰. There was no growth difference between shrimp at the two low salinities or between shrimp at the two high salinities. Survival of juveniles transferred directly from 25‰ to various salinities were 100% at 25‰, 94.2% at 8‰, 67.3% at 4‰, and 63.5% at 2‰. These results suggest that PL-13 and younger brown shrimp would have a better chance of survival by delaying entry into estuaries susceptible to rapid salinity declines. The brown shrimp juveniles would be more densely distributed in areas with salinities greater than 4‰ than in salinities less than 4‰. Although food availability and bottom type also affect shrimp distribution survival and growth, salinity may also greatly affect the shrimp and its fishery.

Introduction

The Gulf of Mexico accounts for approximately 70% of the shrimp fishery of the United States (Holliday and O'Bannon 1991), and the brown shrimp *Farfantepenaeus aztecus* makes up 58% of that fishery (Nance et al. 1994). Due to the economic importance of the shrimp fisheries, it is critical that we understand their life history and environmental requirements. Brown shrimp spawn offshore in oceanic seawater, then the planktonic larvae and postlarvae are carried by currents into estuaries, where they become demersal and remain for several months (Arreguin-Sanchez and Castro-Melendez 2000). The juveniles later migrate offshore to mature and spawn. There are two peaks of migration of *F. aztecus* into estuaries: late February through March and August through September (McTigue and Zimmerman 1991; Rogers et al. 1993; Wenner and Beatty 1993). Salinities in the estuaries are highly variable, generally ranging from freshwater at the head to oceanic seawater at the mouth, depending on tides, rainfall, wind, and riverine discharge. Since salinity tolerance is a critical factor that affects the distribution, survival, and growth of shrimp as well as their predators and preys (Gracia 1991), it has a profound impact on the shrimp fishery.

Most Gulf Coast states have attempted to model postlarval brown shrimp recruitment into estuaries in order to predict annual harvests. These models use abundance measurements such as those described by Baxter (1963), and incorporate salinity as a major component of their calculations (Zein-Eldin and Renaud 1986). Model results by Nance et al. (1994) and Arreguin-Sanchez and Castro-Melendez (2000), suggest that the survival of and fishery for brown shrimp in estuaries have a significant impact on the offshore fishery.

Within estuarine systems, postlarvae (PLs) disperse using several cues including salinity, organic matter abundance, and refuge such as *Spartina* spp. marshes (Benfield and Aldrich 1992; McTigue and Zimmerman 1998; Rosas et al. 1999). Brown shrimp have been caught in salinities ranging from 1‰ to 69‰ (Simmons 1957; Zein-Eldin and Renaud 1986) but no solid correlations between salinity and abundance, survival and growth have

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been reported. Rozas and Zimmerman (2000) observed a decrease in *F. aztecus* abundance with an increase in salinity while Howe and Wallace (2000) found no correlation between *F. aztecus* and salinity. All the previously mentioned studies have attempted to evaluate a relationship between PL size and salinity tolerance, disregarding the actual age of the shrimp. The salinity tolerance of PLs alters with age (Kumlu and Jones 1995; Tsuzuki et al. 2000), creating an age distribution relationship. Kumlu and Jones (1995) and Tsuzuki et al. (2000) found that the acclimation capacity of *Penaeus indicus* and *Farfantepenaeus paulensis* to low salinities increases after PL-10 but then decreases after PL-40. Before we attempt to model the recruitment and distribution of *F. aztecus* PLs in estuaries, we need to understand their salinity tolerance at various ages. The objective of the present research was to determine an age-salinity relationship for postlarval and juvenile *F. aztecus* (gulf brown shrimp). We studied the short-term survival of a range of postlarval stages of *F. aztecus* at various water salinities. We also evaluated the long-term survival and growth of juvenile brown shrimp maintained in waters of various salinities and the 48-hr survival of juvenile *F. aztecus* transferred from 25‰ to lower salinity waters.

Materials and Methods

Postlarval (PL-8) *F. aztecus* were obtained from a commercial hatchery in Texas and maintained in reconstituted seawater (Instant Ocean) at 26‰ and 29°C in a 144-L (0.6 × 0.6 × 0.4 m) polyethylene tank connected to a biological filter at the Auburn University Fisheries Research Station. The PLs were fed *Artemia* (200 per shrimp) and a commercial feed, PL-ready (Ziegler Bros Inc., Gardner, Pennsylvania), at 25–50% body weight daily. Salinity and temperature measurements were taken using a YSI 30 conductivity meter (Yellow Springs Instrument Company, Inc. Yellow Springs, Ohio). The research consisted of a short-term (48-hr) bioassay to assess the tolerance of various ages of postlarvae to low-salinity acclimations, a growth trial to study survival and growth of pre-adults maintained at various salinities, and a 48-hr bioassay to assess the tolerance of pre-adults to rapid declines in salinity.

The first series of experiments was performed on two separate cohorts of shrimp. The 48-hr survival of 10-, 15- and 20-day-old postlarvae (PL-10, PL-15, and PL-20) *F. aztecus* at salinities of 1‰, 2‰, 4‰, 8‰, 12‰, and 26‰ was investigated using one cohort of shrimp and the 48-hr survival of PL-13, PL-17, and PL-23 at the same salinities was tested using a second cohort. At the beginning of each test, 25 shrimp were randomly taken from the holding tank and individually weighed to the nearest 0.1 mg. During acclimation tests, 15 PLs were transferred to each of a series of white cylindrical containers (594 cm^2, 30 cm deep, containing 2 L of water at 28°C and 24‰) and aerated with an air diffuser. Shrimp in the containers were offered PL-ready and *Artemia* twice daily. Each battery of 4 replicate containers was supplied with filtered freshwater from a separate water tank using a submersible pump and irrigation-style flow restrictors. Salinity reduction protocols used were similar to those established by McGraw et al. (2002). Salinity reduction was adjusted to 4‰ hr^{-1} by changing the flow restrictors and reducing the water volume in the containers back to 2 L every hr until the target salinity or 6‰ was reached. For target salinities less than 6‰ the dilution rate was reduced to 2‰ hr^{-1} until the target salinity was reached. Surviving shrimp in each container were counted 48 hr after initiation of the salinity reduction. Survival in the 26‰ treatment was used as a control.

At PL-30, shrimp maintained in the polyethylene tank were gradually acclimated to 4‰ over a 2-d period and then transferred to 60 L glass aquaria. They were maintained in the aquaria at 4‰ and 30°C and offered crumbled shrimp feed (Rangen Inc., 35% protein) for 3 wk. One wk before the start of the growth trial, 4 recirculating systems consisting of four 144-L (0.6 × 0.6 × 0.4 m) polyethylene tanks were filled with reconstituted seawater (Crystal Sea, Marine Enterprises International) at 4‰. Water from each system flowed through a common drain into a sump tank where it was circulated through a trickling biological filter and returned to the tanks. Temperature was maintained at 29°C ± 1°C using submersible heaters placed in the sumps.

At the onset of the growth trial, groups of 15 shrimp were randomly removed from holding facilities, weighed to the nearest 0.01 g and placed into batteries of four replicate tanks. Salinity in two of the batteries was then increased over a 2-hr period to 8‰ and 12‰ by adding 60‰ reconstituted seawater, and was reduced to 2‰ by adding freshwater in another of the batteries. Salinity in the fourth battery was maintained at 4‰. Shrimp were fed crumbled shrimp feed (Rangen Inc., 35% protein) 4 times daily at a rate that assumes a weekly doubling in size and a 2:1 feed conversion ratio. Shrimp in each tank were counted weekly and their feed ration was adjusted accordingly. Four wk after stocking, the shrimp from each tank were counted and weighed.

In the third experiment, groups of 13 PL-80 juveniles (0.78 g ± 0.06; mean ± SE) acclimated to 25‰ were transferred into tanks containing salin-

TABLE 1. Forty-eight hour survival of *Farfantepenaeus aztecus* postlarvae at various salinities. Results are mean percent survival. PLs with similar superscripts (* and #) are from the same cohort. Survival numbers within the same column that have similar superscripts are not significantly different from the control (26 ppt) based on Dunnett's *t*-test. PSE indicates Pooled Standard Error.

	PL Age: Weight:	10 d* 0.0011 g	13 d# 0.0022 g	15 d* 0.0034 g	17 d# 0.0054 g	20 d* 0.0193 g	23 d# 0.0145 g
Salinity	1‰	0.0	0.0	10.0	28.3	47.5	1.7
	2‰	0.0	0.0	55.0	63.3	80.0	51.7
	4‰	0.0	5.0	73.3^{a}	78.3^{b}	100^{c}	96.7^{d}
	8‰	5.0	0.0	78.3^{a}	95.0^{b}	100^{c}	100^{d}
	12‰	13.3	43.3	93.3^{a}	85.0^{b}	100^{c}	100^{d}
	26‰	96.7	91.7	90.0^{a}	93.3^{b}	100^{c}	98.3^{d}
PSE		2.18	4.04	8.15	4.45	4.53	3.27

ities of 2‰, 4‰, and 8‰, thus emulating the rapid ingression of freshwater into estuaries during low tide, causing a rapid drop in salinity. Groups of 13 shrimp were also weighed and placed in 25‰ salinity as a control. Each treatment consisted of 4 replicates. Surviving shrimp in each container were counted 48 hr after transfer.

Statistical analyses were performed using SAS (V6.1, SAS Institute Inc. Cary, North Carolina). Mean body weights and mean survival of the shrimp in the various waters was estimated. Shrimp survival at low salinity was compared to survival at 26‰. Data were analyzed using ANOVA to determine significant ($p < 0.05$) differences among treatments. Student-Newman-Keuls test was utilized to determine differences ($p < 0.05$) among treatments and Dunnett's *t*-test was used to determine differences between treatments and controls.

Results

Survival at 26‰ was at least 90% at all PL stages and was similar for the two cohorts of shrimp tested. Forty-eight-hour survival of PL-10 and PL-13 at all other salinities tested was significantly lower than survival of the controls. Survival of PL-15 shrimp and older was not significantly different from the controls at all salinities except at 2‰ and 1‰ (Table 1).

In the long-term growth experiment, there was no significant difference in survival between treatments (Table 2). Growth at 8‰ and 12‰ was significantly greater than growth at 4‰ and 2‰. There was no significant difference in growth between shrimp at 8‰ and 12‰, or between shrimp at 2‰ and 4‰. Survival of juveniles transferred directly from 25‰ to various salinities were 100% at 25‰, 94.2% at 8‰; 67.3% at 4‰, and 63.5% at 2‰ (Fig. 1). Shrimp transferred to 2‰ and 4‰ had significantly poorer survival than the control (25‰).

TABLE 2. Survival and growth of juvenile *Farfantepenaeus aztecus* (mean initial weight 0.2 g) maintained for 4 weeks in various salinity waters. Values in the same row with the same superscript are not significantly different from each other based on Student-Newman-Keuls test. PSE indicates Pooled Standard Error.

Treatment (‰):	12.0	8.0	4.0	2.0	PSE
Survival (%)	98.3^{a}	98.3^{a}	93.3^{a}	95^{a}	3.88
Final biomass (g)	22^{a}	21.4^{a}	14.5^{b}	12.7^{b}	0.84
Final wt/shrimp (g)	1.5	1.5	1	0.9	0.03
Weight gain (%)	689^{a}	614^{a}	374^{b}	33.16	

Discussion

Based on the results observed in the present study, the capacity of *F. aztecus* postlarvae to acclimate to low salinity waters improves after PL-13. Before this age the PLs are not tolerant to low salinity waters. Similar tolerances were observed in *Penaeus vannamei* (Bray et al. 1994), *F. paulensis* (Tsuzuki et al. 2000), *P. indicus* (Kumulu and Jones 1995), and *Litopenaeus setiferus* (Rosas et al. 1999). It appears that postlarvae younger than 13 days would not be able to survive the low salinities found in many estuaries.

Shrimp postlarvae actively control their entrance into estuaries by swimming up into incoming tidal currents and down near the bottom during ebb tides (Hughes 1972; Matthews et al. 1991; Rogers et al. 1993). An increase in salinity with the incoming tide is thought to cue active vertical swimming. Results of the present study suggest that salinity changes might not cue an upward swimming behavior in PL younger than 13 days, and delay their

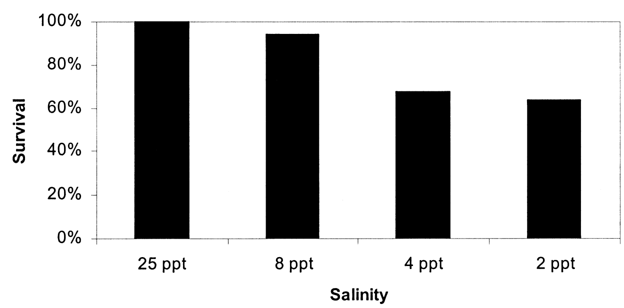

Fig. 1. Percent survival of *Farfantepenaeus aztecus* juveniles 48 hr after direct transfer from 25‰ to various salinities. Based on Dunnet's t-test, survival of shrimp transferred to 4‰ and 2‰ were significantly lower than those transferred to 8‰.

entrance into estuaries until they are capable of acclimating to low salinities.

Once within the bays, the shrimp are thought to disperse along salinity gradients (Zein-Eldin and Aldrich 1965; Weinstein 1979; Zimmerman et al. 1990; Wenner and Beatty 1993). Survival, growth, and energetics of PLs and juveniles of various species of shrimp in various salinities have been studied with varying results being reported (Bray et al. 1994; Kumulu and Jones 1995; Rosas et al. 1999; Tsuzuki et al. 2000). Howe et al. (1999) report a weak correlation between salinity and brown shrimp abundance in Mobile Bay, Alabama, while Howe and Wallace (2000) detected no correlation between salinity and brown shrimp in the same estuary. Zein-Eldin (1963) found that brown shrimp grow better at 25‰ than at 5‰, 10‰, or 40‰, while Zein-Eldin and Aldrich (1965) report a low correlation between growth and salinity of *F. aztecus* and Zein-Eldin and Griffith (1969) did not find any difference in growth of postlarvae at salinities between 2‰ and 40‰. A negative correlation between brown shrimp abundance and salinity was also detected by Rozas and Zimmerman (2000). No researchers found significant differences in survival of brown shrimp postlarvae at various salinities. Results of the present study corroborate findings of equal survival at various salinities but demonstrated a reduction in growth at salinities below 4‰. There were no differences in natural productivity or other environmental variables among treatments so growth differential was attributed to the effects of salinity. Since slow growing shrimp are less equipped to compete for resources and are more susceptible to predation, the PLs probably settle in areas with salinities above 4‰. However, there are several environmental factors other than salinity that could affect survival and growth and consequently distribution of PLs within an estuary.

Salinities within estuaries along the Gulf of Mexico fluctuate considerably depending on rainfall, storm surges, tides, and wind. Salinity can vary from below 1‰ to above 20‰ in less than an hour. For example, salinity on the southeastern side of Mobile Bay dropped from 12‰ to c. 1‰ in less than an hour in May 1999 and remained at that low level for the duration of a tidal cycle (Saoud unpublished data). In all three experiments presented in the present paper, *F. aztecus* postlarvae and juveniles did not respond favorably to salinities below 4‰.

Postlarvae that were acclimated to low salinities survived at those salinities as juveniles. When juveniles older than PL-80 were acclimated to high salinities, they did not exhibit good survival when transferred to salinities below 4‰. Similar results were observed in *P. indicus* and *F. paulensis,* both of which lost their capacity to acclimate to rapid drops in salinity after PL-40 (Kumlu and Jones 1995; Tsuzuki et al. 2000).

Estimates of numbers of brown shrimp entering bays (Baxter 1963) are used in conjunction with environmental factors such as salinity by most Gulf states to model brown shrimp abundance in nursery areas (Zein-Eldin and Renaud 1986). Freshwater inflow into most of the estuaries in the Southern U.S. is regulated by dams and discharge could be regulated while taking into consideration the biological requirements of economically important fisheries such as penaeids. Zein-Eldin and Renaud (1986) suggest that consideration be given to total volume of water released, the time of release in relationship to the arrival of the young of the year, and the interaction of temperature and salinity (i.e., maintain higher salinity in cold temperature). By using the age-salinity relationships reported in the present study, models of seasonal salinity profiles in estuaries during freshwater discharge and rain runoff, and limitations on the inshore shrimping season and areas, fisheries managers could positively affect the total brown shrimp fishery in terms of both pounds and revenue (Nance et al. 1994). If a combination of river discharge and the salinity tolerances described in the present paper are incorporated into habitat suitability indexes such as the one developed by Rodgers (2001) for Mobile Bay, resource managers could better regulate fishing pressure inshore thus increasing offshore recruitment and consequently the total *F. aztecus* fishery in the Gulf of Mexico.

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