RECRUITMENT, SPATIAL DISTRIBUTION, AND FINE-SCALE MOVEMENT PATTERNS OF ESTUARINE DEPENDENT SPECIES THROUGH TIDAL INLETS IN TEXAS

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ABSTRACT

Information on geographical recruitment patterns of estuarine-dependent fish is critical to understanding their ecology. Red drum (*Sciaenops ocellatus*), southern flounder (*Paralichthys lethostigma*), blue crab (*Callinectes sapidus*), and penaeid shrimp (*Farfantepenaeus aztecus*, *F. duorarum*, *Litopenaeus setiferus*) use estuaries as nurseries; therefore, they make ideal model species for this study. Estuaries are considered nurseries in that they provide plentiful food supplies for growth and structured habitat types for protection from predators. While generalities concerning estuarine recruitment dynamics are somewhat understood, spatial recruitment patterns from an inlet are unknown. The purpose of this research is to characterize how far red drum, southern flounder, blue crabs, and penaeid shrimp disperse from an inlet before settling into a nursery habitat (e.g., seagrass meadows) and to examine the effects of a new inlet on recruitment. Packery Channel is a natural tidal inlet that connects Corpus Christi Bay to the Gulf of Mexico and was closed since the 1930's until recently opened. This is a unique opportunity to study recruitment patterns in an area that was previously inaccessible to newly settling fishes and crustaceans. On a smaller scale, I also assessed the effect of artificial habitat and corridors within tidal inlets on red drum recruitment dynamics as well as fine-scale movement patterns of newly settled wild and hatchery-reared red drum using mark and recapture techniques. To examine the effect of distance and the effect of opening Packery Channel on the recruitment of juvenile fishes and decapod crustaceans, I evaluated densities of juvenile red drum, southern flounder, blue crabs, and penaeid shrimp in seagrass beds of *Halodule wrightii* at varying distances from Aransas Pass and Packery Channel pre- and post-opening. I found that densities of these species were repeatedly higher at sites closest to the inlet, suggesting that high levels of recruitment occur at the first extensive seagrass meadows new recruits encounter. Prior to the opening of Packery Channel, newly settled individuals typically did not occur in areas near Packery Channel. However, after the opening of Packery Channel, densities of small individuals of all species were high in these areas suggesting they are recruiting through the new inlet. Once fully opened, the Packery Channel could have a great impact on the densities of recruiting nekton in the upper Laguna Madre. I also examined the role that settlement habitat within an inlet plays on recruitment to seagrass beds within the bay. My results suggest that seagrass beds within the tidal inlet do not affect the densities of red drum within a bay and that these fish are not using the habitat in the channel as corridors. I also evaluated the use of visible implant elastomer (VIE) for mark and recapture studies on juvenile red drum and performed a preliminary study on the fine-scale movement patterns of red drum within a seagrass bed. I found that VIE is an effective method for marking small red drum, and they may have a much larger dispersal potential than previously suspected. Overall, seagrass beds nearest to the inlet appear to be the most important for settling juvenile fish and crustaceans, and the opening of Packery Channel has allowed access to habitats in upper Laguna Madre that were previously inaccessible to newly settling juveniles, possibly enhancing fisheries productivity in that area.

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INTRODUCTION

Many nations rely on fishery resources as a major economic activity and food source, consequently there is worldwide public interest in their status (Hilborn et al. 2003). This reliance has lead to detrimental impacts to fish stocks. It is estimated that 33% of the U.S. fish stocks are overfished or depleted (NMFS 2003) and 50% are fully exploited (Pauly et al. 2002; Christensen et al. 2003). While overfishing has played a primary role in their collapse (Jackson et al. 2001), other anthropogenic activities have contributed to or may be preventing the recovery of certain fish stocks (Hilborn et al. 2003). For example, habitat destruction, particularly nursery habitat, has become a foremost concern in the demise of some fisheries.

Problems within fisheries require scientists and managers to deal with a network of interactions within dynamic ecosystems, the most basic being the relationship between fish and their habitat. Access to high quality habitat is fundamental for reproduction, growth, migration, and survival of fish populations (Levin and Stunz 2005). Estuaries provide high- quality habitat that serve as feeding and nursery grounds for economically important fisheries species that comprise 75 % of U.S. commercial landings (Chambers 1991). Numerous economically and ecologically important species of fish spawn offshore producing young that migrate into estuarine nursery grounds where they mature. Estuarine ecosystems are characterized by very high levels of primary production, forming the basis of a food web that supports a high biomass of fisheries species (Minello 1999).

Habitats, such as seagrasses, within estuaries play a key role in their high productivity and support a large number of marine organisms. Seagrasses are submerged aquatic vegetation (SAV) that are considered to be one of the most productive and valuable habitats in estuarine systems (Quammen and Onuf 1993; Levin et al. 1997). Seagrasses typically support greater abundances and richness of fauna than unvegetated habitats (Rozas and Minello 1998; Beck et al. 2001). Seagrasses function as nursery habitat for recruiting juvenile fish and invertebrates (Heck and Thoman 1981; Levin et al. 1997; Beck et al. 2001; Heck et al. 2003) providing structurally complex habitat (Heck et al. 2003), protection from predation (Rooker et al. 1998*a*; Stunz and Minello 2001), and increased growth rates (Holt et al. 1983; Heck and Thoman 1984; Stunz et al. 2002*b*; Heck et al. 2003). Since habitat can have an effect on growth rates and mortality of juvenile fish, understanding interactions between fish and their habitat is essential. It is estimated that relatively small variations in mortality rates, growth rates, or stage duration in the early life of fishes can have tenfold or greater fluctuations in recruitment (Houde 1987). Despite the importance of seagrass beds to recruiting juvenile fishes and invertebrates, they have undergone declines resulting from anthropogenic disturbances such as dredging (Quammen and Onuf 1993), eutrophication, and mechanical damage (Short and Wyllie-Echeverria 1996; Duarte 2002).

Tidal inlets play an important role in determining the dynamics and structure of marine fish populations, because they provide a means of access from the open ocean to these high-quality estuarine nursery habitats (Connell and Jones 1991; Eggleston 1995). Clearly, understanding how fish access nursery habitat and their subsequent dispersal is critical for examining fish recruitment. However, not all inlets are similar in habitat availability. For example, nursery grounds may be inaccessible, because of a high mortality risk associated with larvae and juvenile fishes crossing large expanses of nonvegetated or channeled bottom to reach suitable nursery habitats. Since the majority of economically important fishes are dependent upon these areas during critical phases of their life cycle, it is important to document recruitment through these inlets. Considerable gaps in our knowledge exist for many important fishery species regarding their exact spatial patterns of habitat use once they have been transported through tidal inlets.

Spatial patterns of fishes and crustaceans in habitats within an estuary are not evenly distributed. Recruitment patterns result from the interaction of various physical and biological processes that occur between the time the egg is released and subsequent settlement into suitable juvenile habitat. Physical parameters such as distance from a tidal inlet, tidal flux, current, wind, topography of the coastline, water quality, and structural complexity of the habitat (Rozas and Minello 1998) can have a large effect on the distribution of estuarine-dependent species within an estuary (Boehlert and Mundy 1988; Miller 1988; Akin et al. 2003; Brown et al. 2005). Biological parameters such as variations in larval supply (Jenkins and Black 1994; Brown et al. 2005), behavior of the larvae, active selection of habitat, and duration in the planktonic phase, can also have an effect on recruitment patterns (Bell and Westoby 1986; Boehlert and Mundy 1988). Post-settlement factors such as mortality, predation, food resources, and competition can also affect abundance and length distributions of fishes and invertebrates in nursery habitats (Jenkins et al. 1997; Levin et al.1997). Due to such factors, fishes and crustaceans are not distributed randomly throughout an estuary. Because of this, seagrass beds in certain areas within an estuary may be more valuable to recruiting juvenile fishes and crustaceans than those in areas that do not receive recruits.

Recruitment may also be affected by loss of habitat in areas between spawning sites and nursery grounds. Post larvae and juveniles sometimes must travel over many kilometers of nonvegetated bottom increasing their risk of predator-related mortality. Artificial seagrass units (ASUs) can aid in the examination of the potential for artificial habitats to function as "corridors" for recruiting fish to established seagrass beds that may be unavailable because of predator-related mortality or starvation due to lack of appropriate habitat (Micheli and Peterson 1999). They may also allow fisheries managers to predict suitable future restoration sites. Artificial seagrass units have been successfully used by many investigators to determine recruitment of estuarine-dependent fishes (Bell et al. 1985; Bell et al. 1987; Bell et al. 1988; Sogard 1989; Bologna and Heck 2000; Upston and Booth 2003). These studies have shown that ASUs attract fauna similar to the assemblage of fish and invertebrates that colonize natural seagrass beds.

Once estuarine-dependent species access and settle in estuarine habitat it is important to understand their movement patterns within that habitat. Mark and recapture studies may provide a useful technique to assess fine-scale movement patterns of juvenile fish within a nursery habitat. However, examining the fine-scale movement patterns of juvenile fish is difficult because few techniques exist to mark small fish. Nonetheless, characterizing and documenting the movement patterns and fate of the fish is important for understanding their recruitment dynamics and to manage for sustainable fisheries. Visible implant elastomer (VIE) is a two-part silicone based material that is mixed before use and injected as a liquid beneath transparent or translucent tissue. The liquid cures into a pliable solid and is externally visible. VIE has not been evaluated for use on juvenile red drum and may be a viable technique to quantify movement patterns within nursery habitats.

My research was designed to characterize recruitment patterns of red drum, southern flounder, blue crab, and penaeid shrimp at varying distances from Aransas Pass and Packery Channel using a series of field collections. Field and laboratory experiments were used to evaluate the effect of artificial settlement habitat on migrating red drum in tidal inlets lacking in suitable habitat. VIE was used as a tagging technique for marking small red drum in laboratory and field experiments, and I performed a preliminary experiment examining the fine-scale movement patterns of wild and hatchery-reared red drum. My research will provide critical information that will allow managers to make informed decisions concerning recruitment patterns of these commercially and recreationally important species. Specifically my objectives were:

(1) Examine density patterns of juvenile red drum, southern flounder, blue crabs, and penaeid shrimp in nursery habitats at varying distances from the Aransas Pass and Packery Channel tidal inlets

(2) Assess the effect of a new tidal inlet, the Packery Channel, on the recruitment of those species

(3) Examine the corridor effect via artificial settlement habitat on migrating fish in tidal inlets that are lacking in suitable settlement habitat

(4) Evaluate the usefulness of visible implant elastomer for tagging red drum and examine fine-scale movement patterns of wild and hatchery-reared red drum within a nursery habitat

CHAPTER I

RECRUITMENT OF RED DRUM, SOUTHERN FLOUNDER, BLUE CRAB, AND PENAEID SHRIMP AT VARYING DISTANCES FROM A TIDAL INLET

Introduction

Recruitment patterns of estuarine-dependent fish to nursery habitats results from the interaction of various physical and biological processes that occur between the time the egg is released and subsequent settlement into nursery habitat. Two phases of movement are necessary for recruitment of estuarine-dependent species that spawn offshore and the juveniles settle into estuarine habitats. The first phase involves the transport of the planktonic larvae to the nearshore zone, and the second is their accumulation at tidal inlets and their subsequent movement into the estuary. The first phase is generally thought to be passive because the larvae are planktonic, however behaviors such as directed vertical movement may enhance shoreward movement (Boehlert and Mundy 1988). Longshore drift plays a key role in the accumulation of larvae at an inlet, and physical factors near inlets may serve as stimuli for larval behavioral responses to facilitate recruitment (Boehlert and Mundy 1988). Once the larvae have passed through a tidal inlet, there are many factors that can have an effect on their distribution within an estuary. Physical parameters such as distance from the tidal inlet, tidal flux, current, wind, topography of the coastline, and water quality can have a great effect on the distribution of estuarine-dependent species within an estuary (Boehlert and Mundy 1988; Miller 1988; Rozas and Minello 1998; Akin et al. 2003; Brown et al. 2005). Biological parameters such as variations in larval supply (Jenkins and Black 1994; Brown et al. 2005), active selection of habitat, and duration in the planktonic phase, can also have an effect on distribution patterns (Bell and Westoby 1986; Boehlert and Mundy 1988). Post-settlement processes such as food resources, mortality, competition, and predation may also be important factors when considering the distribution and sizes of fishes and invertebrates within estuarine nursery habitats (Jenkins et al. 1997; Levin et al.1997).

Access to nursery habitats for recruiting juvenile fish and crustaceans is crucial for successful recruitment into adult populations. Seagrasses function as nursery habitat for recruiting juvenile fish and invertebrates (Heck and Thoman 1981; Levin et al. 1997; Beck et al. 2001; Heck et al. 2003) providing structurally complex habitat (Heck et al. 2003), protection from predation (Rooker et al. 1998*a*; Stunz and Minello 2001), and increased growth rates (Holt et al. 1983; Heck and Thoman 1984; Stunz et al. 2002*b*; Heck et al. 2003). Since habitat can have an effect on growth rates and mortality of juvenile fish, understanding interactions between fish and their habitat is essential. It is estimated that relatively small variations in mortality rates, growth rates, or stage duration in the early life of fishes can have tenfold or greater fluctuations in recruitment (Houde 1987). Despite the importance of seagrass beds to recruiting juvenile fishes and invertebrates, they have undergone declines resulting from anthropogenic disturbances such as dredging (Quammen and Onuf 1993), eutrophication, and mechanical damage (Duarte 2002; Short and Wyllie-Echeverria 1996). Therefore, it is important to accurately identify the seagrass beds used by early life stages of fishes and invertebrates.

Tidal inlets allow access from the open ocean to high-quality estuarine nursery habitats and play an important role in the dynamics and structure of marine fish populations (Connell and Jones 1991; Eggleston 1995). Understanding how fish access nursery habitat and their subsequent dispersal is critical for determining fish recruitment. The opening of Packery Channel near Corpus Christi, Texas, provides an excellent opportunity to study the recruitment dynamics of estuarine-dependent fishes and decapod crustaceans through a newly formed tidal inlet. Packery Channel is a natural tidal inlet near the upper Laguna Madre that has been naturally closed since the 1930's. The channel was dredged and reopened in July 2005 creating a direct link to abundant nursery habitats in Corpus Christi Bay as well as the upper Laguna Madre that were previously inaccessible to marine fishes and crustaceans that spawn in the Gulf of Mexico.

Few studies have examined spatial recruitment patterns (e.g., distance from tidal inlets) of estuarine-dependent species within a nursery habitat. Bell et al. (1986) proposed the "settle and stay" hypothesis that states recruiting juvenile fishes will settle into the first seagrass bed they encounter and remain there regardless of physical complexity. If a fish settles into the first bed they encounter and remain there they will probably have a greater chance of survival than those fish that remain planktonic and disperse to more distant habitats. These authors theorize that fish will relocate to more complex areas within the seagrass bed to avoid predation risks associated with re-entering the plankton. If this theory holds true, densities of newly settled estuarine-dependent species should be high in the first seagrass bed they encounter within an estuary. Bell et al. (1988) examined differences in species composition and richness of juvenile fish and decapod crustaceans in seagrass beds at different distances from an inlet within an estuary using sites in each of two arms of the estuary for comparison. They found that the location of a seagrass bed within an estuary has a significant effect on the abundance of juveniles of many species of fish and decapod crustaceans, and these effects were due to location of the bed and not its physical complexity. They attributed the differences in abundance to distribution and availability of competent larvae within the estuary. Other studies have shown that densities of estuarine-dependent fishes and decapods are highest at sites closest to the tidal inlet (Young and Wadley 1979; Loneragan et al. 1986; Heck et al. 2001; Etherington and Eggleston 2003). However, the role that increasing distance from a tidal inlet plays on distribution of estuarine-dependent species remains unclear.

Red drum (*Sciaenops ocellatus*), southern flounder (*Paralichthys lethostigma*), blue crab (*Callinectes sapidus*), and penaeid shrimp (*Farfantepenaeus aztecus*, *F. duorarum*, *Litopenaeus setiferus*) represent fishery species where more information on recruitment dynamics and nursery habitat use is needed. Red drum occur in the western Atlantic and throughout the Gulf of Mexico from Florida to Tuxpan, Mexico (Pattillo et al. 1997). Historically, red drum supported an impressive commercial fishery in the Gulf of Mexico and Atlantic Ocean (Pattillo et al. 1997) until the fishery was closed in 1990 due to overfishing and habitat destruction (Swingle et al. 1984; McEachron and Daniels 1995; Scharf 2000). The red drum is also considered to be the most important recreational sciaenid species as well as one of the seven most sought-after gamefish in the Gulf of Mexico (Pattillo et al. 1997). In Texas alone, red drum are sought by 800,000 recreational saltwater anglers; and in 1994, 275,000 red drum weighing >1 million kg were landed by recreational anglers (McEachron and Daniels 1995). The economic impact generated by this species is vital to Texas and to numerous other coastal economies (TPWD 1995).

Generalities concerning red drum habitat use have been well-documented (Holt et al. 1983; Pattillo et al. 1997; Rooker and Holt 1997; Rooker et al. 1998*b*; Scharf 2000;

Stunz et al. 2002*a*). Red drum spawn near passes and tidal inlets from September-January (Holt et al. 1983; Rooker et al. 1998*b*) and subsequently their eggs and larvae are carried by tides and currents into shallow estuaries and bays where they settle from the water column into nursery habitat. Red drum are in the pre-competent planktonic phase for approximately 15-30 days (Rooker et al. 1999; Brown et al. 2005), after which they settle into nursery habitat at approximately 6-8 mm standard length (SL) (Holt et al. 1983; Rooker et al. 1997; Rooker et al. 1998*a*), where they remain during the early juvenile stages ($\leq$ 40 mm) (Rooker et al. 1998*a,b*). Seagrass beds and marshes often have been cited as the primary nursery habitat for young red drum (Holt et al. 1983; Pattillo et al. 1997; Rooker and Holt 1997; Rooker et al.1998*a, b*; Stunz et al. 2002*a*).

The southern flounder is an economically and ecologically important fishery in the Gulf of Mexico and is a prized recreational fish sought by many anglers. The life history of southern flounder is similar to that of the red drum, where adults spawn offshore and the larvae migrate to estuarine nursery areas. Southern flounder have a spawning season that occurs between September and April and immigration of juveniles into Texas bays begins in January and increases into February (Gilbert 1986). Although little is known about the habitat requirements of juvenile southern flounder, a primary nursery habitat is considered to be *Halodule wrightii* seagrass beds (Nanez-James 2006; Enge and Mulholland 1985). Although southern flounder are an important species in Texas bays, little is known about recruitment dynamics such as the distance that juvenile southern flounder migrate from a tidal inlet before settling in estuarine nursery habitats.

Blue crabs and penaeid shrimp are estuarine-dependent decapod crustaceans with a similar life history to that of red drum and southern flounder. Blue crabs support a considerably large recreational and commercial fishery in the Gulf of Mexico (Pattillo et al. 1997). Their life history is such that the spawning occurs year-round with peaks in late spring and early fall. The eggs hatch near the mouths of estuaries and the zoeal larvae are carried offshore. Newly hatched larvae develop through seven planktonic zoeal stages and remain offshore for up to one month. Following the zoeal stages, larvae metamorphose into the megalops larval stage and re-enter estuarine waters. The megalops stage lasts for 6-12 days, after which the crab is in the juvenile stage and is 2.2-3.0 mm carapace width (CW) (Pattillo et al. 1997). The peak blue crab recruitment period for juveniles in Texas bays is reported to be from July to September and October to March (Thomas et al. 1990). Juvenile blue crabs rely heavily on submerged aquatic vegetation (SAV) as nursery areas (Heck and Thoman 1981; Heck et al. 2001) and seagrassess have been found to support higher densities of blue crabs than either marsh or sand bottoms (Thomas et al. 1990).

Penaeid shrimp represent one of the largest commercial fisheries in the Gulf of Mexico. Shrimping has been ranked as the second most valuable commercial fishery in the United States (Pattillo et al. 1997). There are three important species of penaeid shrimp in the Gulf of Mexico: brown shrimp (*Farfantepenaeus aztecus*), pink shrimp (*F. duorarum*), and white shrimp (*Litopenaeus setiferus*). The life cycle of penaeid shrimp is similar to that of blue crabs where the adults spawn offshore and the post larvae are transported into estuarine nursery habitat. Transport into the estuary is species specific. Brown, pink, and white shrimp are typically found in estuaries in greater abundance during the spring, winter, and summer respectively (Howe et al. 1999). Submerged aquatic vegetation such as *H. wrightii* and marsh have been cited as primary nursery habitat for brown and pink shrimp (Zimmerman et al. 1984; Zimmerman and Minello 1984; Minello and Zimmerman 1991; Pattillo et al. 1997). White shrimp have been found to use seagrass and marsh as well as non-vegetated bottom (Zimmerman and Minello 1984; Howe et al. 1999).

To examine the role of distance of nursery habitat from a tidal inlet on settlement patterns, I examined densities of juvenile red drum, southern flounder, blue crabs, and penaeid shrimp in seagrass beds at varying distances from a tidal inlet.

Methods

Study Site

Recuitment of various estuarine-dependent species was examined over a large spatial scale. The study area extended from the Aransas Pass at Port Aransas, TX, south towards Packery Channel, and into the upper Laguna Madre. The study site included the major bays of Corpus Christi and upper Laguna Madre, TX. Site 1 was located 11 km from the Gulf of Mexico at Aransas Pass in the first extensive seagrass bed that fish and crustaceans encounter when recruiting through the Corpus Christi Ship Channel. The remaining sites were located approximately every 2 km from the first seagrass bed in Corpus Christi Bay to 51 km away in the upper Laguna Madre (Fig. 1). Packery Channel was dredged near site 9 approximately 39 km from the Aransas Pass. Distances were measured from the mouth of Aransas Pass at the Gulf of Mexico through the Corpus Christi Ship Channel.

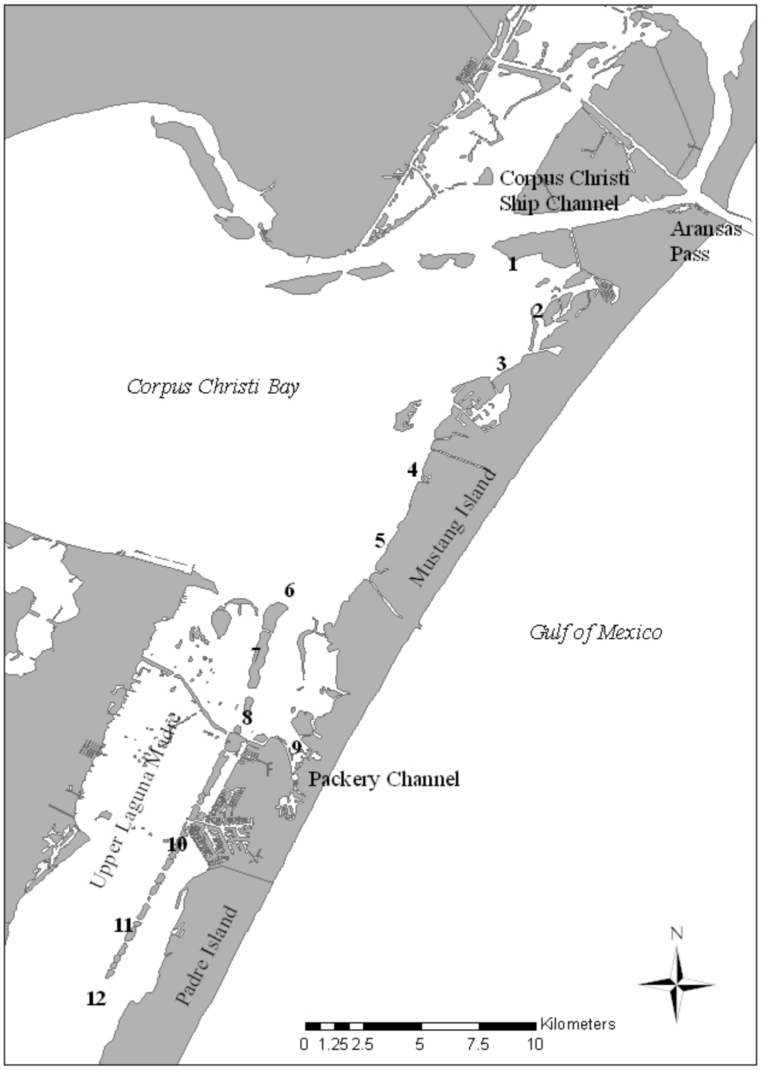

Figure 1. Map of study area and study sites at varying distances (km) from Aransas Pass in Corpus Christi Bay and upper Laguna Madre, TX. Site 1 was located 11 km from the Gulf of Mexico in the first seagrass bed that recruiting fish and crustaceans encounter after traveling through the Corpus Christi Ship Channel. The remaining sites were approximately 2 km apart and extended to 51 km at site 12 in the upper Laguna Madre. Packery Channel was dredged near site 9 approximately 39 km from Aransas Pass.

Corpus Christi Bay is a positive primary bay located on the southern coast of Texas and is the largest bay in the Corpus Christi Bay system. Corpus Christi Bay has a maximum depth of 3.1 m (Britton and Morton 1989), a surface area of 497 km^2, and a mean salinity of 22 ppt (USEPA 1999). Freshwater inflow is from the Nueces River and Oso Creek, and during the initial phase of this study, the only water exchange with the Gulf of Mexico occurs through Aransas Pass. The Aransas Pass is a narrow tidal inlet approximately 400-500 m wide, allowing exchange of water as well as serving as a major navigation channel (TPWD 2005). Water entering through Aransas Pass is directed into one of three channels: Corpus Christi Ship Channel (CCSC), Aransas Channel, or Lydia Ann Channel. The CCSC leads directly into Corpus Christi Bay towards site 1 and is 14 m deep and 120-180 m wide (Brown et al. 2005), and lacks suitable nursery habitat. *H. wrightii* is a primary nursery habitat in Corpus Christi Bay, supporting commercially and recreationally important species such as red drum (Holt et al. 1983; Rooker et al. 1998*b*; Tunnell 2002).

Directly south of Corpus Christi Bay is the Laguna Madre, a negative bar-built estuary divided by the Rio Grande Delta to form two separate lagoons (upper and lower): the Laguna Madre of Texas, USA, to the north and Laguna Madre de Tamaulipas, Mexico, to the south. Collectively, these lagoons make up the largest of five hypersaline systems in the world (Javor 1989). Laguna Madre of Texas is the southernmost major semi-enclosed coastal body of water in Texas, extending from Corpus Christi Bay to the Brazos-Santiago Pass near the mouth of the Rio Grande River, encompassing 1550 km^2 with an average depth of slightly less than 1 m (Britton and Morton 1989). The Laguna Madre of Texas is divided further into the upper Laguna Madre and the lower Laguna Madre by a land-bridge extending from Padre Island to the mainland (Tunnell 2002). The Laguna Madre of Texas is a hypersaline system because freshwater inputs are intermittent and connections to the Gulf of Mexico are few and minimal (Quammen and Onuf 1993). However, the primary reason is that evaporation exceeds precipitation, sometimes by a factor of two to three (Tunnell 2002). Salinities in the upper Laguna Madre are typically 40 ppt, but historically have reached 100 ppt (Quammen and Onuf 1993). Seagrasses are the predominant subtidal habitat in the upper Laguna Madre, providing high primary productivity and valuable nursery habitat for fish and crustaceans. The primary seagrass is *H. wrightii* most likely because of its high tolerance to hypersalinity and rapid colonization ability (Quammen and Onuf 1993). The upper Laguna Madre supports diverse communities of fishes and invertebrates, including many economically valuable species (Sheridan 2004). Despite the prevalence of habitat these areas are a great distance from a tidal inlet, approximately 30 km from the Aransas Pass, and therefore availability to juvenile fish and crustaceans may be limited.

Packery Channel is a natural tidal inlet located in the southeastern quadrant of Corpus Christi Bay at the Mustang/Padre Island boundaries. Although the inlet historically allowed intermittent water exchange with the Gulf of Mexico, it has been closed since the late 1930's except during temporary storm openings. Recently a project by the U.S. Army Corp of Engineers dredged and reopened the channel, and in July 2005 the channel was opened prematurely by Hurricane Emily. The opening of Packery Channel will provide another source of water exchange for both Corpus Christi Bay and the upper Laguna Madre, and may have substantial impacts on the recruitment of estuarine-dependent species to the upper Laguna Madre, as these abundant seagrass beds will be in close proximity to a tidal inlet.

Tide and wind-driven currents are important factors that greatly impact circulation patterns in shallow Texas bays, and therefore may impact nekton dispersal to estuarine habitats. The Gulf of Mexico predominately experiences diurnal or mixed diurnal and semidiurnal tides. Although these tides are influential, winds are more important for creating circulating currents. Wind direction is also important in dictating current patterns because typically currents flow in the direction of the prevailing winds (Britton and Morton 1989). On the south Texas coast, the prevailing wind direction is from the southeast with strong north winds associated with cold fronts during the winter months (Smith 1979). In the bays a southeasterly wind will push water away from the barrier island shores and currents will flow toward the mainland, while during northerly winds the current will flow toward and pile water on the south barrier island side of the bay (Britton and Morton 1989). These patterns may have an effect on the distribution of nekton within habitats since the larvae of many species are carried to estuarine habitats via tides and currents.

Habitat Use Patterns

Habitat use patterns of juvenile red drum, southern flounder, penaeid shrimp, and blue crabs were assessed at varying distances from two tidal inlets. Twelve sites were chosen approximately every 2 km from the tidal inlet at Aransas Pass to the upper Laguna Madre, TX along the eastern portion of Corpus Christi Bay. Twelve sites were located at 11, 14, 16, 22, 26, 30, 34, 37, 39, 43, 47, and 51 km from the Aransas Pass (Sites 1-12; Fig. 1). Following the opening of Packery Channel in July 2005, distances of the sites were adjusted to correspond to the nearest inlet (either Aransas Pass or Packery

Channel) for the remaining fall 2005 and winter 2006 samples. After the opening of Packery Channel, juvenile dispersal from Aransas Pass was established by sampling sites 1-6 (distances 11, 14, 16, 22, 26, and 30 km from Aransas Pass, respectively). Sites 9, 8, 10, 11, and 12 were sampled for dispersal patterns from Packery Channel, and the distance of each site was re-measured from Packery Channel (2, 5, 11, 15, and 18 km from Packery Channel respectively). After the opening of Packery Channel site 7 was not sampled, because it was an intermediate site between the two inlets. Sampling took place before and after the opening of Packery Channel to assess the impact on recruitment and dispersal of these species into the upper Laguna Madre.

I collected recruiting nekton at these sites pre- and post-opening of Packery Channel. Sampling occurred during the peak recruitment season for red drum, southern flounder, penaeid shrimp and blue crabs. Fall sampling occurred from October to November in 2004 and October to December in 2005. Winter sampling occurred from February to March in both years. Collections were performed twice during fall 2004 and winter 2005 at all sites except site 12. Samples were collected four times seasonally at all sites in fall 2005 and sites 1-10 in winter 2006. Because southern flounder occurred at such low densities, an extra sampling event in winter 2006 was conducted to assess their recruitment patterns.

Nekton were collected using triplicate sled tows with an ebibenthic sled, a fixed-frame sampling device that has been used by several investigators for sampling nekton (Holt et al. 1983; Stunz et al. 2002*a*). The 0.6 m (length) x 0.75 m (height) metal frame was fitted with a 1-mm mesh conical plankton net and connected to a 17-m rope. Samples were taken by placing the sled on the bottom and walking a semicircular route around the sampling area to avoid disturbance. The sled was towed by hand for ~ 17 m and covered a total bottom area of 10 m^2. Samples were only taken in stands of *H. wrightii*, the primary nursery habitat reported for red drum (Holt et al. 1983; Rooker et al. 1998*b*) and southern flounder (Nanez –James 2005 pers comm.). Samples were roughly sorted in the field and fixed in 10% formalin. Salinity (ppt), water temperature (°C), dissolved oxygen (DO) (mg/L) data were collected at each site using a refractometer and YSI DO 200 meter. Water depth (cm) was also recorded at each site using a depth gauge on the epibenthic sled.

In the laboratory, fish and decapod crustaceans were identified and measured to the nearest 0.1 mm and preserved in 70% ethanol. Standard length (SL) of red drum and southern flounder was measured and is the distance from the tip of the snout to the end of the last vertebrae. Carapace width (CW), the distance between the two lateral spines, of each blue crab was measured. Total length (TL) of penaeid shrimp was measured as the distance from the tip of the rostrum to the end of the telson. If more than 20 individuals were captured, a subsample of the largest and smallest plus 20 random individuals were measured to assess size distribution.

Statistical Analysis

Spatial patterns of red drum, southern flounder, penaeid shrimp, and blue crab recruitment were analyzed with Analysis of Variance (ANOVA) and Simple Linear Regression. The significance value was set at ($\alpha = 0.05$). All observations were converted to number of individuals/m^2 (density) and log (x+1) transformed to minimize heteroscedasticity. Mean density and length for each species during their peak recruitment time pre- and post-opening of Packery Channel was calculated at each site and used in the regression analysis. Sites where the species were not collected were not used in the length analysis. Densities and lengths of red drum in areas surrounding Packery Channel pre- and post-opening were analyzed using a Student's *t*-test. The significance value was set at ($\alpha = 0.05$).

Results

Physical Parameters

Salinity (ppt), DO (mg/L), water temperature (°C), and water depth (cm) were taken at each site for each sampling event pre-(Table 1) and post-opening (Table 2). Depth was not taken for one of the sampling events in fall 2004. Overall, physical parameters were similar among sites during each season pre- and post-opening.

Table 1. Physical parameters (± SE) at each site during fall 2004 and winter 2005 pre-opening of Packery Channel.

	Salinity (ppt)		DO (mg/L)		Temp (°C)		Depth (cm)	
Site	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Fall 2004								
1	31.00	(0.00)	5.35	(0.65)	24.00	(2.40)	55.00	(0.00)
2	30.50	(0.50)	6.75	(0.15)	23.80	(3.20)	60.00	(0.00)
3	30.50	(0.50)	4.95	(1.05)	23.35	(2.35)	55.00	(0.00)
4	30.50	(0.50)	4.35	(1.05)	23.00	(2.40)	55.00	(0.00)
5	30.50	(0.50)	5.95	(0.85)	25.70	(0.00)	60.00	(0.00)
6	31.50	(2.50)	7.90	(0.00)	24.00	(5.80)	45.00	(0.00)
7	32.00	(0.00)	7.60	(0.00)	17.90	(0.00)	25.00	(0.00)
8	36.00	(0.00)	7.30	(0.00)	16.00	(0.00)	20.00	(0.00)
9	32.00	(0.00)	7.20	(0.00)	18.10	(0.00)	25.00	(0.00)
10	33.00	(1.00)	8.20	(0.00)	26.40	(5.40)	15.00	(0.00)
11	33.00	(0.00)	6.90	(0.00)	20.50	(0.00)	35.00	(0.00)
Winter 2005								
1	27.33	(1.20)	8.92	(0.75)	16.97	(1.79)	31.67	(3.33)
2	26.33	(0.67)	9.03	(0.33)	16.47	(1.68)	30.00	(7.64)
3	26.33	(0.67)	8.46	(0.53)	16.37	(2.22)	30.83	(5.83)
4	28.00	(0.58)	9.42	(0.21)	16.23	(2.43)	26.67	(1.67)
5	28.67	(1.20)	9.74	(1.09)	16.07	(2.21)	31.67	(8.33)
6	28.33	(0.88)	9.00	(1.14)	15.53	(3.32)	33.33	(4.41)
7	28.67	(0.88)	8.27	(0.39)	16.03	(2.27)	30.00	(5.00)
8	29.33	(0.33)	8.05	(0.48)	15.77	(1.83)	35.67	(2.33)
9	28.00	(1.16)	7.83	(0.37)	15.07	(2.53)	26.67	(7.27)
10	28.33	(0.88)	8.59	(0.67)	15.17	(2.61)	33.33	(7.27)

Table 2. Physical parameters (± SE) at each site during fall 2005 and winter 2006 post-opening of Packery Channel. Site 7 was not sampled post-opening.

	Salinity (ppt)		DO (mg/L)		Temp (°C)		Depth (cm)	
Site	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Fall 2005								
1	34.00	(1.87)	8.91	(2.04)	27.20	(2.80)	25.00	(7.64)
2	35.50	(1.19)	7.81	(1.65)	26.18	(3.02)	35.00	(2.89)
3	36.00	(1.00)	8.52	(1.76)	26.43	(2.53)	33.33	(6.01)
4	36.50	(0.96)	8.05	(1.53)	26.43	(2.83)	40.00	(2.89)
5	37.00	(0.82)	8.09	(1.29)	26.90	(2.74)	45.00	(0.00)
6	39.00	(1.96)	7.03	(0.62)	26.40	(3.27)	46.67	(7.27)
8	39.25	(2.39)	7.75	(0.79)	26.33	(3.37)	38.75	(3.15)
9	38.00	(2.74)	6.62	(0.49)	26.30	(3.04)	25.00	(5.00)
10	42.25	(1.60)	8.58	(1.52)	26.73	(3.56)	41.25	(2.39)
11	44.00	(2.38)	8.33	(0.65)	26.58	(3.58)	42.50	(2.50)
12	46.00	(1.58)	9.24	(1.09)	26.50	(3.70)	38.33	(1.67)
Winter 2006								
1	34.60	(0.51)	8.42	(1.03)	19.52	(1.46)	27.00	(2.00)
2	35.00	(0.32)	8.11	(0.76)	18.82	(1.52)	38.00	(2.55)
3	34.00	(1.05)	7.79	(0.57)	18.78	(1.32)	34.00	(4.30)
4	36.20	(0.58)	7.95	(0.43)	18.64	(1.61)	37.00	(5.83)
5	36.40	(0.87)	7.81	(0.29)	18.74	(1.65)	39.00	(5.79)
6	35.40	(0.93)	8.01	(0.46)	19.04	(1.55)	35.00	(5.48)
8	37.80	(0.37)	7.87	(0.31)	18.74	(2.09)	33.00	(3.00)
9	35.40	(1.89)	7.69	(0.17)	17.90	(1.83)	24.00	(5.10)
10	38.60	(0.40)	7.55	(0.32)	18.38	(2.48)	35.00	(2.24)

Red Drum Habitat Use Patterns

In fall 2004, pre-opening of Packery Channel, red drum were most numerous and smaller near Aransas Pass. Red drum abundance decreased and size increased as distance from the tidal inlet increased. There was a significant relationship between densities of red drum and distance from Aransas Pass in fall 2004 ($R^2 = 0.672$; $P = 0.002$; $N = 11$) prior to the opening of Packery Channel (Fig. 2). Densities of red drum were greatest at sites within 26 km of Aransas Pass with the highest densities observed at sites 1 and 3, distances 11 and 16 km (1.33 m^{-2} ± 0.47 SE and 1.43 m^{-2} ± 0.63 SE respectively). At sites beyond 16 km densities of red drum decreased to 0.20 m^{-2} ± 0.06 SE and 0.53 m^{-2} ± 0.18 SE at 22 and 26 km. The densities continued to decline to near zero at the remaining sites at further distances (Table 3). A regression on the lengths and distance from the inlet in fall 2004 showed a significant relationship between distance from Aransas Pass and SL ($R^2 = 0.752$; $P = 0.005$; $N = 8$) (Fig. 3). Red drum were smallest at sites closest to the inlet. At distances 11, 14, and 16 km (sites 1, 2, and 3) red drum mean SL was 9.53 mm ± 0.36 SE, 8.24 mm ± 0.15 SE, and 9.98 ± 0.18 SE, respectively. Beyond 16 km, red drum size increased to 22.80 mm ± 2.69 SE at 37 km, and 17.05 mm ± 5.45 SE at 39 km (Table 4).

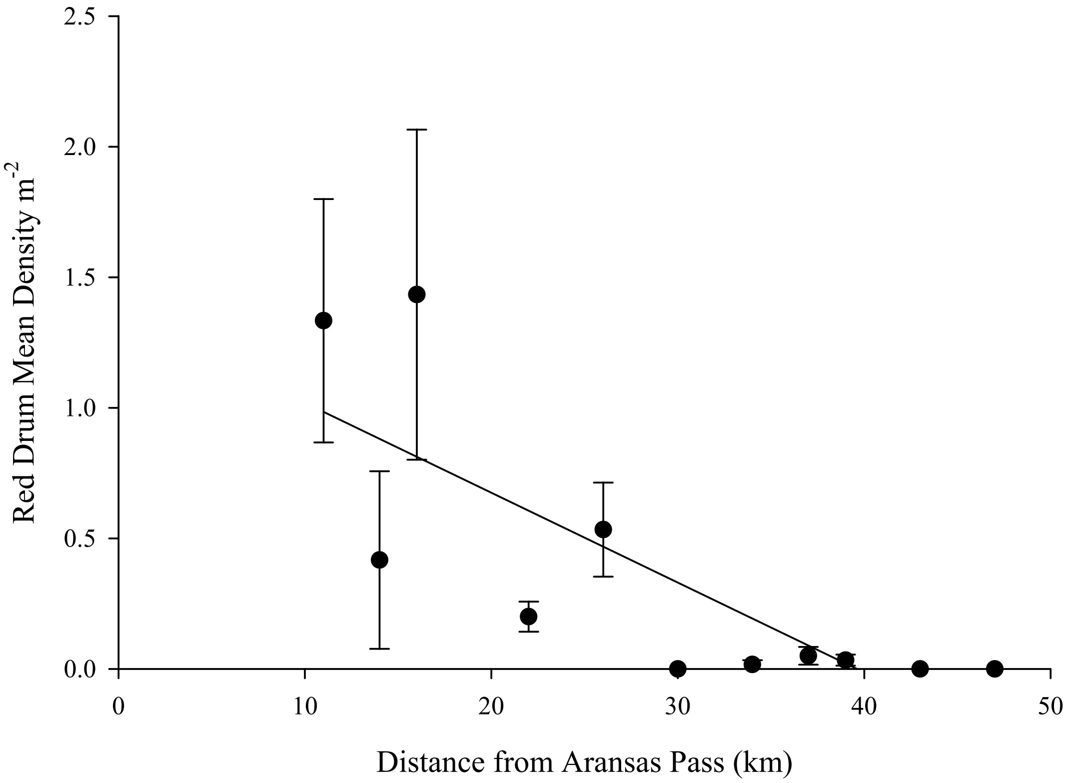

Figure 2. Mean densities of red drum (± SE) in fall 2004 at varying distances from Aransas Pass pre-opening of Packery Channel. The relationship between mean density and distance was analyzed with a simple linear regression. Regression model: density = -0.01 (distance) + 0.40; N = 11, $R^2 = 0.672$, P = 0.002.

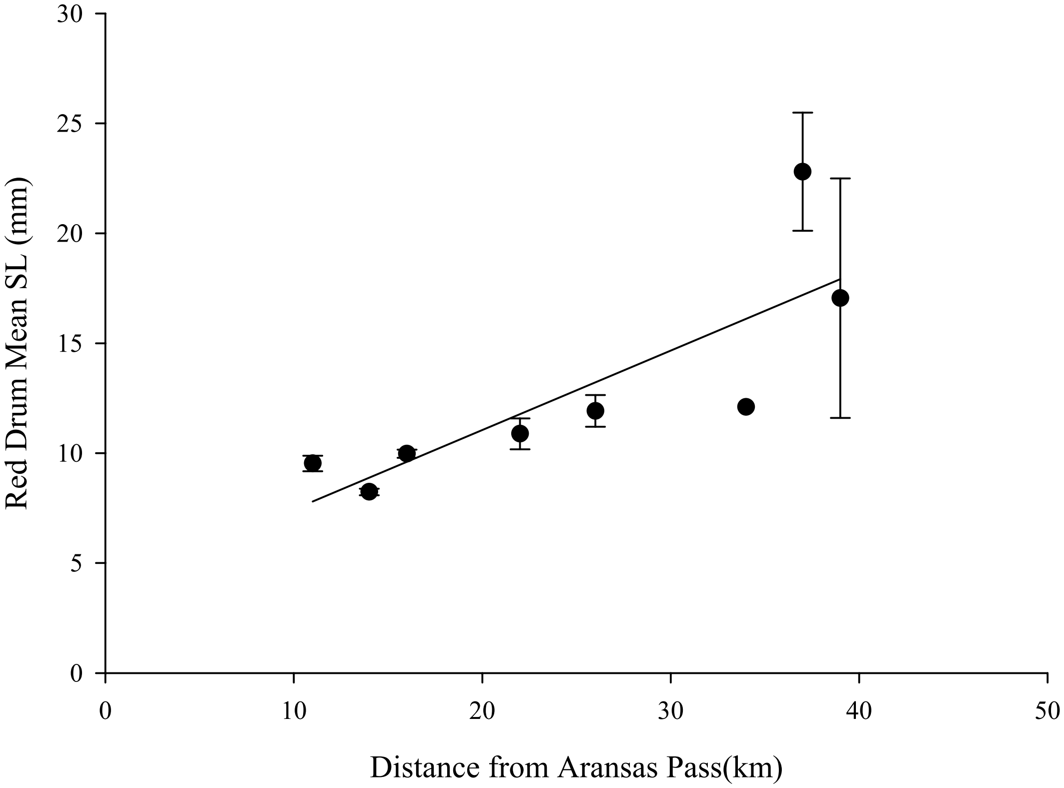

Figure 3. The relationship between mean standard length of red drum (mm ± SE) and distance from Aransas Pass (km) pre-opening of Packery Channel analyzed with simple linear regression. Regression model: SL = 0.01 (distance) + 0.85; N = 8, $R^2 = 0.752$, P = 0.005.

Table 3. Mean density (± SE) of red drum, southern flounder, blue crabs, and penaeid shrimp at varying distances from Aransas Pass and Packery Channel pre- and post-opening of Packery Channel. Pre-opening sampling took place from October 2004 to March 2005, and post-opening sampling took place October 2005 to March 2006. Red drum and southern flounder were only sampled during peak recruitment times (Oct-Nov and Feb-March respectively). N equals the number of sled tows per site. Southern flounder were not sampled at 47 km pre-opening and 15 and 18 km post-opening and therefore were not recorded (n/a).

Site (Distance)	**Red Drum**			**Southern Flounder**			**Blue Crabs**			**Penaeid Shrimp**		
	n	**Density**	**SE**	**n**	**Density**	**SE**	**n**	**Density**	**SE**	**n**	**Density**	**SE**
Pre-Opening												
1 (11)	6.00	1.33	(0.47)	9	0.07	(0.03)	15	1.27	(0.22)	15	2.72	(0.40)
2 (14)	6.00	0.42	(0.34)	9	0.00	(0.00)	15	0.26	(0.07)	15	2.62	(0.81)
3 (16)	6.00	1.43	(0.63)	9	0.01	(0.01)	15	0.18	(0.07)	15	1.12	(0.37)
4 (22)	6.00	0.20	(0.06)	9	0.00	(0.00)	15	0.23	(0.08)	15	1.20	(0.54)
5 (26)	6.00	0.53	(0.18)	9	0.00	(0.00)	15	0.25	(0.05)	15	2.11	(0.81)
6 (30)	6.00	0.00	(0.00)	9	0.00	(0.00)	15	0.17	(0.05)	15	0.45	(0.13)
7 (34)	6.00	0.02	(0.02)	9	0.00	(0.00)	15	0.22	(0.08)	15	0.87	(0.21)
8 (37)	6.00	0.05	(0.03)	9	0.00	(0.00)	15	0.25	(0.10)	15	1.65	(0.39)
9 (39)	6.00	0.03	(0.02)	9	0.00	(0.00)	15	0.55	(0.16)	15	1.85	(0.43)
10 (43)	6.00	0.00	(0.00)	9	0.01	(0.01)	15	0.21	(0.04)	15	1.53	(0.35)
11 (47)	3.00	0.00	(0.00)	n/a	n/a	n/a	3	0.03	(0.03)	3	0.67	(0.03)
Post-Opening												
1 (11)	12	0.52	(0.26)	9	0.01	(0.01)	24	1.99	(0.37)	24	3.43	(0.64)
2 (14)	12	0.06	(0.03)	9	0.00	(0.00)	24	0.58	(0.16)	24	1.79	(0.46)
3 (16)	12	0.03	(0.02)	9	0.00	(0.00)	24	0.46	(0.11)	24	1.46	(0.42)
4 (22)	12	0.00	(0.00)	9	0.00	(0.00)	24	0.17	(0.04)	24	0.99	(0.25)
5 (26)	12	0.18	(0.12)	9	0.00	(0.00)	24	0.73	(0.14)	24	2.81	(0.60)
6 (30)	12	0.01	(0.01)	9	0.00	(0.00)	24	0.23	(0.06)	24	0.81	(0.24)
8 (5)	6	0.03	(0.02)	9	0.03	(0.02)	24	0.36	(0.09)	24	4.38	(1.16)
9 (2)	6	0.00	(0.00)	9	0.02	(0.01)	24	4.28	(1.60)	24	2.42	(0.60)
10 (11)	6	0.02	(0.02)	9	0.00	(0.00)	24	0.19	(0.04)	24	2.60	(0.38)
11 (15)	6	0.08	(0.05)	n/a	n/a	n/a	12	0.28	(0.07)	12	2.25	(0.23)
12 (18)	6	0.02	(0.02)	n/a	n/a	n/a	12	0.09	(0.04)	12	1.08	(0.08)

Table 4. Mean standard length (SL) of red drum and southern flounder (± SE), mean carapace width (CW) of blue crabs (± SE), and mean total length (TL) of penaeid shrimp (± SE) at each distance from Aransas Pass and Packery Channel pre- and post-opening of Packery Channel. N equals the number of individuals captured at each distance. N/A represents sites where the density was zero.

	Red Drum			**Southern Flounder**			**Blue Crabs**			**Penaeid Shrimp**		
Site (Distance)	**n**	**SL**	**SE**	**n**	**SL**	**SE**	**n**	**CW**	**SE**	**n**	**TL**	**SE**
Pre-Opening												
1 (11)	79	9.53	(0.36)	6	16.27	(6.02)	185	8.98	(0.32)	353	16.48	(0.46)
2 (14)	24	8.24	(0.15)	0	n/a	n/a	39	12.20	(0.86)	214	14.42	(0.47)
3 (16)	84	9.98	(0.18)	1	10.20	(0.00)	26	9.18	(0.99)	125	19.92	(1.08)
4 (22)	11	10.88	(0.70)	0	n/a	n/a	35	10.21	(1.06)	156	19.91	(0.85)
5 (26)	32	11.92	(0.73)	0	n/a	n/a	37	11.30	(0.96)	171	17.52	(0.81)
6 (30)	0	n/a	n/a	0	n/a	n/a	23	17.30	(0.82)	55	20.81	(2.25)
7 (34)	1	12.10	(0.00)	0	n/a	n/a	27	16.85	(0.94)	154	24.07	(1.24)
8 (37)	3	22.80	(2.69)	0	n/a	n/a	41	12.62	(0.86)	203	20.35	(0.86)
9 (39)	2	17.05	(5.45)	0	n/a	n/a	55	15.25	(1.02)	215	23.69	(1.01)
10 (43)	0	n/a	n/a	1	16.80	(0.00)	27	15.01	(2.05)	189	21.43	(1.03)
11 (47)	0	n/a	n/a	0	n/a	n/a	1	36.60	(0.00)	18	33.90	(6.07)
Post-Opening												
1 (11)	62	12.72	(0.74)	1	24.60	(0.00)	330	7.37	(0.29)	456	16.60	(0.37)
2 (14)	7	8.79	(0.41)	0	n/a	n/a	126	8.24	(0.44)	289	17.47	(0.53)
3 (16)	3	9.57	(0.43)	0	n/a	n/a	109	7.23	(0.45)	257	18.55	(0.66)
4 (22)	0	n/a	n/a	0	n/a	n/a	40	8.14	(0.86)	174	18.54	(0.77)
5 (26)	22	12.91	(1.40)	0	n/a	n/a	172	8.50	(0.44)	567	17.60	(0.33)
6 (30)	1	9.50	(0.00)	0	n/a	n/a	58	9.00	(0.72)	139	17.27	(0.71)
8 (5)	4	8.80	(1.53)	3	8.70	(0.40)	88	9.52	(0.66)	608	19.94	(0.39)
9 (2)	0	n/a	n/a	2	8.50	(0.30)	240	5.96	(0.30)	346	18.66	(0.61)
10 (11)	2	12.30	(1.70)	0	n/a	n/a	40	8.12	(0.82)	480	19.97	(0.55)
11 (15)	9	8.09	(0.42)	NR	n/a	n/a	33	8.93	(0.60)	267	31.07	(0.84)
12 (18)	2	13.60	(4.70)	NR	n/a	n/a	11	8.82	(2.45)	127	32.56	(1.23)

In fall 2005, following the opening of Packery Channel, red drum were collected at varying distances from Aransas Pass, as well as from Packery Channel. Lower densities of red drum were collected in fall 2005 than in fall 2004, and there was no significant relationship between density of red drum and distance from Aransas Pass ($R^2 = 0.256$; $P = 0.306$; $N = 6$; $1-\beta = 0.160$). However, high densities were still captured at sites closest to Aransas Pass. At 11 km (site 1) from Aransas Pass, the mean density was 0.52 m^{-2} ± 0.26 SE, and the densities were near zero at the remaining sites, except at 26 km where the density was 0.18 m^{-2} ± 0.12 SE (Fig. 4). Densities of red drum showed no relationship to distance from Packery Channel in fall 2005 ($R^2 = 0.369$; $P = 0.277$; $N = 5$; $1-\beta = 0.168$) (Fig. 5) post-channel opening. Densities were very low around Packery Channel with the highest densities (0.15 m^{-2} ± 0.10) 15 km from the inlet (Table 3). In fall 2005 there was no significant relationship between red drum SL and distance from either Aransas Pass ($R^2 = 0.0005$; $P = 0.971$; $N = 5$; $1-\beta = 0.027$) (Fig. 6) or Packery Channel ($R^2 = 0.199$; $P = 0.554$; $N = 4$; $1-\beta = 0.069$) (Fig. 7).

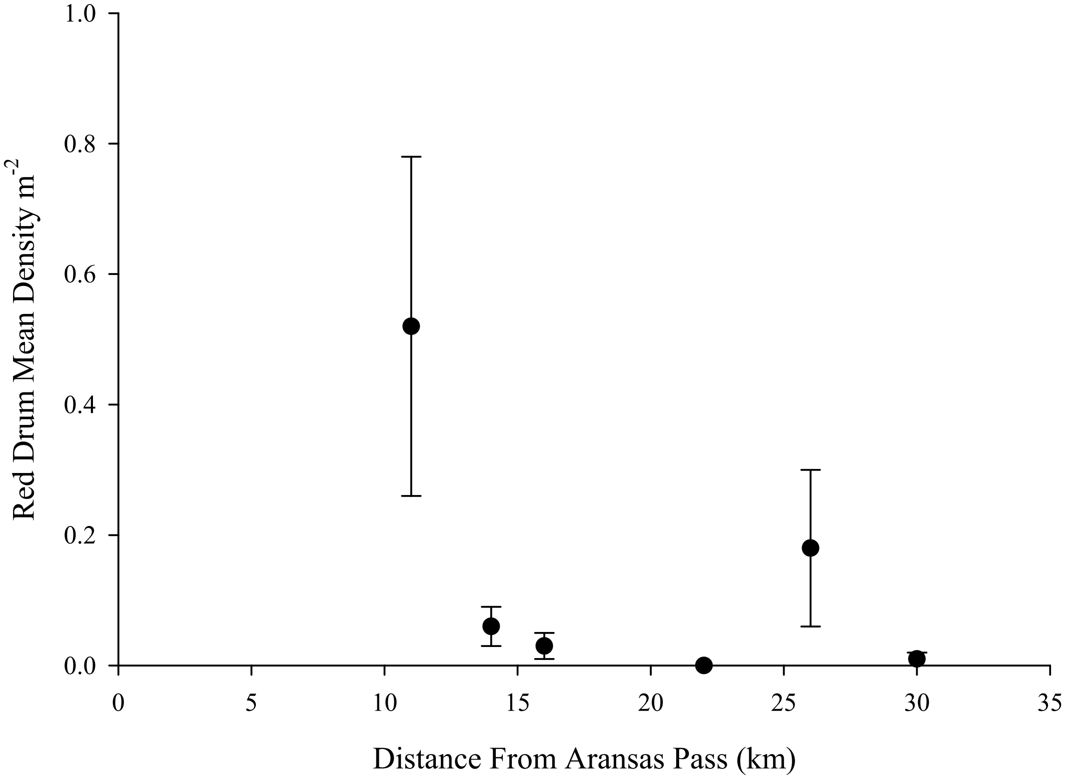

Figure 4. The relationship between mean red drum density (m^{-2} ± SE) and distance from Aransas Pass (km) in fall 2005 post-opening of Packery Channel analyzed with simple linear regression. Regression model: density = -0.005 (distance) + 0.142; N = 6, R^2 = 0.256, P = 0.306.

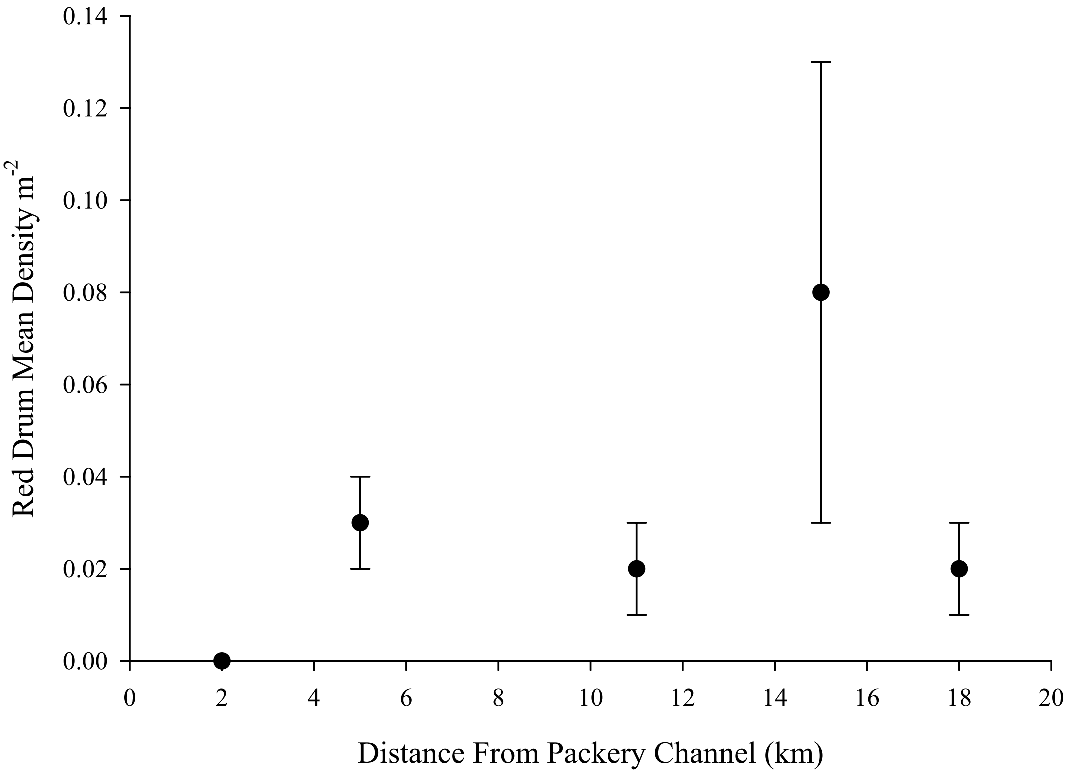

Figure 5. Relationship between mean red drum density (m^{-2} ± SE) and distance from Packery Channel (km) in fall 2005 post-opening analyzed with simple linear regression. Regression model: density = 0.001 (distance) + 0.002; N = 5, $R^2 = 0.369$, P = 0.277.

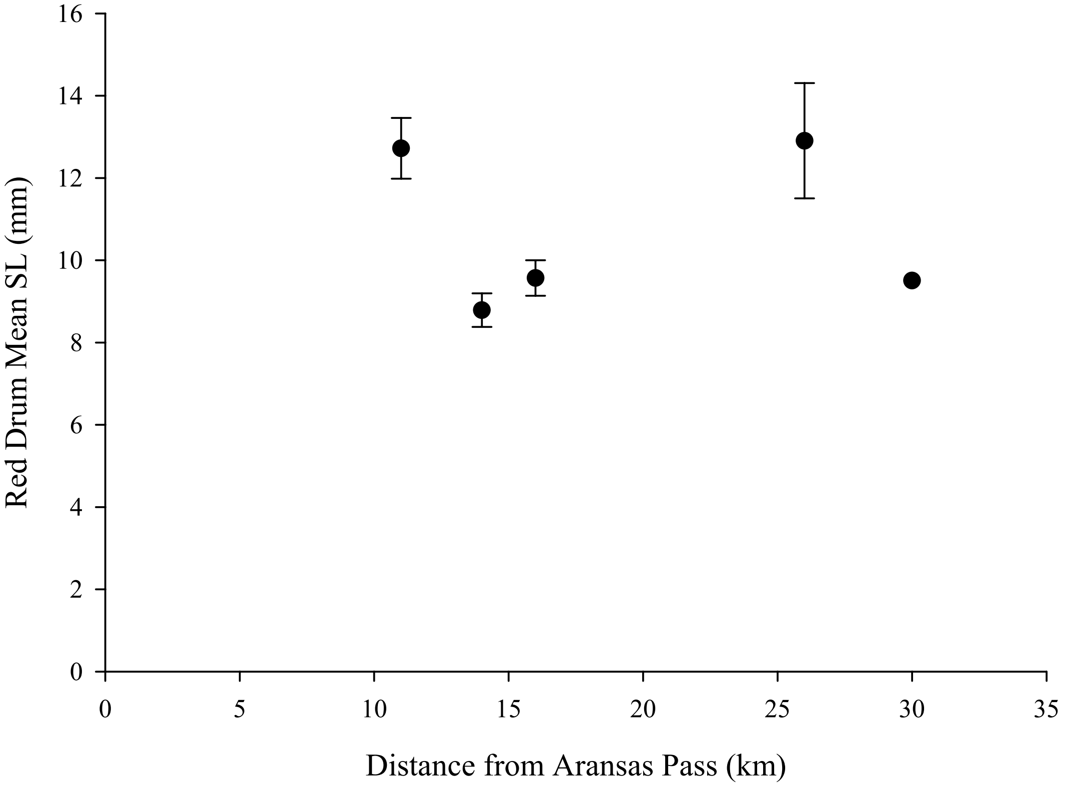

Figure 6. Mean standard length of red drum (mm ± SE) at varying distances from Aransas Pass (km) in fall 2005 post-opening of Packery Channel. The relationship between mean SL of red drum and distance was analyzed with a simple linear regression. Regression model: SL = -0.0002 (distance) + 1.066; N = 5, R^2 = 0.0005, P = 0.971.

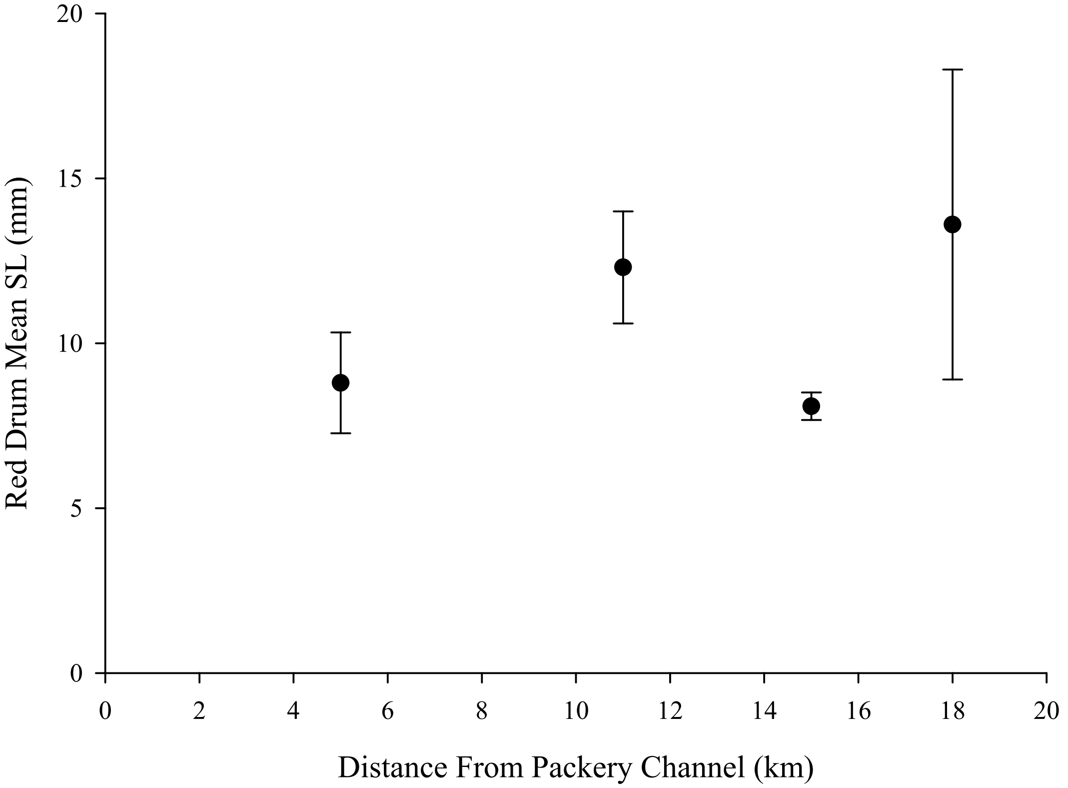

Figure 7. Mean standard length of red drum (± SE) at varying distances from Packery Channel in fall 2005 post-opening. The relationship between mean SL of red drum and distance was analyzed with a simple linear regression. Regression model: SL = 0.00773 (distance) + 0.963; N = 4, $R^2 = 0.199$, P = 0.554.

To assess the effect of opening Packery Channel on red drum recruitment, densities of red drum were combined from the sites surrounding Packery Channel and compared pre- and post-opening. A Student's *t*-test was performed to evaluate whether red drum densities were higher post-opening. There was no significant difference between red drum densities pre- and post-opening of Packery Channel ($P = 0.783$; $N = 27$ Pre, $N = 72$ Post; $t = 0.276$; $1-\beta = 0.050$; $df = 97$) (Fig. 8). However, the mean length of these red drum were significantly smaller post-opening ($P = 0.009$; $N = 6$ Pre, $N = 20$ Post; $t = 5.193$) (Fig. 9). The mean lengths of red drum pre-opening was 19.10 mm ± 2.59 SE and post-opening they were significantly smaller with a mean length of 9.32 mm ± 0.66 SE.

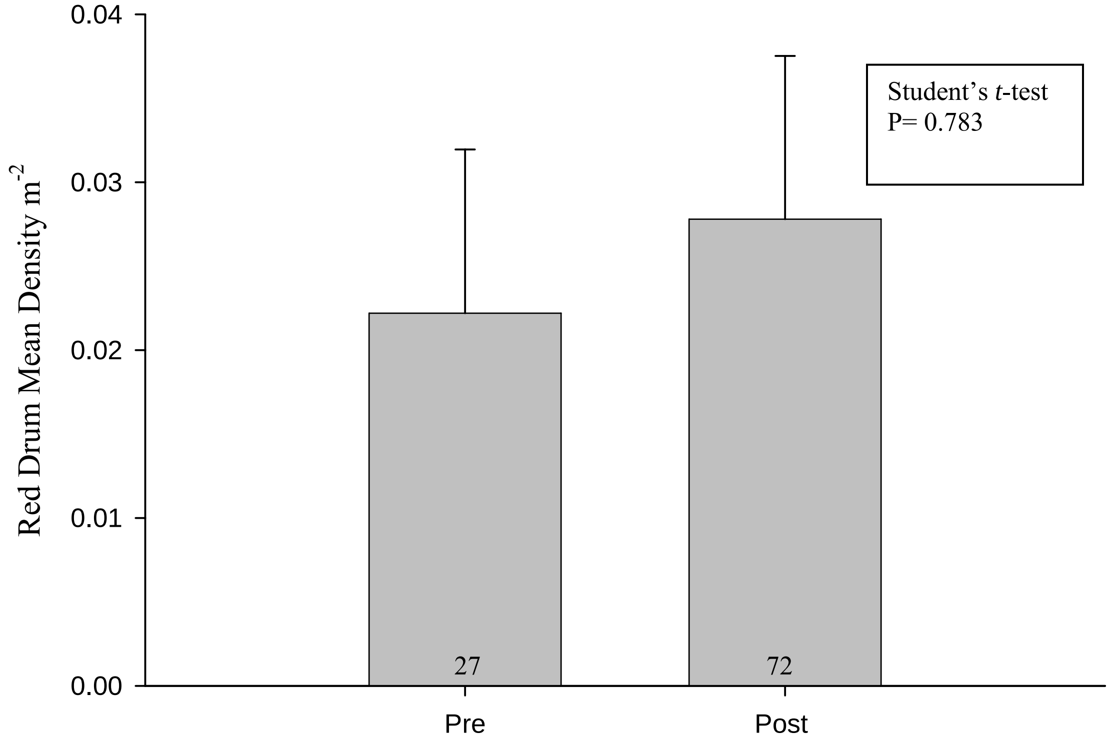

Figure 8. Mean red drum densities (m^{-2} ± SE) at sites surrounding Packery Channel pre- and post-opening. Densities were analyzed using a Student's *t*-test. The number of samples for pre- and post-opening is indicated at the bottom of the bars.

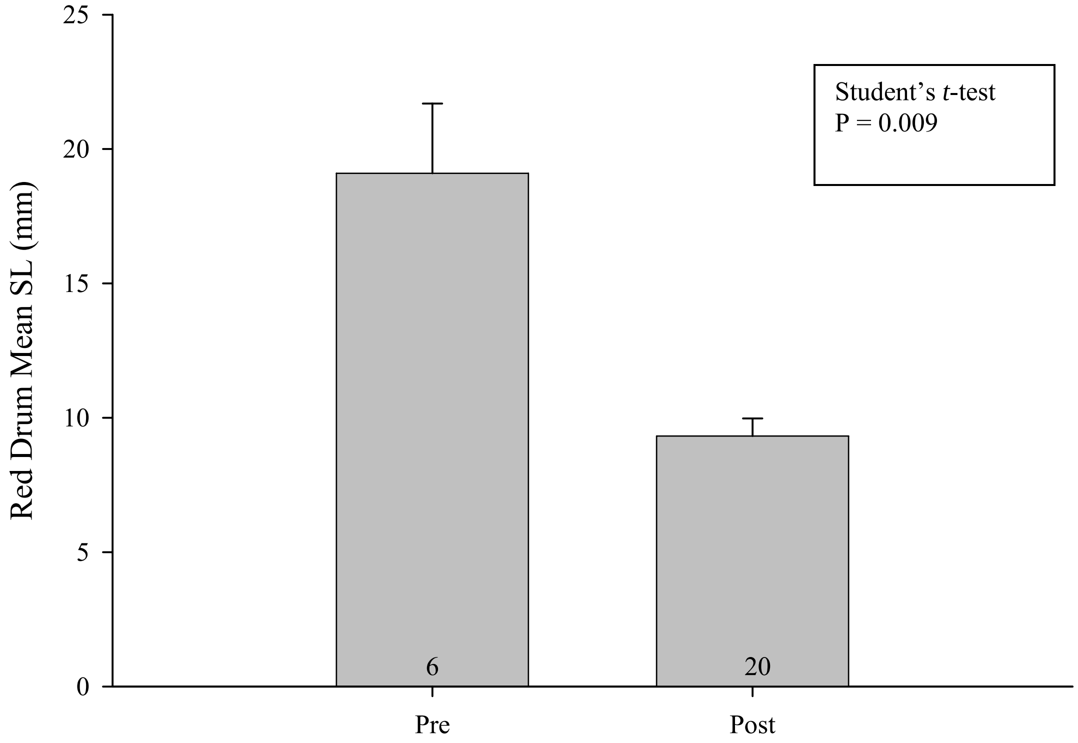

Figure 9. Mean standard length (± SE) of red drum at sites surrounding Packery Channel pre- and post-opening. Mean SL of red drum pre- and post-opening was analyzed using a Student's *t*-test and the number of red drum caught are indicated at the bottom of the bars.

Southern Flounder Habitat Use Patterns

Southern flounder were sampled from February to March 2005 and 2006. Southern flounder occurred at very low densities both years (14 fish total). No significant relationship was determined between density or length and distance from a tidal inlet. Although I found no relationship, the majority of southern flounder were collected at sites closest to the inlet. In winter 2005, prior to the opening of Packery Channel, the highest density (0.07 m^{-2} ± 0.03 SE) of southern flounder was captured 11 km from Aransas Pass. In winter 2006, post-opening of Packery Channel, only one southern flounder was captured in Corpus Christi Bay and this was at site 1, 11 km from Aransas Pass. Densities of southern flounder were also relatively high at sites around Packery Channel post-opening in 2006. At site 9 (2 km from Packery Channel) the density was 0.02 m^{-2} ± 0.01 SE and at site 8 (5 km) the density was 0.03 m^{-2} ± 0.02 SE (Table 3). There was no relationship between length of southern flounder and distance from a tidal inlet pre- or post-opening of Packery Channel. Mean lengths of southern flounder are shown in Table 4.

Blue Crab Habitat Use Patterns

The relationship between blue crab density and distance from a tidal inlet was assessed in fall 2004-2005 and winter 2005-2006, the peak recruitment period for blue crabs. Seasonal densities and lengths were combined for both pre- and post-opening of Packery Channel. Prior to the opening of Packery Channel, blue crabs occurred at high densities throughout the study area and no significant relationship between blue crab density and distance from Aransas Pass was observed ($R^2 = 0.225$; $P = 0.140$; $N = 11$; 1-

$\beta = 0.309$) (Fig. 10). However, a high density (1.27 m^{-2} ± 0.22) of blue crabs was caught at the closest site (11 km) to Aransas Pass (Table 3). Although blue crab density did not increase with distance, the mean size of individuals increased as distance from the pass increased. There was a significant relationship between blue crab CW and distance from Aransas Pass pre-opening of Packery Channel ($R^2 = 0.599$; $P = 0.005$; $N = 11$) (Fig. 11). Mean carapace width was 8.98 mm ± 0.32 SE at 11 km (site 1) and increased to 36.60 mm ± 0.00 SE at 47 km (Site 11) (Table 4).

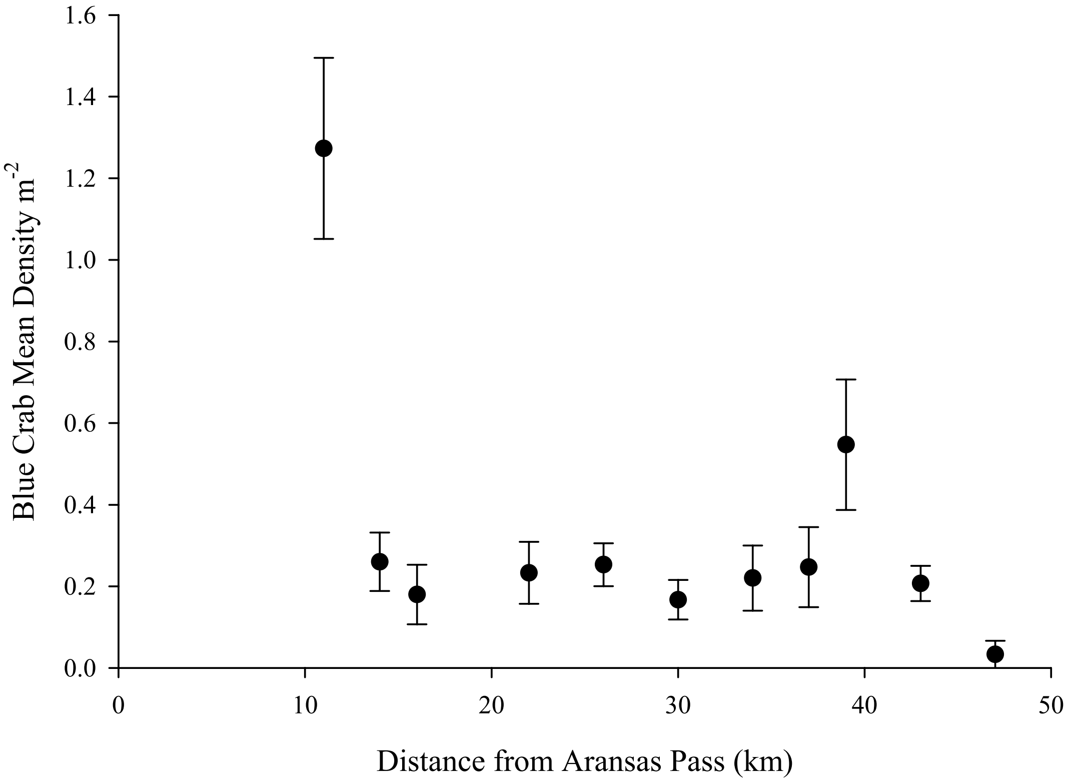

Figure 10. Mean density of blue crab (m^{-2} ± SE) at varying distances from Aransas Pass (km) pre-opening of Packery Channel. The relationship between mean density and distance from Aransas Pass was analyzed using a simple linear regression. Regression model: density = -0.00357 (distance) + 0.218; N= 11, R^2 = 0.225, P = 0.140.

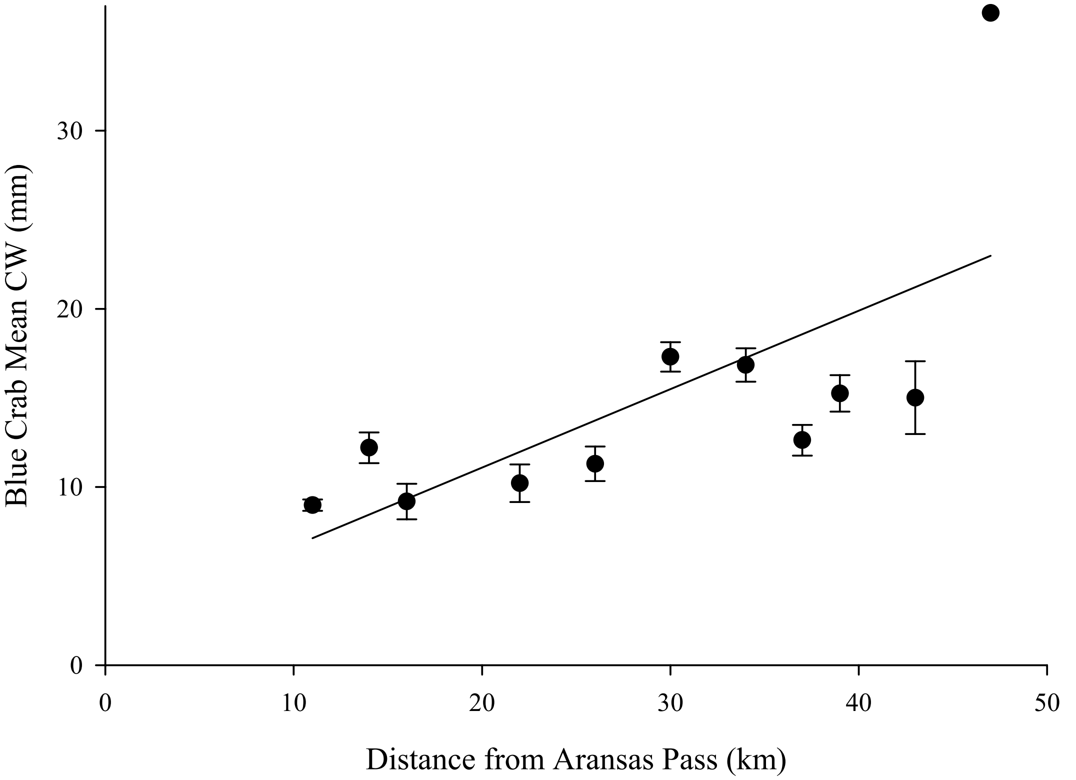

Figure 11. Mean carapace width (CW) (mm ± SE) of blue crab (± SE) at varying distances from Aransas Pass pre-opening of Packery Channel. The relationship between mean CW and distance from Aransas Pass was analyzed using a simple linear regression. Regression model: CW = 0.0103 (distance) + 0.873; N = 11, $R^2 = 0.599$, P = 0.005.

Post-opening of Packery Channel, there was no significant relationship observed between density of blue crabs and distance from Aransas Pass ($R^2 = 0.401$; $P = 0.177$; $N = 6$; $1-\beta= 0.252$) or Packery Channel ($R^2 = 0.556$; $P = 0.148$; $N = 5$; $1-\beta= 0.275$) (Fig. 12; Fig. 13). Similar to the observations prior to opening of Packery Channel, the general trend was that densities were high at sites closest to the tidal inlet and low at distances farther from the inlet. At site 1 closest to Aransas Pass (11 km) mean blue crab density was 1.99 m^{-2} ± 0.37 SE, and at the remaining distances the density remained < 0.75 m^{-2}. The same trend was observed at sites near Packery Channel; high densities in habitats nearest the inlet at 2 km (4.28 m^{-2} ± 1.60 SE) while densities fell below 0.50 m^{-2} at other sites further from the inlet (Table 3). There was a significant relationship between mean blue crab CW and distance from Aransas Pass ($R^2= 0.664$; $P= 0.048$; $N= 6$) post-opening of Packery Channel (Fig 14). Blue crab mean CW was 7.37 mm ± 0.29 SE at 11 km and increased to 9.0 mm ± 0.72 SE at 30 km from the inlet. Although there was no significant relationship between mean CW and distance from Packery Channel ($R^2 = 0.329$; $P = 0.312$; $N = 5$; $1-\beta= 0.150$) (Fig. 15), the general trend was for smaller blue crabs collected at habitats nearer the inlets. Mean CW at 2 km from Packery Channel was 5.96 mm ± 0.30 SE and increased to over 8 mm at the greater distances from the inlet (Table 4).

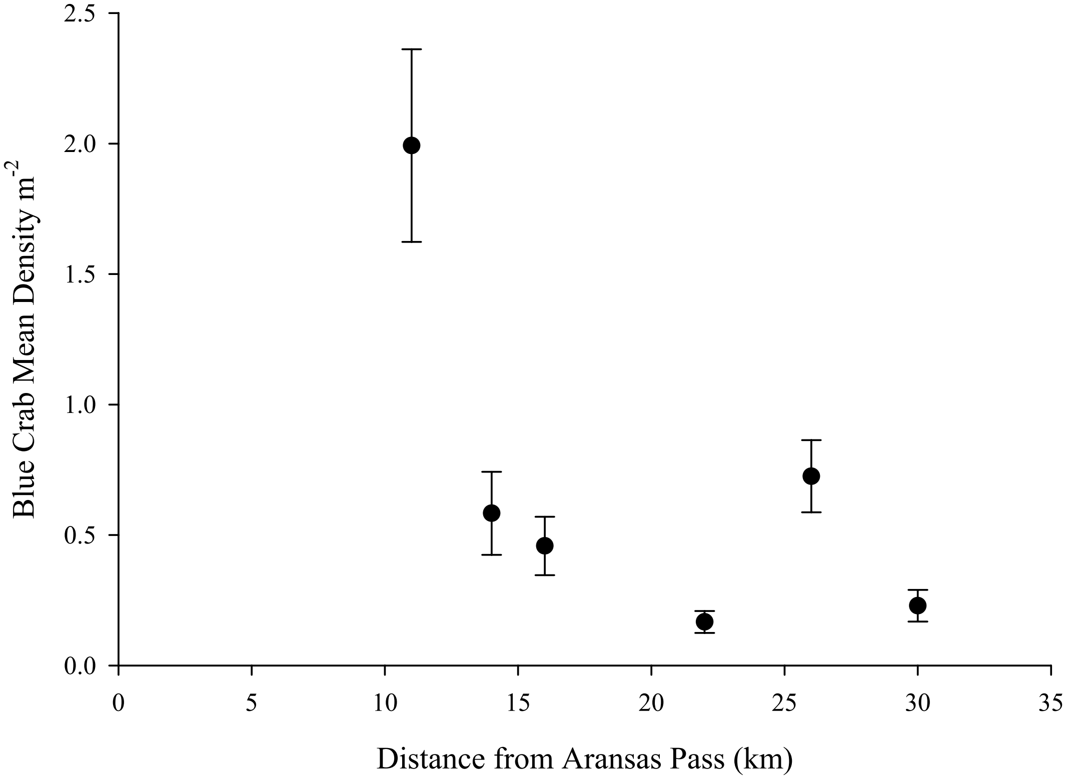

Figure 12. Relationship between mean blue crab density (m^{-2} ± SE) and distance from Aransas Pass post-opening of Packery Channel analyzed with simple linear regression. Regression model: density = -0.0127 (distance) + 0.459; N = 6, R^2 = 0.401, P = 0.177.

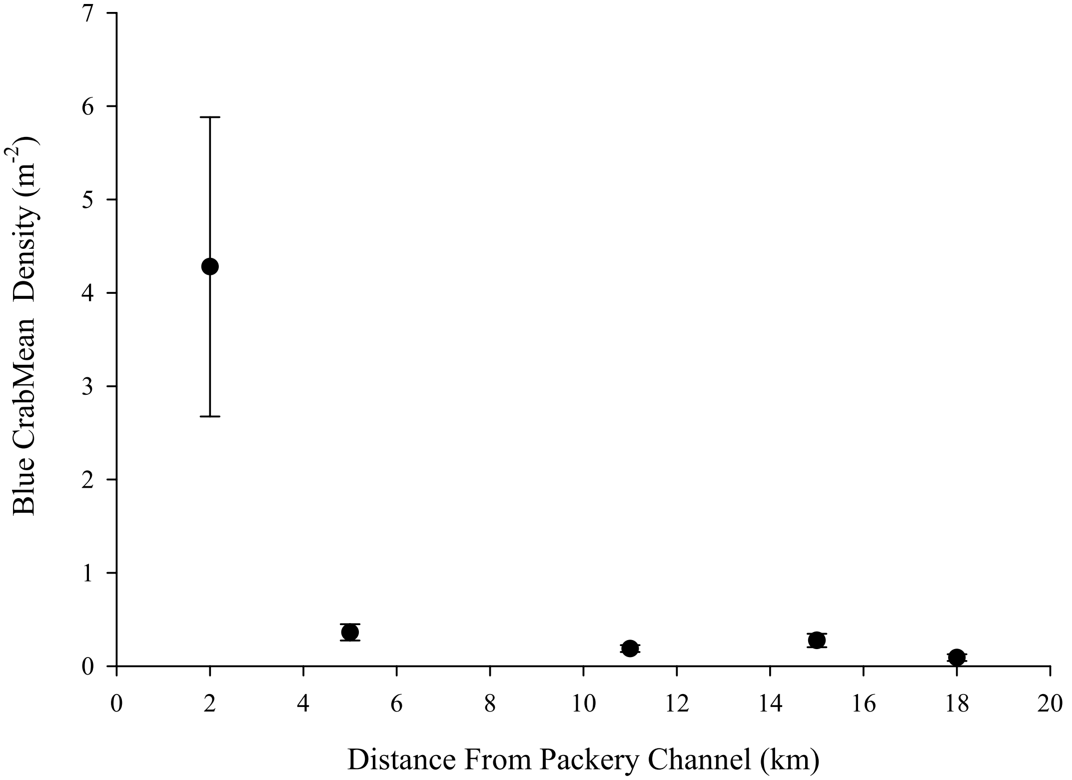

Figure 13. Mean blue crab density (m^{-2} ± SE) at varying distances from Packery Channel post-opening. The relationship between mean density and distance from Packery Channel was analyzed using a simple linear regression. Regression model: -0.0318 (distance) + 0.538; N = 5, R^2 = 0.556, P = 0.148.

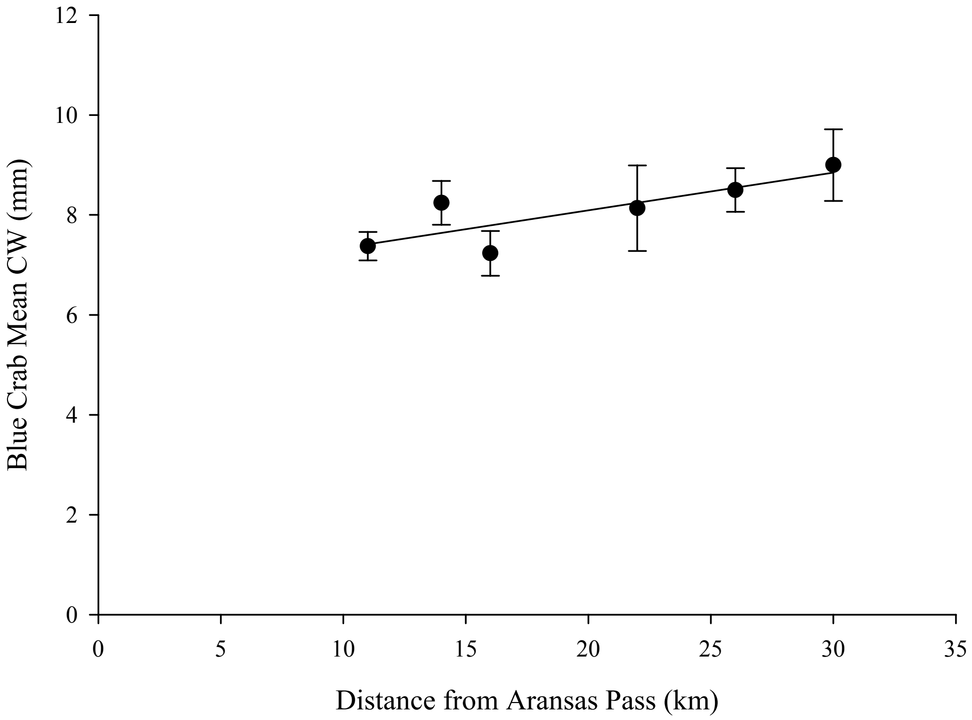

Figure 14. Blue crab mean CW (± SE) at varying distances from Aransas Pass post-opening of Packery Channel. The relationship between mean CW and distance from Aransas Pass was analyzed using a simple linear regression. Regression model: CW = 0.00359 (distance) + 0.887; N = 6, $R^2 = 0.664$, P = 0.048.

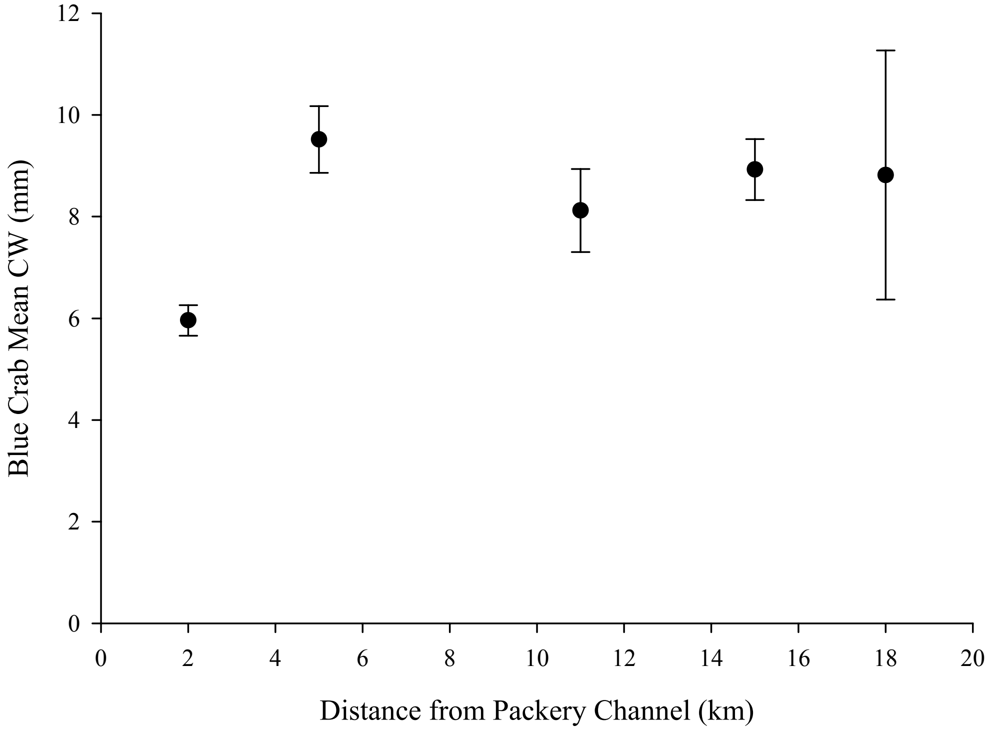

Figure 15. Blue crab mean carapace width (CW) (± SE) at varying distances from Packery Channel post-opening. The relationship between mean density and distance from Packery Channel was analyzed using a simple linear regression. Regression model: CW = 0.00614 (distance) + 0.899; $N = 5$, $R^2 = 0.329$, $P = 0.312$.

Penaeid Shrimp Habitat Use Patterns

Penaeid shrimp were sampled at varying distances from tidal inlets during fall 2004-2005 and winter 2005-2006. Brown shrimp, pink shrimp, and white shrimp were grouped as "penaeid shrimp" because many were within a size range that makes identification very difficult (10-18 mm TL) (Rozas and Minello 1998). Of the identifiable penaeid shrimp, brown shrimp were the predominant species.

Prior to the opening of Packery Channel, there was no relationship between distance from Aransas Pass and density of penaeid shrimp ($R^2 = 0.235$; $P = 0.131$; $N = 11$; $1-\beta = 0.321$) (Fig. 16). Densities of penaeid shrimp varied greatly at the different distances from the inlet. For example, the density at 22 km was 1.20 m^{-2} ± 0.54 SE, increased to 2.11 m^{-2} ± 0.81 SE at 26 km, and then decreased to 0.45 m^{-2} ± 0.13 SE at 30 km (Table 3). However, the densities of penaeid shrimp were high (2.72 m^{-2} ± 0.40 SE) at site 1, the site nearest Aransas Pass (Table 3). There was a significant relationship between distance from Aransas Pass and TL of penaeid shrimp prior to opening of Packery Channel ($R^2 = 0.664$; $P = 0.002$; $N = 11$) (Fig. 17). Penaeid shrimp TL was smallest at sites closest to the inlet and increased as the distance increased. At the site nearest to Aransas Pass TL was 16.48 mm ± 0.46 SE and increased to 33.90 mm ± 6.07 SE at 47 km.

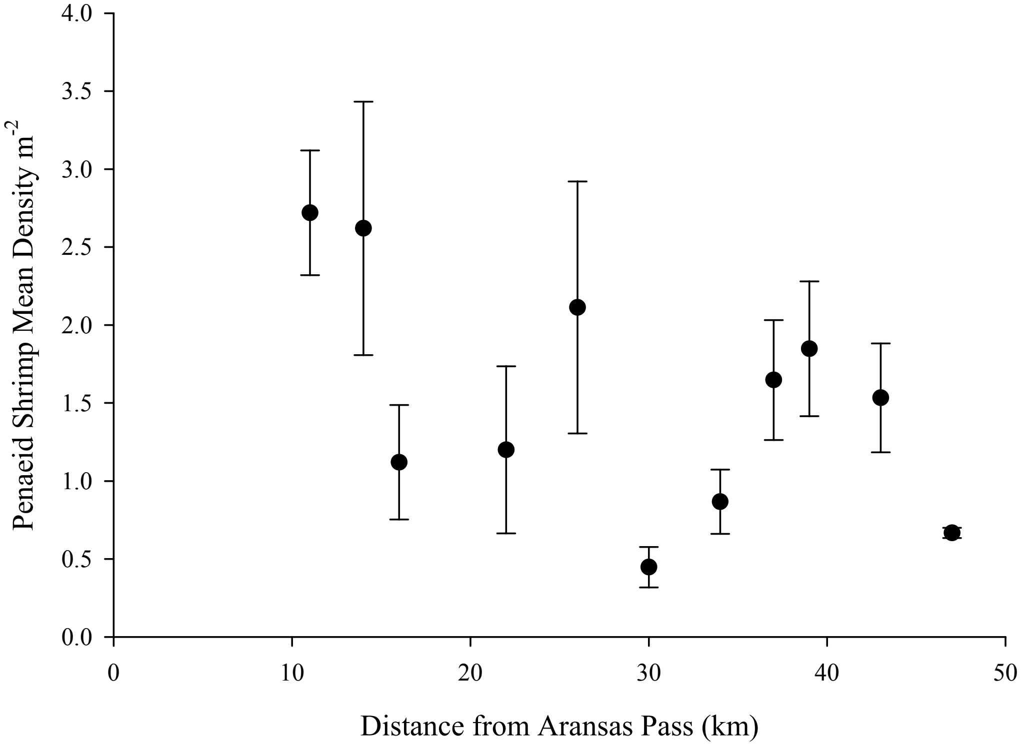

Figure 16. Mean penaeid shrimp density (± SE) in seagrass beds at varying distances from Aransas Pass pre-opening of Packery Channel. The relationship between mean density and distance from Aransas Pass was analyzed using a simple linear regression. Regression model: density = -0.00530 (distance) + 0.536; $N = 11$, $R^2 = 0.235$, $P = 0.131$.

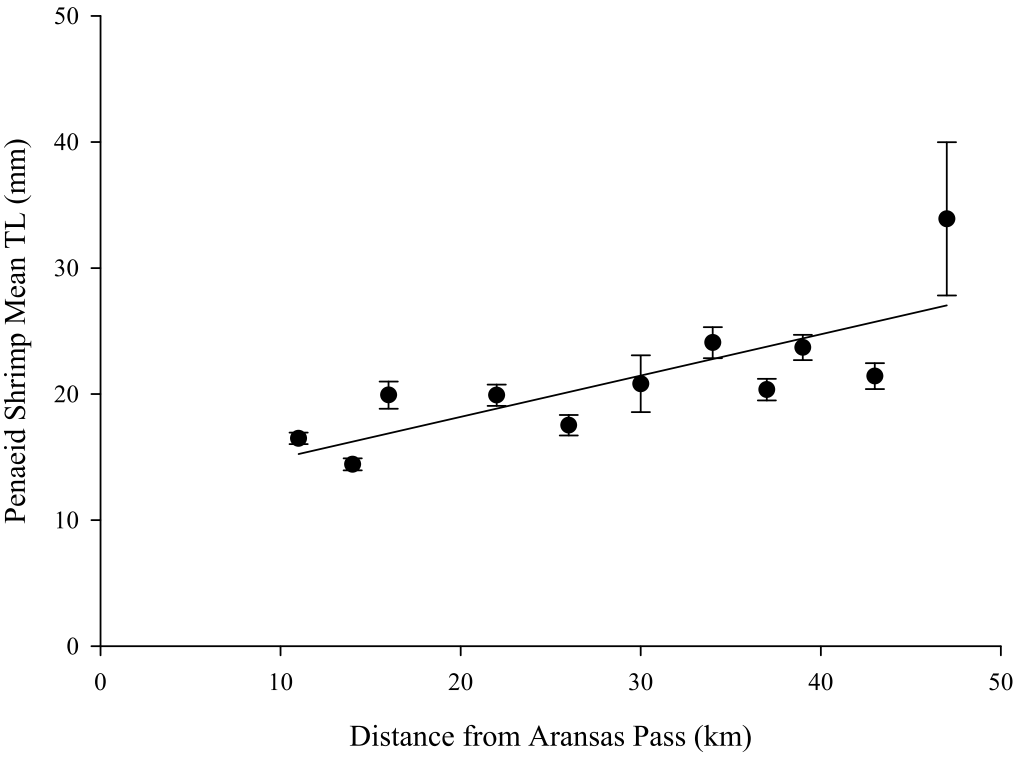

Figure 17. Relationship between penaeid shrimp TL (mm ± SE) and distance from Aransas Pass (km) pre-opening of Packery Channel analyzed with simple linear regression. Regression model: TL = 0.00614 (distance) + 1.157; N = 11, R^2 = 0.664, P = 0.002.

Post-opening of Packery Channel, there was no significant relationship between penaeid shrimp density and distance from either Aransas Pass ($R^2 = 0.270$; $P = 0.290$; $N = 6$; $1-\beta = 0.168$) or Packery Channel ($R^2 = 0.506$; $P = 0.178$; $N = 5$; $1-\beta = 0.241$) (Fig. 18; Fig. 19). However, as in 2004, high densities were captured at sites closest to the inlet. At site 1 (11 km from Aransas Pass) penaeid shrimp density was 3.43 m^{-2} ± 0.64 SE. Although not significant, the general trend was density decreased as distance from Aransas Pass increased. After opening, densities around Packery Channel were high (4.38 m^{-2} ± 1.16 SE) at site 8 (5 km from Packery Channel) and in general decreased at the remaining more distant sites (Table 3). There was no significant relationship between TL of penaeid shrimp and distance from Aransas Pass ($R^2 = 0.0307$; $P = 0.740$; $N = 6$; $1-\beta = 0.049$) post-opening of Packery Channel (Fig. 20). However, the smallest mean TL of penaeid shrimp was found at site 1 closest to the inlet (16.60 mm ± 0.37 SE). There was a significant linear relationship between mean TL of penaeid shrimp and distance from Packery Channel ($R^2 = 0.804$; $P = 0.039$; $N = 5$) (Fig. 21). Penaeid shrimp at 2 km had a mean TL of 18.66 mm ± 0.61 SE and then increased to 32.56 mm ± 1.23 SE at 18 km (Table 4).

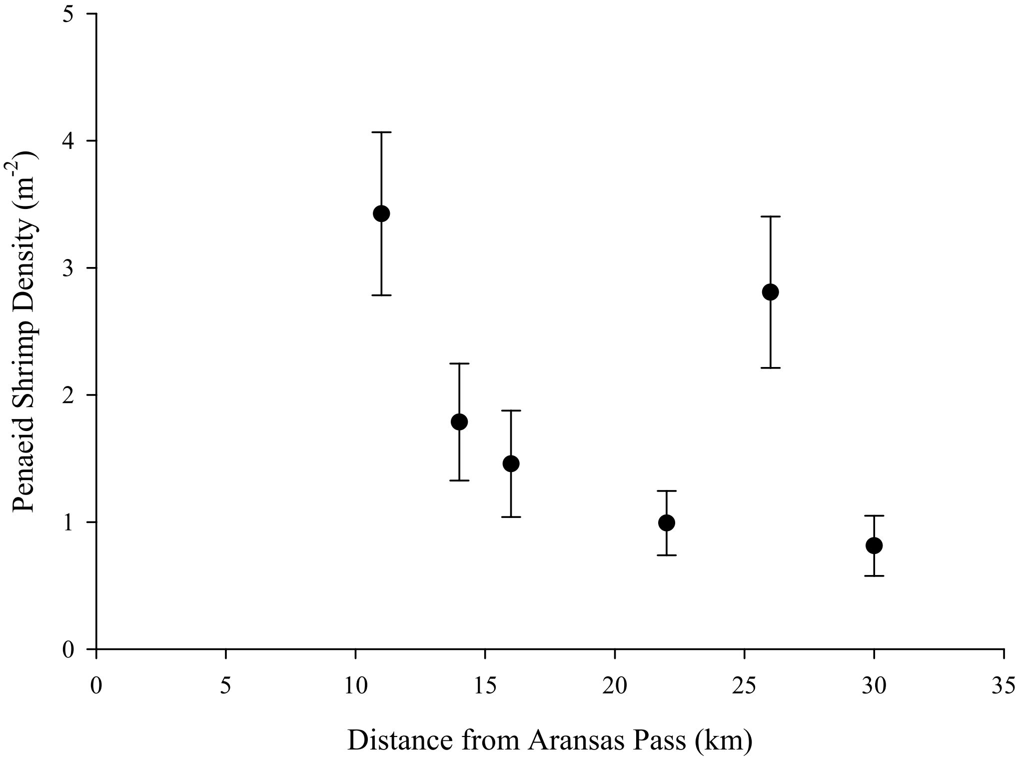

Figure 18. Mean penaeid shrimp density (± SE) at varying distances from Aransas Pass post-opening of Packery Channel. The relationship between mean density of juvenile penaeid shrimp and distance from Aransas Pass was analyzed using a simple linear regression. Densities were combined for fall 2005 and winter 2006. Regression model: density = -0.0108 (distance) + 0.651; $N = 6$, $R^2 = 0.270$, $P = 0.290$.

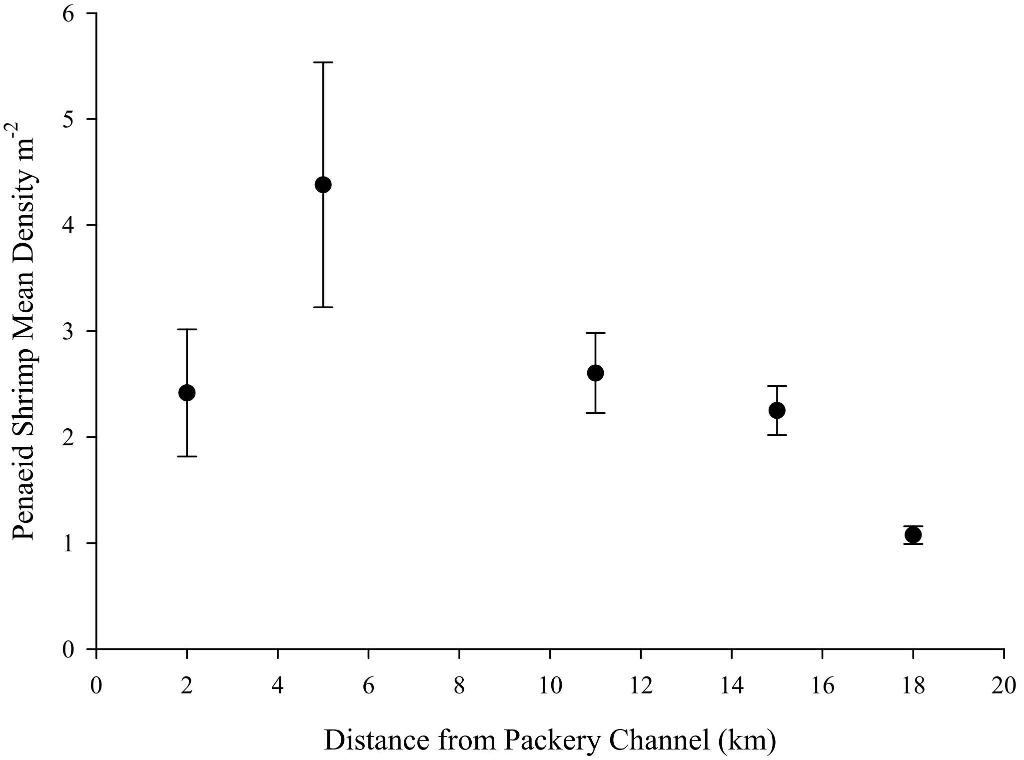

Figure 19. Relationship between mean penaeid shrimp density (m^{-2} ± SE) and distance from Packery Channel (km) post-opening analyzed with simple linear regression. Densities were combined for fall 2005 and winter 2006. Regression model: density = -0.0157 (distance) + 0.690; N = 5, $R^2 = 0.506$, P = 0.178.

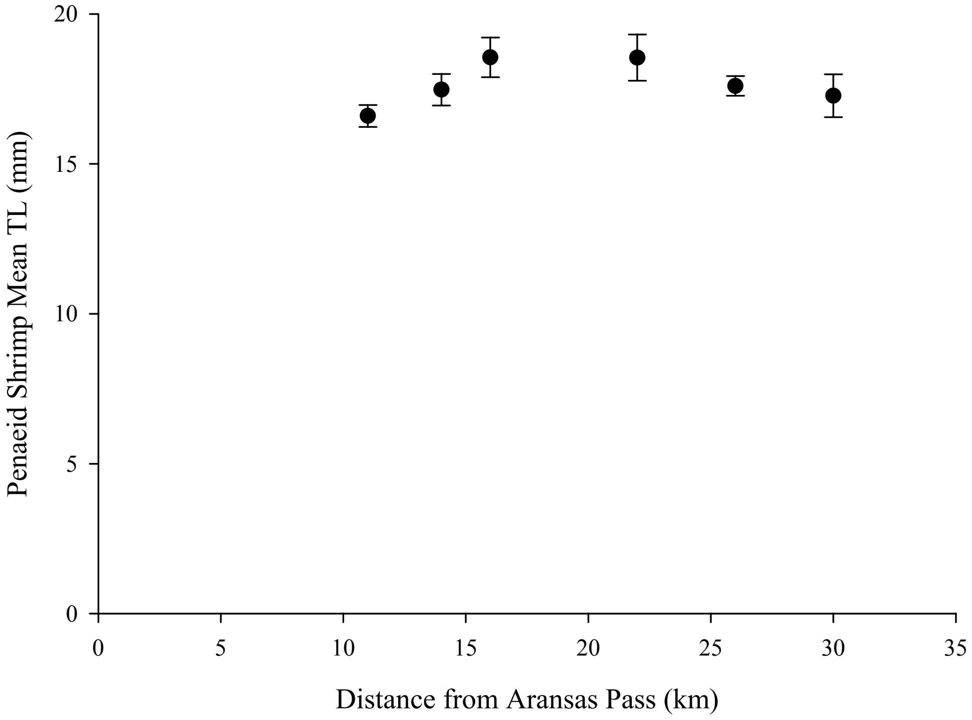

Figure 20. Relationship between penaeid shrimp mean TL (mm ± SE) and distance from Aransas Pass (km) post-opening of Packery Channel analyzed with simple linear regression. Mean TL for each distance was calculated from fall 2005 and winter 2006 samples. Regression model: TL = 0.0004 (distance) + 1.263; N = 6, R^2 = 0.0307, P = 0.740.

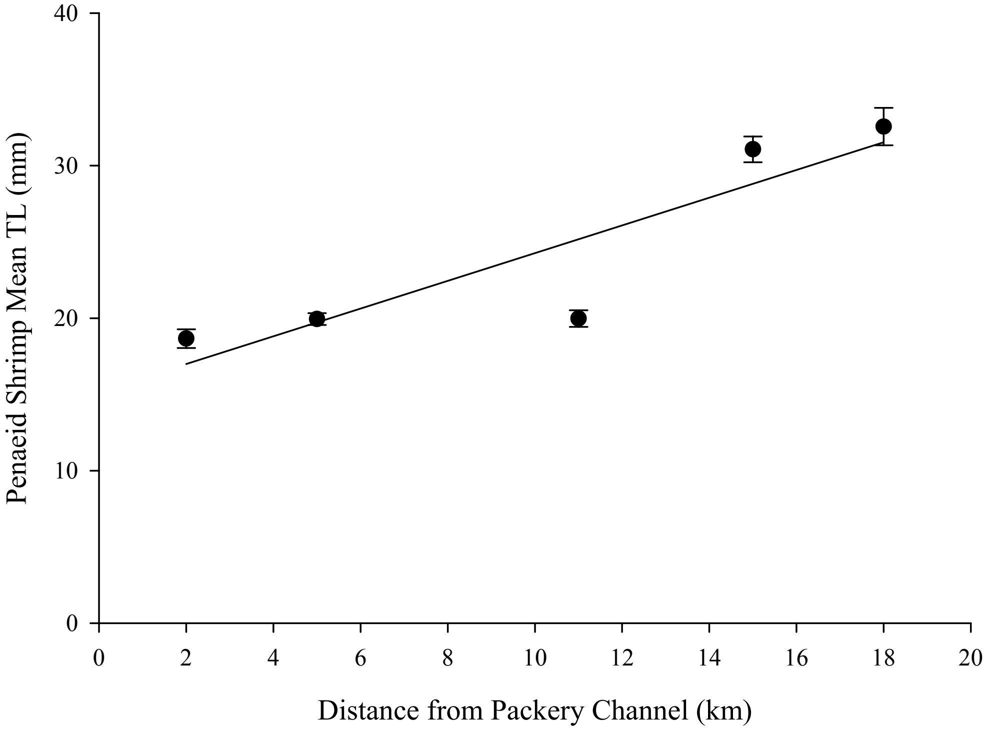

Figure 21. Relationship between penaeid shrimp mean TL (mm ± SE) and distance from Packery Channel post-opening analyzed with simple linear regression. Mean TL for each distance was calculated from fall 2005 and winter 2006 samples. Regression model: TL = 0.885 (distance) -11.426; N = 5, R^2 = 0.804, P = 0.039.

Discussion

Recruitment patterns of estuarine-dependent nekton to nursery habitats result from the interaction of several physical and biological processes that occur between the time the egg is released and subsequent settlement into suitable juvenile habitat. These include interactions such as distance from a tidal inlet, current, wind, and larval supply. These factors can have a great effect on the spatial distribution of juvenile fish and crustaceans within an estuary (Boehlert and Mundy 1988; Miller 1988; Jenkins and Black 1994; Akin et al. 2003; Brown et al. 2005). Post-settlement factors such as mortality, predation, food resources, and competition can also affect abundance and length distributions of fishes and invertebrates in nursery habitats (Jenkins et al. 1997; Levin et al.1997). To examine the role of distance from a tidal inlet on settlement patterns, I analyzed densities of juvenile red drum, southern flounder, blue crabs, and penaeid shrimp at varying distances from two tidal inlets.

Densities of red drum, southern flounder, blue crab, and penaeid shrimp were generally higher at distances nearest tidal inlets, while lengths of each species were typically smaller at these locations. Bell and Westoby (1986) hypothesized that fish and decopods will settle into the first seagrass bed that they encounter when competent to do so, regardless of the physical complexity and later redistribute to more complex areas within that habitat. Because mortality during the planktonic phase is very high, these authors hypothesized that individuals that settle and remain in the first bed they encounter should have higher survival, even if the physical complexity of the habitat is low. My sites located closest to the inlet were the first opportunity for fishes and decapod crustaceans transported through the Corpus Christi Ship Channel or Packery Channel to settle. The observed high densities of small red drum, southern flounder, blue crabs, and penaeid shrimp indicate that many of these larvae settle into the first seagrass bed they encounter. The mean length of each species collected at these sites was near the reported lengths that they settle from the plankton.

Other researchers have reported high densities of small red drum at areas nearest to a tidal inlet. Pearson (1929) captured the greatest number of newly-settled red drum in areas nearest to and in a direct line with the inlet. Pearson sampled at different distances from both Aransas and Corpus Christi Passes and found that 68% of the red drum were captured within 1-2 km of the inlet and were 8-29 mm, 29% were within 3-6 km of the inlet and were 11-34 mm, and the remaining 3% were within 8-19 km of an inlet and were 19-23 mm (Pearson 1929). Although he found that red drum densities were highest at sites within 1-2 km of the pass, the results of this study are comparable because fish that travel through the Corpus Christi Ship Channel do not encounter seagrass for approximately 11 km.

Not only were the highest densities of red drum collected nearest the tidal inlet, but I also observed a significant relationship between density and distance, and length and distance from Aransas Pass pre-opening of Packery Channel in fall 2004. The mean density of red drum decreased with increasing distance from Aransas Pass while the mean length of the red drum increased. This suggests that most small red drum settle into seagrass beds closest to the inlet and disperse and grow after some period of time. Highest mean densities were collected within 16 km of Aransas Pass. However, red drum were able to disperse as far as 30 km from Aransas Pass, but were encountered at very low densities. These results suggest that red drum do not have great dispersal capabilities from a tidal inlet, and that habitats nearest the tidal inlet may be most important for red drum recruitment. Brown et al. (2005) using circulation and particle transport models determined that competent red drum could be transported by wind-driven currents to the southern and western portions of Corpus Christi Bay, however, I collected very few small newly settled red drum at farther distances. Increased sampling on larger spatial scales throughout the entire Corpus Christi Bay will lead to a better understanding of the spatial patterns of recruitment of red drum.

While there was a relationship between both red drum density, length, and distance from an inlet, there was considerable variability observed among sites. The variability among sites was most likely due to hydrodynamic processes as well as post-settlement processes such as predation or competition. It is widely accepted that larval supply and hydrodynamics, especially tidal force, wind force, and flow through an inlet can have a strong effect on the distribution of settling nekton (Rooker and Holt 1997; Rooker et al. 1998*b*; Xie and Eggleston 1999; Brown et al. 2000; Brown et al. 2004; Brown et al. 2005). Tidal forcing can be effective at transporting larvae a distance of 10-15 km into bays (Brown et al. 2000), and stochastic wind forcing can interact with the topography of the coastline and the geographic locations of inlet sources of larvae to produce spatio-temporal variations in larval supply to estuarine nursery habitat (Xie and Eggleston 1999). Brown et al. (2005) used a numerical circulation model coupled to a particle transport model to determine the role that physical processes play in the dispersal of red drum larvae. They found that the supply of passive particles to estuarine nursery areas depended on the interaction of regional physical forcing, bathymetry, and shoreline configuration. Variability among sites may also be due to physical characteristics associated with sites such as plant height, blade density, or water depth (Holt et al. 1983; Bell and Westoby 1986).

I had the unique opportunity to examine red drum recruitment before and after the opening of Packery Channel, a new tidal inlet. Packery Channel is approximately 39 km from Aransas Pass. Prior to the opening, red drum recruitment was low in areas surrounding Packery Channel because red drum did not disperse farther than 30 km from Aransas Pass. In fall 2005, Packery Channel was open and flowing, and I observed different recruitment patterns. However, there was no relationship between red drum densities or length and distance from Aransas Pass or Packery Channel post-opening. Overall, in fall 2005 (post-opening) red drum densities were considerably lower than in fall 2004. This may explain why no relationships were found between density or length of red drum and distance from Aransas Pass or Packery Channel. Similar to pre-opening results, red drum did not disperse more than 30 km from Aransas Pass and small red drum were found in high densities at sites closest to Aransas Pass.

In sites near Packery Channel, I encountered densities of red drum exceeding those found pre-opening. Post-opening, red drum were found in low densities at the site closest to Packery Channel and in high densities 15 km from Packery Channel. Although densities were not high at the site closest to the inlet, 15 km is still relatively close to the inlet and should have demonstrated high recruitment. Lengths of red drum were small at the sites closest to Packery Channel and larger at more distant sites, suggesting that they are growing as they are dispersing from Packery Channel post-opening. Although red drum were collected near Packery Channel, they were at low densities and were not significantly higher than pre-opening densities. Overall, the mean SL of red drum was significantly smaller post-opening. Although I did not find differences in densities, Reese (2006) did find significant differences in densities of red drum pre- verses post-opening of Packery Channel. Variable and low densities of red drum coupled with more intensive sampling in areas surrounding Packery Channel by Reese (2006) may account for the difference. Although there was a difference, she captured very low densities of small red drum in areas surrounding Packery Channel. These results suggest that red drum were being transported through the inlet but not at high densities. The lower densities observed may be because Packery Channel was not fully dredged during the fall 2005 sampling. Although water was flowing through the inlet, the volume of water and flow rate may not have been substantial enough for high densities of larvae to be transported through Packery Channel.

Previous research in areas near Packery Channel suggest that these habitats can support high densities of red drum. Pearson (1929) sampled areas near Aransas Pass as well as Corpus Christi Pass, now known as Packery Channel, while it was flowing. He found that densities of red drum were more extensive in the isolated patches of seagrass near Corpus Christi Pass than near Aransas Pass. Corpus Christi Pass later silted in and until the dredging of Packery Channel, no inlet has allowed direct access to the habitats in the upper Laguna Madre or southern portions of Corpus Christi Bay. These historical data suggest that the habitat of the upper Laguna Madre can support high densities of red drum after Packery Channel is completely dredged.

I also examined spatial patterns of habitat use of southern flounder at varying distances from tidal inlets. Southern flounder densities were not correlated to distance from a tidal inlet. Flounder occurred at very low densities and were represented by 14 individuals in both years of sampling. Therefore, caution should be used when interpreting these results. Most of the southern flounder that were captured were at sites closest to the inlet. Nanez-James (2006) found similar results of southern flounder densities being highest at sites closest to Aransas Pass in the Aransas-Copano Bay complex, TX. She also found that southern flounder were significantly smaller at sites closer to the inlet. These combined results suggest that habitats nearest to the inlet are important nursery grounds for southern flounder. However, because of the low densities found, further work and increased sampling directly targeting southern flounder is necessary to make strong conclusions about dispersal patterns and the effect that distance from an inlet has on recruitment.

Blue crab recruitment patterns were examined at varying distances during fall 2004-2005 and winter 2005-2006 pre- and post-opening of Packery Channel. Blue crabs occurred at high densities throughout the study area, and no relationship was seen between density and distance from Aransas Pass or Packery Channel, pre- or post-opening. In general, blue crab densities were high at sites closest to the inlet, while mean CW was smallest. Other studies have shown that high densities of small juvenile blue crabs occured at sites closest to inlets (Heck and Thoman 1984; Morgan et al. 1996; Etherington and Eggleston 2000; Heck et al. 2001; Etherington and Eggleston 2003). Etherington and Eggleston (2003) hypothesized that blue crabs have primary and secondary dispersals that are determined by wind events. Primary dispersal leads to clumping in the estuary primarily in areas near an inlet, and secondary dispersal occurs within a month of benthic settlement when the juveniles re-enter the plankton and disperse throughout the estuary. There was no relationship between blue crab density and distance from Aransas Pass or Packery Channel pre- or post-opening. However, there was a significant relationship found between mean CW and distance from Aransas Pass for both years of sampling. Small juvenile blue crabs were found at the sites closest to Aransas Pass and increased in size as distance increased. The pattern of high densities of small juvenile blue crabs near the inlet and lower densities of larger blue crabs at greater distances supports the distribution patterns proposed by Etherington and Eggleston (2003). As with red drum and southern flounder, blue crab distribution is most likely affected by physical processes, especially wind.

Densities and lengths of penaeid shrimp were examined at varying distances from tidal inlets during fall and winter both pre- and post-opening of Packery Channel. Penaeid shrimp occurred at high densities throughout the study area. Penaeid shrimp density and length results showed a trend similar to that of blue crabs. There was no significant relationship between density of penaeid shrimp and distance from Aransas Pass or Packery Channel pre- or post-opening; however, densities of penaeid shrimp were high at sites closest to Aransas Pass and low at sites farther from the inlet pre- and post-opening. The mean total lengths of penaeid shrimp increased significantly with distance from Aransas Pass pre-opening. After the opening of Packery Channel, there was no relationship between TL and distance from Aransas Pass. However, there was a relationship between distance from Packery Channel and TL post-opening; penaeid shrimp were smallest at sites closest to Packery Channel and larger at greater distances. This suggests that although there was no relationship to density, penaeid shrimp were entering the estuary and growing as they dispersed to distant seagrass beds, as was the case with blue crabs. As with red drum and blue crabs, physical processes such as current, wind, and tidal flux most likely play a significant role in penaeid shrimp distribution throughout an estuary. However, blue crabs and penaeid shrimp seem to have greater dispersal capabilities from a tidal inlet. High densities of blue crabs and penaeid shrimp were found 50 km from Aransas Pass, while juvenile red drum and southern flounder were apparently unable to disperse such distances.

Red drum, southern flounder, blue crabs, and penaeid shrimp have similar life histories in that the adults spawn offshore and their eggs and larvae are carried through tidal inlets where they settle into estuarine nursery habitat. These species spawn at different times of the year and have differing peak recruitment periods, with changes in wind and circulation patterns within the bay. However, the general trend was similar for all species; densities of small individuals were highest near the tidal inlet. This partially correlates with the "settle and stay" hypothesis posed by Bell and Westoby (1986) stating that fish and decapod crustaceans settle into the first available seagrass bed that they encounter. However, in my study decapod crustaceans were found to have much greater dispersal patterns throughout Corpus Christi Bay and upper Laguna Madre. My results indicate that these species settle into the first seagrass bed, but they may disperse further into the estuary after some period of time as suggested by Etherinton and Eggleston (2003). Although this trend was apparent, many other factors such as larval behavior and physical processes including tidal flux, wind force, topography of the coastline, and others may play an additional role in the distribution of juvenile fish and decapod crustaceans within an estuary.

These results suggest that seagrass habitats at close proximity to a tidal inlet are of substantial importance to recruiting nekton and measures should be taken to protect these habitats. Nursery habitats near tidal inlets are clearly vital to the perpetuation of these species providing refuge, protection from predation, and increased growth rates during early life stages. Loss of habitat in close proximity to tidal inlets could have a profound affect on adult populations since only slight decreases in survival or growth of recruiting larvae and juveniles has been found to have significant effects on year class strength of a species.

CHAPTER II

ARTIFICIAL HABITAT AS RECRUITMENT CORRIDORS

Introduction

Seagrasses are a valuable nursery habitat for many recreationally and commercially important species of fish and invertebrates. Seagrasses are termed submerged aquatic vegetation (SAV) and are considered to be one of the most productive and valuable habitats in estuarine systems (Quammen and Onuf 1993; Levin et al. 1997) typically supporting a greater abundance and richness of fauna than unvegetated habitats (Rozas and Minello 1998; Beck et al. 2001). Seagrasses function as nursery habitat for recruiting juvenile fish and invertebrates (Heck and Thoman 1981; Levin et al. 1997; Beck et al. 2001; Heck et al. 2003) providing structurally complex habitat (Heck et al. 2003), protection from predation (Rooker et al. 1998*a*; Stunz and Minello 2001), and increased growth rates (Holt et al. 1983; Heck and Thoman 1984; Stunz et al. 2002*b*; Heck et al. 2003). Despite the importance of seagrass beds, they have undergone declines resulting from anthropogenic disturbances such as dredging (Quammen and Onuf 1993), eutrophication, and mechanical damage (Duarte 2002; Short and Wyllie-Echeverria 1996). Seagrass declines can have a profound effect on fishery species that depend on seagrass for refuge, foraging areas, and nursery habitat (Heck et al. 2003). Restoration of seagrass beds by transplantation has previously been employed to offset these losses (Sheridan 2004).

Tidal inlets play an important role in determining the dynamics and structure of marine fish populations, because they provide a means of access from the open ocean to high-quality estuarine nursery habitats (Connell and Jones 1991; Eggleston 1995).

Clearly, understanding how fish access nursery habitats is critical for analyzing fish recruitment. Bell and Westoby (1986) hypothesized that recruiting fishes and invertebrates settle in the first seagrass bed that they encounter regardless of its physical complexity. However, favorable settlement habitats may be many kilometers from spawning grounds. Because of this, nursery grounds may be inaccessible because of a high mortality risk associated with larvae and juvenile fishes crossing large expanses of nonvegetated or channeled bottom, such as in the Corpus Christi Ship Channel, to reach suitable nursery habitats.

In areas where fish must travel over long stretches of non-vegetated bottom, habitat "corridors" may aid in the dispersal of juvenile fish and crustaceans recruiting to nursery habitats. A corridor defined simply is a linear feature of vegetation that differs from the surrounding environment and connects at least two patches of habitat. When corridors are considered in terms of movement of fauna it is important to recognize that the corridor allows movement from one area to another (Hobbs 1992). Future restoration sites could focus on providing corridors that could act as intermediate habitats for recruiting juvenile fish to potentially increase survival. These areas would provide nearby habitat for nekton to settle and minimize time in plankton, where mortality rates are very high. In addition, these are would provide a means of access to more extensive seagrass meadows. Artificial seagrass units can be used as a proxy to examine the potential for artificial or restored habitats to serve as corridors for recruiting fishes to established seagrass beds that may be unavailable because of predator-related mortality or starvation due to lack of appropriate habitat (Micheli and Peterson 1999). Few studies have examined movement along corridors (Hobbs 1992), and even fewer studies exist on the movement of marine fishes along corridors. Mumby et al. (2004) found that mangrove forests can serve as an intermediate nursery habitat that may increase the survivorship of young fishes. Mangroves strongly influenced the community structure of fishes on adjacent coral reefs and may have served as a corridor. In the case of red drum, corridors may aid in the dispersal to established seagrass beds during transport into an estuary.

Artificial seagrass units (ASUs) can aid in the examination of how future restoration sites will affect recruiting fish. These ASUs have been successfully used by many investigators to determine recruitment of estuarine-dependent fishes (Bell et al. 1985; Bell et al. 1987; Bell et al. 1988; Sogard 1989; Bologna and Heck 2000; Upston and Booth 2003). These studies have shown that ASUs attract faunal assemblages similar to those of fish and invertebrates that colonize natural seagrass habitats.

Red drum can be used as a model species to examine the effect of artificial habitats and corridors on the recruitment patterns of various other estuarine-dependent species. Red drum recruiting through Aransas Pass and subsequently the Corpus Christi Ship Channel must travel over 11 km of non-vegetated bottom before encountering the first available seagrass beds in Corpus Christi Bay. Mortality of early life stages of red drum from predation over nonvegetated habitats has been shown to be significantly higher than in seagrass beds (Stunz et al. 2002*a*), and seagrass coverage can affect early-life survival of red drum (Rooker et al. 1998*a*). Therefore, transport over expansive areas of nonvegetated bottom may result in high mortality rates. In contrast, the Lydia Ann Channel, the most seaward branch of the Aransas Pass tidal inlet, is lined with extensive and continual seagrass on both sides of the channel. If this seagrass acts as a corridor, one might expect densities of red drum to be higher in Aransas Bay than in Corpus Christi Bay. This represents an excellent natural experiment and a method to test the hypothesis that corridors may aid in the recruitment of dispersing juvenile fishes through the use of artificial settlement habitat.

The purpose of this study was to examine the effect of ASUs on the recruitment of juvenile red drum in Corpus Christi Ship Channel, and assess whether the restoration of seagrasses could serve as a corridor for recruiting estuarine-dependent species by comparing red drum recruitment in the habitat-limited Corpus Christi Ship Channel to the habitat-rich Lydia Ann Channel.

Methods

Study Site

To assess recruitment potential in a habitat-limited versus a habitat-rich inlet, two study locations were selected in two arms that branch from Aransas Pass inlet, the Corpus Christi Ship Channel (CCSC) and Lydia Ann Channel (LAC) (Fig. 22). Water entering from the Gulf is directed into one of three channels, the CCSC, LAC, and Aransas Channel. Aransas Pass is a narrow tidal inlet approximately 400-500 m wide. Aransas Pass connects Corpus Christi, Nueces, Aransas, Redfish, Copano, and St. Charles Bay to the Gulf of Mexico.

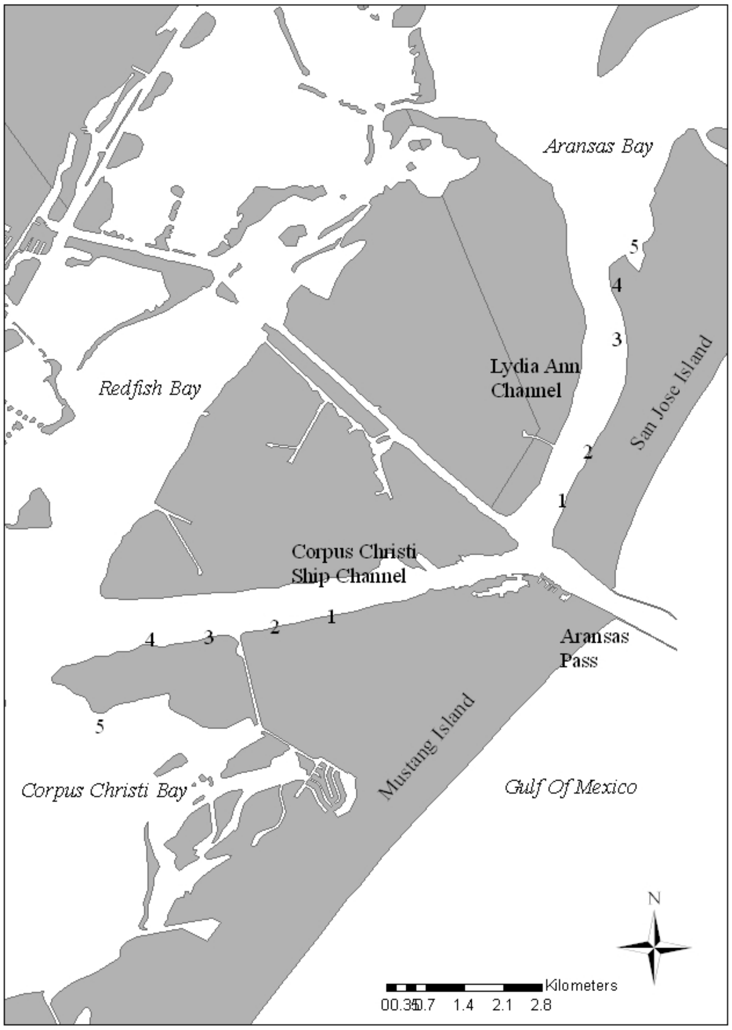

Figure 22. Map of study area and study sites in the Corpus Christi Ship Channel and Lydia Ann Channel, TX. Sites within the Lydia Ann Channel were in seagrass beds of *Halodule wrightii* and sites in the Corpus Christi Ship Channel were located on non-vegetated bottom. The sites in Aransas and Corpus Christi Bay were located in seagrass beds.

The CCSC is 14 m deep and 120-180 m wide and leads directly into Corpus Christi Bay (Brown et al. 2005). The CCSC is very limited in submerged aquatic vegetation. *Halodule wrightii* is the primary habitat in both Corpus Christi and Aransas

Bays, supporting commercially and recreationally important species such as red drum (Holt et al. 1983; Rooker et al. 1998*b*; Tunnell 2002). Corpus Christi Bay is a positive primary bay located on the southern coast of Texas and is the largest bay in the Corpus Christi Bay system. Corpus Christi Bay has a maximum depth of 3.1 m (Britton and Morton 1989), a surface area of 497 km^2 and a mean salinity of 22 ppt (USEPA 1999).

The LAC was selected as a "control." It is 5-7 m deep and 200-300 m wide near the entrance of Aransas Pass decreasing to a depth of 4 m and a width of 40 m in Aransas Bay (Brown et al. 2005). The channel is lined on either side with extensive *H. wrightii* seagrass beds, the primary nursery habitat reported for red drum. Aransas Bay is a positive primary bay located to the north of Corpus Christi Bay. Aransas Bay has a maximum depth of 3.1 m (Britton and Morton 1989), a surface area of 539 km^2 and a mean salinity of 15 ppt (USEPA 1999). Freshwater inflow into Aransas Bay is supplied by the Aransas and Mission Rivers and also by Copano Creek, and is connected to the Gulf by Aransas Pass (Britton and Morton 1989). *Halodule wrightii* is an extensive and primary nursery habitat in Aransas Bay.

Artificial Seagrass Units and Corridor Affect

Artificial seagrass units (ASUs) were used to assess how artificial habitats affect migrating fishes. The ASUs were constructed from a polyvinyl chloride (PVC) frame and monofilament fishing line. Green polypropylene ribbon was used to approximate the natural length and shoot density of *H. wrightii*, 10,000 leaves m^{-2} (Johnson and Heck 2003). Control PVC frames lacked the polypropylene ribbon. Six ASUs and six controls were placed at each of four sites along the Corpus Christi Ship Channel (Fig. 21). This channel was chosen because it lacks suitable nursery habitats for settlement of recruiting fish and decapod crustaceans. Control PVC frames were placed on non-vegetated bottom adjacent to the ASUs. The ASUs and controls were sampled with a drop sampler custom built to fit tightly around the perimeter of the PVC frame. The drop sampler was pushed into the substrate surrounding the ASU and dip nets were used to sweep the bottom of the trap to remove nekton, until no organisms were left on the ASU. Samples were fixed in 10% formalin and further processed in the laboratory. Epibenthic sleds were also used to take triplicate samples on non-vegetated bottom at the ASU sites in the Corpus Christi Ship Channel (CCSC) as well as 4 sites in the Lydia Ann Channel (LAC). A fifth site was selected at the termination of each channel in the first large seagrass bed in Corpus Christi and Aransas Bays, and these areas were sampled with triplicate epibenthic sled tows at the same time as the CCSC and LAC sites. The epibenthic sled is a fixed-frame sampling device that has been used by several investigators for sampling nekton (Holt et al. 1983; Stunz et al. 2002*a*). The 0.6 m (length) x 0.75 m (height) metal frame was fitted with a 1 mm mesh conical plankton net and connected to a 17 m rope. Samples were collected by placing the sled on the bottom and walking a semicircular route around the sampling area to avoid disturbance. The sled was towed by hand for ~ 17 m and covered a total bottom area of 10 m^2. All samples were fixed in 10% formalin in the field and further processed in the lab. Red drum were sorted, identified, and measured to the nearest 0.1 mm SL and preserved in 70% ethanol. Salinity (ppt), water temperature (°C), and dissolved oxygen (DO) (mg/L) data were collected at each site using a refractometer and YSI DO 200 meter. Water depth (cm) was also recorded at each site using a depth gauge on the epibenthic sled.

This sampling design allowed for the comparison of recruitment densities between the first two extensive seagrass meadows in each bay, and thus, the examination of a “corridor” effect. The site in Aransas Bay is preceded by seagrass beds that line the LAC, while the site in Corpus Christi Bay is the first seagrass bed that recruiting fish and crustaceans encounter. Samples were taken weekly for four weeks beginning 21 October 2005 during the peak red drum recruitment period.

Statistical Analysis

Densities and lengths of red drum between the two channels were analyzed using a Student’s *t*-test. The significance value was set at ($\alpha = 0.05$). All observations were converted to number of individuals/m^2 (density) and a log (x+1) transformation was used to minimize heteroscedasticity. Mean densities and lengths of red drum were combined for all sampling events. A mean density for sites within each channel, as well as sites in Corpus Christi and Aransas Bays were calculated.

Results

Physical Parameters

At each site in the Corpus Christi Ship Channel and Lydia Ann Channel, the salinity (ppt), DO (mg/L), water temperature (°C), and depth (cm) data were collected at each site (Table 5). Physical parameters were similar among sites. The mean salinity in the CCSC was 33.85 ppt ± 0.292 and in the LAC the mean salinity was 31.65 ppt ± 0.280 SE. The mean DO in the CCSC was 6.614 mg/L ± 0.064 SE, and 8.398 mg/L ± 0.569 SE in the LAC. The mean temperature in the CCSC was 26.93 °C ± 0.107 SE, and 27.48 °C

± 0.125 SE in the LAC. Mean depth in the CCSC was 36 cm ± 16.33 SE, while in the LAC it was 25.40 cm ± 2.95.

Table 5. Physical parameters (± SE) at each site in the Corpus Christi Ship Channel (CCSC) and Lydia Ann Channel (LAC).

	Salinity (ppt)		DO (mg/L)		Temp (°C)		Depth (cm)	
Site	Mean	SE	Mean	SE	Mean	SE	Mean	SE
CCSC								
1	34.00	(1.53)	6.46	(0.33)	26.97	(2.84)	45.00	(0.00)
2	34.00	(1.53)	6.50	(0.43)	26.73	(2.00)	45.00	(0.00)
3	33.50	(1.56)	6.74	(0.31)	26.80	(1.91)	25.00	(0.00)
4	33.00	(1.47)	6.59	(0.29)	26.83	(2.05)	30.00	(0.00)
5	34.75	(2.14)	6.78	(1.25)	27.33	(2.71)	35.00	(7.64)
LAC								
1	32.25	(1.55)	9.83	(1.18)	27.68	(2.59)	35.00	(0.00)
2	32.25	(1.25)	6.69	(0.47)	27.38	(2.14)	16.33	(1.86)
3	31.50	(1.19)	9.42	(1.20)	27.55	(2.03)	25.00	(5.00)
4	30.75	(1.65)	7.73	(0.63)	27.05	(2.18)	25.33	(6.74)
5	31.50	(0.96)	8.32	(0.33)	27.75	(2.28)	25.33	(2.91)

Artificial Seagrass Units

To evaluate the effect of artificial habitat on recruitment, six ASUs and six control units were placed on unvegetated bottom at each site in the CCSC. The CCSC is a high use channel with multiple large barges and other ocean-going ships traveling the channel daily displacing and moving large volumes of water while passing. According to the Port of Corpus Christi, 7,378 ships and barges traveled through the ship channel in 2005 (The Port of Corpus Christi 2006), approximately 20 per day. The ASUs were unable to withstand this high-energy area, and therefore, were all lost within three weeks. Nine

ASU's and seven controls were sampled within that time, and three penaeid shrimp and six blue crabs were collected on the ASU's and two blue crabs on the controls. No red drum were captured. No analysis was run on this data due to the low number of individuals captured.

Corridor Effect

In addition to ASUs, epibenthic sleds were also used to sample at the 5 locations in the CCSC and also at 5 locations in the LAC to compare red drum densities in an inlet with a high coverage of nursery habitat to the seagrass-limited CCSC. Densities and lengths from sites 1-4 were combined for each channel and compared using a Student's *t*-test ($\alpha = 0.05$). Site 5 from both channels were then compared. There was a significant difference between mean red drum densities at sites 1-4 in the CCSC and LAC (Student's *t*-test $P<0.001$; N = 48 CCSC, N = 47 LAC; $t = -4.513$) (Fig. 23). The mean density of red drum in the CCSC was 0.040 (± 0.018) and 0.54 (± 0.13) in the LAC. Although densities were significantly higher at the LAC sites 1-4, there was no significant difference between red drum densities at site 5 (the first large seagrass meadow) in either bay (Student's *t*-test $P = 0.621$; N = 12 CCSC, N = 11 LAC; $t = -0.502$; $1 - \beta = 0.05$; $df = 21$) (Fig. 24). When mean lengths of red drum were compared within the CCSC and LAC there was no significant difference (Student's t-test $P = 0.713$; N = 19 CCSC, N = 254 LAC; $t = 0.368$; $1 - \beta = 0.05$; $df = 271$) (Fig. 25). However, red drum were significantly larger at CCSC site 5 (12.10 ± 0.41) than at LAC site 5 (8.57 ± 0.18) (Student's t-test $P< 0.001$; N = 80 CCSC, N = 104 LAC; $t = 10.041$) (Fig. 26). I further analyzed the lengths by producing length frequency diagrams for the red drum from each channel and at the end sites in each bay. The distribution of lengths between the two channels was similar with most fish ranging between 6 – 8 mm SL (Fig. 27, Fig. 28). However, the distributions of red drum lengths between CCSC site 5 and LAC site 5 were very different. The distribution at CCSC site 5 had peak abundances between 9-12 mm SL (Fig. 29). Fish were captured at various size ranges, with two fish >20 mm SL. In contrast, the distribution of fish at the LAC site 5 was skewed to the left, with most fish in the smaller size ranges (Fig. 30). The fish were much smaller with the majority between 7 – 9 mm SL. No fish >17 mm were collected.

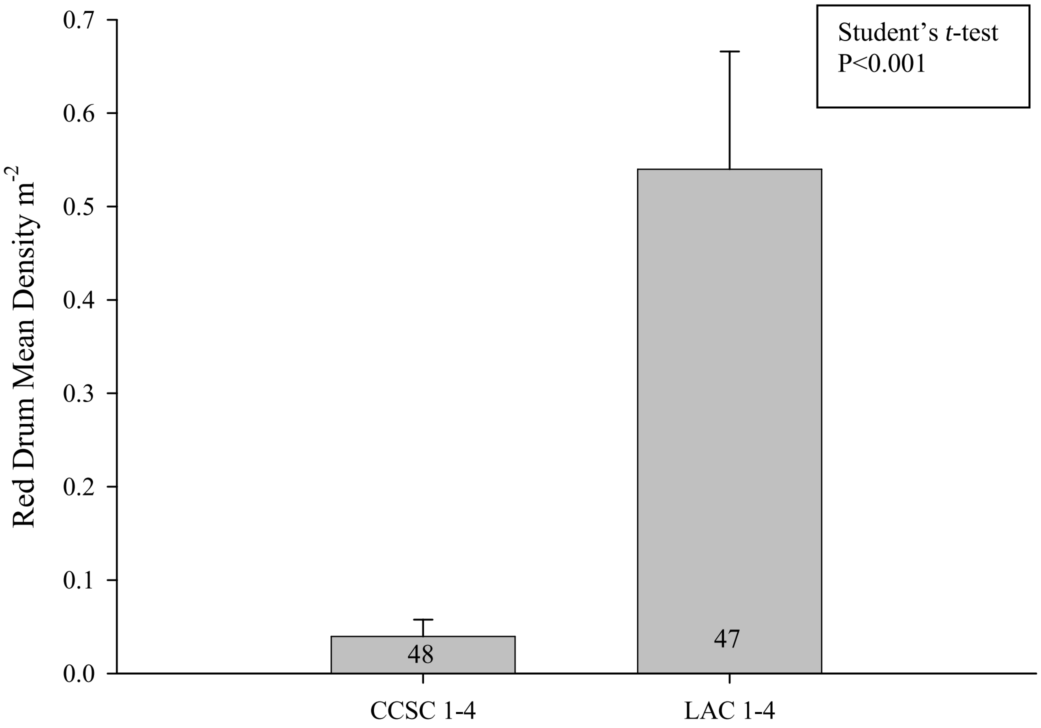

Figure 23. Mean red drum densities (m^{-2} ± SE) in the Corpus Christi Ship Channel (CCSC) and Lydia Ann Channel (LAC). Densities were combined from all sampling events and sites within the CCSC and LAC. Sites 1-4 were located along each of the channels and were on bare bottom in the CCSC and in seagrass in the LAC. The number of samples taken in each channel is indicated at the bottom of each bar. Densities of red drum in each channel were analyzed using a Student's *t*-test.

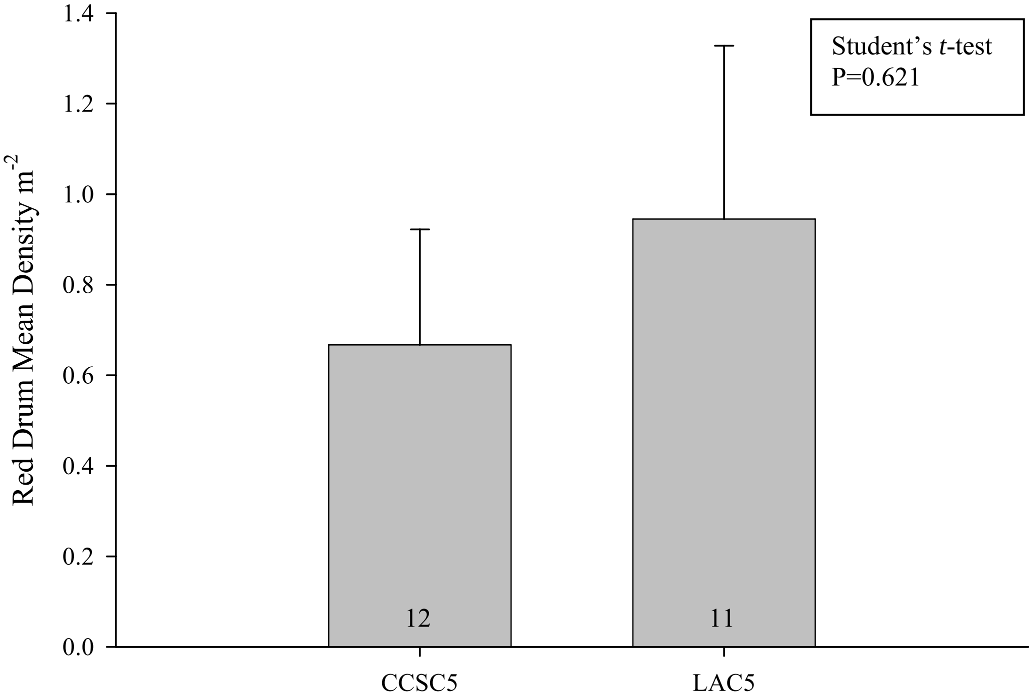

Figure 24. Mean red drum densities (m^{-2} ± SE) at the Corpus Christi Ship Channel (CCSC) and Lydia Ann Channel (LAC) site 5. These sites were located in the first seagrass bed outside of each channel. The CCSC5 was located in Corpus Christi Bay, and LAC5 was located in Aransas Bay. Densities were combined from all sampling events. The number of samples taken in each channel is indicated at the bottom of each bar. Densities of red drum in each bay were analyzed using a Student's *t*-test.

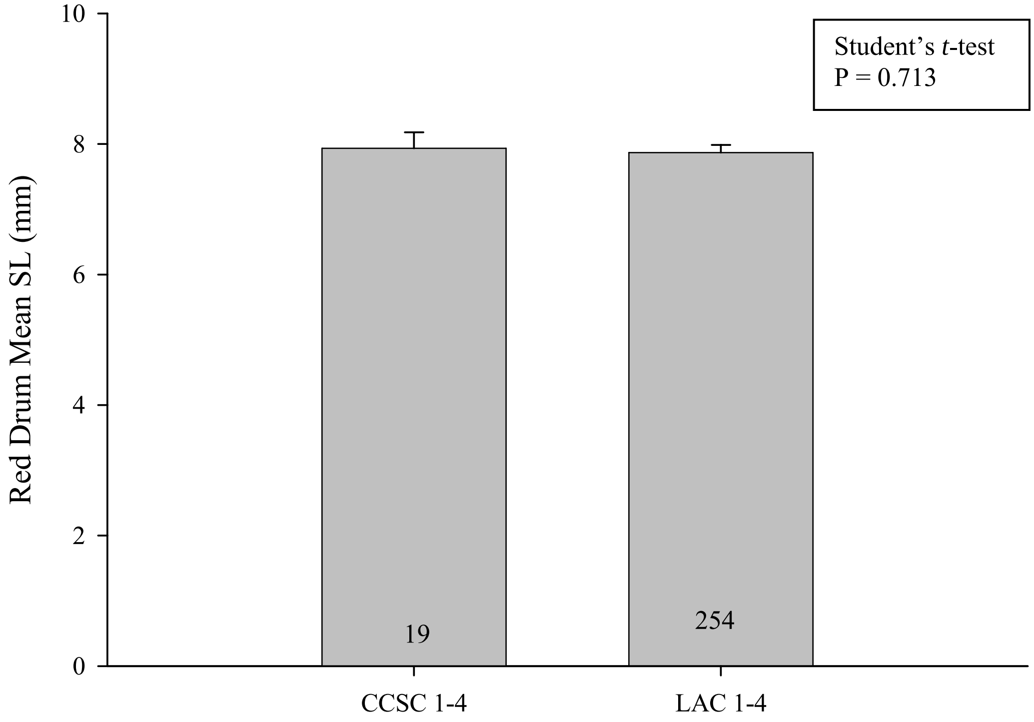

Figure 25. Mean red drum SL (mm ± SE) in the Corpus Christi Ship Channel (CCSC) and Lydia Ann Channel (LAC). Mean SL was calculated from all sampling events and sites within the CCSC and LAC. Sites 1-4 were located along each of the channels and were on bare bottom in the CCSC and in seagrass in the LAC. The number of fish taken in each channel is indicated at the bottom of each bar. Lengths of red drum in each channel were analyzed using a Student's *t*-test.

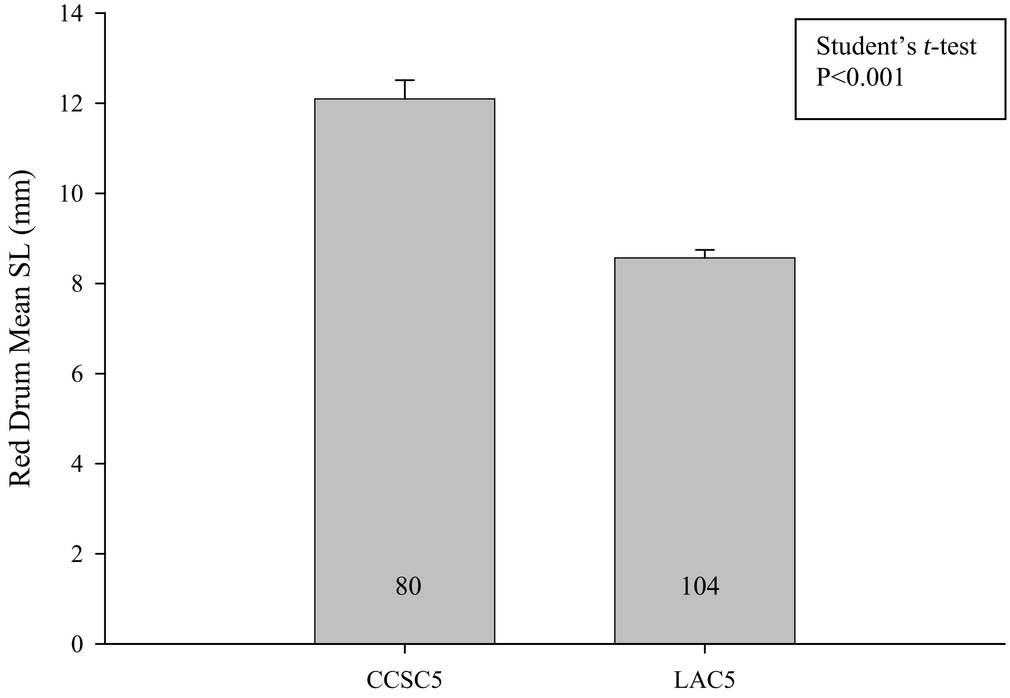

Figure 26. Mean red drum SL (mm ± SE) at the Corpus Christi Ship Channel (CCSC) and Lydia Ann Channel (LAC) site 5. These sites were located in the first seagrass bed outside of each channel. CCSC5 was located in Corpus Christi Bay, and LAC5 was located in Aransas Bay. Mean SL was calculated from all sampling events. The number of fish taken in each channel is indicated at the bottom of each bar. Lengths of red drum in each bay were analyzed using a Student's *t*-test.

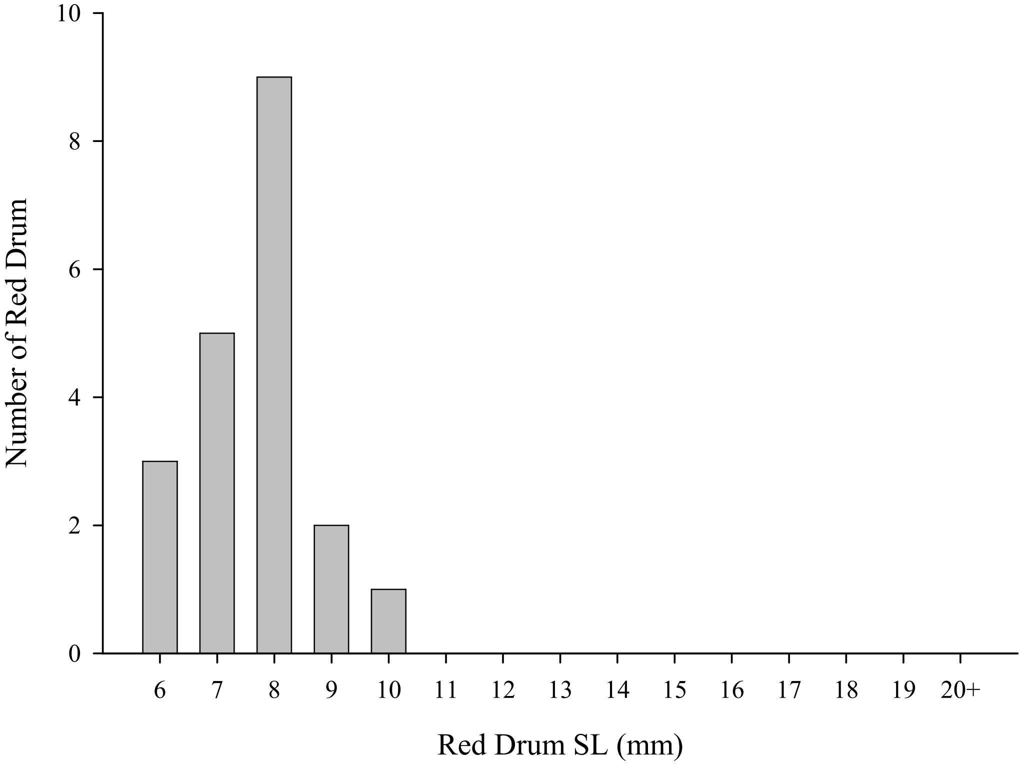

Figure 27. Length frequency histogram for red drum captured in the Corpus Christi Ship Channel (CCSC) sites 1-4 during peak red drum recruitment in fall 2005. Sites in the CCSC were located on non-vegetated bottom.

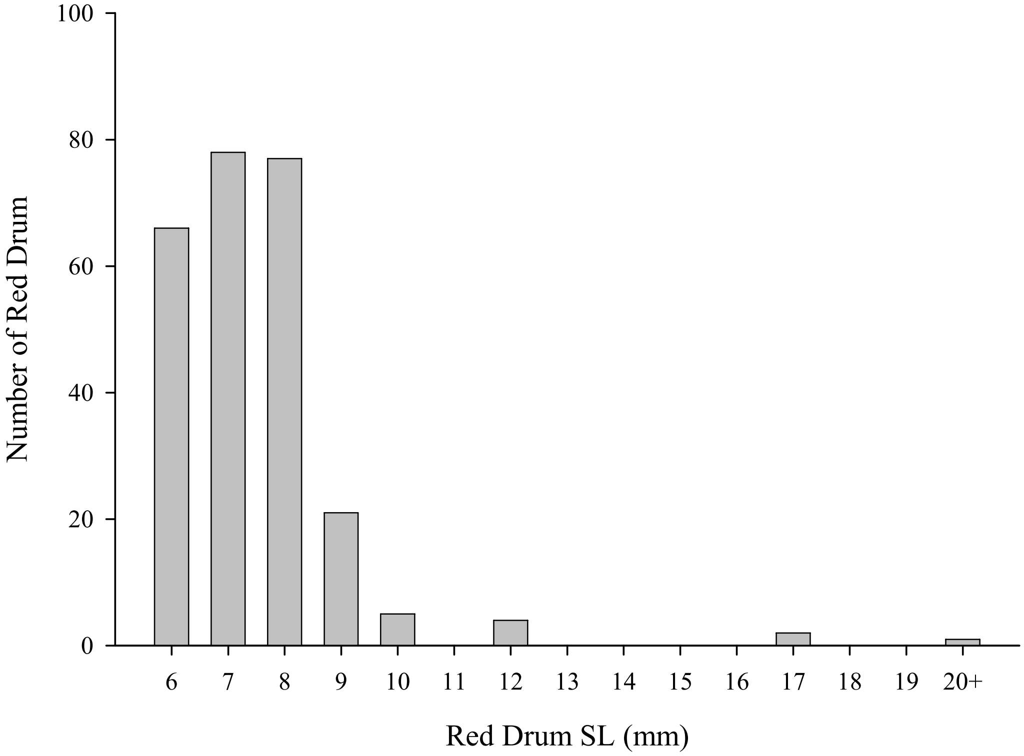

Figure 28. Length frequency histogram of red drum captured in the Lydia Ann Channel (LAC) sites 1-4 during peak red drum recruitment in Fall 2005. Sites in the LAC were located in seagrass *H. wrightii*.

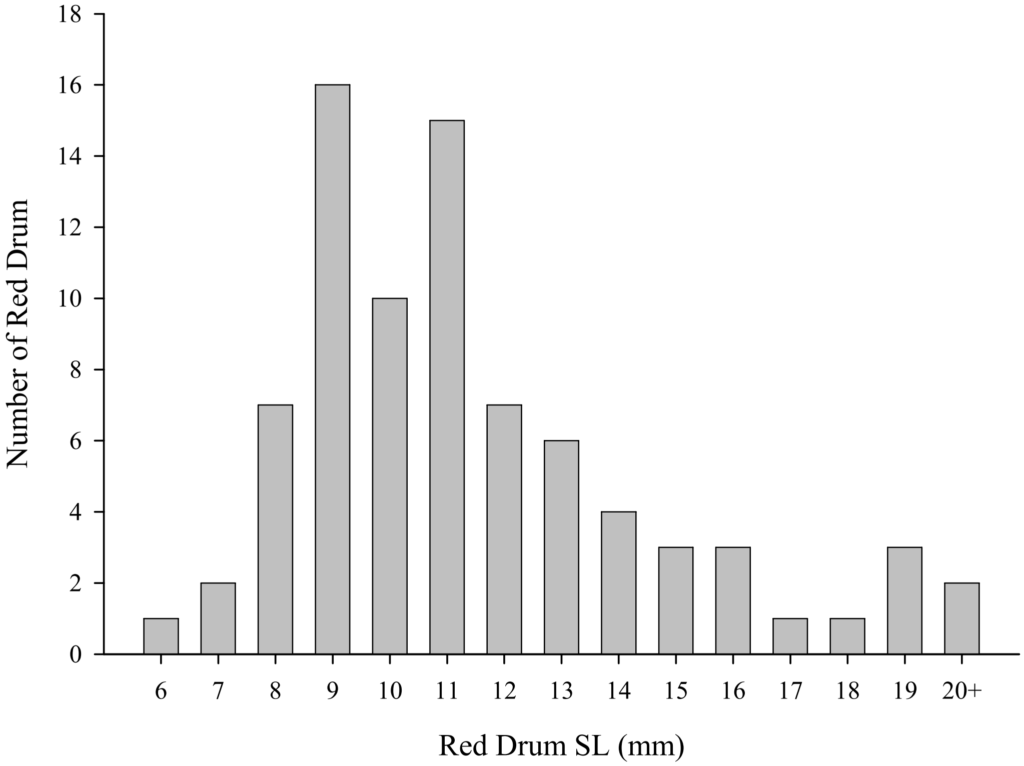

Figure 29. Length frequency histogram for red drum captured in Corpus Christi Ship Channel (CCSC) site 5, during peak recruitment in fall 2005. CCSC site 5 is the seagrass bed in Corpus Christi Bay that fish and invertebrates encounter when recruiting through the CCSC.

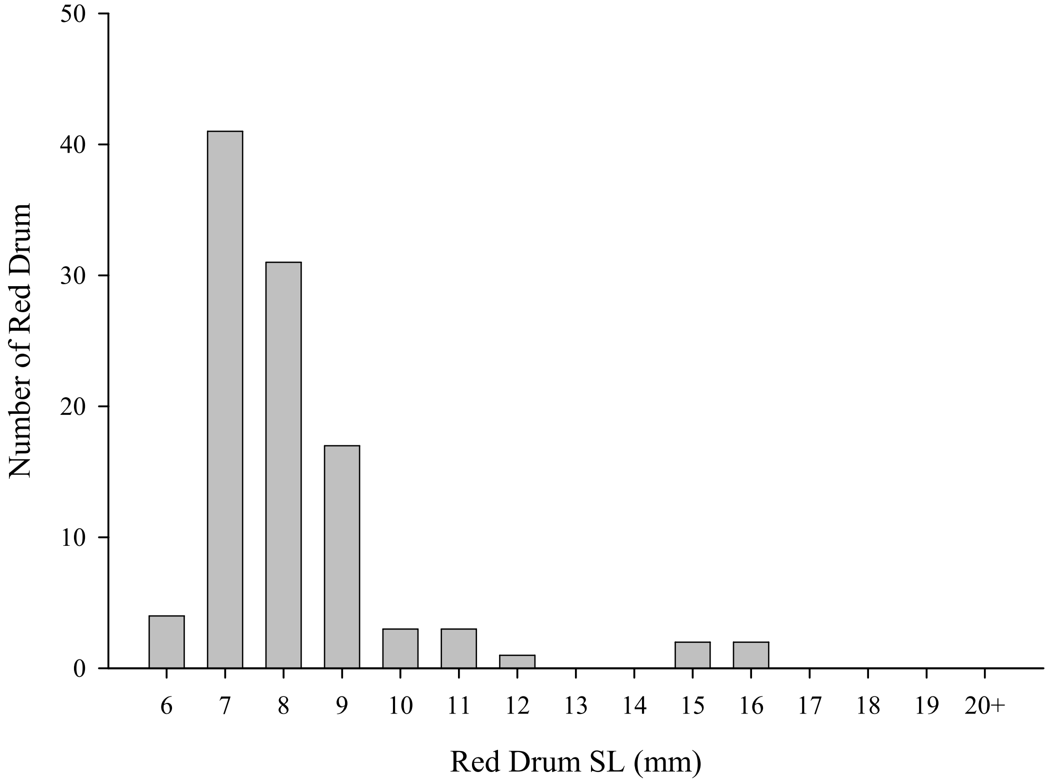

Figure 30. Length frequency histogram for red drum captured in Lydia Ann Channel (LAC) site 5 during peak red drum recruitment in fall 2005. This site is the first large seagrass meadow in Aransas Bay that fish encounter when recruiting through the LAC.

Discussion

This study evaluated the potential for corridors to enhance recruitment of estuarine-dependent species through habitat-limited tidal inlets. Seagrass corridors within a habitat-limited tidal inlet may increase recruitment to the extensive seagrass beds within the bay because these nursery grounds may be inaccessible due to a high mortality risk associated with larvae and juvenile fishes crossing large expanses of nonvegetated or channeled bottom as present in the Corpus Christi Ship Channel. In such cases, corridors may aid in the dispersal of juvenile fish and crustaceans recruiting to nursery habitats.

Through the use of artificial seagrass units (ASUs) it is possible to examine the effect of future restoration sites or corridors on recruiting fish. Artificial seagrass units were placed in the CCSC to assess whether red drum recruiting through the habitat-limited channel would use ASUs as intermediate nursery habitat before dispersing to the larger seagrass beds within the bay. However, the ASUs were unable to withstand the heavy boat traffic and high-energy environment within the channel and were lost. No red drum were captured on the units. Because this channel is very high energy, it would be very difficult to transplant or restore habitat in this environment.

Densities of red drum were examined in the habitat-rich LAC versus the habitat-limited CCSC to assess whether seagrass beds within an inlet can serve as a corridor and increase recruitment to seagrass beds within the bay. Red drum densities in the LAC that contained nursery habitat for settling red drum were significantly higher than densities of red drum collected at the CCSC sites lacking seagrass. However, there was no significant difference in red drum densities at the first large seagrass meadows in either bay. These results suggest that seagrass beds within the tidal inlet do not affect the densities of red drum within the bay. Densities of red drum collected in the LAC indicate that they may be using this habitat as a corridor to disperse to the larger more established seagrass beds in Aransas Bay. However, settling red drum may be using the patches of seagrass in the LAC as nursery habitat and not dispersing to the larger seagrass beds within the bay. This would agree with the "settle and stay" hypothesis posed by Bell and Westoby (1986) that states fish settle into the first habitat they encounter regardless of physical complexity and do not disperse. Differentiating between the corridor and habitat functions of patches of vegetation requires knowing whether the patch increased animal movement to connected habitats (Rosenberg et al. 1997). It is difficult to determine whether the seagrass beds in the LAC increased dispersal and therefore recruitment levels to Aransas Bay. Results from the CCSC sites suggest that these fish are not using habitat in the channel as corridors, since the densities of red drum in Corpus Christi and Aransas Bay were not significantly different. However, larval supply (Bell et al. 1988, Brown et al. 2005), flow (Rooker et al. 1998*b*) and other physical factors could play an important role on the abundance of red drum in the two bay systems. A mark and recapture study could aid in determining the movement patterns of red drum once they have settled into a nursery habitat, and also evaluate whether corridors increase dispersal of settling red drum.

Lengths of red drum within the CCSC and LAC, as well as at the end point in Aransas and Corpus Christi Bays, were also examined. Lengths of red drum in the CCSC and LAC did not differ significantly. However, the mean length of red drum at the end site in each bay was significantly different. Red drum in Corpus Christi Bay were significantly larger than those from the Aransas Bay site. When a length frequency histogram was analyzed for red drum at the sites within Corpus Christi and Aransas Bays it is apparent that lengths are more evenly distributed in the Corpus Christi Bay site. Red drum sizes were spread out over various size classes, while red drum in Aransas Bay were much smaller, with most of the fish being in smaller size ranges. This may be caused by the quality of the habitat between the two sites. Sub-optimal habitat has been shown to cause a substantial reduction in growth rates and individuals with reduced growth rates are less likely to survive (Sogard 1994). Although no physical difference between the seagrass beds were observed, my results suggest that red drum recruiting to the Corpus Christi Bay site are settling and surviving while the red drum in the Aransas Bay site are settling and dispersing further into the bay or potentially not surviving. The former is most likely the case since larger fish are routinely collected in other studies (Holt et al. 1983) Although the functionality of the seagrass beds within the different bays was not the focus of this research, these findings are very interesting and warrant future investigations.

I examined the effect of ASUs on the recruitment of juvenile red drum in CCSC, and assessed whether the restoration of seagrasses could act as a corridor for recruiting red drum by comparing recruitment in the habitat-limited Corpus Christi Ship Channel to the habitat-rich LAC. The artificial seagrass units were unable to withstand the high-energy channel, suggesting that transplanting or restoring seagrass in this area would be unsuccessful. However, transplanting seagrasss in this channel is unnecessary since my results suggest that seagrass beds within the tidal inlet do not impact the densities of red drum within at the first seagrass bed in the estuary. Densities of red drum within the LAC indicate they may be using this habitat as a corridor to disperse to the larger more established seagrass beds in Aransas Bay. However, similar densities of red drum at the end site (first seagrass meadow) in each bay indicate that the corridor of seagrass within the LAC does not increase recruitment to seagrass beds within the bay. These data suggests that red drum may not be using the seagrass in the channel for movement and may be settling there. A mark and recapture study could aid in determining the movement patterns of red drum once they have settled into a nursery habitat and also evaluate whether corridors increase dispersal of settling red drum.

CHAPTER III

EVALUATION OF VISIBLE IMPLANT ELASTOMER FOR MARKING JUVENILE RED DRUM (*Sciaenops ocellatus*)

Introduction

Marking and tagging is an effective tool for fisheries biologists to gain information about life history and migration patterns of fishes; however, there are few techniques for marking small or juvenile fish whose total length (TL) is < 50 mm. Techniques such as fin-clipping (Haines and Modde 1996), cold branding (McFarlane et al. 1990), subcutaneous wire microtags (Bumguardner et al. 1990; Malone et al. 1999), spray paint marking (Szedlmayer and Howe 1995) otolith marking (Hendricks et al. 1994; Negus 1999; Jenkins et al. 2002), and genetic markers (King et al. 1993) have been used on small fish. However, fin clips and cold branding can be hard to identify (Guy et al. 1996), and spray paint marking can have high mortality and low retention rates (Szedlmayer and Howe 1995). Many of the other techniques such as wire microtags, otolith and genetic markers require that the fish be sacrificed for identification and can be expensive techniques.

Visible implant elastomer (VIE) is a marking technique that is relatively easy to apply, allows for visible identification, and is inexpensive. Visible implant elastomer is a two-part silicone based material that is mixed before use and injected as a liquid beneath transparent or translucent tissue. The liquid cures into a pliable solid and is externally visible. The VIE method is advantageous due to the pliability of the tag and only a small volume of the material is required to make a visible tag (Northwest Marine Technology, Inc.). Many studies have examined the use of VIE for marking fish > 50 mm (For example, Bonneau et al. 1995; Morgan and Pavely 1996; Hale and Gray 1998; Close 2000; Catalano et al. 2001; Close et al. 2002; Goldsmith et al. 2003; Fitzgerald et al. 2004; Olsen et al. 2004; Brennan et al. 2005). The few studies that have experimented with the use of VIE on fish < 50 mm have shown that it is a viable technique for marking small fish with low mortality and high retention rates (Dewey and Zigler 1996; Haines and Modde 1996; Frederick 1997; Olsen and Vollestad 2001). However, this marking technique has not been evaluated for red drum *Sciaenops ocellatus*, a very economically important species. Assessment of a tagging technique for small individuals (< 50 mm) would greatly benefit future studies by providing an efficient means of marking young juvenile red drum and other species.

Red drum are an estuarine-dependent sciaenid found in the western Atlantic and throughout the Gulf of Mexico from Florida to Tuxpan, Mexico. The red drum is considered to be the most important recreational sciaenid species and one of the seven most sought-after game fish in the Gulf of Mexico (Pattillo et al. 1997). Adults spawn near passes and tidal inlets from September - January (Holt et al. 1983; Rooker et al. 1998*a*), and their eggs and larvae are carried by tides into shallow estuaries, where they settle into nursery habitat when they are approximately 6 - 8 mm standard length (SL) (Holt et al. 1983; Rooker et al. 1997; Rooker et al. 1998*a*). However, more information is needed concerning residence time and fine-scale movement patterns within their selected nursery habitats.

Clearly, this information is vital to understanding the population dynamics of this important marine finfish. However, it is also crucial to understand the movement patterns of hatchery-reared red drum, as the Texas Parks and Wildlife stocking program may play an important role in enhancing the natural populations of red drum. Texas initiated a red drum stock enhancement program in 1983 with approximately 20-30 million red drum fingerlings introduced into Texas bays annually (McEachron et al. 1998). Success of this program lies in the survival of released fish, and marking with VIE is one means to assess survival and movement patterns of hatchery-reared red drum.

Previous marking studies involving red drum have used oxytetracycline hydrochloride (OTC) to mark otoliths of individuals before release (Bumguardner 1991; Szedlmayer and Howe 1995; McEachron et al. 1998; Jenkins et al. 2002). These studies reported that red drum immersed in OTC can provide an accurate means of marking red drum. However, Jenkins et al. (2002) suggested that OTC may not be appropriate for short-term studies on small fish because marks were not detectable on fish sampled 56 d after immersion due to interference from autofluorescence. Another disadvantage of OTC is that fish must be sacrificed to remove the otoliths for identification. These disadvantages make this technique impractical for mark and recapture studies of small red drum where large numbers of fish are recaptured, and marked individuals must be quickly identified in the field.

Other marking studies involving small juvenile red drum have examined the use of coded wire microtags (Bumguardner et al. 1990; Szedlmayer and Howe 1995), spray paint, and external plastic minitags (Szedlmayer and Howe 1995). Coded wire microtags have variable retention rates depending on tagging location and is a very labor intensive technique (Bumguardner 1990; Szedlmayer and Howe 1995). When small juvenile red drum (48-95 mm SL) were marked with spray paint and external plastic minitags, Szedlmayer and Howe (1995) found that spray paint marking resulted in high mortality and low retention rates and external plastic minitags showed significant tag loss compared to other methods such as OTC marking. VIE may provide a fast and reliable mean to effectively tag juvenile red drum.

The purpose of this study was to examine tag retention, mortality, and growth rates of juvenile red drum marked with VIE under laboratory conditions. I also evaluated the usefulness of VIE in mark and recapture studies with wild and hatchery-reared red drum and performed a preliminary study on the fine-scale movement patterns of wild and hatchery-reared red drum within a seagrass meadow.

Methods

Laboratory evaluation of VIE

To assess VIE tag retention, and the affect of tagging on growth and mortality of red drum, I set up 12 replicate aquarium tanks (51 cm L x 26 cm W x 31 cm H; 37.9 L) to house four treatment groups with three replicates of five fish per group (60 total fish). The treatment groups were two tagging locations and two control groups (no tagging) with and without anesthesia. The two tagging locations were chosen in peripheral muscle tissue away from vital organs, as suggested by Frederick (1997) and Olsen and Vollestad (2001); below and parallel to the dorsal fin and above and parallel to the anal fin. Three replicate tanks were randomly assigned a tagging treatment or control group. Hatchery-reared red drum were obtained from the Texas Parks and Wildlife Department/Coastal Conservation Association (TPWD/CCA) Marine Development Center (MDC) in Flour Bluff, Texas. The fish ranged in size from 29.6 - 38.7 mm SL with a mean length of 34.2 mm (± 0.23 SE). Three treatment groups of red drum were anesthetized in a saltwater solution of tricaine methanesulfonate (MS-222, 50 mg/L) for 5 min or until no longer swimming and measured (SL) to the nearest 0.1 mm. Fish in the tagged treatments were then marked using a manual injector with a 0.3 cc insulin syringe and 29 gauge needle (Northwest Marine Technologies Inc.). One replicate was tagged at a time, and the replicates were randomly tagged. Fish were tagged in the left or right side with one of three colors of VIE (orange, yellow, or green) to differentiate individual fish. The needle was pointed toward the front of the fish and inserted parallel to but just under the skin. Elastomer was injected as the needle was retracted and stopped before removing the needle leaving a path of elastomer. Excess elastomer was wiped from the injection site. One control group was anesthetized with MS-222 and measured. The remaining control treatment group was measured but not anesthetized. The tanks were on constant filtration with salinity and dissolved oxygen maintained between 25 - 30 ppt and 6 - 7 mg/ml, respectively. The fish were fed daily to satiation with commercial ‘fry feed’ (Rangen) during the 14 d study. Each fish was measured at the end of the 14 d period. A one-way analysis of variance (ANOVA; $\alpha = 0.05$) was used to test for differences in growth rates between treatment levels.

Field evaluation of VIE

To examine the effectiveness of VIE under field conditions and assess fine-scale movement patterns of wild-caught and hatchery-reared red drum, a field study was conducted from November - December 2005 during the peak red drum recruitment season using wild-caught and hatchery-reared red drum marked with VIE. One hundred fifty wild-caught red drum were collected with a bag seine in seagrass meadows near the study site. The bag seine was 6 m in length with 5 mm mesh wings and a 3 mm mesh bag. The fish ranged in size from 15.2 - 32.7 mm SL with a mean length of 22.0 mm (± 0.27 SE). Hatchery-reared red drum were obtained from Perry R. Bass Marine Fisheries Research Center in Palacios , Texas and ranged in size from 18.8 mm - 32.0 mm SL with a mean length of 25.6 mm SL (± 0.14 SE). The red drum were anesthetized with MS-222 and marked below the dorsal fin. This location was easier to tag and yielded a lower mortality rate in the laboratory study. To allow for differentiation between hatchery-reared and wild-caught red drum, I tagged hatchery-reared fish on the right side and wild-caught on the left. The hatchery reared fish were tagged in the laboratory and the wild-caught fish were seined and tagged on site. All fish were monitored for any abnormal behavior prior to release. After tagging, 50 hatchery-reared and 50 wild-caught red drum were released at three replicate sites 200 m apart in a continuous seagrass bed of *Halodule wrightii* in Corpus Christi Bay, Texas (27° 49.001’ N, 97° 06.892’ W). Fish were marked with a different color VIE (orange, yellow, green) at each release site for the purpose of identification and calculation of distance traveled from release point. Sampling was accomplished by establishing a circular grid with ranges of distances (0-15, 15-30, 30-45, 45-60, 100, and 200 m) from the release point. Red drum were collected by pulling a bag seine for approximately 15 m at three random replicate sites at each distance of the circular grid. These seining sites along each circular grid distance were randomly chosen for each sampling event. I seined for marked red drum 1, 3, 7, and 14 d post-release. The distance from release site to capture site was recorded and fish were released.

Results

Laboratory evaluation of VIE

I observed high tag retention and low mortality of red drum from VIE tagging. There was no mortality for control fish. Overall tag retention and mortality of tagged fish after 14 d were 100 and 10%, respectively. Mortality for fish tagged below the dorsal fin was 0%, whereas fish tagged above the anal fin had a mean replicate mortality of 40% (± 30.5 SE) (Table 6). Overall, six red drum tagged above the anal fin died, one fish on day 3 and all five fish from one anal tagged replicate tank died on day 4. This replicate was excluded from the growth analysis. All marks on the surviving fish were visible 14 d after tagging, although marks below the dorsal fin were more easily seen than those above the anal fin. An ultra-violet light and amber-shaded glasses aided in the identification of tags above the anal fin. Mean growth rate for fish tagged below the dorsal fin was 0.43 mm/d (± 0.087), above the anal fin was 0.30 mm/d (± 0.049), control was 0.35 mm/d (± 0.071), and control with MS-222 was 0.56 mm/d (± 0.074). The mean growth rates among treatment groups were not significantly different ($P = 0.176$; $F = 2.198$; $df = 3, 7$; $N = 3$; ($N = 2$ anal tagged fish); $1-\beta = 0.201$, Table 6, Figure 31).

Field evaluation of VIE

A total of 100 (50 hatchery-reared and 50 wild-caught) red drum were released at each of the three replicate seagrass beds. Of the 300 fish released, I recaptured four fish (1.3%) (Table 7). I recaptured two hatchery-reared red drum 1 d post-release at 15-30 m and 30-45 m away from their release point, respectively. One wild-caught and one hatchery-reared red drum were captured 3 d post-release at 200 m from their release point. Recapture rates for hatchery-reared and wild-caught fish were 2% and 0.7%, respectively. All of the VIE tags on the recaptured fish were easily visible.

Table 6. Laboratory evaluation of VIE. The laboratory study consisted of four treatment groups with 3 replicates of five fish per treatment. N represents the number of fish in each replicate, and mortality (N) represents the number of fish that died per treatment group. The treatment groups were two tagging locations, above the anal and below the dorsal fin, and two control groups, MS-222 and control. Control fish were not anesthetized or tagged, and MS-222 fish were anesthetized but not tagged. Tag retention in surviving fish was 100% for both tagging locations and overall mortality for all treatment levels was 10%. Five fish from one anal tag replicate died simultaneously on day 4 and most likely was due to an unknown tank effect rather than from the VIE tag. This replicate was excluded from the growth analysis. The mean growth rates among treatment levels was not significantly different (P = 0.176; F = 2.198; *df* = 3, 7; N = 3, (N = 2 anal tagged fish); 1-β = 0.799)

Treatment	Replicates	N	Mortality (N)	Mean Replicate Mortality (% ± SE)	Tag Retention (%)	Growth Rate (mm/d ± SE)
Anal Tag	3	5	6	40 ± 30.5	100	0.30 ± 0.049
Dorsal Tag	3	5	0	0	100	0.43 ± 0.087
Control	3	5	0	0	n/a	0.35 ± 0.071
MS-222	3	5	0	0	n/a	0.56 ± 0.074

Table 7. Percent of recaptured wild-caught and hatchery-reared red drum during field evaluation of VIE in Corpus Christi Bay, Texas. Overall recapture rate was 1.3%.

	Number Released	Total Number Recaptured	% Recaptured
Hatchery-reared	150	3	2.00
Wild-caught	150	1	0.7

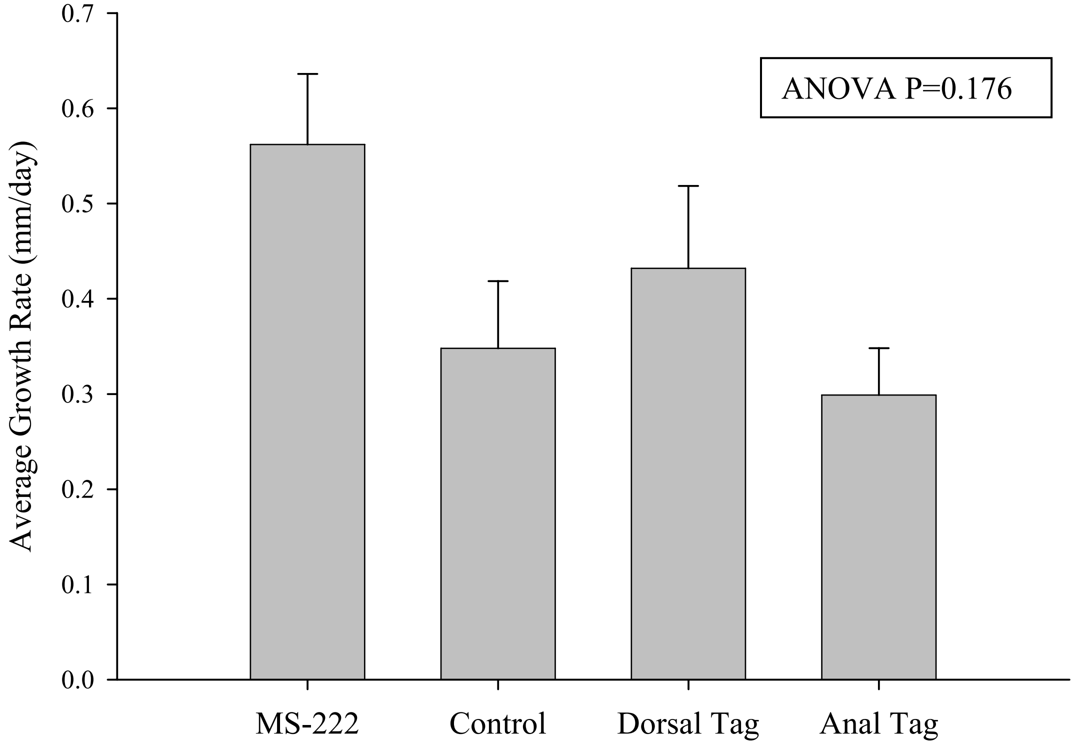

Figure 31. Average growth rates (± SE) of red drum in the laboratory evaluation of VIE. Each treatment level consisted of three replicates with the exception of fish tagged above the anal fin which had two replicates. Each replicate represents five fish.

Discussion

Our results suggest that VIE elastomer marking has little effect on mortality and growth when tagged dorsally with 100% tag retention, and that VIE is a viable tool for experiments requiring identification of small juvenile red drum. Moreover, our field experimentation suggests that VIE is a useful tool for tagging red drum under field conditions.

I found the most effective tagging location of red drum was below the dorsal fin. This location allowed for less handling and easier injection of the elastomer, resulting in no mortalities. Mortality rates were 0%, 20%, and 100% for the anal tagged replicate tanks. Five fish from one replicate tank died simultaneously on day 4 and was most likely due to an unknown tank effect rather than from the VIE tag. The mortality of the other anal tagged fish may have been caused by increased handling or insertion of the needle too deeply during VIE application since tagging above the anal fin proved to be slightly more difficult than below the dorsal fin. The tags below the dorsal fin were also more visible than tags above the anal fin because the VIE may have been injected more shallow below the dorsal fin. Frederick (1997) evaluated VIE for marking Acanthuridae and Lutjanidae spp. (10-56 mm SL). She marked fish in several locations including below the dorsal fin and above the anal fin and found that shallow injections made into peripheral musculature near the dorsal fin caused the least mortality. Dewey and Zigler (1996) evaluated VIE for marking bluegills *Lepomis macrochirus* by marking juveniles (34 - 55 mm TL) in four body locations including below the dorsal fin. Although they did not differentiate between the four tagging locations, they also found no effect of the mark on growth or survival of juvenile bluegills.

Although there were no significant differences in growth rates among our controls and treatments, I found that fish that were anesthetized were much easier to handle, measure, and tag. Thus, I recommend using MS-222 anesthetic when tagging young juvenile red drum. Olsen and Vollestad (2001) marked brown trout *Salmo trutta* between 28.9 and 44.1 mm fork length and found that tagging had no significant effect on growth. Frederick (1997) found that marking success of small fish (<20 mm) was affected by the tagging experience of the investigator. Both investigators stressed the importance of experience and skilled application of the elastomer for keeping the mortality rates low. To control for the experience level of the tagging personnel and to ensure proficiency with applying VIE, I performed several preliminary tagging trials on juvenile red drum and other small fishes prior to the laboratory tagging study.

Under field conditions I found that VIE was easy to use, and the tags were visible upon recapture for young juvenile red drum. I recaptured 1.3% of the released red drum within 3 d of release. Our recapture rates were lower than expected, and this may be due to a small sample size released into a relatively large area. The fish were released into a large continuous seagrass bed, but they could have migrated out of the study area. I was unable to make strong conclusions about post-settlement movements of red drum due to the low recapture rate. I hypothesized that the released red drum would have relatively small movement patterns, however, these results suggest that young red drum of this size have a much larger dispersal potential than previously suspected (Holt et al. 1983), and assessing movement patterns of young juvenile red drum merits further investigation.

In summary, VIE is relatively inexpensive, easy to apply, has high retention rates, low mortality when tagged dorsally, and no effect on growth rates when tagging juvenile red drum for laboratory and field experiments. This method is useful for tagging small numbers of fish and is practical for relatively small-scale short term studies where the identification of individual fish is not necessary.

SUMMARY AND CONCLUSIONS

The early life history of fishes and invertebrates is a very critical yet vulnerable stage that can impart great implications on year class strength and recruitment levels (Houde 1987). Many ecologically and economically important fishery species spawn offshore with larvae and juveniles being transported through tidal inlets, where they settle into estuarine nursery habitats such as seagrass. Several studies have examined the recruitment dynamics of such fish and invertebrate demonstrating that recruitment and distribution of estuarine-dependent species from offshore spawning grounds results from a suite of physical and biological interactions (Boehlert and Mundy 1988; Miller 1988; Jenkins and Black 1994; Rozas and Minello 1998; Akin et al. 2003; Brown et al. 2005). However, few studies have examined the effect of distance from a tidal inlet on the distribution of recruiting juveniles, and how far these individuals travel from a tidal inlet. There are also gaps in our knowledge base as to the effect that corridors have on recruiting nekton and the movement patterns of juvenile fishes once they have settled into estuarine nursery habitats.

To examine the effect of distance on the recruitment of juvenile fishes and decapod crustaceans, I evaluated densities of juvenile red drum, southern flounder, blue crabs, and penaeid shrimp at different distances from two tidal inlets. Densities of these species were repeatedly higher at sites closest to an inlet, suggesting that high levels of recruitment occur at the first extensive seagrass meadows larvae encounter. This supports the long-standing “settle and stay” hypothesis proposed by Bell and Westoby (1986). However, these patterns were observed for our model species, red drum, while decapod crustacean appear to have much larger dispersal ranges. For example, red drum densities decreased significantly with increased distance from a tidal inlet while their length increased during the first year of sampling. Small red drum did not disperse much farther than 30 km from Aransas Pass in Corpus Christi Bay, suggesting that they have rather limited dispersal capabilities. Southern flounder densities were very low and no conclusions could be made regarding their distribution within the estuary. Blue crabs and penaeid shrimp seem to have more widespread dispersal patterns with densities of small individuals found 50 km from a tidal inlet. Lengths of blue crabs and penaeid shrimp were typically smallest at the sites closest to the inlet and increased in size with increasing distance. These results suggest that seagrass beds closest to tidal inlets are important during early life stages, and decapod crustaceans may have greater dispersal patterns than previously thought.

The opening of Packery Channel provided a unique opportunity to study the recruitment and dispersal patterns of nekton resulting from a newly-opened tidal inlet. Although the inlet was open during the peak recruitment period of red drum, the densities of red drum in the upper Laguna Madre seagrass beds adjacent to Packery Channel were similar both pre- and post-opening. However, the lengths of red drum were much smaller post-opening suggested that red drum were recruiting through Packery Channel at low densities. Low densities may have resulted from minimal flow through the channel since it was not completely dredged at the time of sampling. Southern flounder, blue crab, and penaeid shrimp densities were also analyzed after the opening of the channel. It is difficult to assess the recruitment patterns of southern flounder from Packery Channel because they were collected in such low densities. Blue crabs and penaeid shrimp densities showed no relationship to distance from Packery Channel which may be due to their great dispersal potential. However, densities of small individuals were typically high in areas near Packery Channel suggesting that they are recruiting through the new inlet. Once fully opened, Packery Channel could potentially have a great impact on the densities of recruiting nekton in the upper Laguna Madre.

In many estuarine systems planktonic larvae and young recruits must transverse large areas of habitat limited areas where mortality rates are typically very high. I assessed the role of habitat in these areas and how this impacts recruitment to extensive seagrass area in the bay. Artificial seagrass units (ASUs) were placed in the Corpus Christi Ship Channel (CCSC) (a habitat limit channel) to examine their effect on the recruitment of estuarine dependent species such as red drum. Red drum densities were also compared between the habitat-limited CCSC and habitat-rich Lydia Ann Channel (LAC) to determine whether the restoration of seagrasses could act as a corridor for recruiting red drum by comparing red drum densities. My results suggest that seagrass beds within the tidal inlet do not affect the densities of red drum within the bay. Densities of red drum in the LAC indicate they may be using this habitat as a corridor to disperse to the larger more established seagrass meadows in Aransas Bay. However, settling red drum may be using seagrass in LAC as nursery habitat and not dispersing to larger seagrass beds within Aransas Bay. The results from the CCSC suggest these fish may not using habitat in the channel as corridors, since the densities of red drum in Corpus Christi and Aransas Bay are not significantly different. However, larval supply (Bell et al. 1988, Brown et al. 2005), flow (Rooker et al. 1998), and other physical factors could have an effect on the abundance of red drum in the two bay systems. A mark and recapture study could aid in determining the movement patterns of red drum once they have settled in a nursery habitat, and also to evaluate whether corridors increase dispersal of settling red drum.

Details of fine-scale movement patterns of red drum once they have settled into a seagrass bed was not well understood. The primary reason is few effective tagging methods for mark and recapture studies on small fish exist. I evaluated the usefulness of visible implant elastomer (VIE) for mark and recapture studies on juvenile red drum and performed a preliminary study on the fine-scale movement patterns of red drum within a seagrass bed. I found that VIE is an effective method for marking small red drum that has zero mortality, and there was no effect on growth when marked below the dorsal fin. When red drum were marked and released into a seagrass bed, I was unable to make strong conclusions about post-settlement movements of red drum due to the low recapture rate. I hypothesized that the released red drum would have relatively small movement patterns, however, these results suggest that young red drum have a much greater dispersal potential than previously suspected (Holt et al. 1983), and evaluating movement patterns of young juvenile red drum merits further investigation.

Overall, seagrass beds closest to the inlet appear to be the most important for recruiting juvenile fish and crustaceans. However, larger individuals at increasing distances from an inlet combined with the preliminary results from the fine-scale movement study suggest that some species may have larger dispersal patterns than previously thought. The opening of Packery Channel has allowed new access to habitats in the upper Laguna Madre that were previously inaccessible to newly settling juveniles, potentially boosting fisheries productivity in that area. Further research is necessary to determine the distribution of recruiting fishes and crustaceans as well as to determine their fine-scale movement patterns once they have settled. A better understanding of recruitment patterns of estuarine-dependent species will allow fishery managers to better prioritize and manage estuarine nursery habitats and may lead to more efficient management of these important living resources.

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