DETERMINING MOVEMENT PATTERNS AND HABITAT USE OF BLUE CRABS (*CALLINECTES SAPIDUS* RATHBUN) IN A GEORGIA SALTMARSH ESTUARY WITH THE USE OF ULTRASONIC TELEMETRY AND A GEOGRAPHIC INFORMATION SYSTEM (GIS)

by

AMANDA BRIDGETTE WRONA

(Under the Direction of James T. Hollibaugh)

ABSTRACT

Estuarine habitat in Georgia is under increasing threat of degradation, which can negatively impact ecologically and commercially important species that reside there. Blue crabs (*Callinectes sapidus*) are the second highest valued fishery in Georgia yet little is known about their essential habitat requirements within either subtidal or intertidal areas. Ultrasonic telemetry was used to track 57 crabs, over 4 years, in the Duplin River estuary, near Sapelo Island, GA in order to assess movement patterns and habitat use. Crabs tagged with ultrasonic transmitters ranged in size from 4 to 13.3 cm CW and varied in sex and ontogenetic stage. Crab locations, substrate type, depth, and molting habitat was organized and analyzed within a geographic information system (GIS). Reproductively mature females used the greatest total area 1,052 m^2 on average over 8 days and movement was emigrational at average speeds of 657 m/day out of the estuary into the higher salinity Doboy sound. Male crabs did not, on average, use as large an area 108 m^2 on average over 7 days and movement patterns showed a high degree of meander and retention within the system. Movement speeds averaged 82 m/day. Immature female crabs were intermediate with a larger degree of meander than mature females with average movement speeds of 150 m/day, but used less total area (157 m^2 on average over 8 days). Crabs were tracked going onto and off of the flooded vegetated marsh surface and found on patches of oyster reefs located along edges of the subtidal zone indicating their habitat use. Crabs tagged with specialized molting transmitters were tracked to their molting habitat, which consisted of the vegetated marsh surface. The use of vegetated marsh edge is very important to crabs and was recoded frequently among all sexes and sixes of crabs. The adjacent marsh, therefore, is an essential part of blue crab habitat, it defines the subtidal creek habitat and provides essential habitat for molting crabs.

INDEX WORDS: blue crabs, essential fish habitat, ultrasonic telemetry, Duplin River, GIS, molting habitat, Georgia coast, estuary

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December 2004

DEDICATION

This work is dedicated to my major professor, the late Dr. Richard. G. Wiegert (1932-2002). The first time I met Dick, I was interviewing universities to find a school from which I would earn a master's degree. I walked into his office where he was sitting behind his desk, looking out the window, thinking, as I would find him many times later. We talked about Adrian College (our Alma matter), our home state of Michigan, what we both liked to do there in the winter, what I had been doing with my life up until that moment, and finally what I would like to study if I came to UGA. Out of all of the interviews I had been on for graduate school, Dick was the only professor to ask me what I wanted to study rather than the "how do you fit into my lab" questions that I had been asked by so many other professors. I knew then, that was the beginning of a beautiful relationship. With Dick's wonderful sense of fun, creativity, and intelligence, I completed a master's degree with him and after 2 years in the working world, decided to come back to work with him again for a Ph.D.

Dick was a supporter of all ideas that were creative, unconventional, and sometimes not well thought out, and so supported my ideas to use ultrasonic telemetry with blue crabs in Georgia. Together we wrote a grant proposal and in the process of review were told by the 'experts' that it could not be done. Both he and I took this as a challenge. Dick was never one to say "you can't do that" but would rather watch, and wait to see you learn of your own mistakes. This was his strongest and greatest teaching technique. When we saw how well the telemetry was working we were, I think, both amazed and his encouragement from that point on brought this research to completion.

Dick also recognized how important it was that I satisfied my love of teaching while doing research, and fully supported my teaching in everyway. Dick showed me, by example, that teaching is an integral part of being a scientist.

Dick lived by a sense of ‘work hard, play hard’ standard that I hope I will never lose and in his own words said that “procrastination is a form of genius”, and told me never to get disgusted with my ability to get done in the last minute what took other people days.

I am sorry that he did not live to see the completion of this work. I never doubted for one minute that I would finish, because I know that he felt the same. He was a great teacher and friend. I will miss him always.

ACKNOWLEDGEMENTS

I would like to thank Dr. Tim Hollibaugh who after Dick Wiegert's death, stepped in as my surrogate major advisor. This dissertation is not a reflection of the research that comes out of his lab but rather his willingness to take the time to be a part of this end product and to care about a graduate student during a difficult time. Without his attention to detail and his strong motivating techniques, I may have slipped through the cracks. I would also like to thank my committee members Alice Chalmers, Merryl Alber, Mac Rawson, and Randy Walker who were very helpful with analysis of the data and editing of the dissertation and under the circumstances, took on more than would have normally been asked of them. I would also like to thank Karen Payne for her help and guidance with GIS analysis and for being a great sounding board of ideas. I am so very grateful to Craig Weatherby who I began this learning journey with, for reminding that indeed I was doing science, and for kind words of encouragement when I thought I was going nowhere.

Tom Wolcott inspired me to take his ideas and apply them to my own research and I want to thank him for his help in the design of the 'molting tag'. I would also like to thank Jim Godwin for his help with the design and manufacturing the 'molting tag'.

I would like to thank Georgia Sea Grant for their support in purchasing all of the equipment that was needed for this research, in particular Mac Rawson, for recognizing that I was determined to make it work even when the 'experts' said that it couldn't be done.

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CHAPTER 1

BACKGROUND

The blue crab (*Callinectes sapidus,* Rathbun, 1896) is a dominant resident of estuarine wetlands during most of its life cycle. The life history characteristics of the blue crab are complex, including many life stages, each of which play an important ecological role in the marine ecosystem. As planktonic larvae and post larval form, blue crabs serve as food for many pelagic and benthic invertebrates (Olmi and Lipcius, 1991). In the juvenile stage, blue crabs become an important food source for fish and other adult crabs (Zimmer-Faust and Tamburri, 1994); a significant predator of smaller non-portunid crabs such as *Uca sp*. (Fitz and Wiegert, 1991), and of the invasive zebra mussel, *Dreissena polymorpha,* in brackish estuaries (Molloy et al., 1994). As an adult it is an important predator at or near the top of its food chain, foraging heavily on infaunal invertebrates, juvenile fishes, and other blue crabs. The blue crab's multiple positions in the food web coupled with its high biomass implies that it is important in the trophic structure of estuarine ecosystems (Wrona, 1997).

The blue crab supports a commercially important fishery along the Atlantic and Gulf Coasts. Average reported yearly landings of blue crabs in the South Atlantic region (extending from North Carolina to the tip of Florida) exceed 20,865.2 metric tons. (NMFS Annual Commercial Landings Statistics, 2002). In terms of landings and dockside value on the Atlantic and Gulf of Mexico coasts ($148 million dollars in 2002); it is a larger fishery than those for other Brachyuran species in the United States, second only to snow crabs (Rosenfield, 1998). The Georgia blue crab fishery consists primarily of commercial fishermen who use crab traps (or crab pots) for harvest. Power drawn nets are used for harvest when Georgia sounds are opened for shrimp trawling, however, offshore blue crab catches are considered a minor component of the fishery. Other components include a soft-shell crab industry, and the recreational blue crab fishery that contributes to only a small portion of the total harvest.

Georgia crabbers sell most of their catches to seafood distributors who export them to processing plants in North Carolina and to the live crab market in the Chesapeake Bay area. There are no crab processing plants currently operating in Georgia, and very few are sold locally to restaurants or the public.

The current fishery is regulated by the state of Georgia Department of Natural Resources Coastal Resources Division, under the direction of the Coastal Fisheries Advisory Committee. The Advisory Committee that sets; the size limit of harvestable crabs, and the requirement that escape rings exist on traps to exclude juvenile crabs from harvest. It was also responsible for the implementation of a limited entry fishery that determines who fishes and the number of traps that can be set per fisherman. Recently the Georgia State House of Representatives passed a bill that grants the DNR Commissioner the authority “to close salt waters to blue crab fishing in the event of disasters or environmental extremes”. Within the state’s Coastal Fisheries Advisory Committee resides an advisory panel of selected crab fishermen, representing each county, called the Blue Crab Issues Sub-Committee. This committee functions as a means for the industry to provide direct input into all state blue crab dealings.

In the 1980's, blue crab fishing pressures in Georgia increased when declining catches and habitat degradation in the northeastern U.S. coastal states (primarily the Chesapeake Bay area) resulted in some of those fishermen moving to south to enter the relatively undeveloped Georgia fishery. Along with the increase in fishing pressures, a severe decline in blue crab commercial landings also occurred (Evans, 1998; Rogers and Latham, 1990; Figure 1.1).

More recently, the blue crab fishery has suffered a dramatic decline on the east coast of the U.S., with catch declines in 2000 ranging from 10 to 51% compared to the previous 10 year average (Califf, 2000). In coastal Georgia, yearly landings decreased from 4,218.41 metric tons (9.3 million pounds) in 1995 to 680.39 metric tons (1.5 million pounds) in 2003 (NMFS Annual Commercial Landings Statistics, 2002; GADNR-CRD unpubl. data). In July of 1998, managers of the fishery implemented a limited entry law that restricted new fishermen from entering the Georgia fishery. This controlled access system only allows 180 commercial crab fish licenses to be issued a year and limits the number of traps that each crabber may fish at 200 for each license. Currently all 180 licenses are issued to crab fishermen in Georgia and only 58% of those are actively fishing (GADNR-CRD unpubl. Data, Figure 1.2).

Crabs legal for harvest historically included males 12.7 cm or more measured between the lateral spines (or 'spikes') or carapace width (CW), immature females that measure 7.6 cm CW, and any mature female crab. In 2002, pot trapping of gravid females was banned until July, 2005. In 2004 a ban was placed on the harvest of all mature female crabs in the month of March and on the harvest of any immature female crabs March 1st to March 21st, and the soft-shell shedding industry facilities were prohibited from using female crabs in their peeler operations.

The major problem facing the fishery at present is the reduced number of legal sized crabs. Crab landings and fishery-independent data show that population numbers are the lowest ever recorded (Annual Blue Crab Report, GADNR, 2003). The decline in crabs not only translates into economic loss, but also into loss of livelihood for the crabbers. There has been a distinct change in the sociology of the Georgia blue crab fishery. In 1996, 90% of crabbers surveyed reported crabbing as their only source of income while today many crabbers have one or two additional jobs (D. R. Cooley, 2003).

Major threats to the crab population may include (but are not limited to): over harvesting, increased saline conditions of estuaries (seasonal drought conditions and loss of freshwater seepage), habitat loss (development of the coast), and habitat degradation (pollutants, marsh die back, etc.) and disease. In conjunction with severe drought conditions that occurred in Georgia, a parasitic dinoflagellate, *Hematodinium*, has been found in large numbers of crabs in all five of Georgia's major sounds since 1994 (Messick, 1995; Messick and Shields, 2000; Walker et al., 2002). The Duplin River includes one of only two Hematodinium disease monitoring sites in Georgia, where Hematodinium infection prevalence was as high as 40% in 2002 (Wrona unpbl. data).

To date, efforts to manage the blue crab populations in Georgia have been based on limited historical information and biological research (Evans, 1998). Past efforts have focused mostly on describing and quantifying the blue crab substock, which includes collecting data on distribution, seasonal abundance and size composition.

There are many examples from along the Atlantic and Gulf coast of North America where traditional fisheries models have proven to be insufficient tools for predicting blue crab population dynamics (Jordan, 1998). Schnute and Richards (2001) examined the role and application of mathematical models in fish stock assessment and the reasons why models fail. They suggested that many management scenarios, based on mathematic models, contradict one another and that scientists, therefore, must reach beyond mathematics for a resolution. For example, future management models must include the expansion of the knowledge base about the species by the inclusion of biological as well as population numbers data. Currently, we are far from developing an ecological model of blue crabs because a comprehensive understanding of blue crab biology in Georgia does not exist. Life history characteristics are poorly documented or in some cases not known.

Most of what is known about the life history characteristics and population dynamics of blue crabs comes from systems other than Georgia that have differing physiographic and hydrodynamic characteristics. The coast of Georgia is different from estuaries to the north and south with respect to tidal amplitude (greater), current velocity (greater), and lack of sea grass beds or other submerged aquatic vegetation (Blanton, 1980; Blanton and Atkinson, 1978). Thus data from other areas may not accurately reflect blue crab biology in Georgia estuaries.

What is known about Georgia blue crab life history comes from piecing together information about crabs from those other systems with the limited research that has been conducted in the state (see Fitz and Wiegert, 1992; Wrona, 1997; and Evans 1998). The quantification and description of megalopal recruitment, juvenile recruitment, juvenile and adult growth rates, and use of the intertidal marsh by juvenile blue crabs have been documented in Georgia (Fitz, 1990; Fitz and Wiegert, 1991, Wrona et al., 1995; Wrona, 1997). Traditional fishery dependent sampling observations such as trawl and landings data can be used to describe and quantify the distribution, seasonal abundance, population size, and composition of the substock.

The blue crab life history has been thoroughly described in Virginia, South Carolina, and areas of the Gulf of Mexico (see Darnell, 1959; Hines et al., 1987; Archambault et al., 1990; Lipcius et al., 1990). Both juvenile male and female crabs reside in the salt marshes which serve as a nursery ground for their growth to reproductive maturity. At maturity the crabs mate. Once a female is bearing eggs, it migrates out to the sounds to higher saline waters using ebb-tidal transport. Adult males remain in the estuaries where they continue to grow and mate with other female crabs (Tankersley et al., 1998; Hines et al., 1987; Archambault et al., 1990).

Blue crab larvae, called zoea, develop in high saline coastal shelf water and grow through about 7-8 stages, all of which are no larger than about 3 microns in size, in about 31-49 days. These zoea are truly planktonic, floating in the circulating waters of the continental shelf, feeding on small bacteria and other plankton (Van Engel, 1987; Millikin and Williams, 1984). Little is known about actual locations and quantities or migration patterns of zoea in the coastal shelf waters of Georgia.

After the last zoeal stage, there is one post larval stage wherein the crab is known as a megalopae. At this stage, which lasts from 6-20 days, the crab is about 1-3mm in size. Megalopae work their way into the estuaries via vertical migration into the water column during flooding tides. They feed raptorially on copepod nauplii, dinoflagellates, and other zooplankton and also filter feed cyanobacteria and other particles (Van den Avyle and Fowler, 1989). A blue crab recruitment initiative took place along the Atlantic and Gulf coasts (see Proceedings of the Blue Crab Recruitment Proceedings, 1995) that described settlement processes, larval dispersion, and recruitment studies including recruitment in Georgia (Wrona et al., 1995). Recruitment of megalopae into Georgia estuaries most likely occurs between September through February with major recruitment events occurring in September or October (Wrona, 1997; T.D. Bishop per. comm.).

Once the megalopae enter the estuary and have settled, they go through one molt into the first stage juvenile crab, which is about the same size as the megalopa (3 mm) but morphologically looks similar to an adult crab. This molt occurs soon after settlement, sometimes within less than an hour (per observ.). The juvenile crab will remain in its estuarine nursery habitat to grow (Fitz, 1990; Archambault et al., 1990; Hines et al., 1987; Orth et al., 1996). The small crabs are omnivorous and feed on fish larvae, aquatic plants, and small shellfish (Van den Avyle and Fowler, 1989).

As the crab increases in size, its sex can be easily identified by the triangular (pyramid) shape of the female abdomen, or the elongated ‘Washington monument’ shaped abdomen on the male crab (Williams, 1984). Sex ratios in populations are usually 1:1 (Fitz, 1990). Growth from juvenile to adult crab can vary depending on saline condition or food availability, but is mostly determined by water temperature (warmer waters facilitate shorter intermolt period). Intermolt periods are three to four times longer in the winter than in summer and molting reportedly ceases in water temperatures colder than 13 °C.

Male crabs become mature at about 120 cm in carapace width (CW) around the 11 or 14th molt but may continue to grow and molt an additional 4 to 5 times (Wrona, 1997).

Pre-pubertal females, nearing the next molt in which they will be sexually mature, will migrate from shallow creek habitats of lower salinity to larger creeks and tributaries of the estuary with higher salinity water (Hines et al., 1987). The timing and reason for this migration, caller a peeler run, has not been well studied. In the last intermolt period before reproductive maturity, the female will actively seek out a reproductively mature male, via olfactory and visual cues, and initiate mating behavior once a mature male has been recognized (Prager, 1989). Once a reproductively mature male is encountered, the male will grasp the female and carry that female beneath him, protecting her while she goes through her next molt (Jivoff and Hines, 1998). Immediately after she molts, while the female's carapace is still soft, the male will transmit spermataphores by tube-like pleopods into the female's seminal receptacle. Once the female's shell has hardened they separate.

After mating, inseminated females can retain viable sperm for at least one year. During fertilization the female crab will pass eggs through the seminal vesicle before they are extruded to the female's pleopods (Prager, 1989). As this egg clutch grows in size under the abdomen of the female, it is called a 'sponge' and the crab is called a 'sponge crab'. At this point, sponge females migrate out of the fresher estuarine rivers into more saline waters of the larger sounds or beach fronts where eggs mature. When the eggs mature, the crab larvae hatch out as zoea and are then transferred out to the shelf via exporting currents. After spawning the female remains in the higher salinity waters of the sound or beach area and can produce more egg clutches by insemination from stored sperm. Although it has been thought that reproductively mature females do not molt again (that they are in terminal ecdysis) molting of some mature females has been confirmed.

Males remain in the tidal creeks and rivers continuing to grow, feed, and reproduce during warmer months and move out into the sounds into deeper water to over winter during cold months.

All of these descriptions of life history characteristics could be incorporated into a model of blue crab population dynamics. But other factors such as habitat use, movement patterns, emigration or immigration, and natural mortality rates are still unknown.

The conservation of essential fish habitat is an important component of building and maintaining sustainable fisheries**.** The Federal Magnuson-Stevens Act of 1976 calls for direct action to stop or reverse the loss of fish habitat. Through this act, Congress has mandated the identification of habitats essential to managed species and requires management measures to conserve and enhance them. The Act requires cooperation among federal and state agencies, the fishermen, and others in achieving the goals of habitat protection, conservation, and enhancement of essential fish habitat (EFH). Congress defined essential fish habitat for federally managed fish species as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity." Essential fish habitat may include “aquatic areas historically used by fish where appropriate; substrate includes sediment, hard bottom, structures underlying the waters, and associated biological communities; necessary means the habitat required to support a sustainable fishery and the managed species' contribution to a healthy ecosystem; and spawning, breeding, feeding, or growth to maturity covers a species' full life cycle" (EFH Interim Final Rule, 62 FR 66531). Currently the blue crab is not considered a federally managed species; it does not have a defined Fishery Management Plan (FMP). The Georgia Department of Natural Resources is currently considering the construction of such a plan in which identification of essential habitat for blue crabs will be necessary (GADNR per comm.).

The essential habitat for blue crabs cannot be developed until we have a better understanding of their habitat use and movement patterns. The habitat requirements of adult blue crab populations have traditionally been studied using location data gathered by otter trawls and seines (Archambault et al., 1990, Fitz and Wiegert, 1992; Hines et al., 1987; Orth and van Montfrans, 1987), but these approaches do not provide data on movement patterns of individuals, nor can they sample within the tidal wetland.

It is well known that blue crabs use both the subtidal and intertidal zones of the salt marsh. Fitz and Wiegert (1991) determined blue crab use of the intertidal zone in a Georgia salt marsh by measuring the timing and extent of crab movement and feeding habits within this habitat. Heck and Coen (1995) reviewed habitat use of the subtidal zone in estuaries in Virginia, New Jersey, Alabama, Florida and Texas. These salt marsh systems, however, are very different from those in Georgia, where in particular, high tides and strong currents make sampling with suction and block-nets, common methods used in other estuaries, difficult, if not impossible.

Detailed data on juvenile and adult blue crab emigration, immigration, and free ranging growth rates in Georgia's estuarine habitats have been gathered by mark-recapture studies using internal microwire tags and external tags on adults (Fitz and Wiegert, 1991; 1992; Wrona, 1997). However, neither sampling nor tagging approaches provide the critical information about movement patterns and habitat use, particularly the extent of the subtidal zone used by blue crabs. Due to high turbidity and large amounts of organic compounds in estuarine waters, visibility is poor which makes direct observation of crab behavior in the subtidal zone impossible. When direct observation is not feasible, biotelemetry is a powerful tool to obtain environmental, physiological, and behavioral data on an animal in its natural environment (Kenward, 1987; Wolcott, 1995). Ultrasonic telemetry has been used to study movement patterns in a variety of marine fish (Holland et al., 1993), sharks (Morrissey and Gruber, 1993), and crustaceans (Moran and Thorne, 1973; Hill, 1976; Hernkind, 1980). Recently improved ultrasonic telemetry of free-ranging crabs has provided information on muscle activity, timing of ecdysis habitat selection, and movement in the Chesapeake Bay and North Carolina (Wolcott and Hines, 1989; 1990; Hines et al., 1995).

In order to develop a comprehensive understanding of blue crab population dynamics and habitat utilization, data must be collected that is distributed over a range of differing spatial scales. Measurements such as the specific location of individual crabs, water temperature, depth, salinity, and other habitat characteristics must be stored and organized in a spatial array. A Geographic Information System (GIS) is a tool that has often been used to manage and analyze spatial data. Four major functions of a GIS are input, data storage and retrieval, manipulation and analysis, and output

(DeMers, 1997). Winn et al. (1990) used a GIS to store, manage, and analyze telemetry data from wild turkeys. They found that using a GIS increased the visibility of spatial relationships that would normally have taken longer to recognize. Using a GIS can show locations of crabs by mapping them in their habitat, and it can also help to answer questions such as: how much area do they use, what types of habitats do they use, and how are crabs distributed throughout the estuary with regard to size, sex, and density of individuals.

The primary objectives of this study were 1) to quantify and describe blue crab subtidal habitat use of a Georgia estuary, 2) to quantify and describe movements and habitat use in order to define essential fish habitat for Georgia blue crabs, and 3) to develop a conceptual model of blue crab biology in Georgia that can aid in the management of the fishery. The following factors were tested during the course of the study using ultrasonic biotelemetry:

(1) Whether, and to what extent, salinity, temperature, and seasonality affect subtidal habitat use of blue crabs (migration of *C. sapidus* within and migration out of the subtidal zone, and habitat utilization).

(2) How differences among sexes and ontogenetic (molting) stages influence the movement patterns of and habitat usage by *C. sapidus*.

(3) In the absence of seagrass beds, what do blue crabs use as molting habitat?

The next objective was to take this data and other biological data about Georgia blue crabs and incorporate it into a conceptual description of essential habitat for blue crabs in the Duplin River estuary of Georgia.

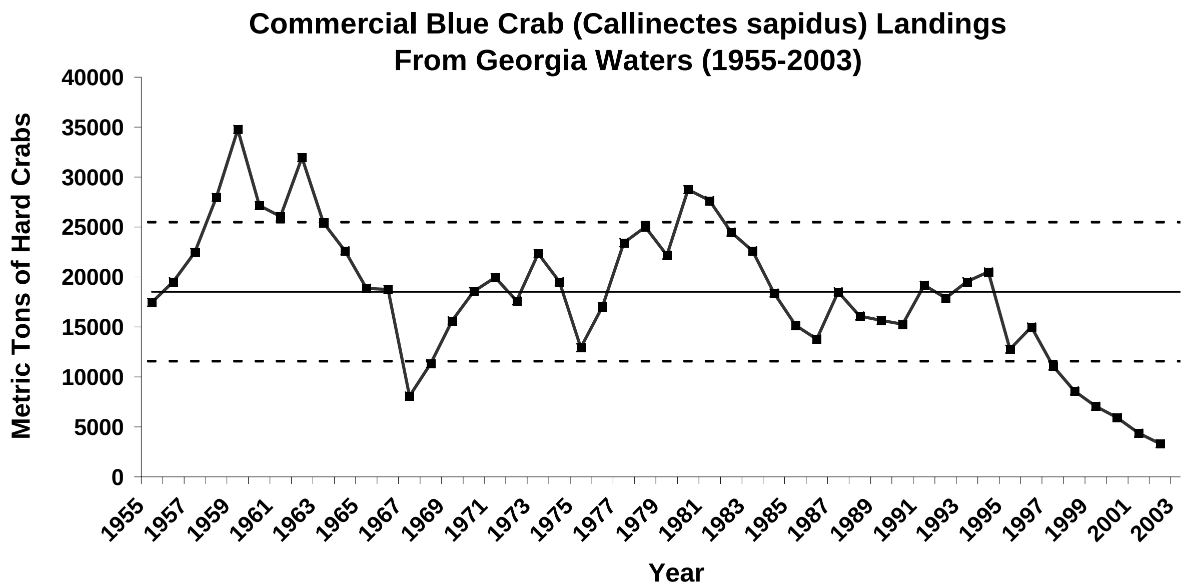


Figure 1.1. Commercial blue crab hard landings from Georgia waters (1955-2003) in metric tons of hard crabs. Solid line represents mean off all landings (all years combined) and dashed lines represent + 1 and - 1 standard deviations of the mean. Data from NMFS Annual Commercial Landings Statistics, 2002.

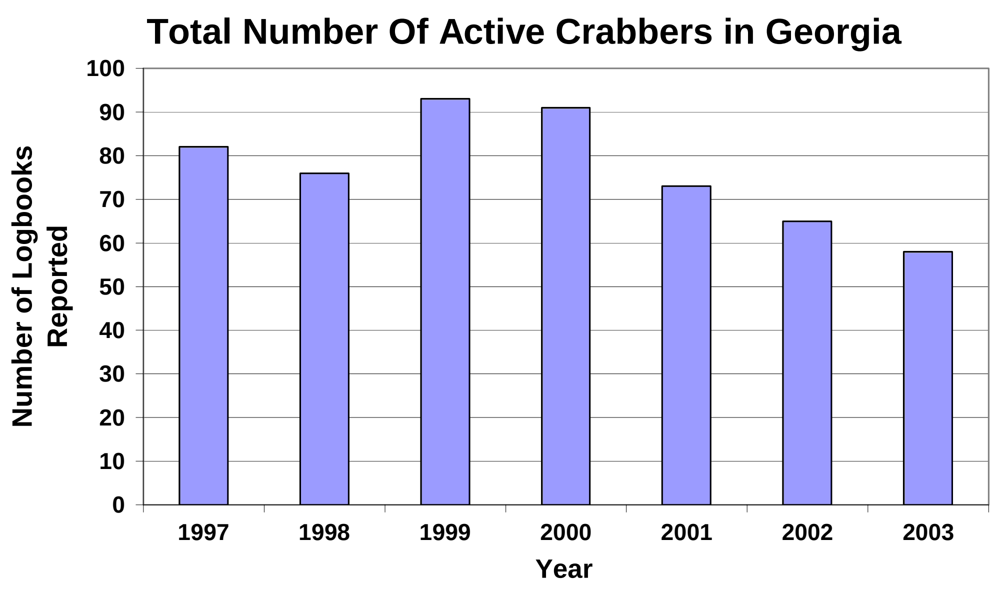


Figure 1.2. Total number of active crabbers in Georgia measured in number of logbooks reported each year from 1997 – 2003.

CHAPTER 2

THE USE OF ULTRASONIC TELEMETRY AND GIS TO DETERMINE MOVEMENT PATTERNS AND HABITAT USE OF BLUE CRABS (*CALLINECTES SAPIDUS*).

Introduction

Telemetry has been used in biological or ecological applications since 1956 when fishery biologists first placed telemetry tags on salmon (Statsko and Pincock, 1977) in order to track their movement up the Columbia River, Washington. Biotelemetry was adapted to terrestrial systems in the 60's, when Eliassen (1960) first described an externally mounted radio frequency transmitter for telemetering heart and wing beats of Mallard ducks (*Anas platyrhynchos*). Shortly after, biotelemetry grew widely in popularity and was a common technique used in wildlife ecology by the mid-1970's (Nielsen, 1992).

Not only can biotelemetry be used to give information about the location of an organism, it can also provide important insight into the behavior, habitat use, and home range of an organism when it cannot be observed directly. New technology has enabled the development of lightweight tags that can provide information on such things as, heart rate, swimming velocity, movement, molting, and tail beats of fish, and can also deliver information about the environment such as water depth, salinity, pH, redox potential, and temperature (Wolcott, 1995).

Biotelemetry typically involves tagging an organism with a small transmitting device that generates an electronic signal. A receiver that can be either manually operated or automated detects the signal. The tag can be physically located by the strength and the direction of the signal, or computerized receivers and recorders in the field can record the location.

The basic tag consists of three major components, a battery, crystal, and a circuit board. The battery provides an electric current that causes a ceramic crystal to vibrate, producing sound waves inaudible to human hearing. The sound can be detected with a hydrophone (another transducer) that sends the signal through a cable connected to a receiver. This receiver translates the signal into a sound audible to human hearing. There are two different types of telemetry tags, radio and ultrasonic. A radio tag produces electromagnetic waves ranging in frequency between 27-300 megahertz (MHz) that are produced by a battery and amplified by the tag's antenna. The signal passes through the antenna and into water or air. The signal can be broadcast over long distances in air with little loss of energy but the electromagnetic waves travel poorly in water and cannot be received by underwater antennae unless they are very close to the transmitter (Statsko and Pincock, 1977). Ultrasonic tags produce acoustic or sound waves with frequencies between 20-300 kilohertz (kHz) that travel easily through water with very little attenuation and can be detected over long distances (Statsko and Pincock, 1977). Because the signal is acoustic and mechanical, rather than electrical, it is not affected by concentrations of dissolved ions and is the only tag that can be used in salt water.

The largest constraining factor in the use of biotelemetry tags is size. In all biotelemetry studies, the effect of the tag on the organism to be observed must be taken into account. Hydrodynamic drag of external transmitters reduces swimming performance (Wilson, et al., 1986) and packaging of the tag should conform closely to the streamline of the body of the organism. The size of the organism and its behavior will dictate the largest tag size that can be used with minimum negative effect. The ideal tag weight for an organism ranges between 10% of the animal's body weight for terrestrial organisms and 2% of the animals wet weight for aquatic organisms (Wolcott, 1995). Effects of tag weight on an animal can differ depending on its life history. In aquatic systems, a lighter tag weight is probably more important for pelagic organisms because a heavier tag would interfere with swimming or buoyancy. A heavier tag could be more tolerable for benthic fish or invertebrates. Since the advent of laptop and hand help computers, circuit boards and processor have become very small and ideal for use in Ultrasonic biotelemetry. Out of the three major components, the battery and the crystal will dictate the size and weight of the tag as well as the duration and frequency of the signal.

High frequencies of ultrasonic waves can be easily absorbed in seawater. Lower frequencies result in a signal that remains strong over long distances and are therefore better for saltwater systems. Tags that emit low frequencies, however, require a large ceramic crystal and a large battery to drive that signal. For example, a 20 kHz frequency tag would require a 4 cm diameter crystal and a tag this size would be too large and heavy to use with fish or invertebrates (Statsko and Pincock, 1977).

The length of time that a tag can emit a signal depends on the power (size and type) of the battery. Tags generally use lithium batteries, which are smaller and last longer than most other battery types.

The range of the tag depends on several factors including, the frequency of the signal, the physical conditions of the water, and other signals detected by the receiver that increase background noise underwater blocking out the sound of the transmitter. There are physical causes of signal attenuation such as rainstorm events and boat traffic or engine noise (per. observ.), as well as biological causes such as algae in suspension (Meister and Laurent, 1960), and submerged aquatic vegetation that trap air bubbles that absorb ultrasonic signals (Wolcott, per. comm.). Other aquatic organisms that produce ultrasonic noise can block out transmitter signals. These include marine mammals and snapping shrimp, both of which are common in estuaries in Georgia. Albers (1965) indicated that noise levels in areas abundant with snapping shrimp could be as high as 25 dB over regular sea state noise.

In addition to minimizing the negative effects of the size and weight of the tag, the process and method of tag attachment to the organism should be considered. In order for the tagging process to be minimally obtrusive, tagging should be quick so the organism can be returned to its natural habitat as soon as possible. There are three major methods of tag attachment in aquatic species, stomach insertion, surgical insertion into the body cavity, and external attachment (Nielson, 1992). For hard-shelled invertebrates the simplest method is external attachment (Wolcott, 1995).

For any type of biotelemetry experiment, once the transmitter is attached it is imperative to observe the tagged animal in the lab where survival and behavior can be monitored for negative effects (Statsko and Pincock, 1977; Kenward, 1987; Nielsen, 1992; Wolcott 1995).

Ultrasonic telemetry has proven to be a useful technique when direct observation is impossible. Several scientific investigations have used ultrasonic telemetry to study emigration and homing in spiny lobsters (Hernkind, 1980), movement tracking of Alaskan king crabs (Monan and Thorne, 1973), movement patterns and habitat utilization of spider crabs in Spain (Gonzalezgurriaran, 1994), foraging behavior (Clarke et al, 2000), agonistic activity (Clarke et al., 1999), and microhabitat of molting blue crabs (Wolcott and Hines, 1990).

There have been several studies conducted using ultrasonic telemetry on the Duplin River, GA. In an unpublished experiment, the effects of environmental conditions on the range and reception of ultrasonic tags was assessed (Cotton, unpbl. data). This study found no significant difference in range reception when the tag was placed in deep (8.8-11.3 m) vs. shallow (0.6-1.5 m) water with the receiver in deep water (4-11.3 m). However, when the receiver was placed in shallow water, there was a significant decrease in the range of reception due to attenuation of signal from surface and bottom reflections. There was also a significant decrease in the range of reception when either the receiver or the tag was placed near a large aggregation of snapping shrimp. The data from this experiment also indicated that tidal flow affected signal reception, with the range of reception of the signal decreasing in the direction of opposite flow.

In a study to measure movements of spotted sea trout (*Cynoscion nebulosus*), 11 fish were surgically tagged and released in the Duplin River (Barbiari and Baribiari, 1999). It was concluded that the telemetry tracking technique was labor intensive and that there was a high loss of tagged fish (only 2 fish were located frequently enough to collect data). For the two fish tracked, one fish stayed in a deep hole over several days and the researchers concluded that it was acting as if injured. In 2001-2002, ultrasonic telemetry was used to track movements of red drum (*Sciaenops oceliatus*) across the marsh surface (Dresser and Kneib unpbl. data). Movement paths measured by ultrasonic telemetry indicated that fish used the marsh surface during high flooding tides. All of these studies indicate that the Duplin River is an acceptable area to use ultrasonic telemetry.

In the summers of 1993-1995, a mark and recapture study was designed to assess growth rates of free ranging blue crabs within the Duplin River, GA. Out of 1,188-tagged crabs, only 28 were recaptured yielding a 2.4% return rate (Wrona, 1997) with tag losses considered negligible. The question then arose, was the loss of crabs due to emigration, predation, or both?

Blue crabs of all sizes are susceptible to predation by other species as well as by other blue crabs. The results of tethering experiments conducted in the field supports the idea of the loss of blue crabs due to predation (Heck and Thoman, 1981 Ruiz et al. 1993) and stomach content analyses indicate that they are highly cannibalistic (Fitz and Wiegert, 1992). Predation from larger conspecifics and fishes has been reported to influence the local distribution and abundance of juvenile blue crabs (Laughlin, 1979; Hines et al., 1987; Orth and Van Montfrans, 1987 and 1990; Thomas et al., 1990;

Williams et al., 1990). It is also known that blue crabs are a very mobile species, capable of traveling long distances (Turner et al., 2003; Hines et al., 1995) suggesting the potential loss of blue crabs due to emigration from the study area.

One of the earliest crab migration studies was done on mature female blue crabs using a mark and recapture technique (using an external tag) in Chincoteague Bay, VA (Cargo, 1958). In this study, the longest time a crab was at large in the field was 305 days and it was recaptured 8 nautical miles from its release site. Other crabs that were at large for fewer days were recaptured as far as 37 nautical miles away from their release site. More recently, blue crabs tracked with ultrasonic transmitters in the estuary of the Rhode River, VA had a mean net distance traveled of 1,390 meters (about 1 nautical mile), mean tracking time was17 days, and moved at speeds in average of 12 meters per hour (Hines et al., 1987).

Blue crabs are a highly motile species and their movement patterns throughout the estuaries, sounds, and coastal shelf waters are related to their life history patterns. Blue crab migration patterns in Georgia are described by anecdotal data from blue crab fishermen that was collected by Rob Cooley (2003). The crabbers description of migration patterns based on their learned knowledge are very similar to known migration patterns documented in scientific literature from other regions such as the Chesapeake Bay. The only other large database of crab migration patterns in Georgia blue crabs comes from the Georgia Department of Natural Resources Coastal Resource Division (DNR-CRD). The DNR-CRD has been conducting trawl survey studies since 1972. Surveys are performed frequently, in some years on a monthly basis but these large-scale surveys measure the size and record the sex of crabs caught over time at set stations in attempts to quantify general population and migration trends. Results from these trawl surveys indicate that the migration patterns are similar to those in South Carolina (Low et al., 1987; Wenner and Read, 1982) but differ from Chesapeake Bay (Land et al., 1996) in that the peeler run (the movement of immature females out of the creeks and into the larger tributaries) in Georgia is earlier in the spring and fall (see chapter 1).

How blue crabs chose and utilize habitat is dependent upon crab size, ontogenetic stage, and what activities the crab is performing such as foraging or mate selection, and behavior. Blue crab habitat may include macroalgae beds, sea grass beds, mud bottomed shallow rivers and creeks, and plants such as *Spartina alterniflora* on the salt marsh proper. Populations of blue crabs are heavily dependent on habitat size (patchiness) and habitat type. Both habitat type and availability (tidal inundation) varies with longitude along the Atlantic coast (Bertness, 2002). In estuaries containing sea grass beds, there is a well-documented dependence on these beds by blue crabs as recruiting megalopae, developing juveniles, molting crabs, and feeding crabs (Wilson et al., 1990). In areas without sea grass, the importance of shallow water habitats is evident as well as the marsh surface in areas where tidal inundation allows access (Zimmerman and Minello, 1984; Mense and Wenner, 1989; Thomas et al., 1990).

Crabs were found as part of the nekton assemblage moving onto the marsh surface with flume weirs (Kneib, 1995). Intertidal salt marsh habitats were used by both juvenile and adult blue crabs. Smaller crabs were more often found farther into the marsh, whereas large crabs occurred near creek bank edges. Migration on and off the marsh surface was studied by mark and recapture techniques using block nets set in marsh drainage creeks to capture crabs leaving the marsh after high tide (Fitz and Wiegert, 1991). Gut content analysis of blue crabs leaving the marsh surface indicated that the intertidal zone was used as a foraging area for natant and resident prey (Fitz and Wiegert, 1991). Blue crab utilization of the subtidal habitats in Georgia is unknown and ultrasonic biotelemetry could be used to better determine habitat use patterns of blue crabs.

Method

Study Site

This study took place in the salt marshes surrounding Sapelo Island, GA (figure 2.1) in the Duplin River (upper and lower), and a tributary of the Duplin, Post Office Creek. The Duplin River (and its associated creeks) is a tidal river located within the Sapelo Island National Estuary Research Reserve (SINERR) and is a relatively pristine and non-perturbed system. Salt marshes in this area are dominated by the cord grass *Spartina alterniflora* and are considered polyhaline. Little direct freshwater input occurrs in these marshes except for local precipitation and run-off from Sapelo Island. Thus the Duplin River estuary is considered an elongated tidal bay. The Duplin River (up to its head water creeks) is approximately 9.44 km in length and at mean low water has an area of 1.66 x 10^6 m^2 (Ragotzkie and Bryson, 1955). The extent of tidal inundation in Georgia estuaries is great (mean tidal range on 2.1 m) and occurs regularly (twice a day), and the vegetated intertidal marsh of the Duplin River estuary is flooded for an average time of 6 to 7 hours a day (Kneib, 1995). Salinity ranges between 17 and 35 psu yearly (data from SINEER monitoring station at Marsh Landing). The major freshwater source is from the Altamaha River, approximately 5 km to the south of Sapelo Island. Two of three deep areas in the river (>9 m in depth) are associated with sharp bends or joining tributaries in the river. The bottoms of these deep spots are hard, course sand. The bottom substrate of the subtidal zone of the Duplin has been described as sand, silt, or mud, with oyster rake near the edges of banks and in smaller creeks (Imberger et al., 1983). Large dead tree and lumber snags occur in the main channel (per. obs). From low tide to about mid-tide level there is an intertidal mud bank zone with no marsh grass (Ragotzkie and Bryson, 1955). This bank zone may be inhabited by oysters in much of the lower one third of the river. Above the intertidal mud bank the tall form of *Spartina alterniflora* dominates up to a level slightly below high tide during neap tides. Beyond this levee is a nearly level plain dominated by the dwarf form of *Spartina alterniflora* much of which is flooded by spring tides but very little of which is flooded by neap tides (Ragotzkie and Bryson, 1955). Maximum rate of tidal transport occurs about 2 hours before high water for either flood or ebb tide and transport is ebb dominated (Ragotzkie and Bryson, 1955). Flooding of the marsh during higher than average tides (such as during a northeastern wind) greatly increases the area inundated by water. A small increase in water (25-50 percent) can result in a 100-400 percent increase in flooded area. There is high turbidity and low visibility within Georgia's tidal rivers and creeks due to rapid mixing and increased current velocities due to strong tidal currents (Ragotzkie and Bryson, 1955). Because of the high turbidity of the Georgia coastal waters, there is no subtidal submerged aquatic vegetation present.

Tagging and Data Collection

The ultrasonic transmitters used in this experiment were designed and built by Sonotronics™. The transmitters used were cylindrical in shape and measured 25 mm in length, 9.5 mm in diameter, and weighed 2.5 g in air. This weight was roughly 5% of the body weight (grams wet weight) of the crabs used in the experiment. These ultrasonic 'pinger' transmitter tags were tested within the Duplin River and had a range of approximately 650 -1000 m at a depth of 1.5 m and salinity of 25 psu which are typical conditions for the Duplin River. The transmitters ranged in frequency between 75 and 78 KHz and were individually coded by sound in order to differentiate among crabs. Before the transmitters were attached to a crab, its claws were secured with rubber bands (figure 2.2a). The tag was attached onto the crab carapace using a monofilament line harness that was tied securely between the longest lateral spines (figure 2.2b). Before release, both the tag and crab were weighed (wet weight), the carapace width (CW) was measured in centimeters length between the notches of the lateral spines, and the sex was recorded. Once the rubber bands were removed from its claws, the crab was released. The crabs were tracked manually in a small boat using a Sonotronic™ ultrasonic hydrophone and receiver. Each tag was individually coded, either by frequency or by the number of pulses it emitted, which allowed the tracking of several individuals in the same area.

Attempts to locate tagged crabs were usually made twice a day, although three crabs were tracked over a 24 hour period. Once located, the crab's position was recorded with a Garmin III™ hand held Geographical Positioning System GPS (capable of accuracy within 10 meters) corrected with a Garmin™ Differential Unit (increasing accuracy to within 1 meter). Depth and substrate type were determined using a small Hummingbird™ sonar 'fish finder'. Soft bottoms like mud and weeds tended to absorb the sonar signal produced by the fish finder whereas hard bottoms such as rock reflected a stronger signal back. These differences in sonar reflections appeared on the fish finder display screen and were used to determine substrate type in deep water. Substrate type in this study was defined as shell, mud, or grass. When in shallow water (<0.3 m) or in grass, substrate type was determined visually and classified as either shell, mud, or grass, and recorded.

In July, 1998, a pilot study was performed to test the tags, tagging methodology, and tracking equipment, and to find suitable study site locations. A total of 8 male crabs of differing sizes were tagged and tracked (table 2.1). Crabs were collected in traps and brought back to the lab to be tagged. Larger crabs were chosen for tagging to ensure that the tag was at most 5% of their wet weight mass. One crab that was only 4 cm CW was tagged with an experimental tag that was smaller than the rest of the tags (that weighed only .5 grams and was 8 mm in diameter, and 25 mm in length). After transmitters were attached, crabs were held in aquaria for 24 hours, with flow through seawater for observation, to test for adverse effects of the tag and to check if the harness was securely attached. They were released into one of two study sites, the upper Duplin River, or the lower Duplin River (figure 2.1).

In July and August 1999, a total of 20 crabs were collected by crab trap or by 4.5 m otter trawl, tagged, and tracked in three areas of the Duplin River (Lower Duplin, Upper Duplin, and Post Office Creek; table 2.2). Larger crabs were again chosen to ensure the tag did not weigh in excess of 5% of the crab's weight.

In this year the methodology was changed so that capture, tagging, and release occurred within the same spot and occurred within minutes.

In the second year of the data collection (June, July, August, and October, 2001 and May 2002), 30 crabs were again collected, tagged, and released as in 1999. Immature crabs were not tagged in May or June because of the lack of immature females in the creeks during this month that were large enough to be tagged. Tagged crabs were tracked over seasons (tables 2.3 & 2.4) and three crabs known to be infected with a parasite (*Hematodinium* sp.) were tracked (results reported elsewhere).

Salinity and temperature data were collected from SINERR and University of Georgia Marine Institute (UGAMI) monitoring stations at Marsh Landing (lower Duplin; figure 2.1). Tide height was taken from NOAA Tide Charts at the Old Tea Kettle Creek, GA station.

Data Analysis

The ArcView Animal Movement extension was used to analyze animal movement patterns. Crab locations were plotted on geo-referenced aerial photographs using ArcView to create maps of crab locations. The Point to Polyline feature was used to determine a straight-line distance between individual crab locations. The sum of these distances were divided by the number of days that the tagged crab was at large to give a net distance traveled per day per crab.

The extension was used to test for randomness between crab locations. Using the spatial test statistic module of the program, random points were generated by the program and a distribution of the test statistic, as generated under the null hypothesis of random distribution, was calculated and compared to observed observations. To perform the test, the user must select the appropriate area to contain the generated random points. Since blue crabs are aquatic species, it was unclear whether or not the test would be biased if salt marsh surfaces were included within the defined study area. It was clear that crabs did not necessarily move among all study sites (i.e. crabs tracked in the Upper Duplin did not travel to Post Office Creek). Therefore three separate areas were delineated: 1) the ‘entire’ area was composed of a polygon drawn around all the portions of Duplin River, Post Office Creek, and Doboy Sound that could be accessed with the sampling boat plus a 1.8 m buffer into the marsh grass where the equipment could pick up a signal at high tide (figure 2.3), 2) a ‘water’ area which composed of all of the water (creeks and rivers) that contained data points plus a 1.8 m buffer (figure 2.3), and 3) sampling sites based on either the ‘water’ study area within the Duplin or the ‘water’ study site within P.O. Creek (figures 2.4 and 2.5). This test was performed for all crabs (the population) and repeated for crabs of different sex and size, and then repeated for different areas, although the water study area (#3) was for analysis with immature female and male crabs only (no mature females were tracked in this area).

ArcView was also used to determine the proportion of habitat type (grass, mud, or oyster shell) available within the study area. Polygon shapes were traced over creek and river areas of digital black and white aerial photographs taken of the Duplin River estuary at low tide in 1992 to represent non-vegetated mud habitat available to crabs. These shapes were then dissolved together to create one polygon shape representing the entire ‘mud’ habitat within the study site. The X-tools extension was used to calculate the area of this polygon. This area was subtracted from the polygon surrounding the ‘entire area’ that was created for the test of random locations (as mentioned above) to get the area of marsh grass available at high tide within the study area. A second method was also used to determine the total grass habitat available to blue crabs at times high enough to flood the marsh surface. Another grass polygon was created by taking the non-vegetated ‘mud’ polygon previously described and adding a 25 m buffer to the inside and outside of the polygon. This buffer distance represents a known distance that large blue crabs are found to migrate into this marsh based on the work by Arnold and Kneib (1983) and Kneib (1995). The ‘mud’ polygon area was then subtracted from the area of the ‘mud and buffer’ polygon to get an estimate of the marsh surface, or grass habitat most likely used by crabs. ArcView coverages of oyster reefs (Cotton et al., 2002) were used to calculate the amount of ‘shell’ habitat available to blue crabs within this study site. Comparisons between the proportions of habitat used vs. available habitat were made to determine if crabs were either choosing habitat or simply found in differential habitat in proportions equal to availability.

Since blue crabs are excellent osmoregulators and their metabolic activities are dependent on water temperature, a regression analysis was used to test the hypotheses that crab movement (movement per day) was independent of salinity and dependent on water temperature. The dependent variable: mean distance per day, did not pass tests for normality or homoskedasticity. A Proc GLM analysis of variance was used to test the hypothesis that there was no difference in crab movements between years (1998, 1999, 2001, and 2002), months (May, June, July, August, October), crab size, and crab ontogenetic stage. Because the data were not normally distributed, the test was run on the ranked values. A Tukey's HSD post hoc test was used to determine which means significantly differed from each other.

Since some crabs were observed in the field longer than others average crab movement over time was examined by plotting average distance traveled per day over days tracked. A proc GLM Analysis of Variance was run to test the hypothesis that there was no difference in movement between days tracked and between sexes.

Lunar phases were taken from NOAA tide and lunar tables (US Dept. of Commerce, NOAA, 1998, 1999, 2001, 2002). The lunar calendar (based on 28 days) begins with lunar day 1 occurring on the first day of the new moon. Lunar quarters were defined as first quarter or new moon (lunar days 26 to 30 and 1 to 4), second quarter (lunar days 5 to 11), full moon or third quarter (lunar days 12 to 18), and fourth quarter (lunar days 19 to 25). A Proc GLM Analysis of Variance run on ranked values was used to test the hypothesis that there was no difference in movement between lunar quarters for each ontogenetic stage and between lunar days.

Results

A total of 57 crabs were tracked during the 4-year study. Crabs were tracked on average every 12 hours over an average of 9 days with the longest crab tracked for 41 days. Two crabs were not found within 12 hours of release and were removed form the data set and not reported. Three crabs (two immature and one mature female) that were tracked less than 1 day are reported but were removed from the data set before analysis. Due to navigational obstructions in South End and Dean's Creek, tracking proved to be impracticable. Three male crabs released there in 1998 were only located after one day and then lost therefore their location data are not included in analysis but are reported (Table 2.1). Out of the total crabs tracked, 14 were reproductively mature females tracked an average of 8 days (range 4-16 d), 12 were reproductively immature females tracked an average of 8 days (range 1-20 d), and 32 were males of varying size and ontogenetic stage tracked an average of 7 days (range 1-18 d) . The 11 male crabs with molting transmitters were not used in analysis until Chapter 3 (see tables 2.2-2.4). Eight crab transmitters (4 from immature females and 4 from males) no longer attached to crabs were found in the marsh grass on levees.

Movement

Nearest neighbor analysis indicated a tendency towards clumping rather than random distribution for all crabs regardless of sex, location, or study area (table 2.5) indicating site fidelity to areas within or near creeks and rivers within the study site.

Crab movement was defined as the distance a crab travels (in meters) normalized to the number of days over which the crab was tracked in the field. Proc GLM analysis indicated that there were significant differences in movement over time and between sexes (table 2.6). On average, mature females traveled significantly greater distances (657 m/day) than male (82 m/day) and immature female crabs (150 m/day; $p<.05$; figure 2.6). Mature females averaged considerably shorter distances as time of tracking continued except on day one after release where the average distance traveled was only an average of 41 m/day (figure 2.7). In this study in the Duplin River estuary, the length of time that the mature females were tracked was limited by the amount of time before the crab and tag reached the deeper and vaster waters of the sound where the signal was lost. One crab that was lost in the sound was found by a crabber who captured it in a trap. He then moved the crab back into the Duplin River estuary so that it could be relocated during the study. The movement of the crab back into the estuary was not of its own accord and therefore, this crab was not used in the analysis. Immature females traveled greater distances than males although the means were not significantly different. Both immature female and male crabs averaged greater movements (average distances traveled per day) early during tracking (figures 2.8 and 2.9).

Crabs were tracked in the months of May (2002), June (2001 and 2002), July (all years), August (1998, 1999, 2001), and October (2002). One mature female crab that was tagged in October (2002), was found two months later by a commercial crabber. Crab movement did not vary between months sampled but did vary between crabs of differing ontogenetic stage (figure 2.10). GLM analysis of variance indicated that there was no significant difference in distance per day between months (p=.07) between years (p=.06) and size (p=.45). There was a significant difference in movement between crabs of different sexes (p=.0025). All stages of crabs (male, immature female, and mature female) moved greatest distances in July. Males traveled the shortest distances in June, and immature and mature female crabs traveled shortest distances in October.

Visual inspection of maps of crab locations indicate that mature females were moving with migrational patterns (moving long distances in a constant direction over short periods of time), typically out of the Duplin River and its tributaries and into Doboy Sound (see figures 2.11 and 2.12). Immature females showed a semi-migratory pattern in their movement but at a finer scale than mature females (figures 2.13 and 2.14), moving out of creeks and into the main channel of the Duplin River. Male crabs did not show an overall migration pattern (figures 2.15 and 2.16) and appeared to exhibit some degree of site fidelity over the time they were tracked, their locations appear visually clumped within small areas.

GLM analysis of variance results indicated that there was no significant difference in daily crab movements among lunar quarters (table 2.7) There were, however, significant differences between lunar days ($p<.028$) A plot of daily movement patterns of all crabs vs. lunar days indicate that in general crabs move larger distances near the new and full moon during higher tidal amplitudes and stronger currents (figure 2.17). These differences were also significant between sexes ($p<.001$; table 2.7). Daily distances traveled by both mature female and male crabs were greatest just after new and full moons (figure 2.18, 2.20). Whereas those movements of immature females increased near full moons (figure 2.19).

Salinities ranged between 20.8 psu (recorded in May 2002) and 33.4 psu (recorded in October, 2002) during the study. There was no obvious relationship between salinity and crab movement. Temperatures ranged between 17.5 to 31.9 °C with the coldest temperatures occurring in October and the warmest occurring in July. Crabs moved most at temperatures ranging from 28-31°C. There was a significant positive relationship between movement and temperature ($p = .0014$; figure 2.21).

Habitat Use

Habitat use was evaluated based on observations of depth, and substrate type associated with each location in which a crab was observed. Crabs were found at water depths that ranged from .5 to 46 meters, but most crabs were located in shallow water depths. The largest number of crab depths recorded was .6 meters of water (figure 2.22). There was no clear relationship between water depth and crab size (figure 2.22). Crabs greater than 8 cm CW in size were found at depths ranging from 0.5 to 46 m. Crabs in the 7 cm size class were found only in shallow water from 0.5 to 5 m in depth. There were different patterns in depth utilization among ontogenetic stages (figure 2.23). Male and immature female crabs were found more often in shallow water habitat. Mature female crabs and reproductively mature female crabs were found in depths greater than 24 meters.

Total subtidal mud habitat available within the Duplin River estuary study site estimated by GIS analysis was 295.455 hectares. Total grass habitat available at high tide was calculated at 812.915 hectares. Total subtidal oyster reef or shell habitat was calculated at 4.355 hectares (figure 2.24a). The grass habitat area calculated by adding a 25 m buffer to the 'mud' polygon was 759.305 which represented a 4% decrease in grass habitat when compared to the first method of determining available grass habitat. Crabs in this study were found more frequently on mud and grass habitat (62% and 24% respectively) than shell or sand (14%) (figure 2.24b). Crabs used habitat in different proportions depending on ontogenetic stage. Mature female crabs were found more often in mud habitat (51%), than on grass (19%) or shell (30%; figure 2.24c). Immature female crabs were found most often on mud (68%) than on grass (25%) or shell (7%; figure 2.24e). Male crabs were also found more often on mud (59%), but a greater proportion was found on grass (28%) than on shell (13%; figure 2.24d). All crabs were found on mud and shell habitat in greater proportion than what was available to them. Mature female crabs were found on shell habitat 30%, males 13% and immature females 7% of the time.

Crabs were found multiple times in commercial crab traps during tracking. The number and placement of commercial crab traps in the Duplin River in July of 1999 were mapped and shown in figure 2.25. A total of 138 traps were in the Duplin River and P.O. creek although about 1% of those traps are reported as not fished (J. Karwacki, crabber, pers. comm.) A total of 13 tagged crabs were found in crap traps, 8 of which were found only once, one crab twice, one crab three times, two crabs six times, and one crab 10 times.

One unexpected result from this study was the recovery of several telemetry tags. One tag was recovered from a dead crab found in a crab pot, while 6 transmitters were recovered from the surface of the marsh (mostly on top of or directly behind vegetated levees). Upon recovery, the tags and harness were undamaged and reused on other crabs.

Discussion

This is the first study to describe detailed blue crab movement patterns and habitat use in Georgia using ultrasonic telemetry. Blue crab movements have been well described with tag and recapture data collected in estuaries other than Georgia. Other blue crab movements were studied with ultrasonic tracking in the Chesapeake and are used here to make comparisons between the two systems (Hines et al., 1987; 1995; Hines and Ruiz, 1995; Ruiz et al., 1993; Tankersley et al., 1989; Turner et al., 2003).

Use of GIS as an analysis tool for telemetry data

Positional data sets generated during telemetry studies can be large, and may contain spatial patterns difficult to discern without spatial analysis tools. A GIS system is a tool specifically designed to manage and analyze spatial data. GIS can show locations of crabs by mapping them in their habitat. GIS was also used in this analysis to answer the questions of: how much and what types of habitats did crabs use, and how are they distributed throughout the estuary with regard to size, sex, and seasonality. Through mapping locations and nearest neighbor analysis, movement and spatial patterns of clumping were easily determined. With the use of GIS, we were able to organize a large data set of georefferenced positions and habitat parameters in a simple way that facilitated easy retrieval for analysis.

Movements and Migration

Crab movement cannot be determined by trapping data alone. Generalizations about migration or habitat use from trapping data can only give information about a crab that visited that trap or area. Recording not only places that a crab visits, or revisits, but also the duration of time that a crab resides there can tell you more about habitat use, or the importance of that visited place than trapping data alone can reveal. Speed or direction of movement can be easily measured with telemetry and reveal the importance of location or extent of habitat use.

Telemetry studies done on blue crabs in the Chesapeake and on spider crabs in Spain (Hines et al., 1995) indicated that crabs exhibit two basic types of movements; slow meandering within a limited area, and rapid directional movements. Movement can be classified into two types. The first is recorded at a fine time scale (daily) and is usually the result of foraging, predator avoidance, or mate selection. The second type of movement is recorded over larger time scales (weeks, months, or years) is considered migrational or dispersal movement (Kenward, 1987).

Energetic costs of movement are high, and animals have reasons to move whether it be to search for food, to select mates, or to avoid predators. Animal movements that are highly clustered can indicate foraging, mate selection, or other needs such as refuge from predation. There was a migrational component to crab movement that was reflected in crabs differing in ontogenetic stages. Mature female crabs migrated significantly larger distances than their immature female or male counterparts.

Female crabs in their pubertal molt stage migrate towards higher salinity water for egg development (Williams, 1984). Once this fertilized female has reached the oceanic water in open sounds or offshore barrier islands, eggs are hatched out in the spring and summer where their larvae are in optimal conditions (temperature and salinity) for development and at a time when food sources for plankton are increased (Hines et al., 1995). Cargo (1958) was the first to describe the migration of mature female blue crabs using a mark and recapture method and found that they were capable of migrating very large distances (60 nautical miles over 109 days). Turner et al., 2003) using telemetry and external tagging methods in the Chesapeake Bay found that post-mating females migrated out of the estuaries in October and spawned the following season.

It is also interesting and ecologically important to examine what these crabs did before they left, for example what type of habitat they used and the speed at which they left the estuary. Turner et al., (2003) found that reproductively mature, post-copulatory females in the upper Chesapeake Bay foraged at high rates, alternating between meandering and direct movement in the areas in which they mated. After weeks to months of this behavior they migrated out of the bay in October. These researchers concluded that after molting to maturity, female blue crabs must acquire energy (through foraging) for oogenesis and for migration to high salinity spawning habitat. They also concluded that in comparison to male crabs in their study, females must allocate more energy into their reproductive tissues than did males.

Although tracking data in this study was limited to only the spring, summer, and fall seasons, the data do support this trend in mature female migration pattern out of the estuary for reproduction. Mature females moved out of the Duplin River sometimes with surprising speed. For example one female crab moved from the upper reaches of the Duplin River out to Doboy Sound (approximately 11.5 km in only 6 days). Mature female crabs moved longer distances overall and made larger small scale (daily) movements than their counterparts. These larger movements were made mostly around the new moon and full moon indicating that the females utilize faster moving water currents associated with spring tides. The use of tidal currents as a transport mechanism is evident in blue crabs as early as the post larval megalopae stage of development (Olmi, 1994). Megalopae migrate to surface waters on flood tides for tidal transport into estuaries after developing on the coastal shelf. Hench et al. (unpubl. data) found that in waters where gravid females are found, female crabs migrate to the surface waters at night at ebb tide and subsequently remain on the bottom during flood tide. The authors suggest that this behavior facilitates the release of larvae into waters where they can be transported offshore for development. This tidal stream migration pattern that the female crabs exhibited in situ continues when the crabs are held in tanks in the laboratory, even in the absence of flowing water the vertical migration was unaffected by the light dark cycle, indicating that ebb-tide transport can also occur during the day (Forward and Cohen, 2003).

Carr et al., (2003) used ultrasonic transmitters to follow 10 ovigerous crabs from lower salinity estuaries to high salinity regions to release their eggs. Crabs exhibited a vertical migration pattern consistent with ebb-tidal transport which the authors describes as a “hopping” behavior in which the migrating crabs alternated between rapid transport in the water column and remaining stationary at the bottom.

In this study, large-scale movements indicative of migration were not obvious in tagged male crabs. Male crab movements were characterized by short total distances traveled, and short successive distances moved between observations. Male crab locations were statistically and visually tightly clumped indicating the dominance of daily maintenance activity or habitat use rather than migration or dispersal movements in their life cycle. Male crab activity (movement measured as distances traveled per day) appears to be only somewhat related to lunar day. There were no large moves made surrounding full or new moons indicating that they do not migrate or move using ebb flowing tidal currents and are retained within the estuary. Male crabs may be displaced locally during high spring tides although they probably do not utilize the currents to migrate out of the estuary like their mature female counterparts.

There may be physiological benefits to male crabs remaining within the estuary where the crabs spend more time in less saline waters which can result in faster growth rates. De Fur et al., (1988) found that crabs grown in lower salinity areas had larger size increments with each molt when compared with crabs grown in higher salinity areas. Since maturing females are also found in the estuary, male crabs may have increased reproduction potential due to being always near to maturing females in the nursery habitat.

Even in October as water temperatures fell, males remained within the Duplin River estuary. Crabbers who work within this study area reported that while they continue to work over winter months, they catch only males. They will move their pots off of the banks and into deeper water within the river where the male crabs are congregated. Ultrasonic tracking during these months would be useful to investigate whether the male crabs are permanently retained within one estuary during their entire lifetime or move between adjacent estuaries during winter or spring months.

In the Chesapeake Bay, male crabs will migrate only when winter water temperatures at all depths begin to get cold (Ruiz et al., 1993). There, blue crabs migrate into winter cold water refuges free from ice, but do not move far from the nursery, seeking deep channels within the estuary (Millikin and Williams, 1984; Schafer and Diaz, 1988; Hines et al., 1995). Since Georgia waters never freeze, blue crabs can remain active within the estuaries.

Immature female crab movement can be characterized as intermediary between male and mature female movement. Observations made during this study indicated that immature female crabs moved out of the Duplin River and Post Office Creek, but did not migrate in the same intensity of speed as the mature females. Movements of immature females were similar to male movement, which possibly reflects the importance of the close proximity of males and females that are close to their pubertal molt. In the Rhode River sub-estuary of the Chesapeake Bay, Shirley et al., (1990) examined the selective pressures that most likely influence the distribution of pre-pubertal females and found that females attract more mates when in rivers than creeks. They concluded that habitat use by immature females is less influenced by predation escape and more influenced by the likelihood that they will encounter a mate. The size of some of the immature females tagged in this study (8 to11 cm CW), suggested that the pubertal molt could likely be the next molt. While they were being tracked they may have been actively seeking a large male to protect and subsequently fertilize them. The highest activity rates (movements per hour) occurred near the full moon when higher velocity tidal currents occur. These currents could transport immature females out of their nursery tidal creeks and into larger tributaries, to places where there are higher concentration of males, or to start their migration seaward before their pubertal molt. Since tags do not interfere with reproduction (Hines et al., 1987), it is possible that some of the immature female movement may have been the result of the male crab carrying the female rather than the immature female crab moving on its own.

In this study, one immature female (8.84 cm CW) was tagged when soft indicating that it had recently molted. The crab was then tracked for 20 days until the tag only was found indicating that the crab had molted (see chapter 3 for discussion). This female was tracked though one cycle of ecdysis and was constantly meandering out of the nursery habitat seaward towards higher saline waters.

In this study there was no evidence to suggest that daily movement patterns either increased or decreased due to the direct effects of water salinity. The blue crab is found in a wide range of salinities over its entire life (Williams, 1984). Although larvae require salinities <20 psu, as the crabs grow they are increasingly euryhaline (Van den Avyle and Fowler, 1989). Juveniles and adults occupy habitats ranging from freshwater to hyper-saline waters. As blue crabs develop, their efficiency at osmoregulation increases from not at all (larvae cannot withstand any freshwater) to excellent (large males found up-river in near fresh water conditions). In the Duplin River estuary, salinity generally varies little from salinities in the Doboy Sound and distribution of crabs were better explained by ontogenetic stage. In Galveston Bay, TX, Zimmerman et al., (1990) concluded that blue crab distributions were not directly affected by salinity gradients. In their study, crab distribution was best explained by the distribution of their prey which was directly influenced by salinity. Based on trawl data within the Charleston Harbor, SC estuary, Archambault et al., (1990) showed that small crabs preferred low salinity areas and migrated to higher salinity areas as they grow. Migration towards the harbor in mature females coincided with their reproductive development and egg brooding. Males also migrated towards the harbor but this movement was attributed to seasonal changes in water temperatures rather than salinity (Archambault et al., 1990).

Overall crab movement did not vary between months but was significantly different between months when classified by sex. There is high activity (larger movements) for males, immature and mature females occurring in July, which coincided with warmer water temperatures. Movement of females (mature and immature) significantly decreased in October when water temperatures fell below 24 °C. Crabs in Georgia continue to feed and grow in the winter months (Oct. through Feb.) as evidenced by laboratory growth studies (Wrona, 1997). The migration or location of crabs in winter was not determined in this study. One mature female crab tagged in October (2001) was found in December (2001) by a crab fisherman, and was moving landward in Doboy sound (figure 2.10). That female did not have an egg mass when tagged and was reported as not having eggs when it was found. Within those two months in cold water temperature, that female probably did not spawn and may have been delaying the development of her eggs until conditions were right to begin egg development. Turner et al., (2003) suggested that even though mature females migrate out of the upper Chesapeake Bay in October, they probably do not spawn until the season after mating. After releasing their eggs, it is unknown whether all females remain off shore or if some return to the estuary. Hench et al. (unpubl. data) found that there was no evidence to support the migration of adult females back into the estuary. They found no reversal of tidal stream transport migration behavior exhibited by mature females after egg release. Further tracking of mature females in open sounds would be beneficial in determining the fate of female blue crabs.

The frequency with which blue crabs return to the same intertidal site was measured by Fitz and Wiegert (1991) using mark and recapture techniques in an intertidal marsh impoundment adjacent to Sapelo Island, GA. Out of 107 tagged crabs, 28 returned once, 7 returned twice, 5 returned 3 times, 2 returned 4 times and 2 crabs returned five times to the same marsh area. These returns occurred soon after release and 85% of returns occurred within 20 tides. They concluded that blue crabs are a possible vector of carbon transport from the intertidal area to the surrounding subtidal areas while the results from this tracking study suggests that female blue crabs are a potential transport of carbon out of the estuary while males remain within the estuary and are probably not a vector of carbon transport out of the system.

Habitat Use

Habitat use is a critical facet in the study of life history or population dynamics of any organism. Habitat provides food and refuge essential for organisms to survive. Kenward (1987) identified important issues in investigating the relationship between habitat and organisms as: 1) what is the availability of habitat to the organism, 2) what is the preference and degree of utilization of the habitat, and 3) which habitat types are critical for the population to survive?

Habitats and refugea that have been identified as important to blue crabs include submerged aquatic vegetation such as seagrass beds, macroalgae, macrophytes, and shallow water (see Wilson et al., 1990). These habitats and habitat availability (tidal inundation) varies longitudinally among estuaries. The estuaries in Georgia are among the most extensive on the U.S east coast and have a large diurnal tidal amplitude (1.5 to 3 m) that inundate the marsh twice daily.

Georgia's blue crab habitat is unique because of the absence of subtidal seagrass beds, which are considered to be important habitats for blue crabs in many other locations (Hovel and Lipcius, 2002; Heck and Coen, 1995; Orth and Van Montfrans, 1990). Fitz and Wiegert (1991) examined the use of the marsh surface by blue crabs in Georgia. This study examined the habitat use of blue crabs within the subtidal zone and therefore adds to the earlier Georgia study in an attempt to describe the total habitat use within the estuary.

In the Duplin River estuary, crabs partition their habitat use by sex and ontogenetic stage. The main subtidal habitats that are available to blue crabs in the Duplin including mud, usually associated with deeper water channels, and oyster reefs, that are usually associated with shallow creeks or edge of main channels. Since the marsh is also inundated with water twice a day for significant portions of time, *Spartina alterniflora* marsh grass is also available habitat for blue crabs. Results from this experiment show that blue crabs were selecting mud habitat in greater proportion than what was calculated as available. This is not surprising since blue crabs are aquatic species and the marsh surface or grass habitat is only available to them a small proportion of the time. Oyster reefs in this estuary are submerged a majority of the tidal cycle and crabs were selecting them in greater proportion than what was available to them indicating their importance as a habitat type in this estuary.

Depth

In other estuaries devoid of submerged aquatic vegetation, water depth is considered an important habitat for blue crabs. Wilson et al., (1990) also suggests that macro algae (such as *Ulva* sp.) and shallow water marsh creeks are essential habitat for juvenile crabs. In the Duplin River, the macroalgae *Ulva* sp. is only found in the winter months when water temperatures are cold and water turbidity is low (pers. obs.).

There was no obvious pattern in depth utilization by blue crabs based on size classes except for the smallest size class of crab (7.0 cm) was found only in depths less than 1.2 meters. The size classes of crab that were tracked were very similar to one another and the assignment into size groups is arbitrary. The important variable to examine with depth utilization is ontogenetic stage. Mature females were found using deeper water habitat than immature female and male crabs. Mature female crabs were the only crabs found in water greater than 6.5 meters deep. This reflects their migration out of the estuary into the deeper, Doboy Sound. Mature females utilized some shallow water habitats, but mostly that shallow water habitat was located atf the edge of the main channel.

Immature female crabs were found in shallow water habitats, rarely greater than 3 m deep, and male crabs were found most often in waters less than 0.5 m deep. When comparing mapped locations of observations, males and immature female crabs were using the same shallow water habitats in a similar way. At shallow depths, crabs were either using tidal creeks, or the edge of the main river channels. In the upper Duplin, where male and immature female crabs were located, the depth of the river rarely exceeds 4 m at high tide. In areas of the river where crabs appeared to be in the middle of the channel, many were on sand or mud bars located near the mouth of small creeks or river bends where sediment accumulates and is shallow.

Male blue crabs are frequently found in shallow water creeks in the Rhode River estuary, VA which, like the Duplin River estuary, is devoid of sea grasses. Because crabs do not have access to submerged aquatic vegetation or marsh grasses, they use these shallow areas as a molting refuge (Hines et al., 1987). Other reasons that crabs congregate in shallow water include responses to deep-water hypoxia (Loesch, 1973).

Substrate Use

The use of substrate types by blue crabs reflects their distribution in the marsh. These choices are based on life stage survival strategies and refuge from molting but can also give insight into how crabs forage for food. Zimmerman, et al. (1990) found that the distribution of crabs in a Texas sub-estuary was best explained by the distribution of their prey.

A large proportion of the blue crab's diet is composed of clams, mussels, and oysters (Hines, et al., 1990), while other common prey items include gastropods, fish, and other crustaceans (Fitz and Wiegert, 1991).

Hard clams (*Mercenaria mercenaria*) and American Oysters (*Crassostrea virginica*) are found within the Duplin River. Hard clams are infaunal bivalves found in a variety of sub-tidal salt marshes (Micheli, 1997). American oysters occur along the lower intertidal edge of the salt marsh (Peterson and Peterson, 1979).

In the Rhode River estuary, crabs aggregate and feed within patchy food resources (clams) and once on a patch, they remain there consuming multiple prey items (Wolcott and Hines, 1989). Oyster reefs are also habitat for common prey items of blue crabs (Fitz and Wiegert, 1991). Substrate use based on crab aggregated locations in this study possibly indicates that crab movements are heavily dependent on foraging activity. All crabs in this study were found multiple times on oyster reefs and mature female crabs were commonly found on oyster reefs and in crab traps indicating that they continue to forage during their migration out of the sound.

Many of the crabs that were tracked in this study, regardless of ontogenetic stage, frequented the marsh edge and marsh surface when it was flooded at higher tides. Fifteen out of 20 males and 8 out of 10 immature females were located multiple times within grass habitat. Immature female crabs and male crabs used the marsh surface more than oyster reefs (as there was more grass habitat available) but used oyster reefs in a greater proportion than what was available (12.5 and 7.3% vs. 0.4%

respectively). Mature females (only 5 out of 13 crabs) were found infrequently in marsh grass habitat. They were found more often on shell habitat and in a greater proportion than was available to them. This substrate selection by the mature female crabs could indicate that their foraging strategy is more dependent on oyster reefs than the marsh surface.

Previous studies in this estuary indicated that blue crabs do move onto and utilize the marsh surface at high tide (Fitz and Wiegert, 1991; Kneib, 1995). Blue crabs also play a key role in the structuring of shallow water and estuarine communities (Kneib, 1995) indicating their frequent presence within these habitats. In salt marshes in Louisiana, tidal inundations of the saltmarsh can range between 0 – 54.0 cm deep on a neap high tide allowing access to blue crabs. Small juvenile blue crabs occurred within the intertidal marsh as far as 40 meters in from the creek edge, demonstrating their use of the interior marsh. Larger crabs were found closest to the creek edge (Peterson and Turner, 1994). In this study, it is not clear how far onto the marsh surface crabs traveled due to the loss of attenuation of the ultrasonic signal within the flooded marsh grass. Blue crabs in Georgia have access to large areas of marsh surface due to the large tidal amplitudes. Access, however, may be restricted by the amount of time that the marsh is inundated, and by their body size (larger crabs are restricted to greater depths than their smaller counterparts). Comparisons of blue crabs collected in flume weir nets in the Duplin River at 5 vs. 25 meters into the marsh interior showed that larger blue crabs are restricted mostly to marsh edge (Kneib, 1995). Determining available grass habitat based on these findings overestimated the available grass habitat by only 4% in both the Duplin River and Post Office Creek study sites. It is interesting to note how accurate the search area that could be reached by boat represented the most likely areas that the crabs would have been using.

One unexpected result from this study was the recovery of several telemetry tags on the marsh surface. There are two ways that the tag could have ended up on the marsh. The crab wearing the transmitter could have died and been eaten (leaving the tag behind) or, the crab wearing the tag could have molted, leaving the tag and exoskeleton behind.

Higher predation rates have been associated with small blue crabs in sea grass beds due to cannibalism (Heck and Coen, 1995). However, tethering experiments on blue crabs have shown that predation rates on large crabs (like the ones used in this experiment) are low unless the crab was in a pre-molt or soft stage (Hines and Ruiz, 1995). From these results the question arises, did blue crabs in this experiment use the marsh surface as molting habitat?

Ultrasonic telemetry has been proven to be an effective tool for documenting movement patterns of blue crabs within the Duplin River estuary. Mapping and defining essential habitat, and developing a conceptual model of blue crab utilization of the Georgia salt marsh will provide necessary information to help fishery biologists manage a sustainable blue crab fishery in Georgia. This data could also lead to the design of a simulation model to determine the effects of physical factors (tidal inundation, salinity gradients, diel period, landscape complexity), biological factors (density, sex, ontogenetic stage), and fishing pressures on spatial requirements and density distribution of crabs.

Table 2.1. Male crabs tagged with ultrasonic transmitters used in pilot study during July-August, 1998. Crabs were measured in centimeters carapace width (cmCW). Dates (MM-DD) represent the first day of release and last day of tracking. Days at large represents the total number of days the crab was tracked.

Crab ID	***Sex***	***Size (cmCW)***	***Location***	***Date Start***	***Date End***	***Days at large***	***Distance (m) moved/day***
Crab 1	m	10.6	Upper Duplin	07-04	07-06	3	1026
Crab 2	m	11.5	Upper Duplin	07-04	07-12	9	71
Crab 3	m	10.3	Upper Duplin	07-18	07-27	10	14
Crab 4	m	10.3	Upper Duplin	07-18	08-02	16	204
Crab 5	m	11	South End Creek	08-04	08-04	1	86
Crab 7	m	10.9	South End Creek	08-06	08-07	2	234
Crab 8	m	4.0	Dean Creek	08-06	08-07	2	125

Table 2.2. Crabs tagged with ultrasonic transmitters July-August, 1999. Sex is denoted as immature female f(i), mature female f(m) or male (m). Dates (MM-DD) represent the first day of release and last day of tracking. Days at large represent the total number of days the crab was tracked.

Crab ID	***Sex***	***Size (cmCW)***	***Location***	***Date Start***	***Date End***	***Days at large***	***Distance (m) moved/day***
357	m	10.7	Post Office Creek	07-04	07-15	12	116
366-1	m	10.2	Post Office Creek	07-04	07-21	18	174
348-1	f(i)	9.64	Post Office Creek	07-05	07-07	3	72
249	m	9.62	Post Office Creek	07-05	07-16	12	81
267	f(m)	10.3	Post Office Creek	07-05	07-20	16	469
339	f(i)	8.84	upper Duplin	07-06	07-26	20	65
258-1	f(i)	8.5	upper Duplin	07-06	07-11	6	200
555	f(m)	10.5	upper Duplin	07-06	07-14	9	301
447-1	f(m)	10.3	Duplin	07-06	07-12	7	2938
456-1	f(m)	11.5	Post Office Creek	07-07	07-07	1	0
348-2	m	8.9	upper Duplin	07-08	07-25	18	66
285	f(m)	10.0	Duplin	07-19	07-25	4	1364
384	m	7.6	Post Office Creek	07-20	07-25	6	133
276	m	7.1	Post Office Creek	07-20	07-28	7	78
446	f(i)	8.5	Post Office Creek	07-20	07-20	1	0
294-1	f(m)	12.2	Duplin	07-21	07-24	6	823
258-2	f(m)	10.5	Duplin	07-21	08-01	12	578
336-2	f(m)	9.9	Duplin	07-22	08-01	11	494
294-2	f(m)	10.00	Duplin	07-24	07-29	10	645
348-3	m	11.4	upper Duplin	07-25	08-01	8	230

Table 2.3. Crabs tagged with ultrasonic transmitters June-October, 2001. Sex is denoted as immature female f(i), mature female f(m) or male (m). Dates (MM-DD) represent the first day of release and last day of tracking. Days at large represent the total number of days the crab was tracked.

Crab ID	***Sex***	***Size (cmCW)***	***Location***	***Date Start***	***Date End***	***Days at large***	***Distance (m) moved/day***
5677-1	f(i)	11.2	Duplin	06-03	06-12	10	262
4555	f(m)	10.9	Post Office Creek	06-06	06-09	4	696
5566-1	m	9.8	Post Office Creek	06-04	06-09	6	33
345	f(i)	8.1	Post Office Creek	07-21	07-21	1	52
5566-2	f(i)	9.2	Post Office Creek	07-28	08-11	15	124
337	f(i)	8.3	Upper Duplin	07-28	08-09	13	720
5677-2	f(i)	9.2	Post Office Creek	07-28	08-08	12	94
456-2	f(i)	9.2	Post Office Creek	07-31	08-08	9	76
246	f(i)	10.5	Post Office Creek	10-21	10-31	11	37
355	f(i)	9.3	Post Office Creek	10-21	10-31	11	24
336	f(m)	11.2	Duplin	10-24	12-04	41	168
234	m	12.3	Duplin	10-24	10-31	8	80
256	f(m)	13.0	Duplin	10-25	10-30	6	55
447-2	m	13.3	Duplin	10-25	10-31	7	47

Table 2.4. Crabs tagged with ultrasonic transmitters May-August, 2002. Sex is denoted as immature female f(i), mature female f(m) or male (m). Dates (MM-DD) represent the first day of release and last day of tracking. Days at large represent the total number of days the crab was tracked. A crab ID of C# represents a crab tagged with a molting tag (discussed in Chapter 3).

Crab ID	***Sex***	***Size (cmCW)***	***Location***	***Date Start***	***Date End***	***Days At large***	***Distance (m) moved/day***
234-02	f(m)	11.9	Duplin	05-12	05-23	12	234
345-02	m	10.6	Duplin	05-12	05-24	13	81
333	m	11.1	Duplin	05-14	05-24	11	47
335	m	9.0	Upper Duplin	05-15	05-27	13	54
444	f(m)	10.3	Duplin	05-16	05-27	11	170
C1	m	10.7	Post Office Creek	06-18	07-01	14	63
C2	m	11.5	Post Office Creek	06-18	06-24	7	72
C3	m	11.2	Post Office Creek	06-19	07-09	16	72
C4	m	13.1	Post Office Creek	07-01	07-02	2	35
C5	m	10.1	Post Office Creek	07-09	07-11	3	67
C6	m	12.2	Post Office Creek	07-09	07-26	18	80
C7	m	10.4	Post Office Creek	07-19	07-20	2	13
C8	m	11.1	Post Office Creek	07-21	07-22	2	14
C9	m	10.3	Post Office Creek	07-24	07-30	7	73
C10	m	11.1	Post Office Creek	07-26	07-28	3	22
C11	m	9.5	Post Office Creek	07-29	08-01	4	6

Table 2.5. Results of nearest neighbor analysis testing on all crabs, crabs of varying ontogenetic stages, and varying sizes of study areas. The entire area is that which includes all of the Duplin River, Post Office Creek, and Doboy Sound that could be accessed with the sampling boat plus a 1.8m buffer into the marsh grass where the equipment could pick up a signal at high tide. The water (Duplin) area is that which includes all of the water (creeks and rivers) that contained data points plus a 1.8m buffer within the Duplin River and the water (Post Office Creek) area is that which includes all of the water (creeks) that contained data points plus a 1.8 m buffer within Post Office creek for analysis with immature female and male crabs only (no mature females were tracked in this area).

Site	***Area (m^2)***	***Crab Sex***	***R value***	***[z] value***	***Non-Random***
Entire	18,753,320	All crabs	0.26	39.8	**Yes**
water (Duplin)	4,032,723	All crabs	0.56	23.4	**Yes**
Entire	18,753,320	Mature Female	0.57	9.2	**Yes**
Water (Duplin)	4,032,723	Mature Female	0.69	8.6	**Yes**
water (upper Duplin)	505,935	Immature Female	0.60	6.7	**Yes**
water (Post Office Creek)	171,969	Immature Female	0.69	8.6	**yes**
water (Duplin)	4,032,723	Male	0.32	18.9	**Yes**
water (Post Office Creek)	171,969	Male	0.80	5.7	**yes**

Table 2.6. Proc GLM analysis of variance results of tests for significant differences in crab movement over time and between ontogenetic sexes.

Source	***F value***	***P<***
Day tracked	0.86	0.03
Sex	4.83	0.001

Table 2.7. Proc GLM analysis of variance on ranked values was used to test for significant differences in crab movement per day between lunar quarters, lunar days, and sexes.

Source	***F value***	***P<***
Lunar Quarter	0.86	0.46
Lunar Day	4.83	0.028
Sex	11.17	0.001

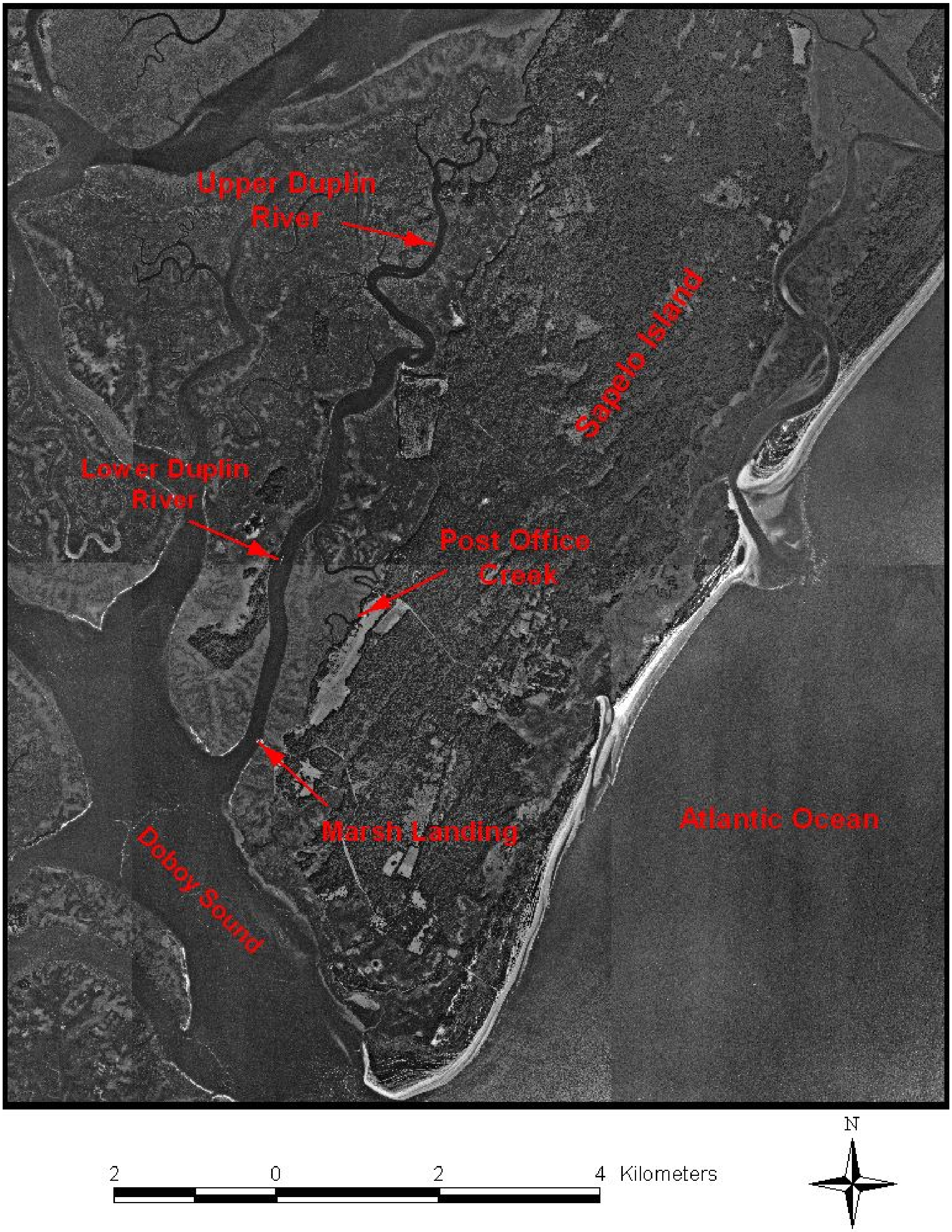


Figure 2.1. Satellite Image of the Duplin River estuary of Sapelo Island, GA. Weather monitoring station is at Marsh Landing.

(a)

(b)

Figure 2.2. Securing the claws with rubber bands (a) Attachment of ultrasonic transmitter to a blue crab with monofilament line (b).

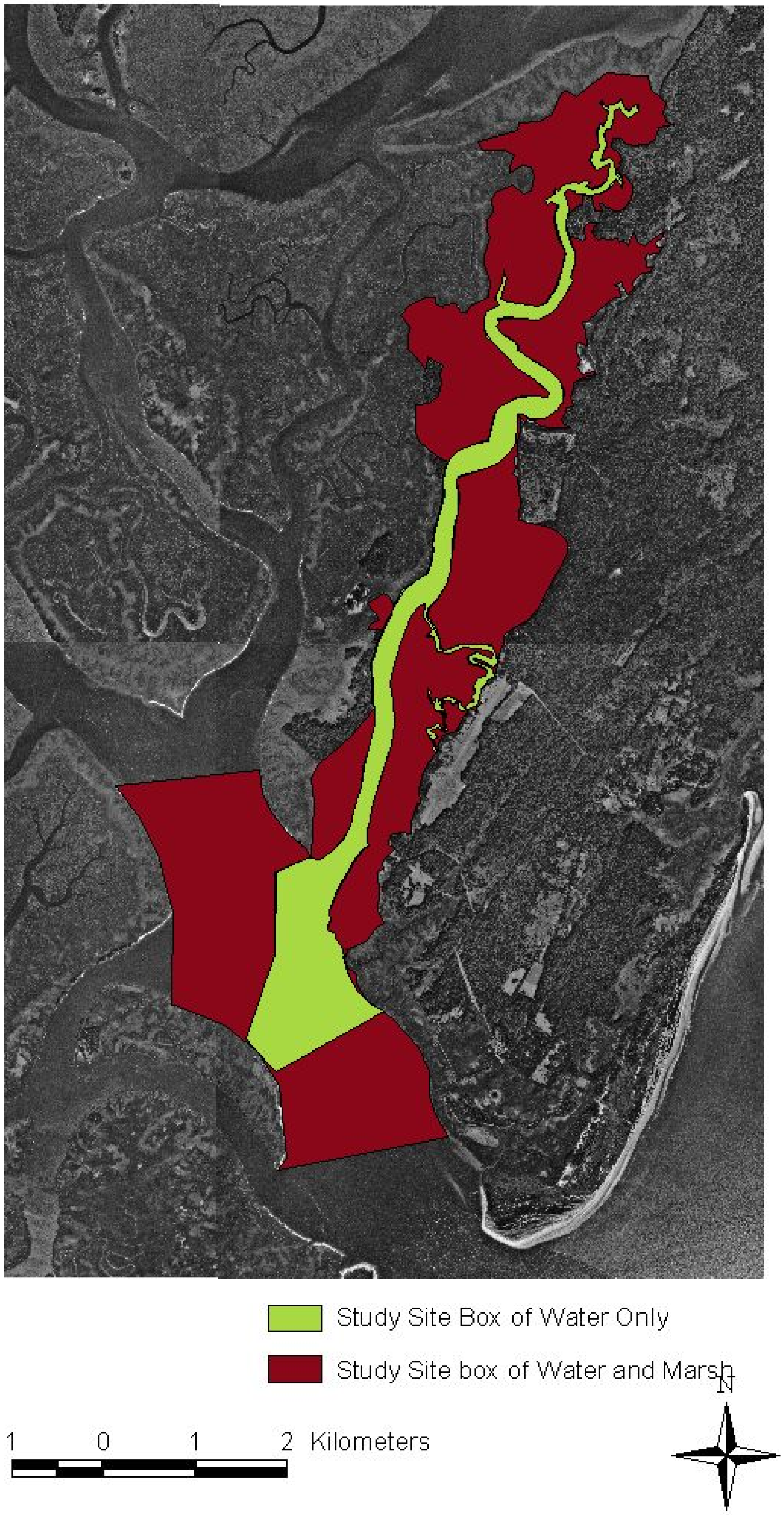


Figure 2.3. Map of area used for nearest neighbor analysis. Colored boxes indicates the area delineated around the Duplin River, Post Office Creek, and Doboy Sound that was accessed with the sampling boat and a 1.8 m buffer into the marsh grass where the equipment could pick up the telemetry signal at high tide.

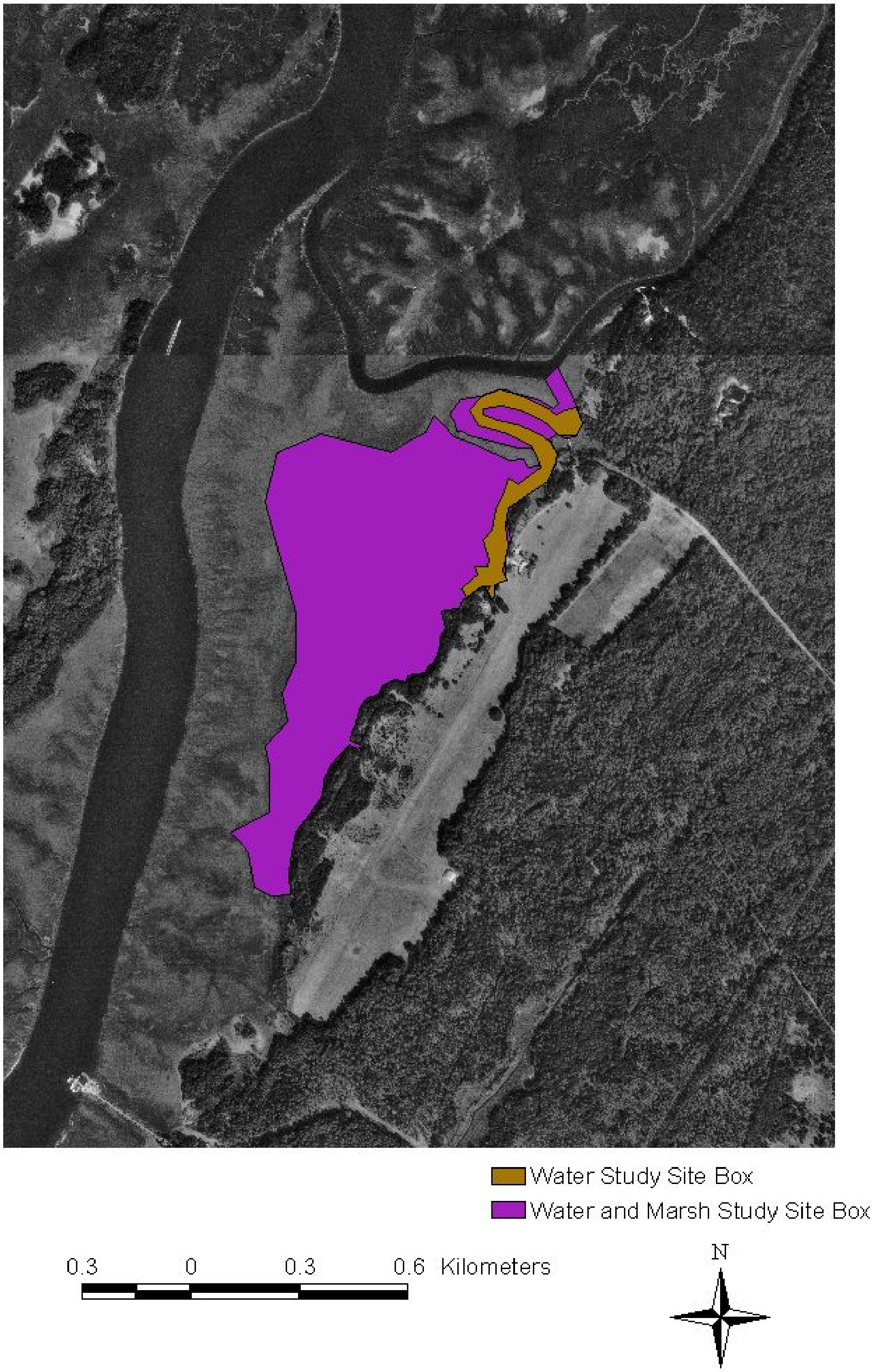


Figure 2.4. Map of Post Office Creek area used for nearest neighbor analysis. Colored box indicates the area delineated around the creeks and rivers of Post Office Creek that contained data points and a 1.8 m buffer into the marsh grass where the equipment could pick up the telemetry signal at high tide.

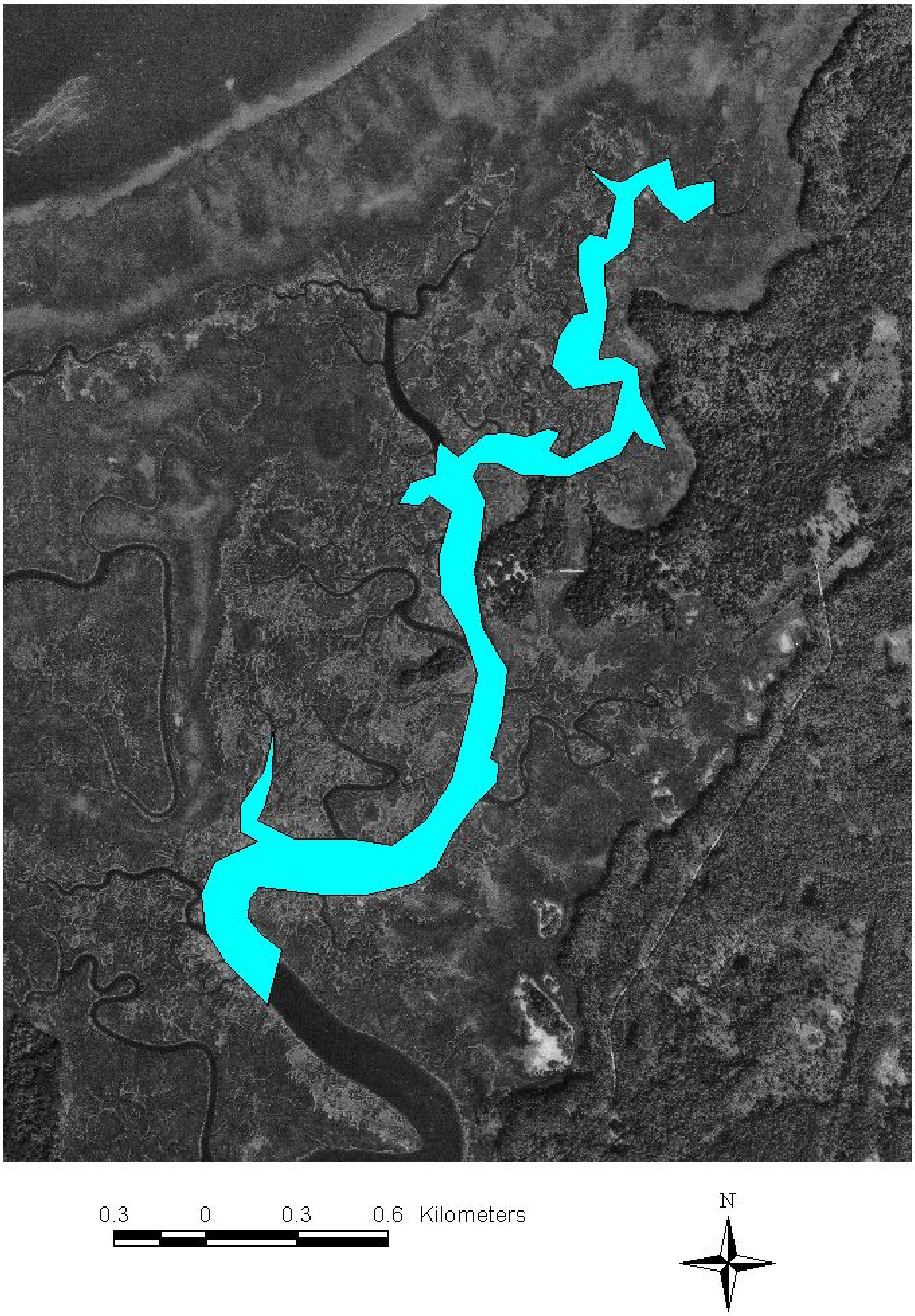


Figure 2.5. Map of area used for nearest neighbor analysis for immature female and male crabs only in the Upper Duplin River. Colored box indicates the area delineated around the Upper Duplin River that contained data points and was accessed with the sampling boat and a 1.8 m buffer into the marsh grass where the equipment could pick up the telemetry signal at high tide.

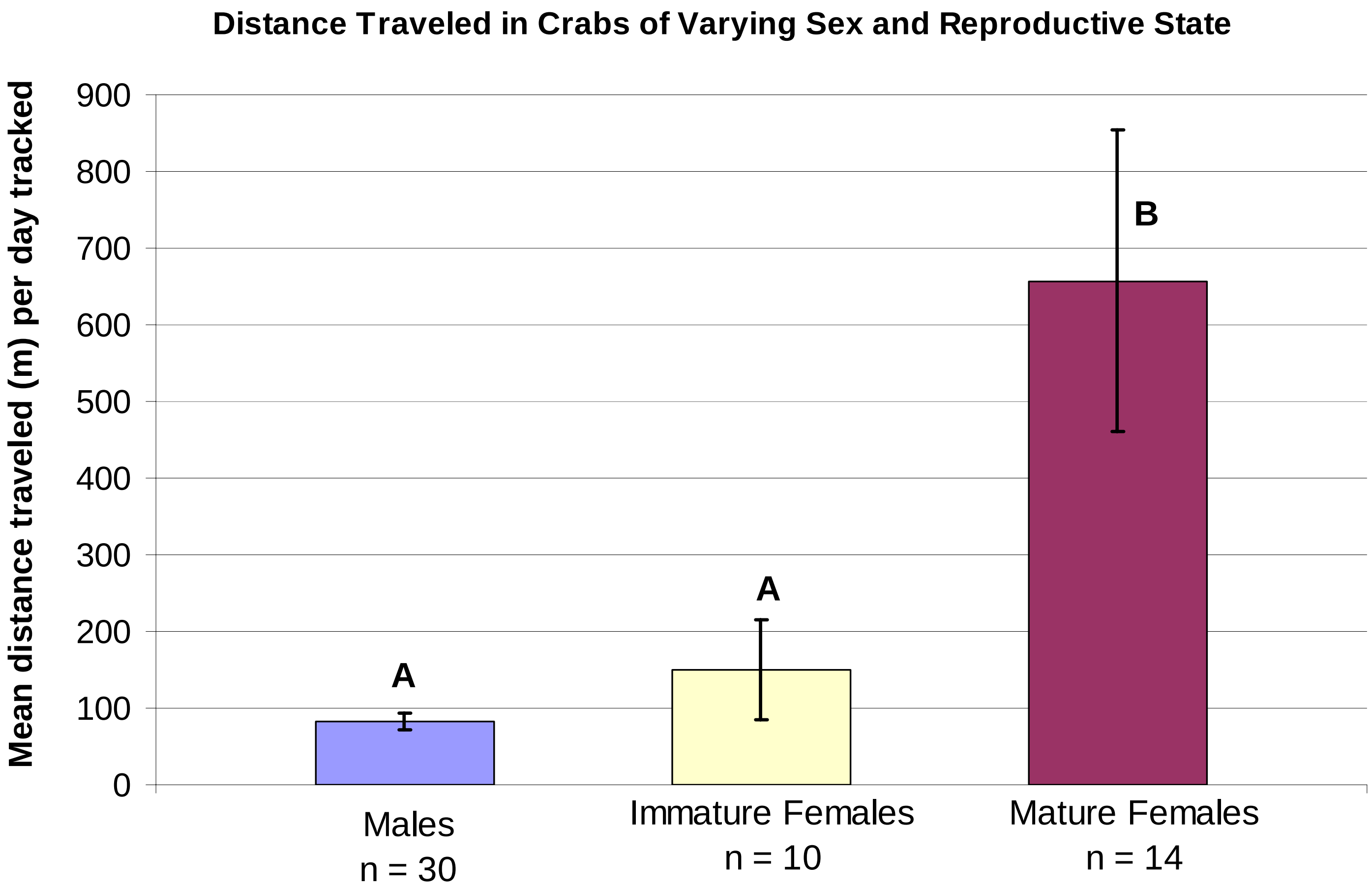


Figure 2.6. Mean distance traveled (m) per day by blue crabs of varying sex and reproductive state, all years combined. Black bars represent standard deviation around the mean. N= number of crabs. Bars with different letters represent significant differences (p<.01).

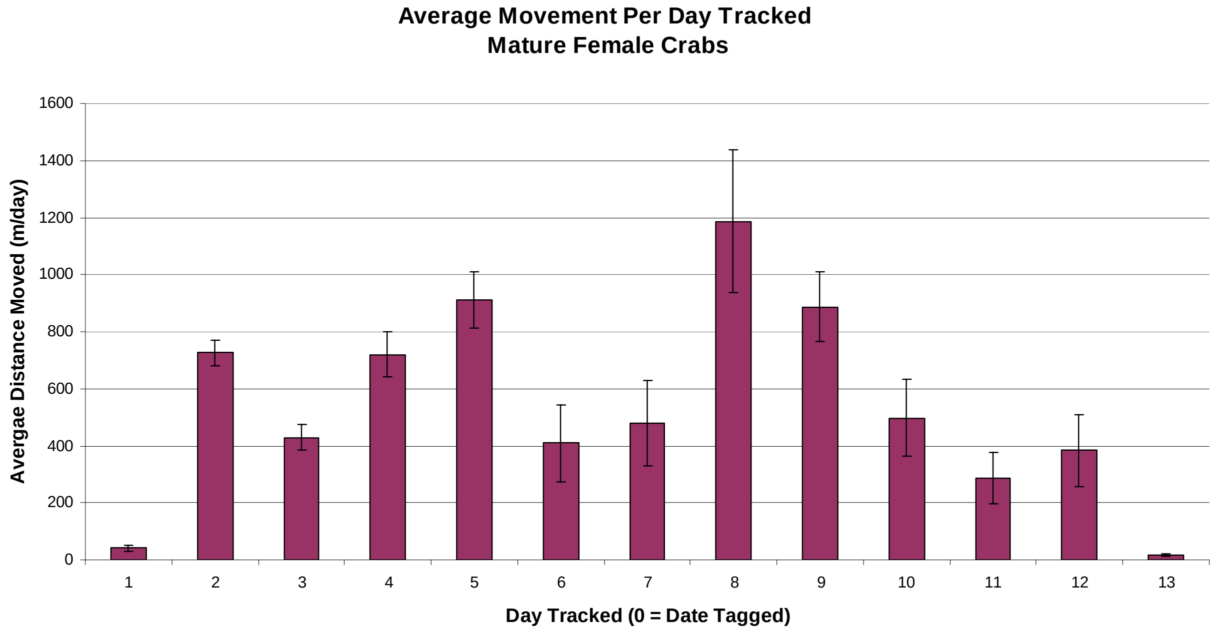


Figure 2.7. Plot of movements of all female reproductively mature blue crabs (*Callinectes sapidus*) combined measured in average distance (m) moved per day over time with standard error bars.

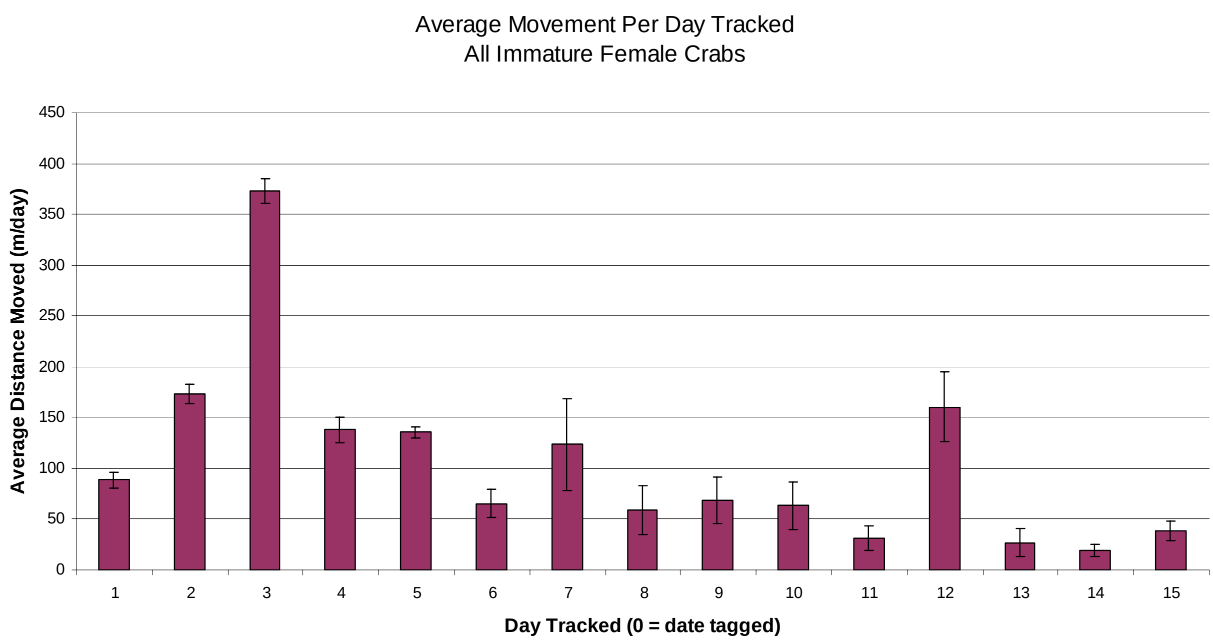


Figure 2.8. Plot of movements of all female reproductively immature blue crabs (*Callinectes sapidus*) combined measured in average distance (m) moved per day over time with standard error bar.

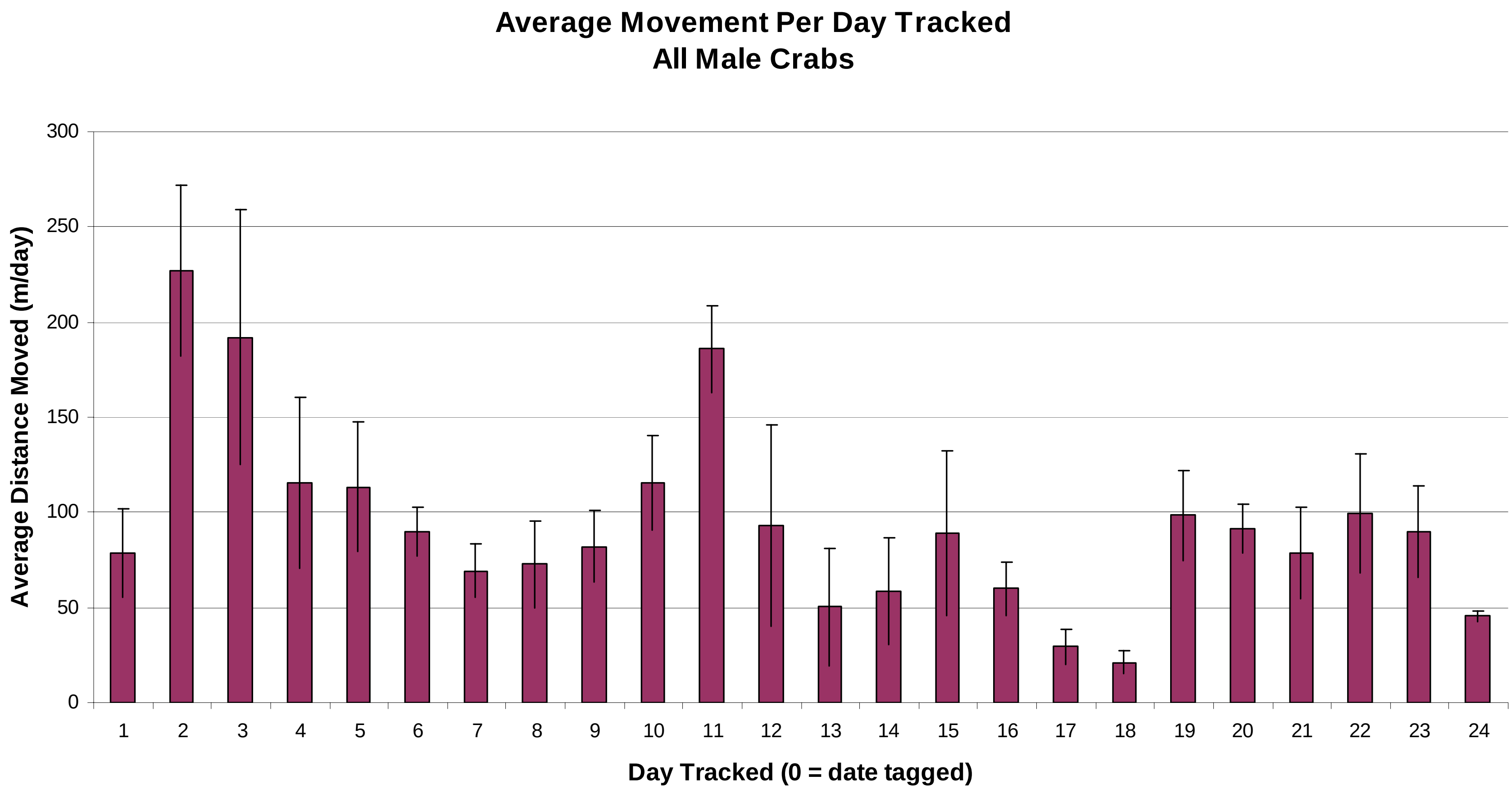


Figure 2.9. Plot of movements of all male blue crabs (*Callinectes sapidus*) combined measured in average distance (m) moved per day over time with standard error bars.

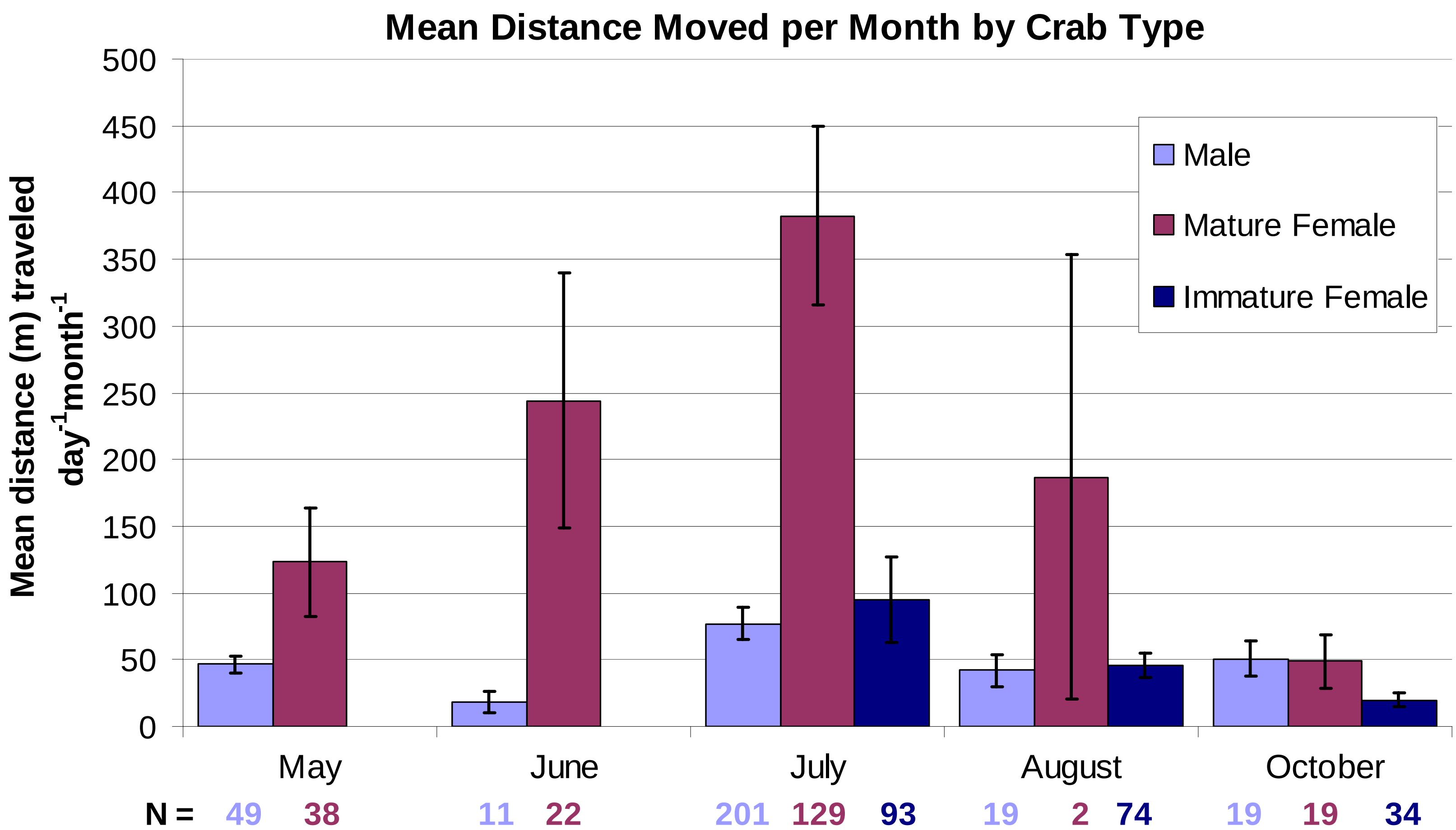


Figure 2.10. Average distance of blue crab movement (m) per day by month and ontogenetic stage, all years combined, with standard error bars.

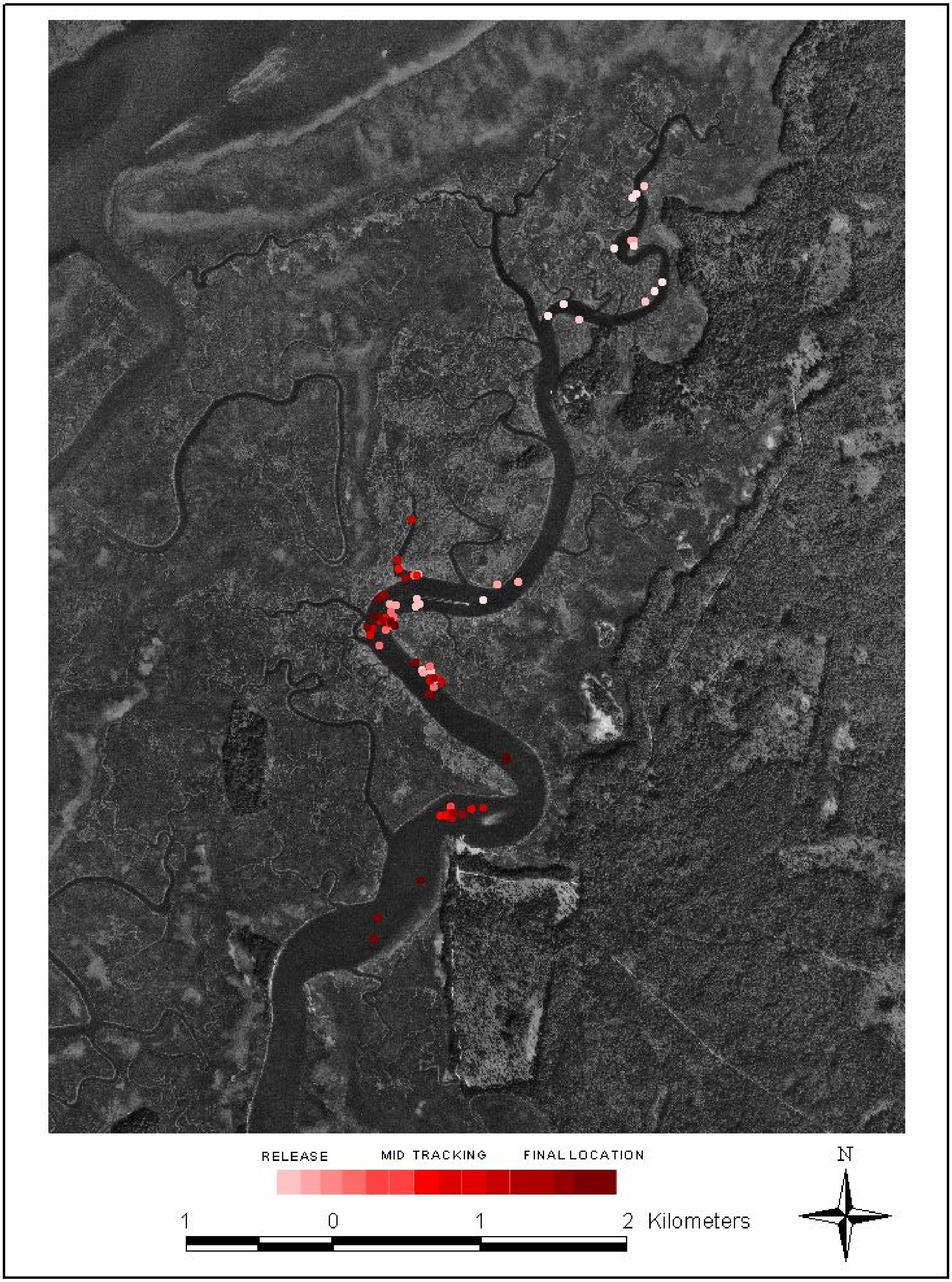


Figure 2.11. Map showing migration of tagged mature female blue crabs out of the upper Duplin River (all years combined).

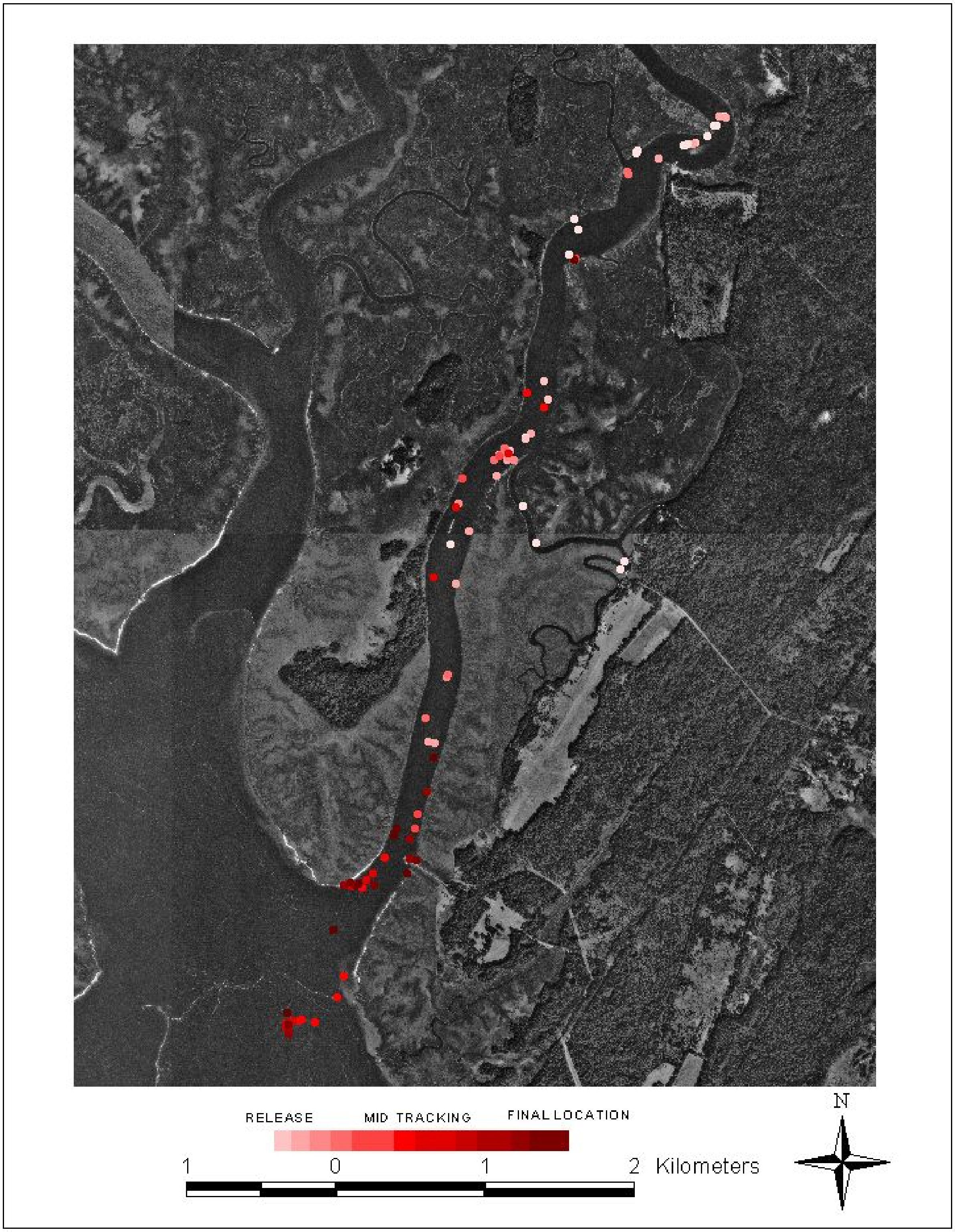


Figure 2.12. Map showing migration of tagged mature female blue crabs out of the lower Duplin River (all years combined).

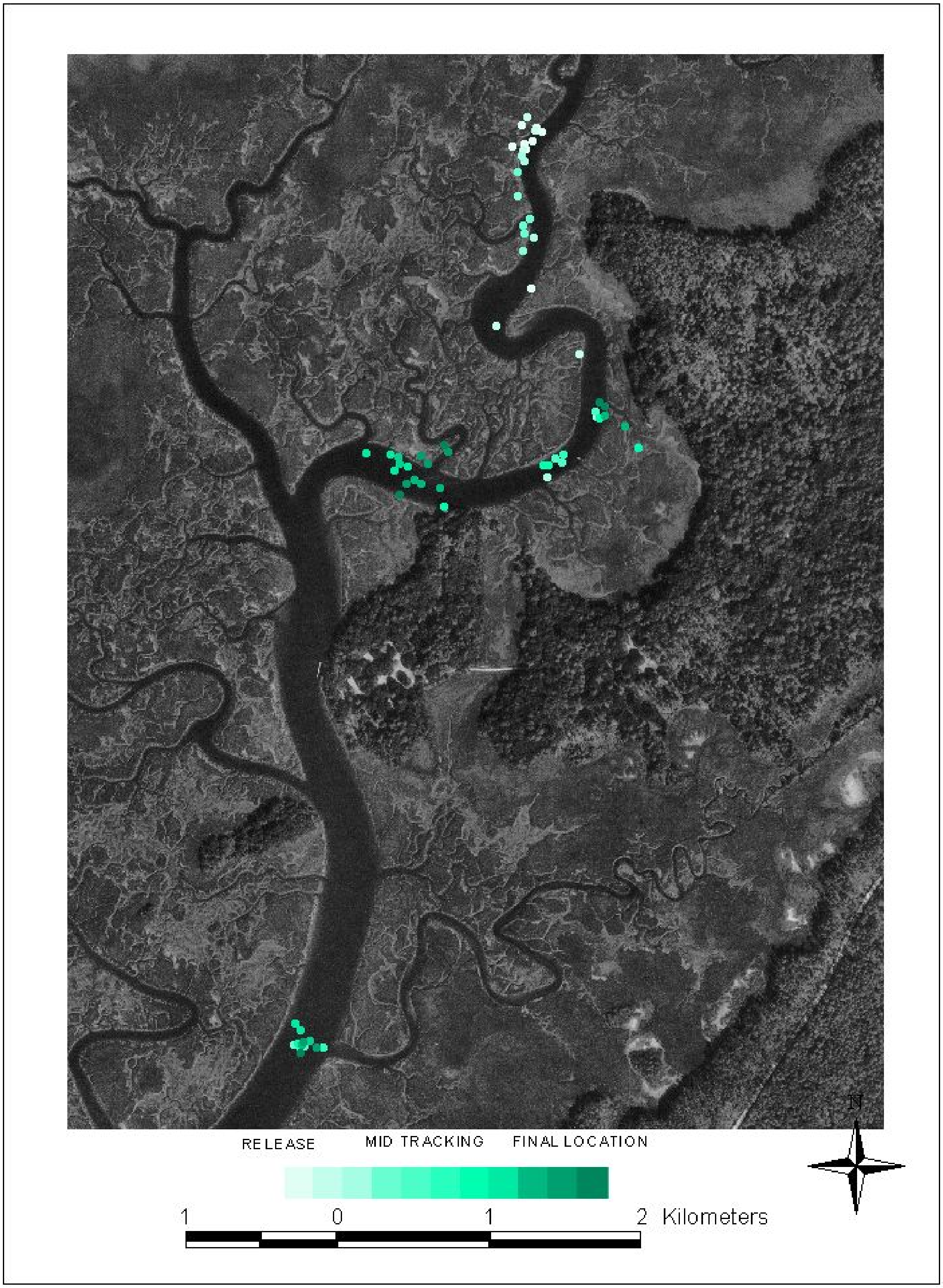


Figure 2.13. Map showing movements of tagged immature female blue crabs within the upper Duplin River (all years combined).

Figure 2.14. Map showing movements of tagged immature female blue crabs within Post Office Creek (all years combined).

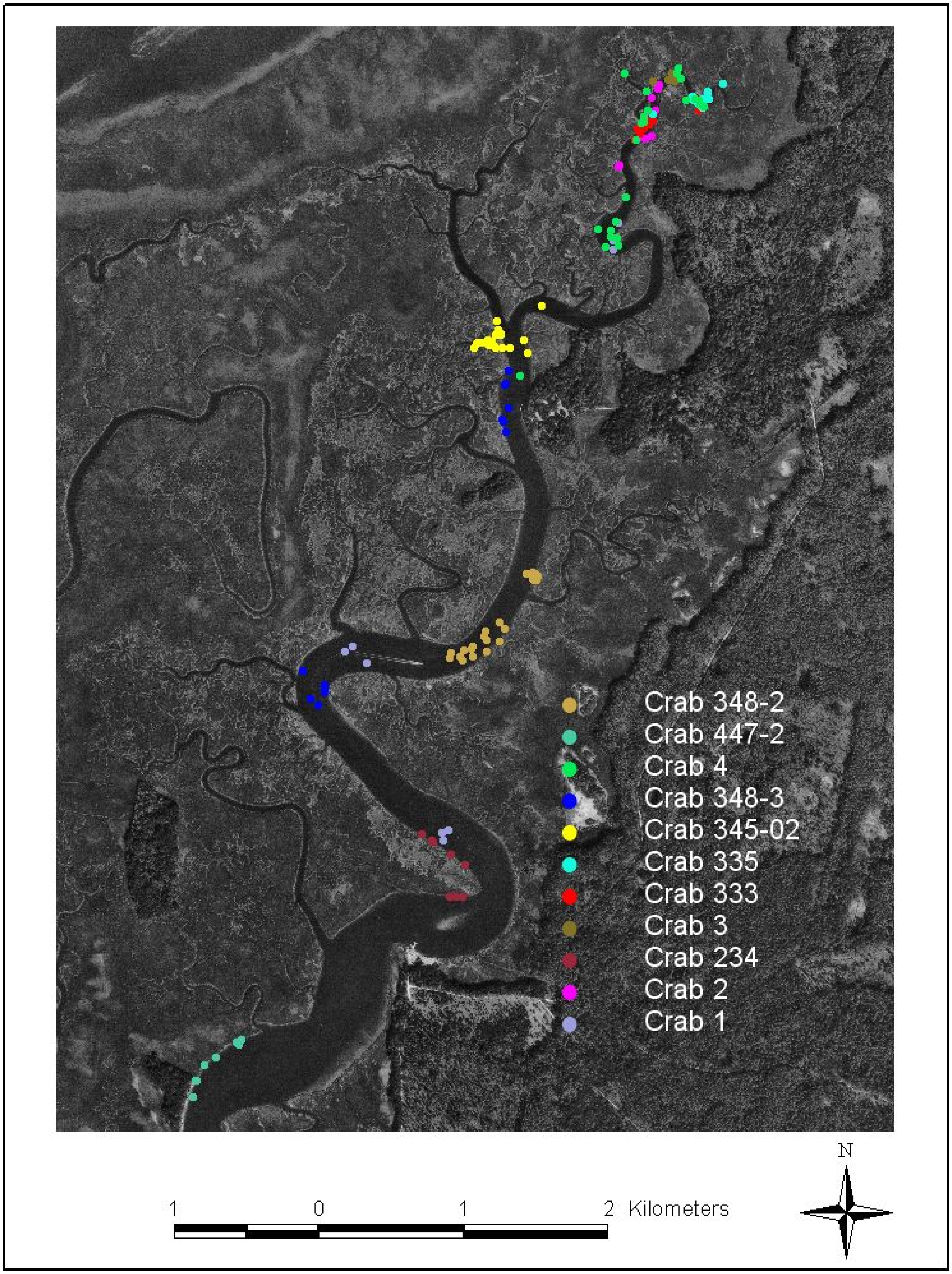


Figure 2.15. Map showing movements of tagged male blue crabs in the upper Duplin River (all years combined). Each color represents one crab's locational fixes.

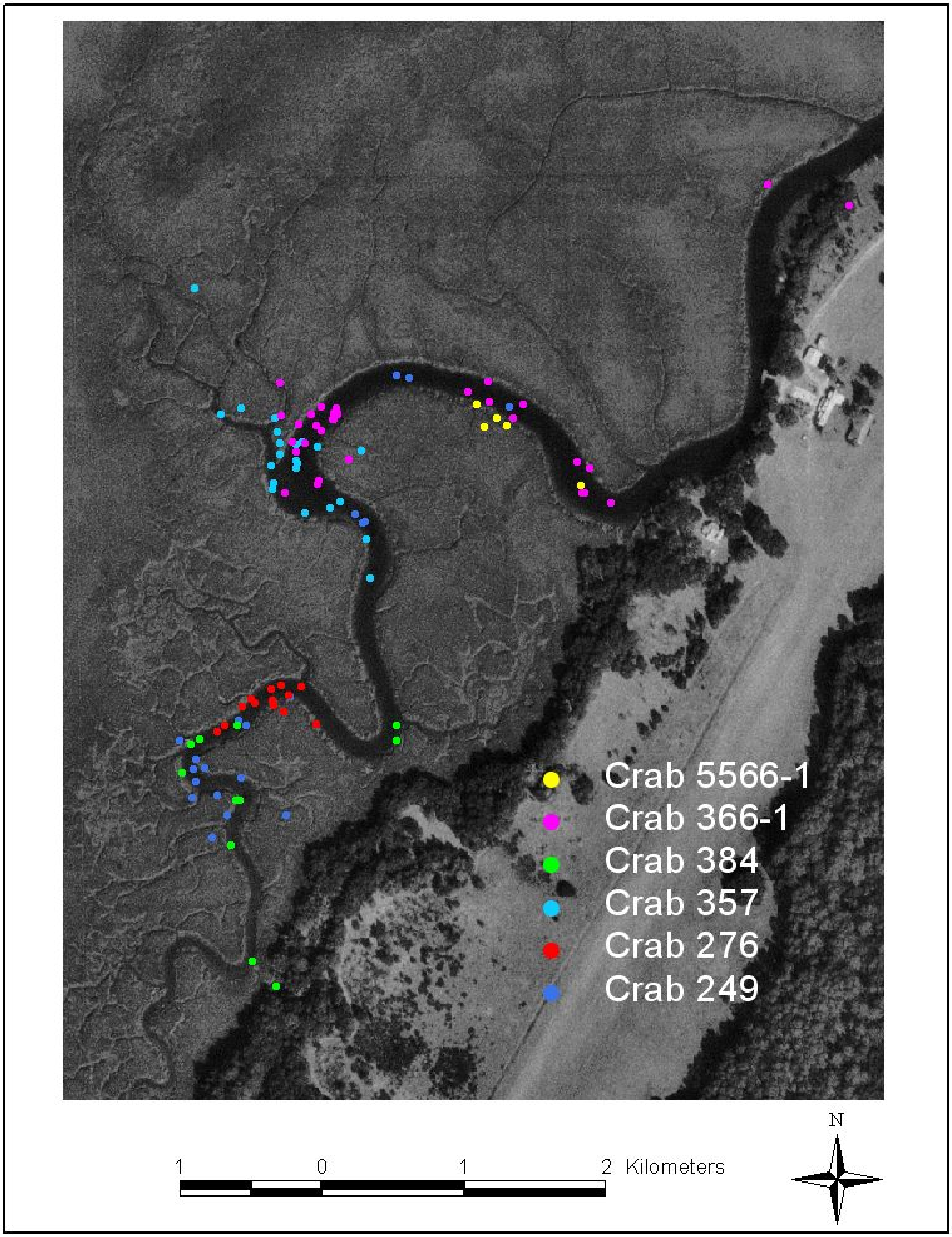


Figure 2.16. Map showing movements of tagged male blue crabs in Post Office Creek (all years combined). Each color represents one crab's locational fixes.

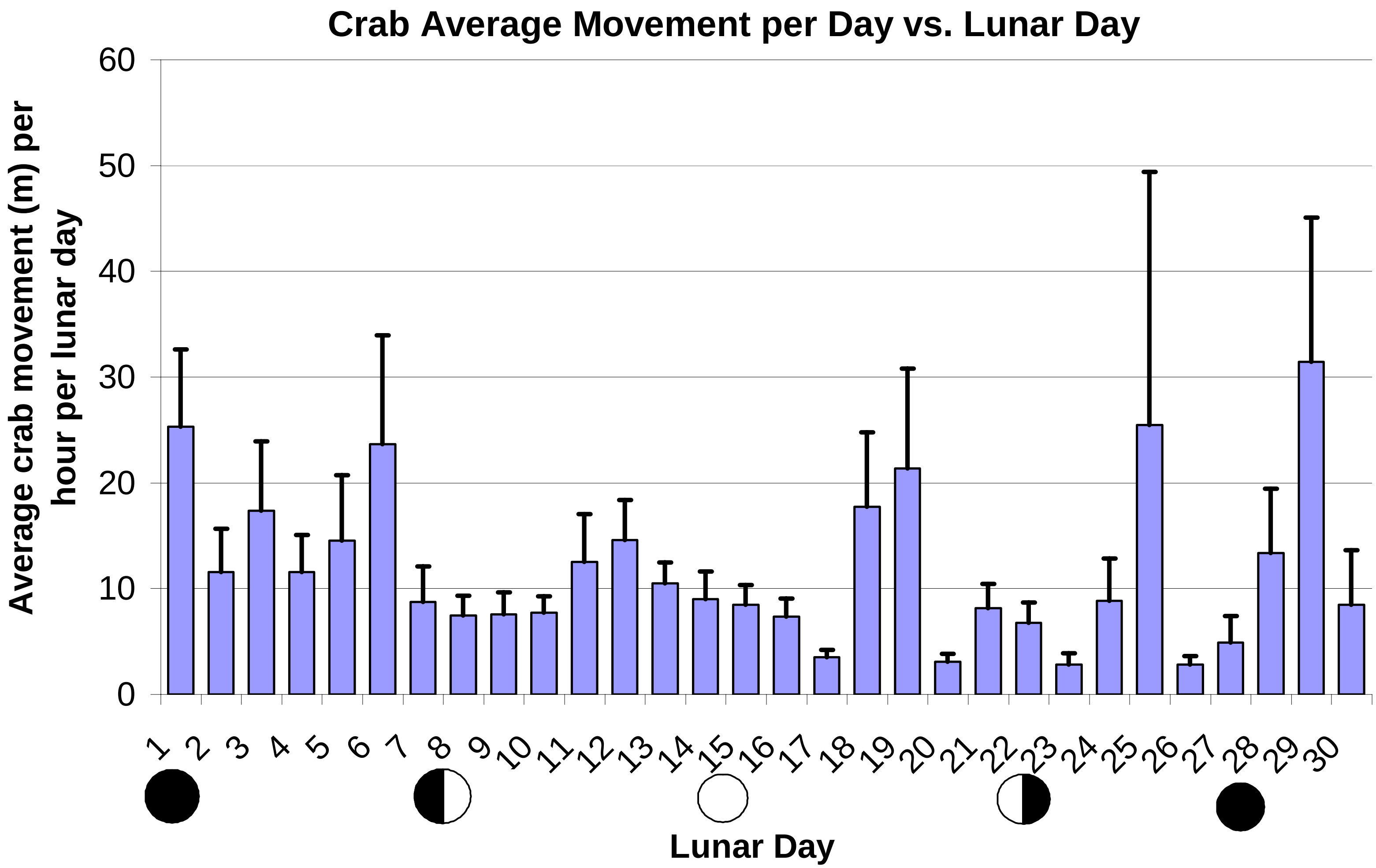


Figure 2.17. Plot of all crab movement by lunar day with standard error bars. Black circle represents new moons, open circle represents full moon.

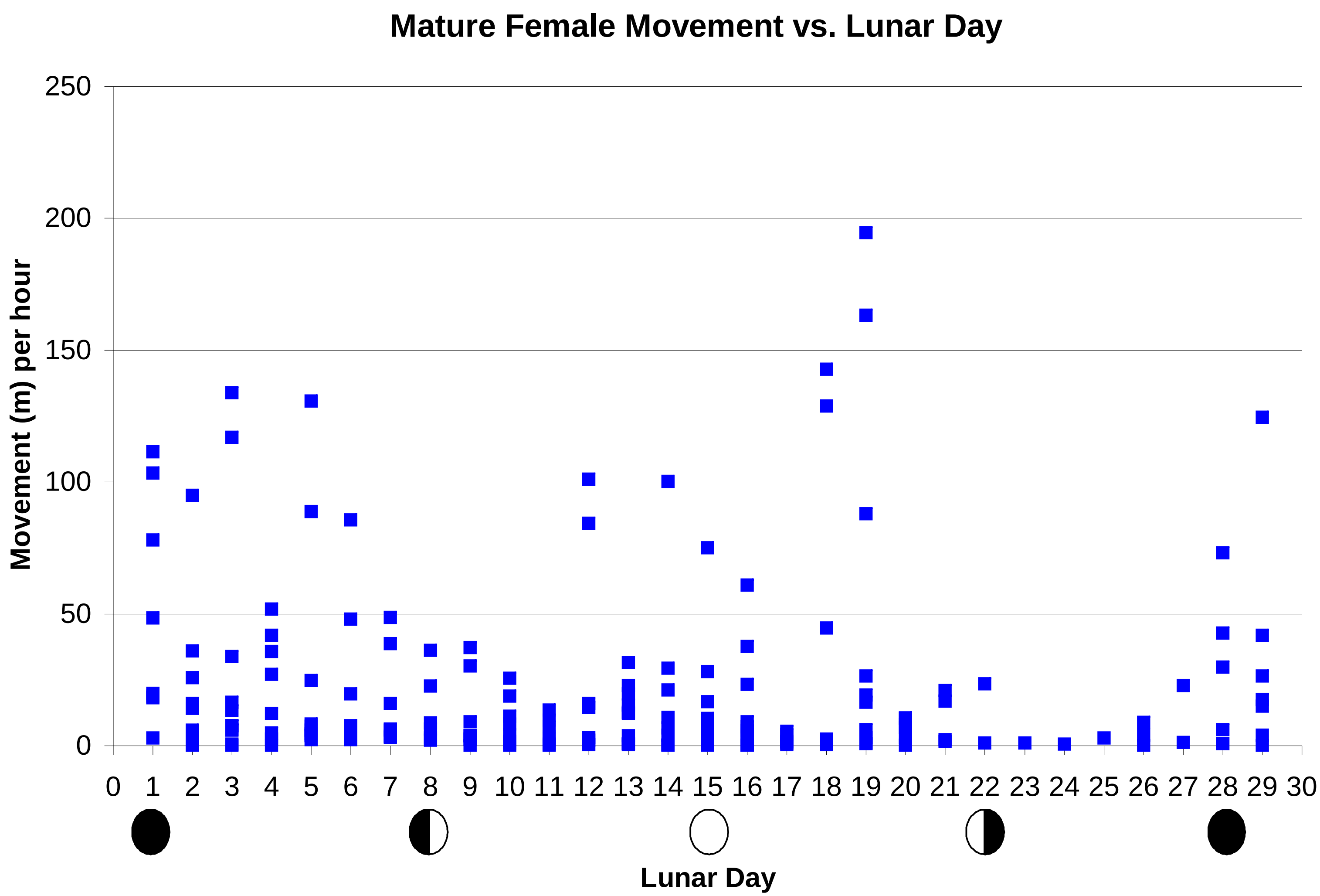


Figure 2.18. Plot of mature female blue crab movement (m) per hour for lunar days. Black circles represent new moons and open circles represent full moon.

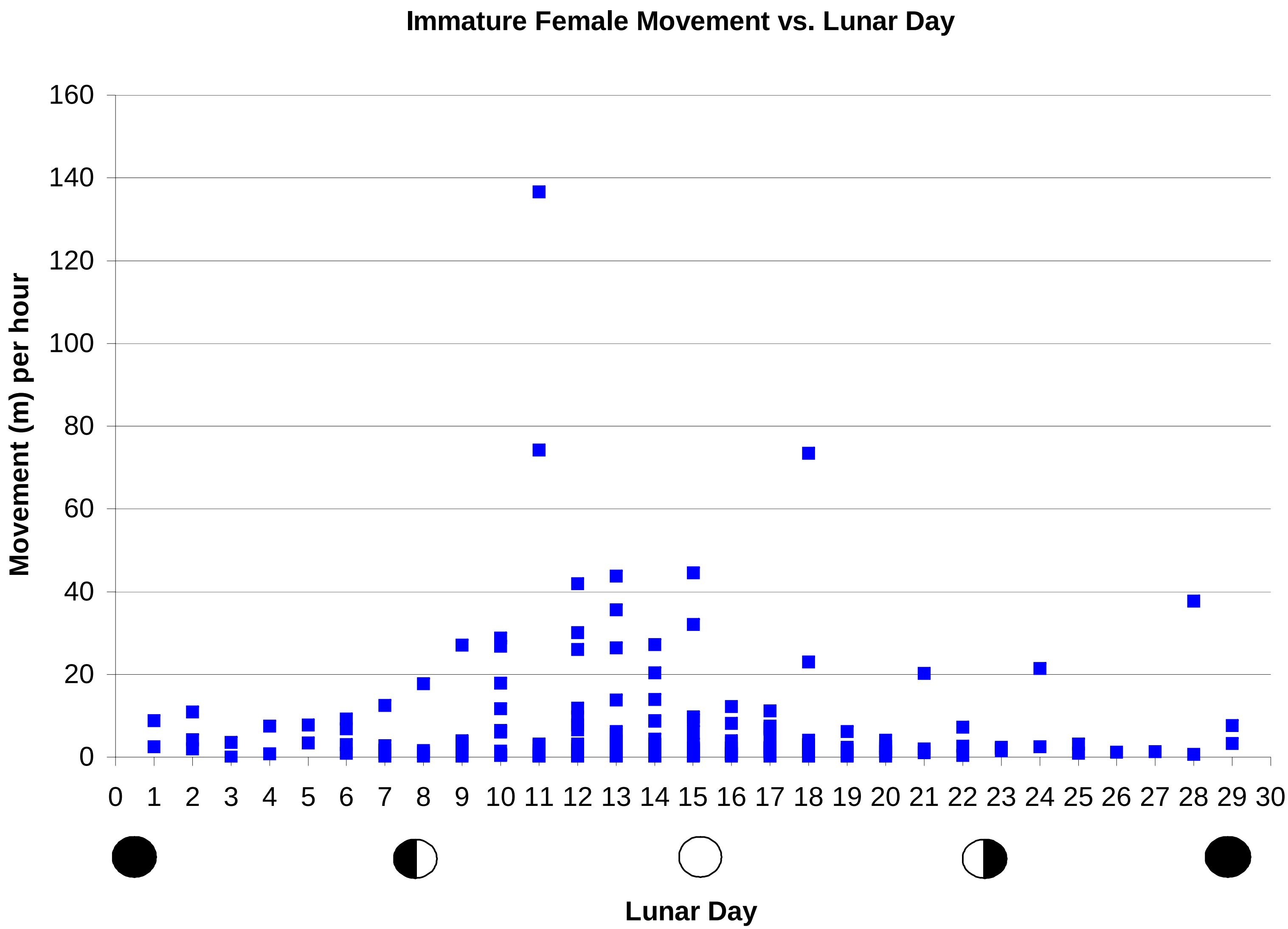


Figure 2.19. Plot of immature female blue crab movement (m) per hour for lunar days. Black circles represent new moons and open circles represent full moon.

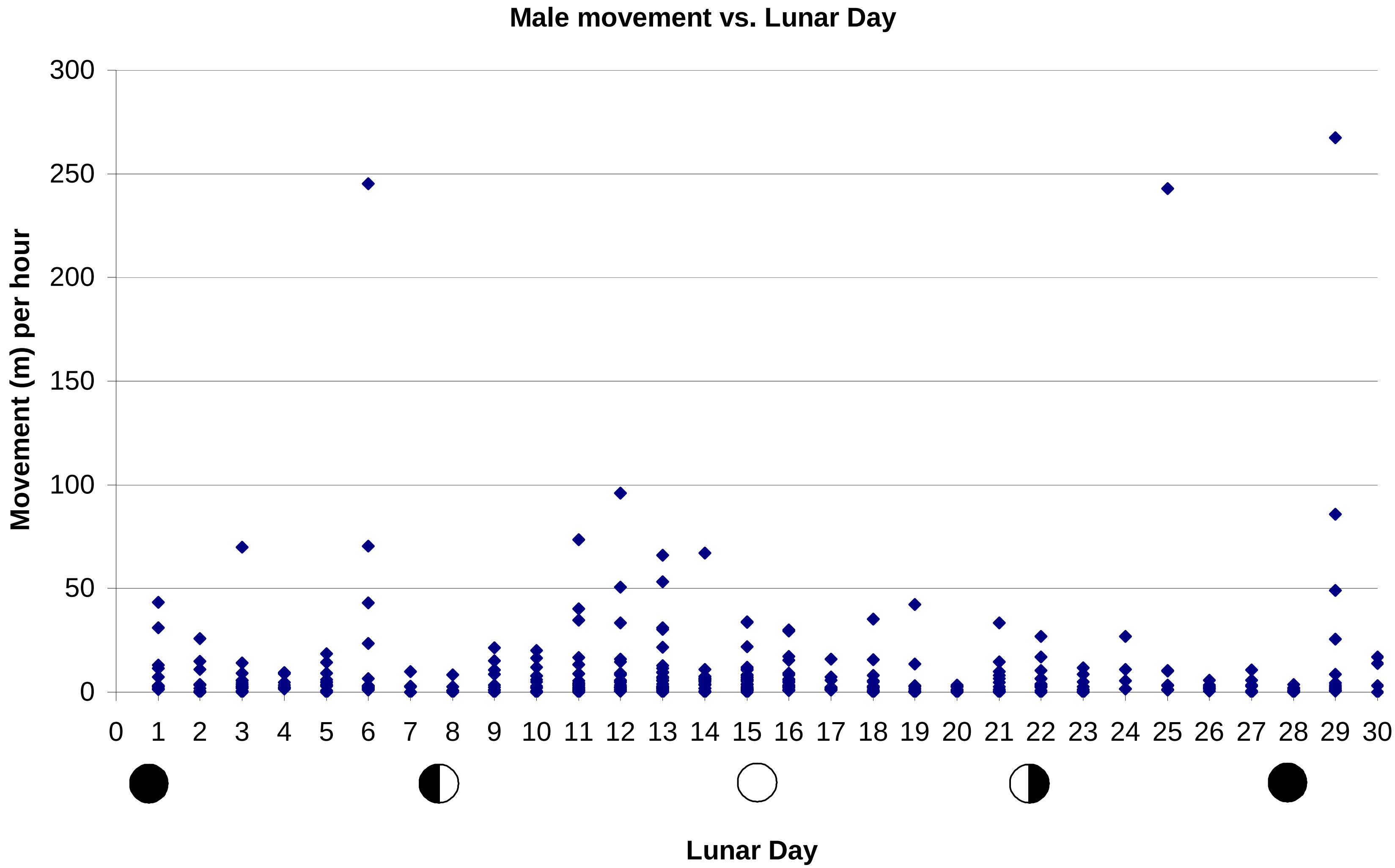


Figure 2.20. Plot of male blue crab movement (m) per hour for lunar days. Black circles represent new moons and open circles represent full moon.

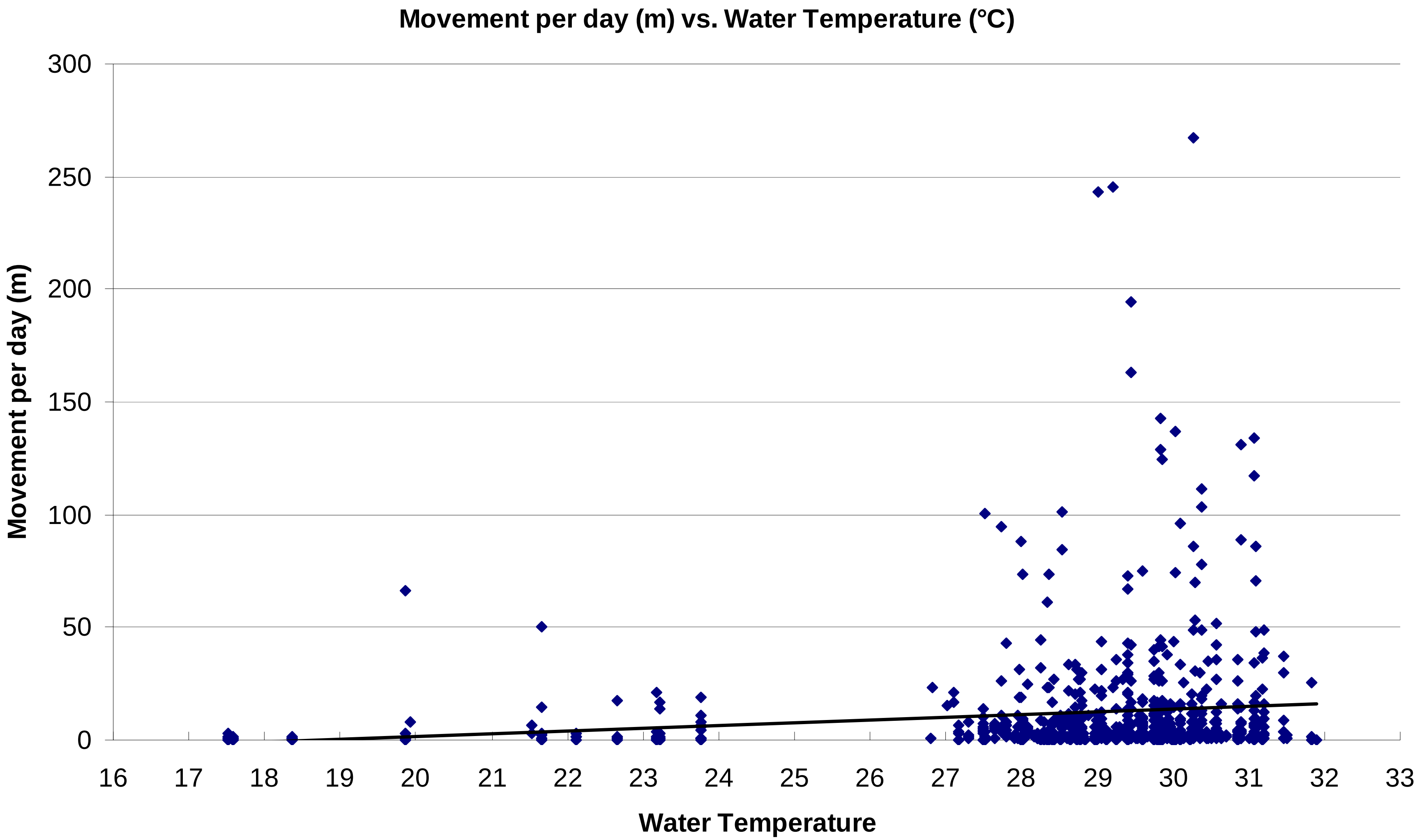


Figure 2.21. Plot of blue crab movements expressed as meters per day (all moves, all crabs, al seasons combined) with water temperature (°C). Black line represents linear regression line that best fits the data (R^2 = 0.013, p = .001).

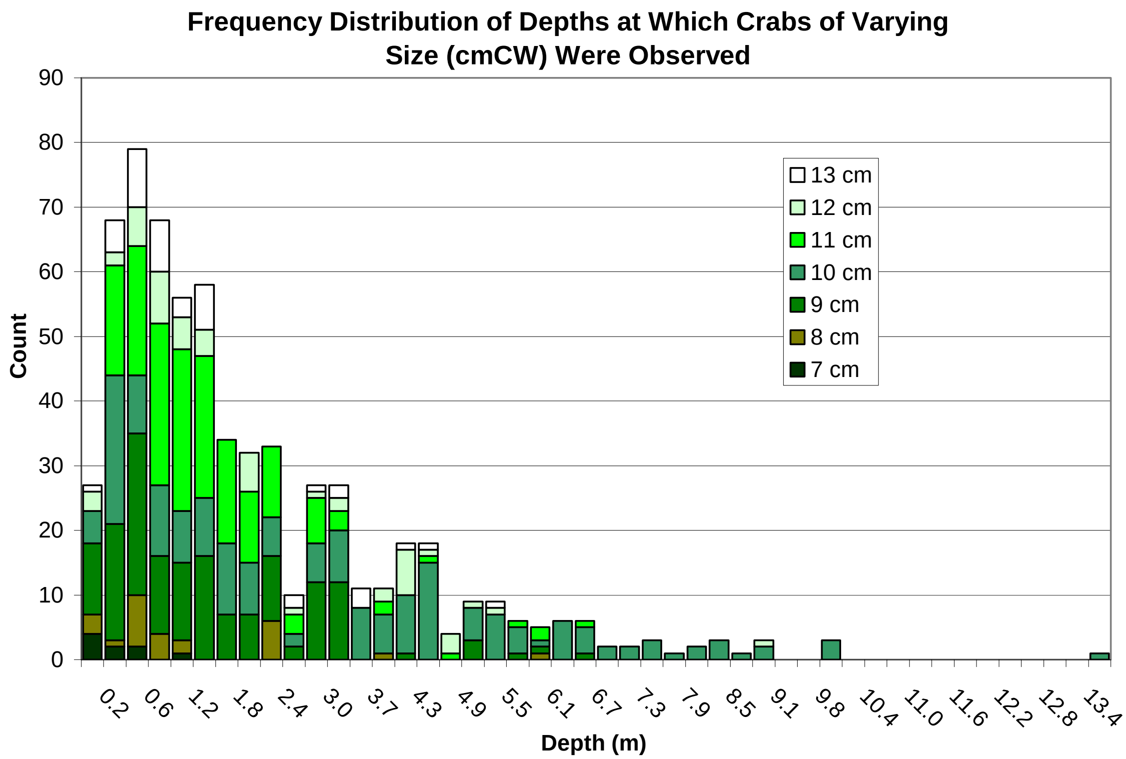


Figure 2.22. Plot of blue crab locations by depth (m) and size of crabs (cm carapace width).

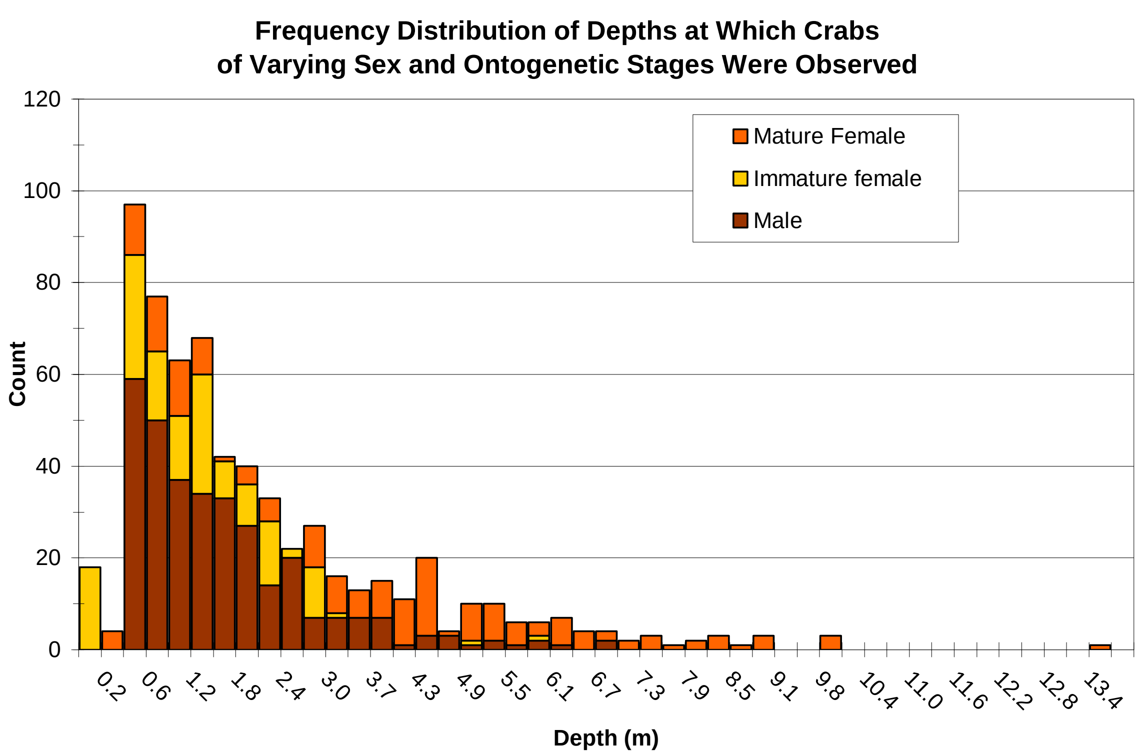


Figure 2.23. Plot of blue crab locations by depth (m) and ontogenetic stage of crab.

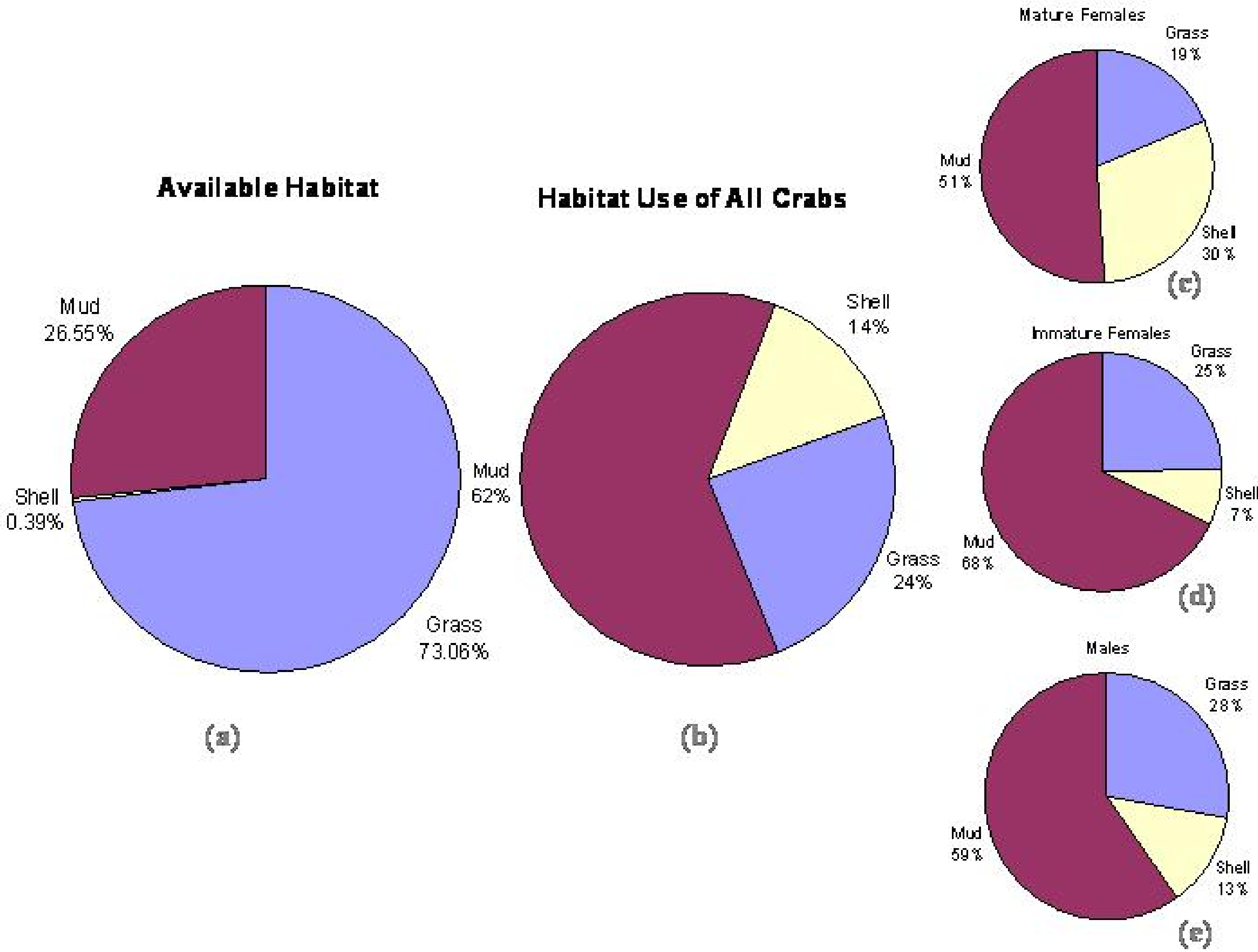


Figure 2.24.Available habitat in the Duplin River Estuary (a) and substrate use of blue crabs, all crabs combined (b), mature female (c), immature female (d) and male (e).

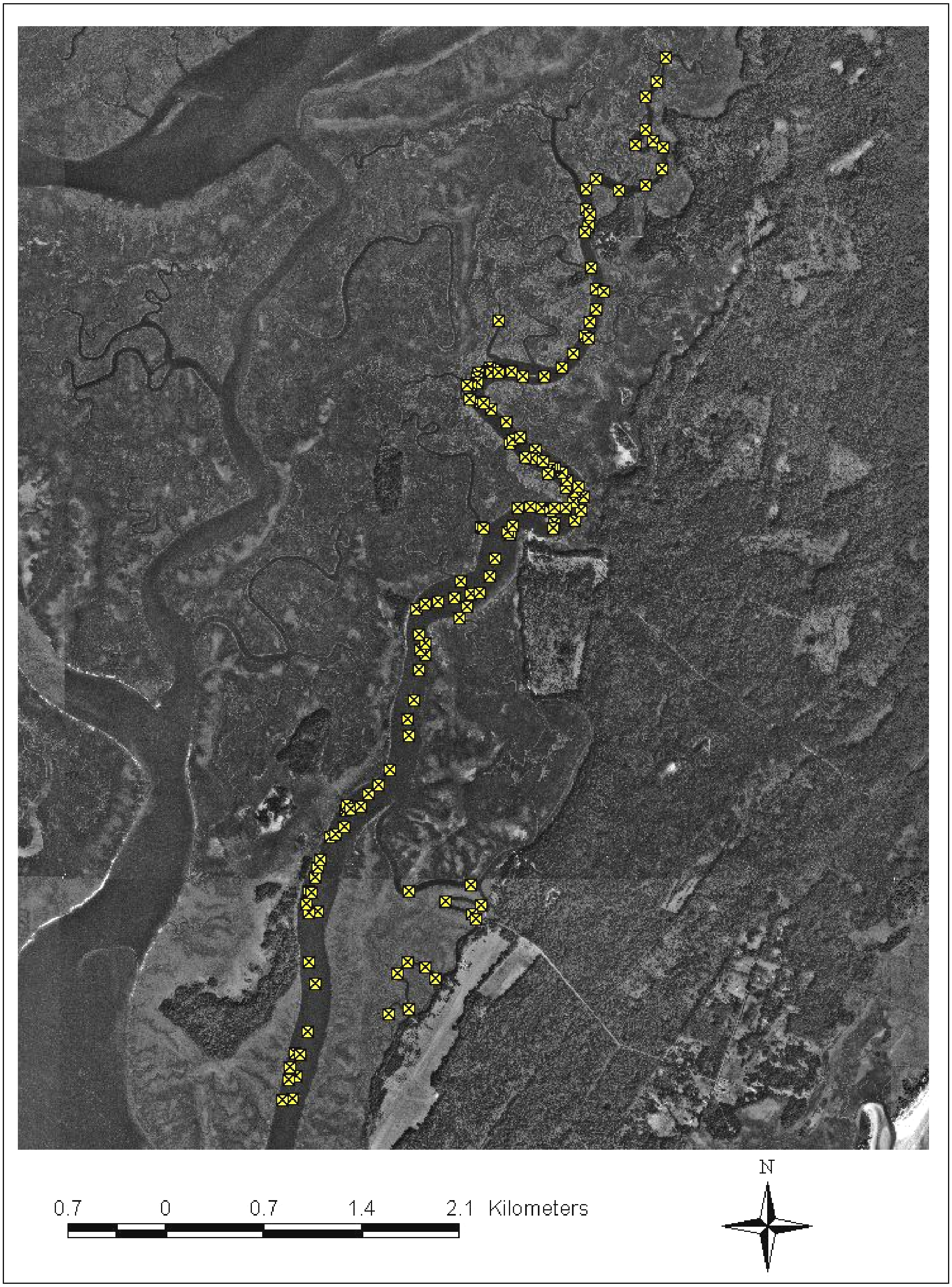


Figure 2.25. Map showing the distribution of crab traps in the Duplin River Estuary in 1999.

CHAPTER 3

THE USE OF ULTRASONIC TELEMETRY AND GIS TO DETERMINE HABITAT FOR MOLTING BLUE CRABS (*CALLINECTES SAPIDUS*)

Introduction

For invertebrates in the Phylum Arthropoda growth is not a continuous process measured in increases in weight, height, volume, etc. over time such as in vertebrates. Many arthropods (including the crustacean shrimps, crabs and lobsters) have a rigid exoskeleton and must go through ecdysis, or molting, in which their exoskeleton is completely shed in order for new growth to occur. Growth, therefore, is a discontinuous process because molting occurs in discrete increments. In blue crabs, *Callinectes sapidus*, individuals increase in size by discrete steps at ecdysis, whereas actual tissue growth and wet weight accumulation occur continuously (Cadman and Weinstein, 1988).

Most of the early descriptions about the molting process in blue crabs come from the commercial “soft shell” industry. The soft shell crab fishery depends on blue crab females that are captured shortly before molting, and then go through the molting process in an aquaculture facility. Information about the growth patterns of juvenile and adult blue crabs also comes from laboratory experiments (Churchill, 1918; Costlow et al., 1959; Leffler, 1972; Freeman et al., 1987, Cadman and Weinstein, 1988; Fitz,

1990) and has been investigated in only a few field experiments (Tagatz, 1968; Souza et al., 1980; Fitz and Wiegert, 1992; Wrona, 1997).

The physiology and endocrinology of the molting process has also been extensively described in scientific laboratory settings (Havens and McConaugha, 1990; Magnum, 1992). Electron microscopy can be used to describe cuticle structure in appendages of blue crabs to more accurately determine molt stage (Posey, perr. com.). There are, however, several external visible features that can indicate molt stage of a crab. At the onset of ecdysis, a narrow white line appears beneath the surface of the exoskeleton, just within the thin margin of the last two joints and the propodus of the 5^{th} or swimming legs. At this stage the crab is approximately 5 to 10 days from molting. In about 3 to 5 days from molting, the white line turns green in appearance as the cuticle of the new shell continues to form. Anywhere from 1-2 days to hours before molting, the peeler crab's narrow green lines change to red, and fine white wrinkles appear on the blue endoskeleton between the wrist (carpus) and upper arm (merus).

During molting the crab’s carapace splits along the posterior most edge of the carapace where dorsal and ventral sides of the crab meet, and the crab backs out of the old exoskeleton. Once the crab has emerged from its shell, it is known as a ‘soft crab’ or ‘soft shell’ crab. The time that it takes for the new exoskeleton to harden enough to be semi-protective can be within 4 hours (per. observation) although it can take 2-3 days until the carapace is fully hardened. The rate at which a soft crab hardens is dependent on water temperature, salinity, and size of crab (Millikin and Williams, 1984).

Smaller crabs molt more often than larger crabs, and all crabs will grow faster in warmer waters and with better food availability (Wrona, 1997). Crabs held in flow-through salt water tanks in Georgia molted more frequently in warmer water temperatures, and even continued to molt in winter months whereas growth ceases in colder water climates such as Virginia. Juvenile crabs can molt every 3-21 days whereas a legal sized crab will molt approximately every 60 days (Wrona, 1997). A crab may molt up to a total of 20 times during its lifetime.

In all arthropod invertebrates, the molting process is important in the regeneration of limbs (Hartnoll, 1982), and in many crustaceans, mating. Pre-pubertal blue crab females actively search out mature males when they approach the beginning of their molting process. The male holds the female under its ventral side during her pubertal molt. When the female crab emerges from her old exoskeleton and still soft, they mate, and the male continues to carry and protect the female until the female shell hardens. This is the only time that the female can mate and this point is thought to be its terminal ecdysis, meaning the female will not molt again (Hartnoll, 1982). The male normally continues growing through an additional four molts and will grow to be considerably larger than the female (Hartnoll, 1982).

From a physiological standpoint, ecdysis is energetically costly for any crab, with a high mortality rate due to the molting process alone (Mangum, 1992). During ecdysis, while the crab is either molting or soft, it is extremely vulnerable to predation, especially from cannibalism. Blue crabs are highly cannibalistic (Hines et al., 1990) and adult conspecifics are the most common predator found attacking tethered juveniles (Smith, 1996). Because of the high vulnerability for newly molted or soft crabs, refuge habitat is thought to be important to crab life history. Several studies have investigated possible habitat refugia for molting crabs in the field. Crabs have been found in varying stages of ecdysis in sea grasses such as *Zostera* sp. and *Thalassia* sp. in estuaries along the Atlantic and Gulf coast (Orth and Van Montfrans, 1990). Both field and laboratory studies have shown that vegetative habitats are characterized by higher overall abundances of blue crabs and lower predation rates than unvegetated habitats (Orth and Van Montfrans, 1990). Juvenile blue crabs are at a particularly high risk of predation due to their small size and frequent molting. In field experiments in the York River, VA, Perkins-Visser et al. (1994) found that early stage blue crabs associated with sea grass beds receive a substantial growth advantage within the refuge.

When submerged aquatic vegetation is absent, shallow water refuges such as small tidal creeks, as well as microhabitat such as creek edge, serve as molting habitat (Ryer, et al., 1997). Hines et al. (1987) showed that in unvegetated areas of the Chesapeake Bay, males use shallow salt marsh creeks as molting habitat while females molt in open-water basins even though the shallow creek habitats may offer superior molting habitat than the larger river. In this system, crabs molting in the deeper river may suffer higher mortality rates than their molting counterparts located within the refuge of shallow creeks (Shirley et al., 1990). However, for females, molting location may be more dependent on location of mature males that will protect them through their pubertal molt (Hines, 1987).

Anecdotal data from Chesapeake Bay fisherman (described in Wolcott and Hines, 1990) indicate that male pre-molt crabs tend to be found in shallow water often in beds of submerged aquatic vegetation (SAV), in shallow water, and that both male and female ‘peeler crabs’ can be caught in “peeler pounds”. Peeler pounds are mesh fences positioned perpendicular to shore that direct pre-molt crabs into a box net in shallow (<1 m) water.

Posey (in submission) found large numbers of small juvenile crabs in pre-molt stages in low salinity shallow water indicating that juvenile crabs use these habitats to molt. Even though these low salinity areas may be metabolically costly for the juveniles because they are outside of their optimal salinity range to live in, they may gain a larger benefit by molting in these habitats. Crabs molting in less saline waters have larger post-molt sizes than crabs from saltier water, due to larger intake of fresh water during the shedding process to expand the body before the shall can harden.

Blue crabs are extremely abundant in the Duplin River estuary (Fitz and Wiegert, 1990) with their abundance estimated at 0.01 per m^2 of salt marsh area. The Duplin River estuary is a tidal slough estuary behind the Georgia barrier island of Sapelo. Its main body of water is the Duplin River, which has been described as a tidal river with little freshwater influence (Imberger et al. 1983). An extensive network of tidal creeks and salt marsh grass primarily *Spartina alternaflora,* surrounds the Duplin. Because of the high tidal amplitude and detritus rich waters, turbidity levels all along the Georgia coast are high. This prevents the growth of any submerged aquatic vegetation in Georgia's estuaries. Yet Georgia's estuaries are prolific nursery habitats for blue crabs and support the second largest fishing industry in Georgia (Evans, 1998). If there is no sea grass in Georgia, and assuming that Georgia blue crabs actively seek out refuge habitat for molting, then what is that habitat?

In the previous chapter it was noted that several crabs were tracked moving onto and off of the marsh surface into the flooded *Spartina* grass. Another result discussed previously was that several transmitters that had been securely fastened to the carapace of the crabs being tracked were found on the marsh surface with their harness intact and no damage to the transmitter. One possible explanation for finding the ultrasonic tags in the marsh is predation. It is possible that when the crabs moved onto the surface to feed, they were killed and eaten by predators, leaving the tag behind. However, many of the crabs used in the study were of adult size, and a large sized crab is at or near the top of the food chain with few natural predators present in the marsh when inundated. Predators that could eat a blue crab of considerable size in a flooded marsh are red fish (*Sciaenops ocellatus*) or dolphins (*Tursiops truncates*), which consume the crab whole and would probably consume the tag along with the crab. An alternative explanation for location of the tags in the marsh is that the tags were shed along with the carapace on the marsh surface during molting.

In Georgia estuaries lacking SAV, blue crabs could either use shallow water habitats such as small tidal creeks, oyster reefs that provide physical substrate, or the marsh surface, when inundated by tides. At high tide, crabs have access to the flooded marsh surface which is covered with dense stands of *Spartina*, for many hours out of the tidal cycle (Ragotzkie and Bryson, 1955). Fitz and Wiegert (1990) observed crabs moving onto the marsh surface at high tide and examined the gut contents of crabs found leaving the marsh on the outgoing tide. In finding significantly fuller gut contents in crabs leaving the marsh surface, they concluded that blue crabs were going onto the surface of the marsh at high tide to feed. Kneib (1994) found a large number of blue crabs (both juvenile and adult) in flume weirs placed both near the edge of the marsh and in the high marsh, indicating movement onto and off of the marsh surface.

Ultrasonic telemetry has been used to determine many activities of animal behavior when direct observation is impossible. Recently ultrasonic telemetry has been used to describe blue crab movement, foraging patterns, and vertical migration swimming behavior (Wolcott and Hines, 1989; Carr et al., 2003; and Hench et al., 2003). Wolcott and Hines (1990) developed an ultrasonic “molt signaling” transmitter that was used on blue crabs in a tidal creek system within the Chesapeake Bay to determine what types of microhabitat blue crabs selected within a tidal creek to molt. They found that crabs remained within small tidal creek habitats and eventually selected shallow water creek banks to molt.

The main objective of this study was to test the hypothesis that blue crabs in Georgia use the inundated marsh surface as molting habitat.

Methods

To test the hypothesis that crabs were using the inundated marsh surface as molting habitat, crabs were tagged with a special tag that would signal a molting event. The molting tag used in this experiment was based on the design of a molting tag used by Wolcott and Hines (1990). The transmitter used separation of the carapace from the abdomen (where the crab backs out of its shell) as an indicator of ecdysis. Each transmitter was controlled by a circuit board that was fitted with a 1 cm diameter, ceramic, 3 volt battery that allowed for a 60 day tag life, and a 65, 70, 75, or 78.5 KHz crystal in order to differentiate among different crabs released in the same area at the same time (figure 3.1). The transmitters produce a regular signal at one pulse per second that changes to almost 2 pulses per second when molting occurs. A magnetic reed switch was attached to the carapace and held closed (electronically) by a magnet attached on the ventral side of the crab's body. As the molting crab backs out of its old shell, the old carapace is lifted away from the lower exoskeleton and the magnet is pulled away from the switch. The circuit is opened and changes the pulse of the signal (figure 3.2; see Wolcott and Hines, 1990, for a functional diagram of the transmitter).

The board and its components were packaged into marine grade electronic shrink tubing and heated to conform the shrink tubing to the transmitter. The ends were then sealed with epoxy so that the package was watertight. The packaging technique was repeated with another layer of shrink tubing with longer ends to allow holes for monofilament line to attach the transmitter to the crab and to shape the transmitter to conform to the shape of a crab's carapace. The entire transmitter and packaging weighed between 20 and 29 grams in air. Before attaching the transmitter to the crabs, each tag was lowered to a depth of 30 meters for about 1 minute to ensure that the packaging was watertight.

The transmitters were attached to the carapace of the crabs by tying a monofilament fishing line harness over the lateral spines of the carapace. The magnetic reed switch was then glued with epoxy onto the carapace just below the transmitter. A magnet attached to a short piece of monofilament line was glued with epoxy to the underside of the crab. The magnet was inserted into a tube glued next to the magnetic reed switch. Tension on the monofilament line held it tight against the back of the crab to prevent snagging. When separation of the crab's carapace occurred during molting, it pulled away the magnet from the switch, changing the pulse frequency of the tag that indicated ecdysis (figure 3.2).

Due to the weight and size of the transmitter, the crabs chosen for this experiment were limited to large sizes (>8 cm carapace width (CW)). Each transmitter weighed less than 10% of the wet body weight of the crab tagged, which is within guidelines for telemetry tagging techniques (Rodgers, 1998). Only male crabs were used because female crabs of the required size were reproductively mature and would not molt again.

Male crabs were collected with commercial crab traps from the Post Office Creek which empties into the Duplin River, GA and held an average of 10 days in individual aquaria until they were close to molting. The propodus of the 5th leg was examined daily for green or red sign which indicated that a crab was within a week of molting. Once fitted with the molting tag, crabs were held another 12-hour period to ensure that the tag was working correctly and that it was securely attached. Crabs were then released back into Post Office creek. In order to minimize disturbance crabs were located only 2 –3 times per day by small boat. A multidirectional hydrophone was used to identify the general location of the crab. Once the tag was heard, a unidirectional hydrophone was used to determine a more precise location. The location of the tag (UTM coordinates obtained by GPS), depth, and substrate were recorded at each tag location until the tag either stopped moving or signaled that the crab had molted. If the tag was located repeatedly in the same spot, but not signaling ecdysis, then the crab was assumed dead. If the tag was signaling ecdysis, but the crab was still moving, the tag was considered to have malfunctioned. If the tag was signaling ecdysis and not moving, the crab was considered to have molted. If the tag signaling ecdysis was in a shallow water area, I attempted to recover the tag at low tide by locating the tags while they were covered with water, marking the location with a physical marker (bamboo pole), and then waiting for the tide waters to recede.

Each location, depth, substrate type record, and molting position was mapped using ArcView (ERSI, 1983). An ArcView® GIS analysis tool called the Animal Movement Analysis Extension (Hodge et al. 1999) was used to determine specific movement characteristics of the molting crabs and to create maps of molting habitat. In ArcView®, the Point to Polyline tool was used to first produce travel paths that were used to display the chronological movement of each crab fitted with a molting tag (Figures 3.3- 3.9). These polylines were used to calculate distance traveled per day tracked and to determine the degree of meandering in their movements. The mean index of meander is determined by the ratio of net to total distance traveled, varying from 0.0 for random movement to 1.0 for straight-line movement. These distances were compared to distances traveled of crabs that had not molted and to those crabs that were assumed to have molted, or those tags that were found on the marsh surface.

ArcView was also used to determine the proportion of habitat type (grass or mud) available within the study area. Polygon shapes were traced over creek and river areas of digital black and white aerial photographs taken of Post Office Creek at low tide. These shapes were then dissolved together to create one polygon shape representing all of the creek and river area (mud) within the study site. The X-tools extension was used to calculate the area of the water polygon. A ‘Post Office creek’ study area polygon was created representing all of the area within Post Office creek that was searched for the molting tags during the study plus a 1.8 m buffer around that area representing the range of the hydrophone that was used to locate the tag signal. The total calculated area of the creek and river area polygon was subtracted from the total area of the polygon surrounding the ‘Post Office Creek study site’ to determine the area of marsh grass within the study site. Even though there are other substrate types such as oyster reefs in Post Office creek, there were no GIS coverages for analysis and so available shell habitats (oyster reefs) are included in the mud or river/creek area.

A Proc GLM analysis of varience was performed to test for differences between means (depth utilization, distance traveled, and index of meander) and in each case, a Tukey’s HSD post hoc test was performed to test which means were significantly different from each other.

Results

Molting transmitter function and recovery

Eleven crabs ranging in size from 8.45 to 13.1 cm CW and were tagged with a molting transmitter and tracked from 1- 20 days. Out of the11 crabs tagged, molting habitat could be determined from 7 crabs. Two crabs were lost and no molting habitat was determined, 1 transmitter had misfired and the crab and transmitter were recovered from a crab trap, 1 crab had stopped moving but could not be recovered. (table 3.1).

Out of the 11 molting transmitter tags, 3 misfired because the epoxy holding the magnet and line to the bottom of the crab had come unglued, and the magnet had fallen out of the tube next to the switch. Although these transmitters were signaling ecdysis the crabs were still moving. While their locations were changing, they were followed until their position remained stationary. Two of these transmitters that malfunctioned were eventually recovered as a transmitter on a crab molt (indicating that the crab had molted), and the third was recovered when the crab was captured in a commercial crab trap. The remaining 6 molting transmitters performed as designed. Four tags were recovered on intact crab molts, and 1 was recovered on a dead crab that had died in the process of molting. One tagged crab was tracked until it remained stationary over a long period of time (10 days) and did not signal molting. It was last located in deep water where the tag could not be recovered and the crab was assumed dead.

Molting habitat and timing of molting

The total grass habitat available to crabs within the Post Office Creek is 60.15 hectares (77% of the total area available) and the total mud or creek habitat was equal to 17.31 hectares (23% of the total available area) although some of this mud habitat includes oyster reefs that were not mapped and therefore not available for analysis. Based on positional fixes only, the crabs spent 70% of their time in shallow mud habitats, 30% of their time in grass habitats, and 0% on oyster reefs up until molting, (figure 3.10). The mean depth that was recorded at each crab location prior to molting was 2.9 m and ranged from 1 to 5 m. All recovered transmitters were found in vegetated areas (with the long form marsh grass *Spartina alternaflora)* that were completely inundated with water at high tide and exposed at low tide (figures 3.3-3.9). Most crabs molted within the first 4 days of release and were tagged as ‘red sign’ crabs indicating that they were to molt within days. One very large crab that molted 1 day after release was not a ‘red sign’ but was tagged as a ‘green sign’ peeler.

Spatial patterns of movement and molting

Mean total distance tracked (the straight line path connecting all of the observations) was 319.9 m, with great variation in tracking times among individuals. The lengths of the tracks (distances measured between locations) ranged from 22.6 to 1145 meters. The mean net distance (shortest possible path from release point to molting point) was much shorter (60.1 m; range 5.1 to 205.9 m) reflecting the highly meandering paths exhibited by the crabs prior to molting. The mean index of meander was 0.444 and ranged between 0.092 to 0.872 (table 3.1).

Molting crabs vs. other tagged crabs

In the previous chapter when crabs with non-molting transmitters stopped moving (remained stationary for more than 24 hours), I attempted to recover these tags and was successful if the transmitters were in shallow water at low tide. Complete transmitters were recovered, with no damage to the transmitters, or harnesses. In some cases, pieces of crab carapace were found near the transmitters. The transmitters of four immature female crabs and 4 males were recovered and in each case were found in vegetative areas on the marsh surface. At this point it was hypothesized that these crabs had molted leaving their transmitters behind. These crabs ranged in size from 8.4 to 11.5 cm CW and were tracked from 3 to 17 days. Locations of these recovered transmitters that were assumed to have molted (referred to as pinger-molt crabs) are reported in table 3.2. Maps of their locations and travel paths are shown in figures 3.11 – 3.18. One immature female (crab 339) was tagged when soft and tracked for 24 days until the transmitter was recovered on the marsh surface (figure 3.18). These crabs were reported at depths averaging 4.1 m before molting (range 2-8 m;

figure 3.19). Based on positional data, crabs were found 45% of the time in mud, 39% of the time in grass, and 16% of the time were located on oyster reefs (figure 3.10(c). The mean total distance traveled for these crabs was 1260.31 m ranging from 196.4 to 3136.97 m). The mean net distance was also shorter (329.19 m; range 61.09 to 763.48 m). These crabs had a mean index of meander number of 0.358 (range 0.019 to 0.506).

The average distance traveled per day was significantly higher in non-molting crabs (all sexes combined) and non-molting male and immature female crabs combined (from chapter 2) than crabs that were tracked with molting tags ($p<.05$; figure 3.20) and higher than the crabs assumed to have molted (i.e. crabs that were tagged with regular non-molting tags that molted; $p<.05$; figure 3.20). There was no significant difference in distance traveled per day between crabs known to have molted and crabs assumed to have molted (figure 3.20). There was no significant difference between mean index of meander between non-molting crabs and crabs with molting transmitters (figure 3.21), but there was a significant difference between crabs that were assumed molted, crabs that had molting transmitters, and crabs that did not molt.

Discussion

Blue crabs that molt within suitable molting habitat have greater chances to survive ecdysis. Ideal habitat would include an environment that provides low physiologic stress (ideal water dissolved oxygen content, salinity, and temperature for molting), and no threat of disturbance from predation from other species or cannibalism during this difficult process. Ryer, et al. (1997) monitored the survival of tethered soft crabs that had just molted in varying habitats (sea grass beds, small tidal creeks, large tidal creeks) in the Chesapeake Bay, VA. There was no difference in survival between small marsh creeks and sea grass beds, but there were differences in survival with highest survival rates in small tidal vs. large tidal creeks. In the marsh creek, micro-habitat influenced post molt survival, with greater survival along the creek edge than in the creek centers. Male crabs that were tagged with molting transmitters by Wolcott and Hines (1990) utilized creek habitats during the premolt period and eventually selected shallow microhabitats along the marsh-lined creek bank for ecdysis. Hines (1987) suggests that crabs may select shallow water habitats just prior to molting because the habitat offers potential advantages such as: 1) reduced predation pressure because numbers of predators in the creeks are less than in larger rivers; 2) there may be reduced cannibalism because of the partitioning of feeding crabs from molting crabs; and 3) increased dietary requirements of post molt crabs. Wolcott and Hines (1990) suggest two further hypothesis 1) the shallow creeks provide superior refuge or that 2) physio-chemical conditions in the shallow creeks may be more favorable for molting.

The results from this study can be used to help define what suitable molting habitat is for Georgia blue crabs. Due to the limited number of individuals in this study, however, these results should be regarded as indicative, rather than definitive but with two to three fixes per day, a clear picture of how these 7 premolt males utilized creek habitats and eventually selected the marsh surface to molt is presented.

Crabs tagged with molting transmitters and crabs that were assumed to have molted were also found at shallower depths than non-molting crabs, staying near the creek edges and rising onto the marsh surface on high tides. Spending time in the shallow water creeks places pre-molt crabs closer to molting refuge.

In this system, there is no submerged aquatic vegetation available to provide refuge during ecdysis. Besides the marsh surface, crabs could use either oyster reefs or shallow water as molting habitat. There are oyster reefs in this area but because they have not been mapped with GIS coverages, the amount of oyster reef habitat available to blue crabs is unknown. Non-molting crabs tracked in this system were found on oyster reef habitat, while crabs tagged with molting transmitters crabs were not. Many species are found foraging on oyster reef habitat including blue crabs. Clarke et al. (1999) found that crabs that aggregated on prey patches (clam beds) had more frequent aggressive interactions. These aggressive interactions include behaviors that could interfere with the molting process. Therefore foraging grounds, like oyster reefs, are not ideal habitat for molting. Crabs that were assumed to have molted spent less time on oyster reefs than non-molting crabs and may reflect foraging behavior leading up to, but not near ecdysis.

Results from this study indicate that in the Duplin River estuary where high tidal amplitudes regularly flood the creek banks and levees, blue crabs migrate onto the marsh surface to molt. Not only were crabs with molting transmitters tracked to grass molting habitats, but the non-molting transmitters found on the surface of the marsh (discussed in chapter 2) were also assumed to have come from crabs that molted because they shared similar behavior prior to molting. These crabs used shallower water depths and traveled shorter distances than non-molting crabs. They also exhibited highly meandering paths prior to molting.

Crabs that were in late intermolt period (just prior to molting) were consistently tracked to habitats out of the subtidal creeks to areas that were covered in *Spartina* grass on creek banks and levees. These are areas that are mostly drained over some portion of the 12-hour tidal cycle. At high tide these areas were covered with at least 0.5 m of water. In some instances, however, these areas were above the low tide water line and emerged as quickly as 1 hour after high tide. This might suggest that the crabs have very little time to actually go through the process of molting. It is necessary for crabs to be in water during and after ecdysis in order to harden. In aquaculture systems for soft-shell blue crab production, crabs are removed from the water immediately after molting to prevent hardening, which can happen as quickly as 1 hour after molting.

The movement or habitat selection of crabs immediately after they molt is not known. They may not remain in the areas in which they molted because of lowering of the water due to the outgoing tide. Based on the locations that tags were recovered and where molting occurred, these crabs would be completely out of the water during some portion of the tidal cycle, and would be unable to harden. However, it may be possible for crabs to move into depressions on the marsh surface that contain water, such as a salt marsh tidal pool. This would allow them a place to harden up until the next high tide in order to avoid predation pressure and other negative effects of increased crab density that awaits them in the non-vegetated subtidal creek. Crabs can withstand high water temperatures and salinities and it would be physiologically possible for them to withstand the conditions in these tidal pools over a tidal cycle.

The large crabs used in this study were chosen because of the size constraints of the tag and therefore it is not clear what habitat smaller sized crabs utilize to molt. Kneib (1998) found small sized blue crabs moving onto the marsh surface and Fitz (1990) found that blue crabs move onto the marsh surface to feed. From the very early megalopal life stage to first juvenile instar, blue crabs demonstrate a thigmotactic (touch) response in which they search out a suitable substrate to molt. It is possible that crabs retain this behavior through adulthood and continue to seek out molting habitat based on thigmotactic response.

Although smaller crabs were not harnessed with molting transmitters, crabs from chapter 2 that are assumed to have molted were smaller in size. These crabs also chose creek banks and levees vegetated with *Spartina* to molt. Smaller juvenile crabs may move even further up into the high marsh to molt to avoid predation by larger crabs that use the marsh surface to feed.

Other than the possibility of seeking physical refuge to molt, crabs may migrate out of the creeks and onto the marsh surface to molt simply to escape the high density of crabs found within the creeks. High crab population density is correlated with increased frequency of aggression related injury (autonomy) and cannibalism in the field (Clarke et al., 1999).

Although this study only took place in the summer months, crabs in Georgia continue to grow throughout the year (Wrona, 1997). Crab use of the marsh surface decreases with decreasing temperature (Fitz and Wiegert, 1991) and molting habitat may change with season.

Movement patterns and habitat use prior to molting

Five of the crabs successfully tracked to molting habitat were released very close to ecdysis (red sign peelers) and molted within days (2-4) after release. Their index of meandering was relatively high compared with molting crabs tracked over longer time periods. Wolcott and Hines (1990) found similar variation in the mean index of meander for molting crabs (mean = 0.342, range = 0.069 to 0.847). Two of the molting tagged crabs and other crabs assumed to have molted were tracked longer periods and can be used to best describe movement patterns up to ecdysis. Similar to Wolcott and Hines' (1990) findings, movement decreased significantly several days prior to molting, as they reduced wandering (daily distances traveled). Crabs (from chapter 2) that had not molted had a mean meander index greater than molting crabs (0.533; range 0.021 to 0.995) which indicates that there is some difference in movement, and possibly behavior, prior to molting. The index of meander number for molting crabs was not significantly different from non-molting crabs probably due to variation in tracking time prior to the molt, as well as inherent variation among individuals.

Observations from aquaculture and laboratory experiments indicate that crabs decrease feeding prior to molting (pers. obs). Examination of movement patterns in this study may indicate that near molting crabs switch from foraging behavior to actively seeking out molting habitat prior to molting. In several cases, individual crabs were located in the same area but simply moved onto and off of the creek bank with the tides.

There are still data gaps that exist in order to fully describe where and when blue crabs molt including differences in molting habitat among seasons, and differing sexes and sizes of blue crabs. Controlled experiments (either in the field or lab) could give more insight into blue crab behavior and how and why the process of molting habitat selection occurres. Future studies should also focus on the fate of crabs after they molt. Availability of refuge has been demonstrated to be a limiting factor for population growth in several species of crustaceans (Vannini and Cannicci, 1995).

Determining the molting habitat of blue crabs will be useful for defining essential habitat necessary to sustain the population of blue crabs in Georgia.

Table 3.1. Results of crabs tagged and released with molting transmitter in P.O Creek. All crabs were male.

Crab	***Size (cm CW)***	***Days***	***Result***	***Habitat***	***Distance (m)/day tracked***	***Total Dist (m)***	***Net Dist (m)***	***Meander Index Number***
1	10.7	14	Misfired found as molt	grass	63	883	205.9	.233
2	11.5	7	Lost	unknown	22			
3	11.3	20	Misfired found as molt	grass	57	1145	105.4	.092
4	13.1	1	Dead, found in process of molt	grass		69.5	37.11	.534
5	10.1	3	Dead no molt	mud	72			
6	12.2	18	Misfired found in trap	unknown	35			
7	10.4	3	Molted	grass	67	26.7	5.1	.191
8	11.1	2	Molted	grass	80	27.1	21.65	.799
9	10.3	7	Lost	unknown	13			
10	11.1	3	Molted	grass	14	65.4	25.41	.389
11	9.5	4	Molted	grass	73	22.6	9.71	.872

Table 3.2. Non-molting 'pinger' transmitters that were recovered (after the crab had stopped moving) in the marsh previous to the molting tag study in the Duplin River. These crabs are assumed to have molted.

Crab	Sex	Size (cm CW)	Days	Habitat	Distance (m) /Day Tracked	Total Dist. (m)	Net Dist. (m)	Meander Index Number
5677-2	F(i)	9.2	12	grass	94	1131.71	536.57	.474
348-1	F(i)	9.64	3	grass	72	214.92	108.76	.506
258-1	F(i)	8.45	5	grass	200	1200.43	538.22	.448
339	F(i)	8.48	24	grass	99	2378.25	763.48	.321
348-2	M	8.89	17	grass	66	1185.53	320.38	.270
366-1	M	10.2	17	grass	174	3136.97	61.09	.019
2	M	12.0	9	grass	71	638.28	205.77	.322
5566-1	M	9.78	6	grass	33	196.4	99.24	.505

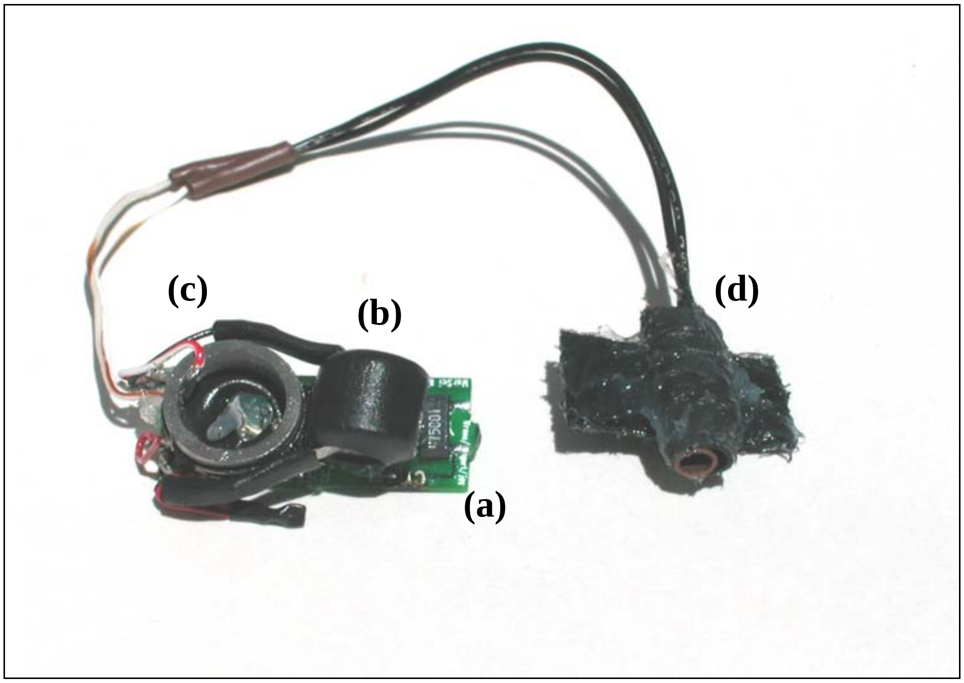


Figure 3.1. The components of the molting tag, the circuit board (a), battery (b) ceramic (c) and the magnetic reed switch (d).

Figure 3.2. Crab tagged with a molting transmitter molting in the lab.

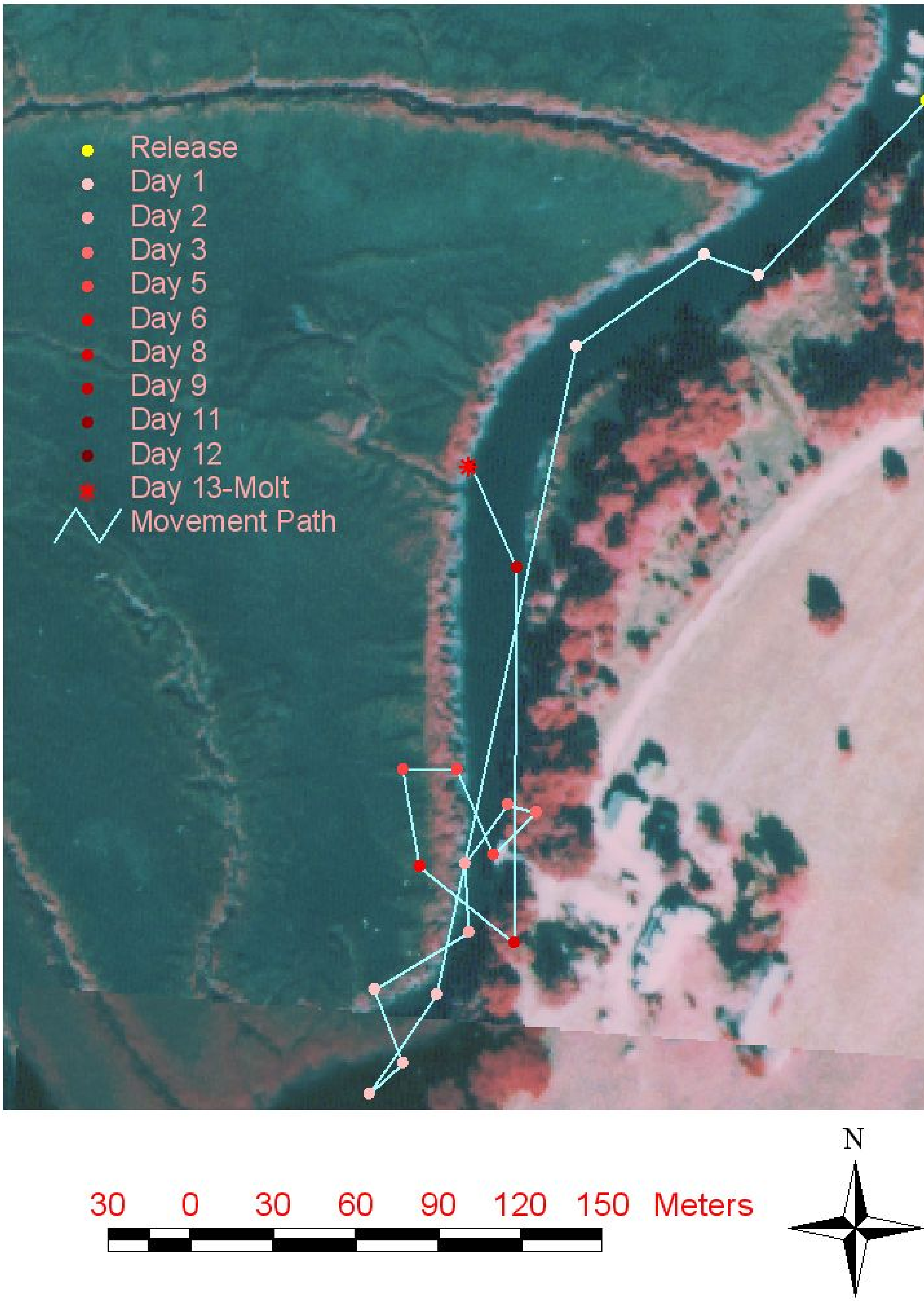


Figure 3.3. Molting crab 1 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 10.7 cm CW that was tracked for 13 days. It traveled a total distance of 883 m before molting in Spartina grass habitat.

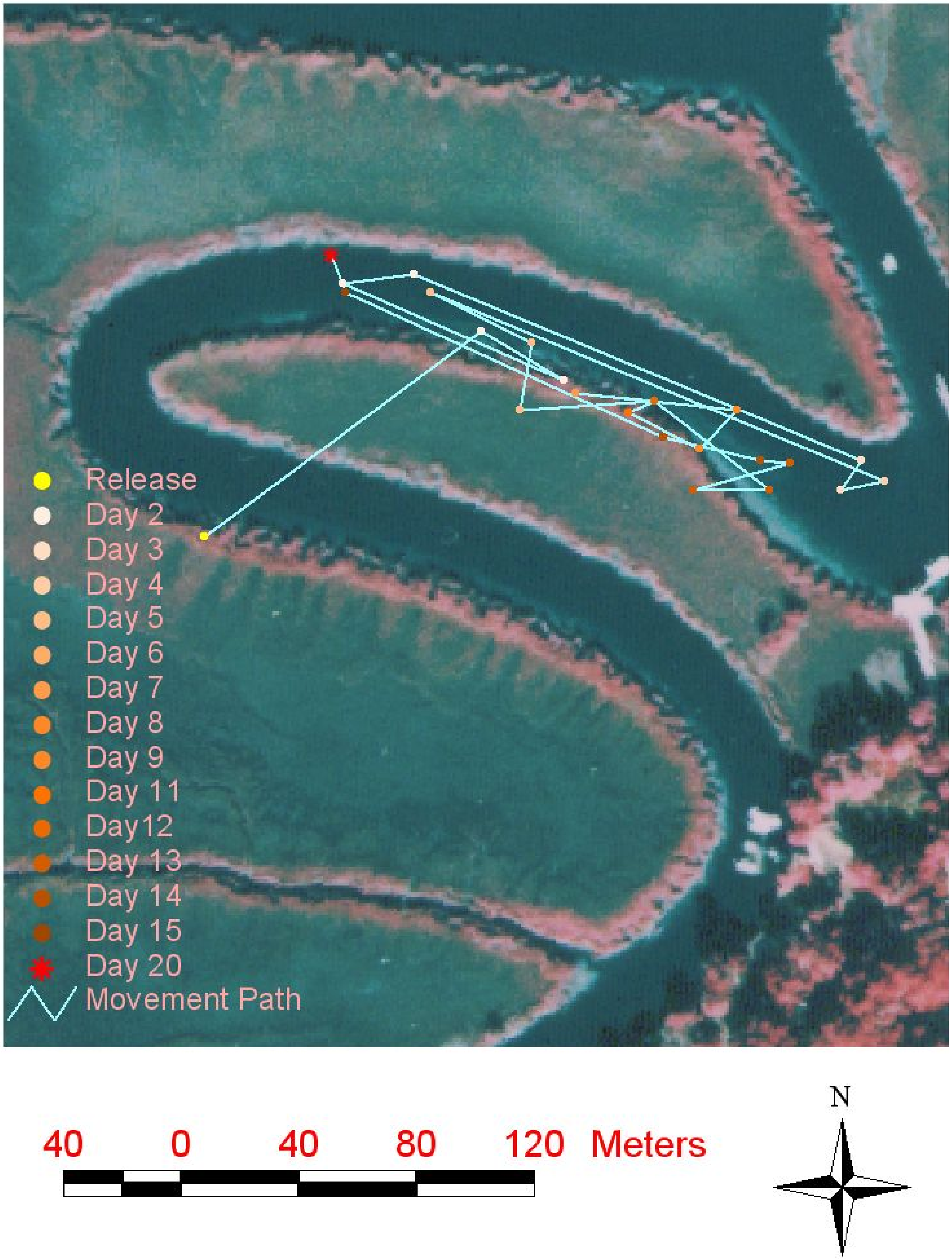


Figure 3.4. Molting crab 3 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 11.3 cm CW that was tracked for 7 days. It traveled a total distance of 1145 m before molting in *Spartina* grass habitat.

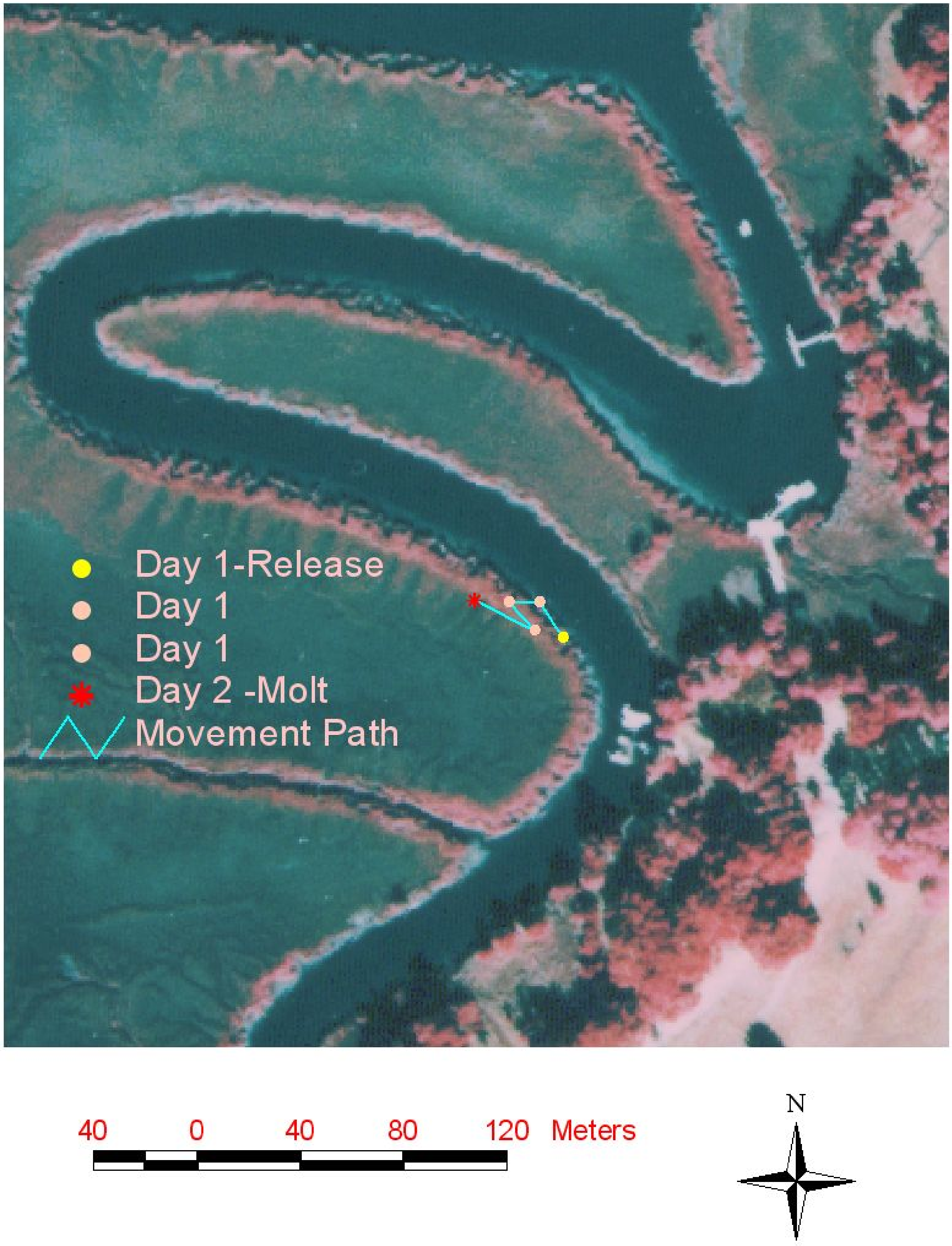


Figure 3.5. Molting crab 4 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 13.1 cm CW that was tracked for 1 day. It traveled a total distance of 69.5 m before molting in *Spartina* grass habitat.

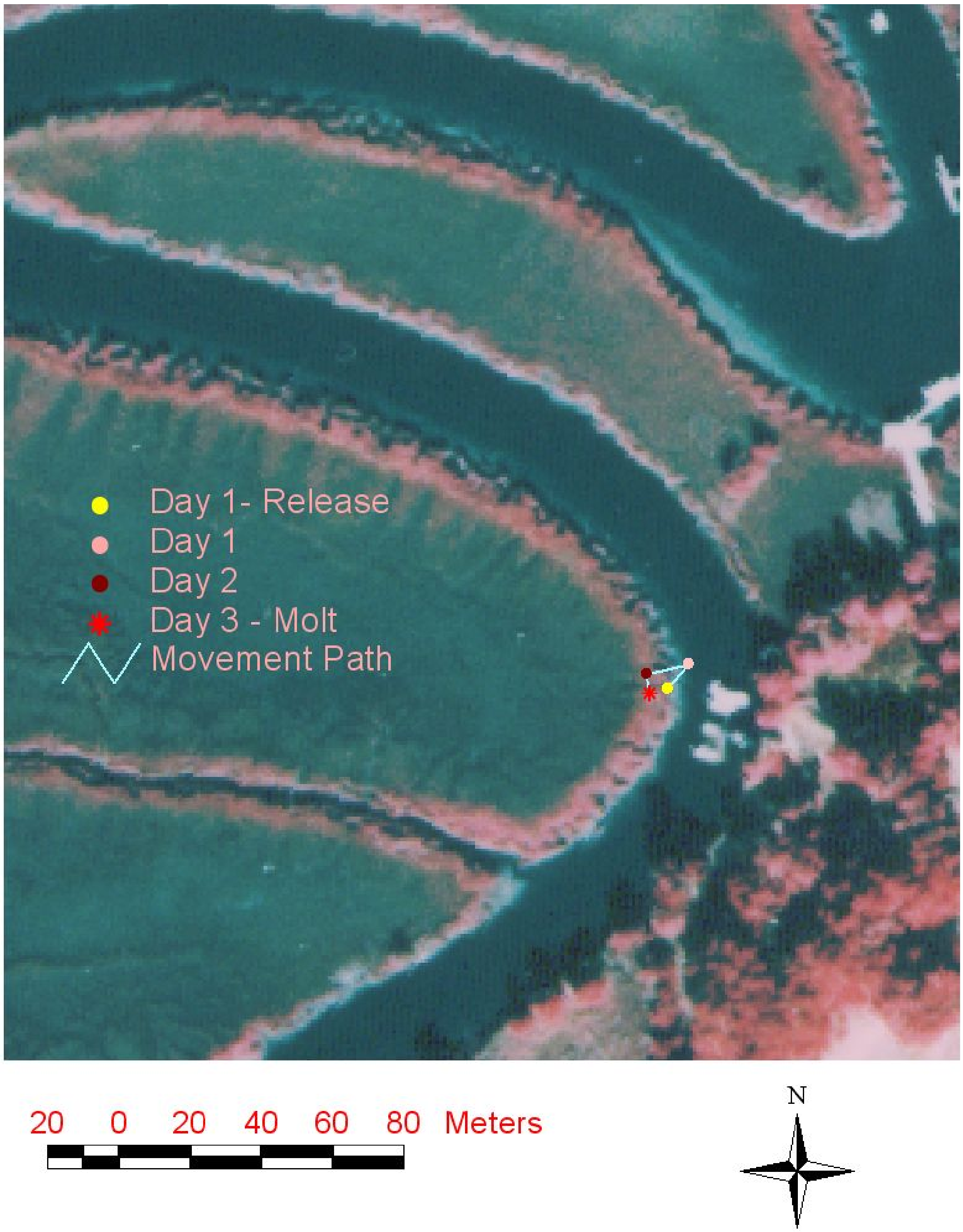


Figure 3.6. Molting crab 7 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 10.4 cm CW that was tracked for 3 days. It traveled a total distance of 26.7 m before molting in *Spartina* grass habitat.

Figure 3.7. Molting crab 8 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 11.1 cm CW that was tracked for 2 days. It traveled a total distance of 27.1 m before molting in *Spartina* grass habitat.

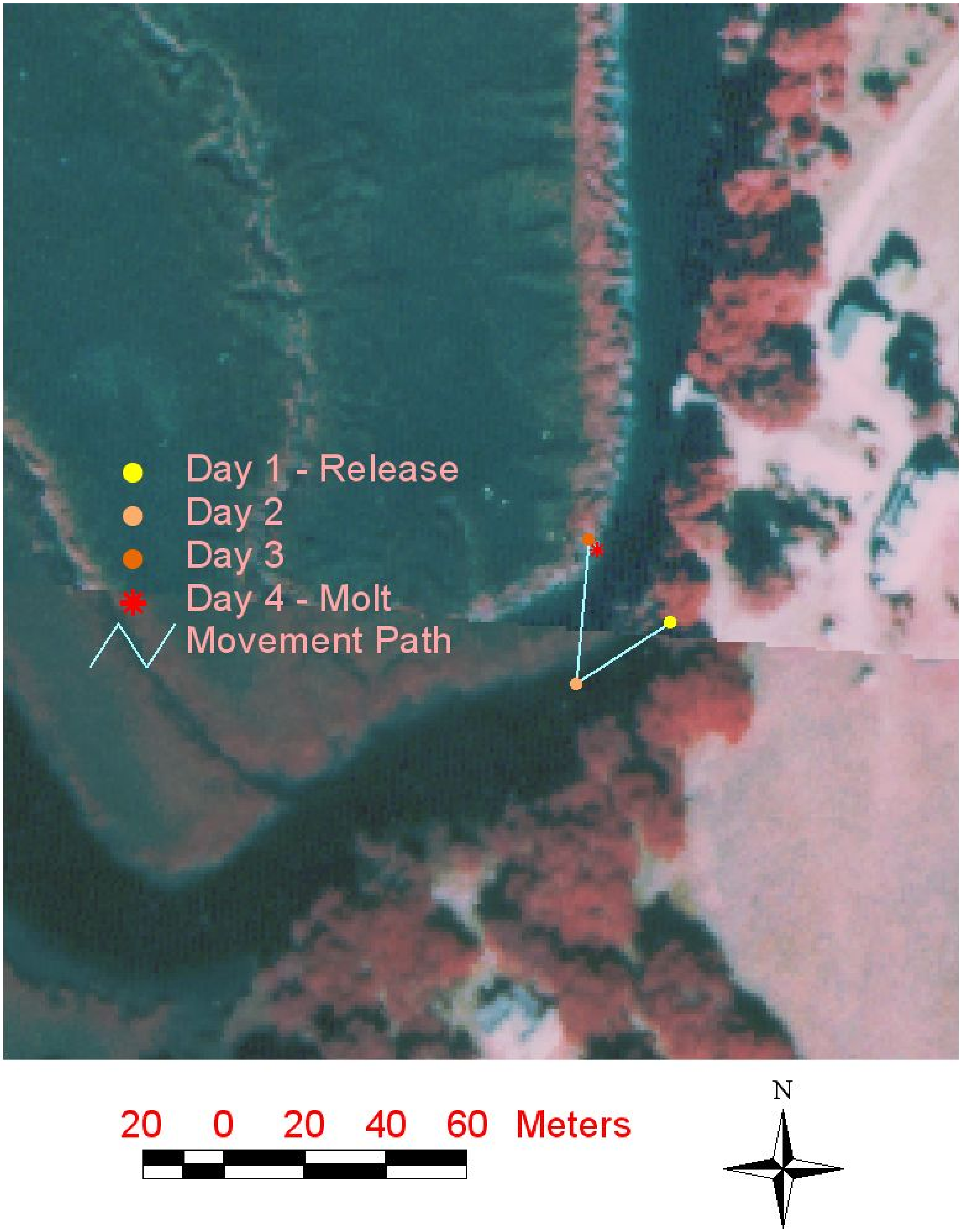


Figure 3.8. Molting crab 10 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 10.1 cm CW that was tracked for 4 days. It traveled a total distance of 65.4 m before molting in *Spartina* grass habitat.

Figure 3.9. Molting crab 11 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 9.5 cm CW that was tracked for 3 days. It traveled a total distance of 22.6 m before molting in *Spartina* grass habitat.

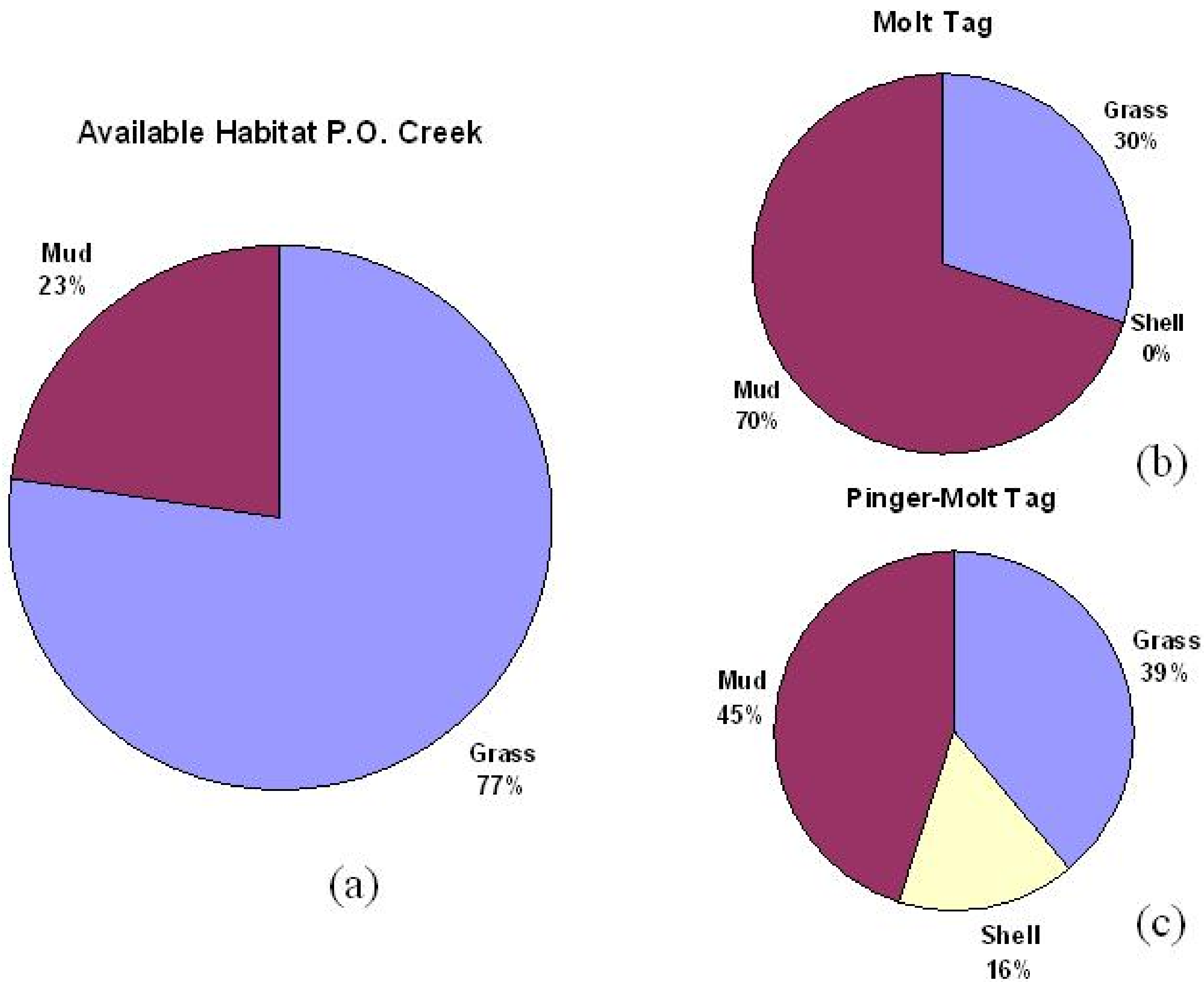


Figure 3.10. Proportion of habitat available in P.O. creek based on GIS analysis (a) and proportion of habitat used by molting crabs (b) and pinger-molt crabs (c) based on location data prior to molting.

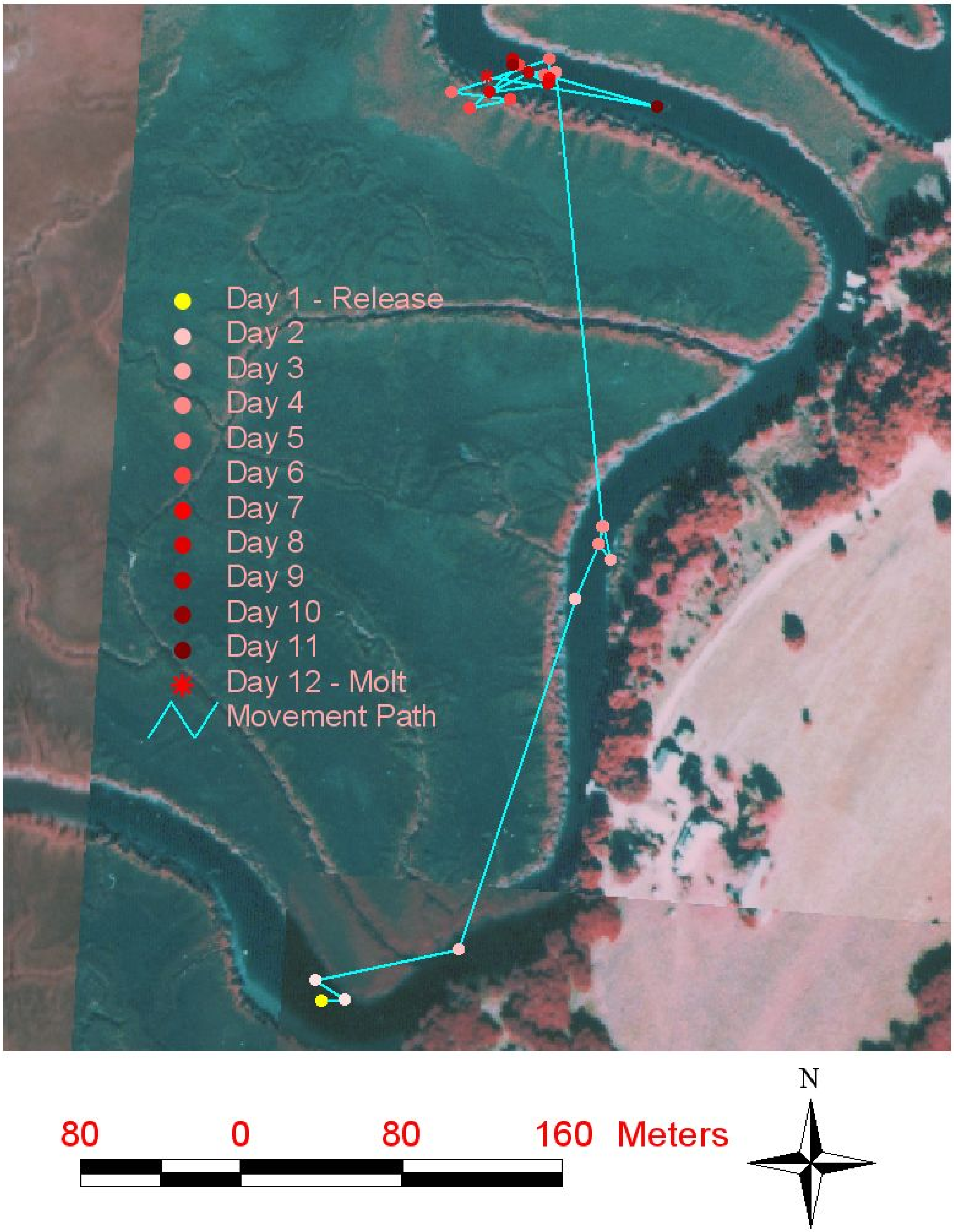


Figure 3.11. Pinger-molt crab 5677-2 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was an immature female, 9.2 cm CW that was tracked for 12 days. It traveled a total distance of 1132 m before molting in *Spartina* grass habitat.

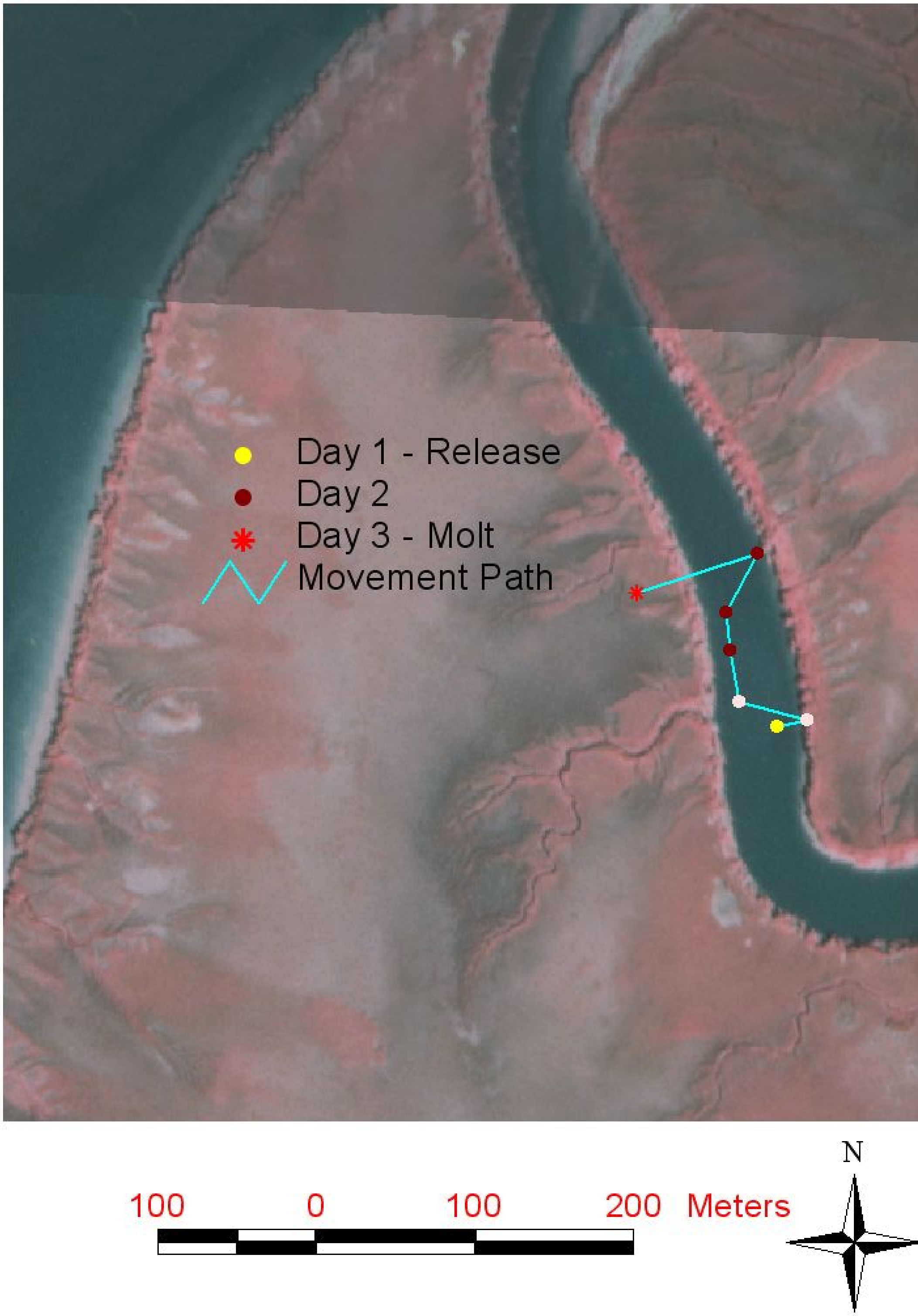


Figure 3.12. Molting crab 348-1 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was an immature female, 9.64 cm CW that was tracked for 3 days. It traveled a total distance of 216 m before molting in Spartina grass habitat.

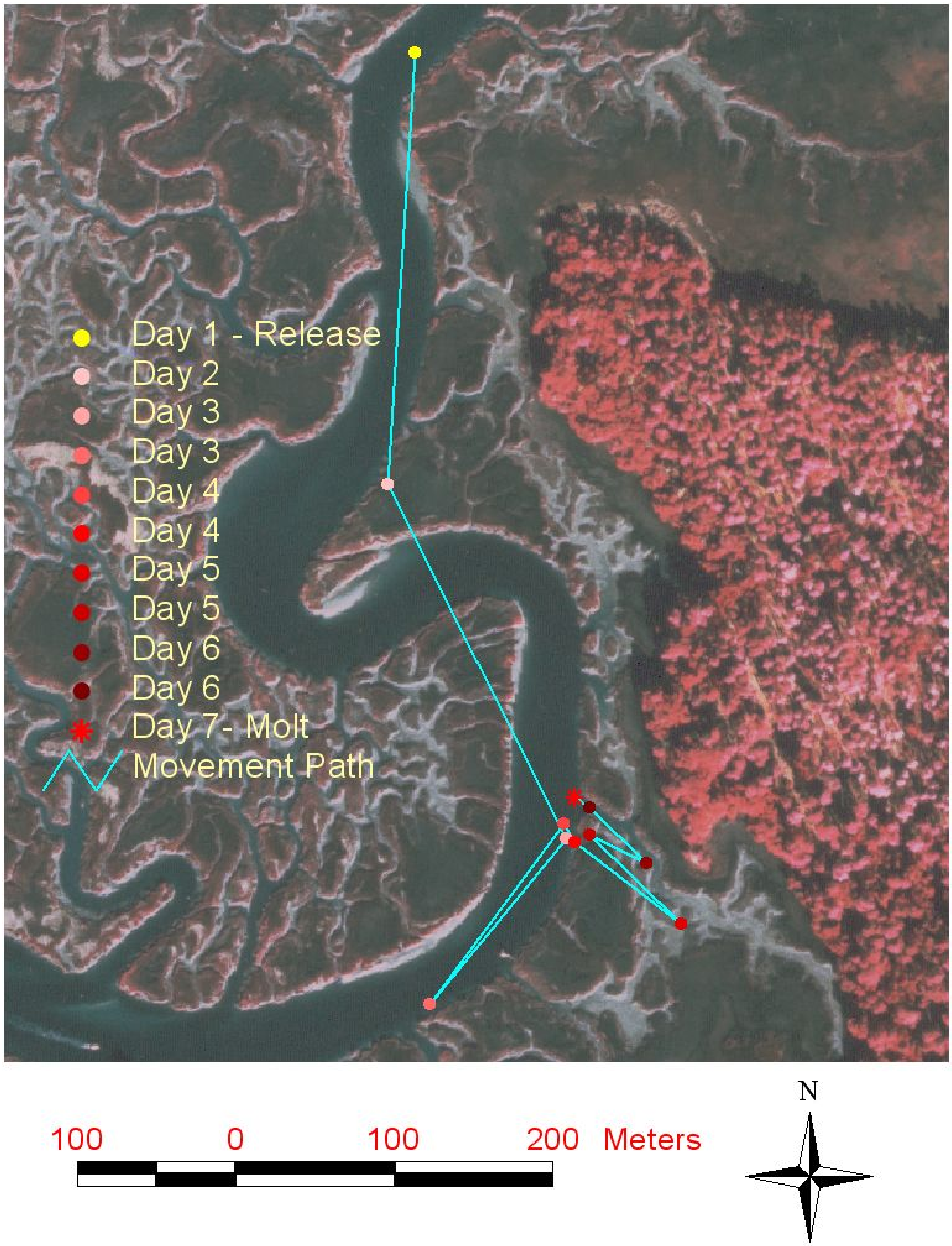


Figure 3.13. Pinger-molt crab 258-1 in the upper Duplin River. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was an immature female, 8.45 cm CW that was tracked for 5 days. It traveled a total distance of 1200.43 m before molting in Spartina grass habitat.

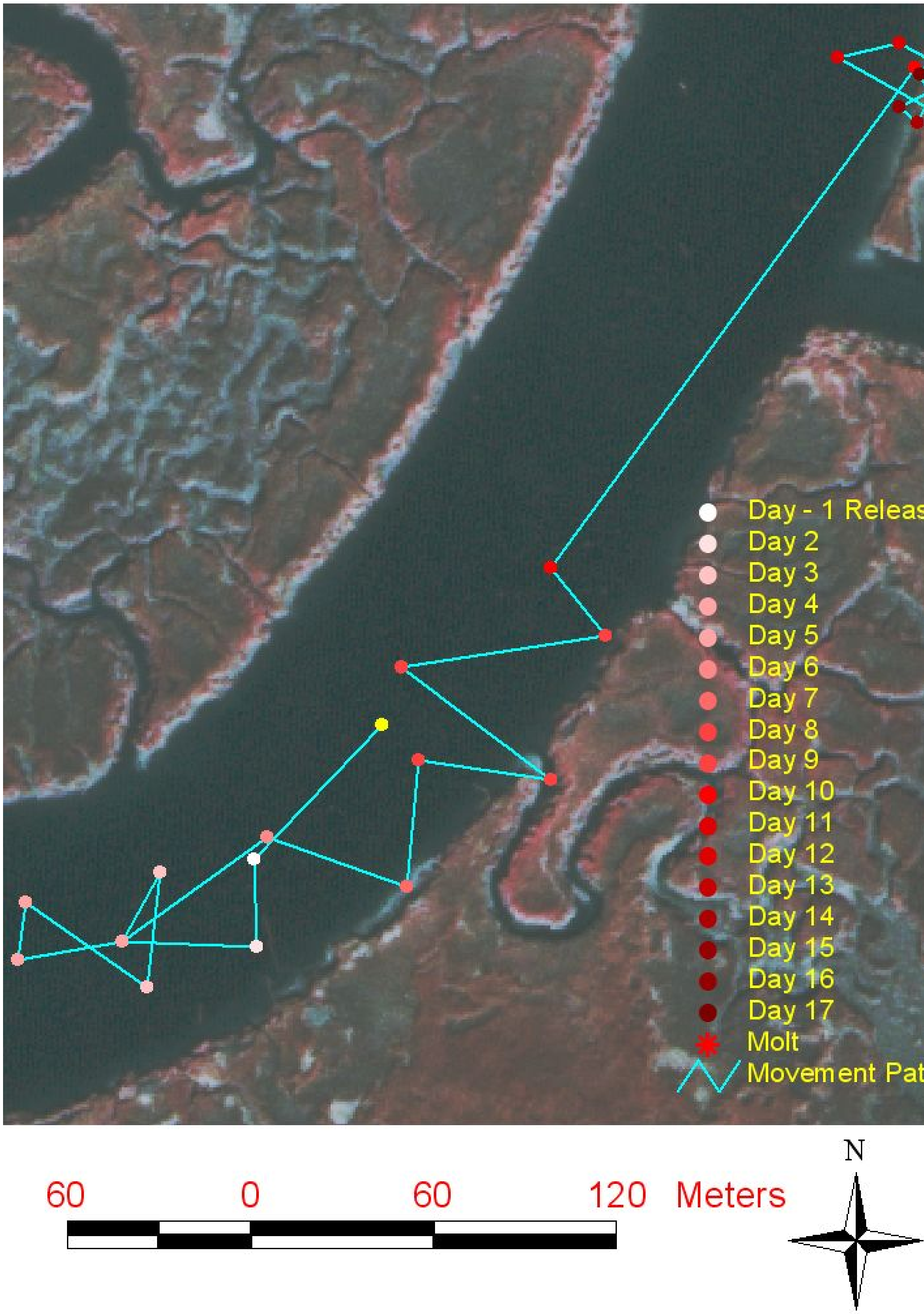


Figure 3.14. Pinger-molt crab 348-2 in the upper Duplin River. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 8.9 cm CW that was tracked for 17 days. It traveled a total distance of 1185.53 m before molting in *Spartina* grass habitat.

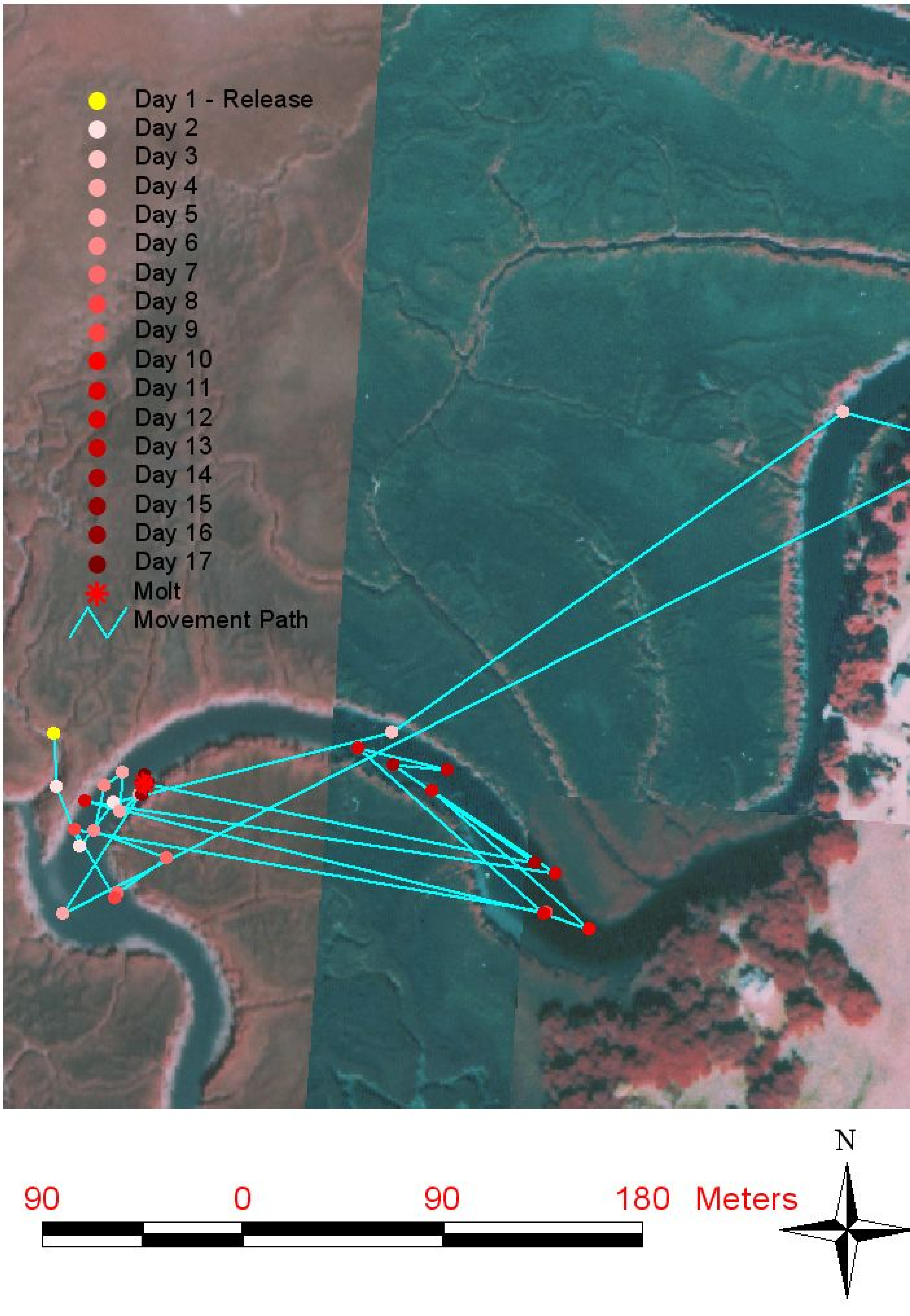


Figure 3.15. Pinger-molt crab 366-1 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 10.2 cm CW that was tracked for 17 days. It traveled a total distance of 3136.9 m before molting in *Spartina* grass habitat.

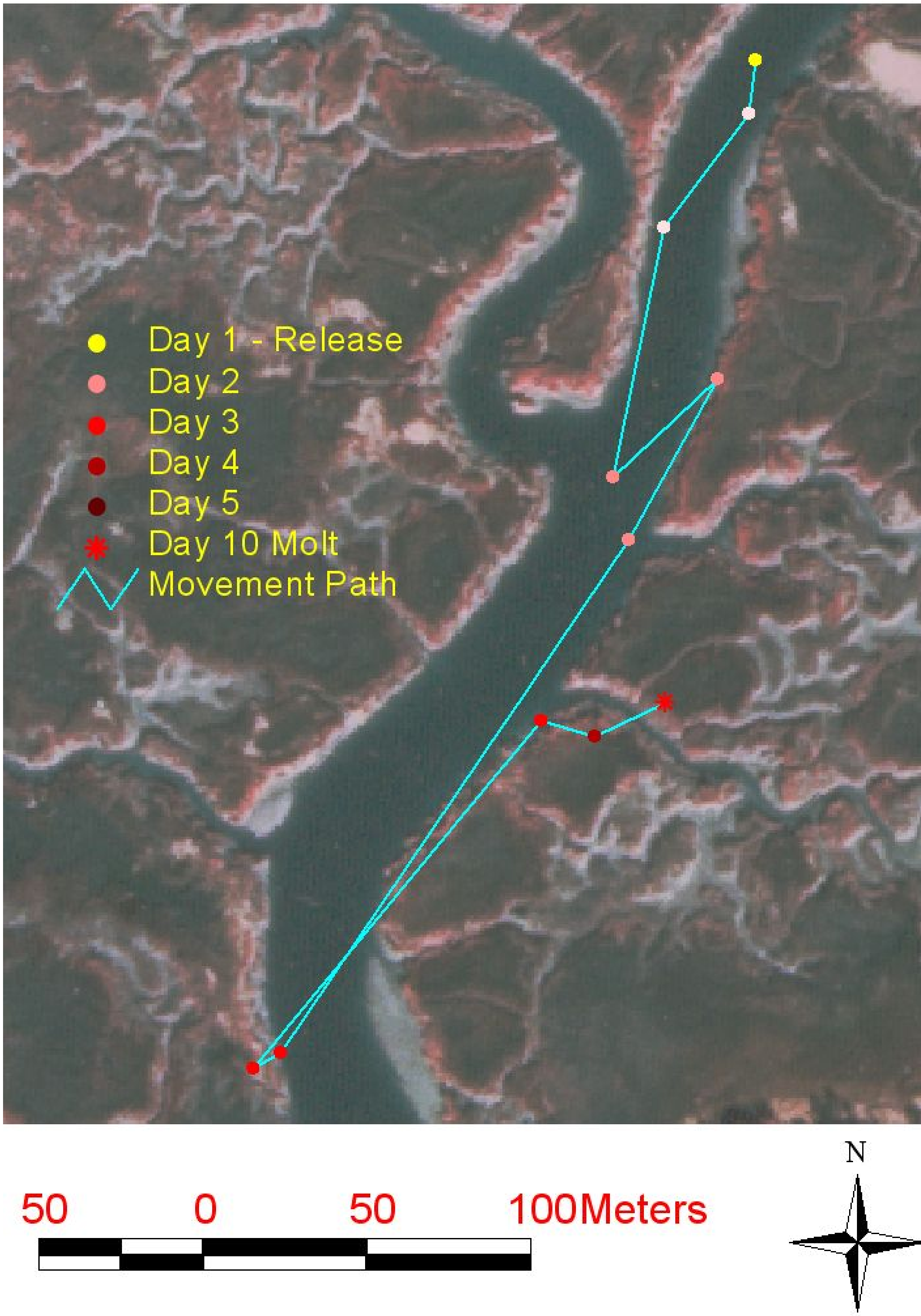


Figure 3.16. Pinger-molt crab 2 in the upper Duplin River. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 12.0 cm CW that was tracked for 10 days. It traveled a total distance of 638 m before molting in *Spartina* grass habitat.

Figure 3.17. Pinger-molt crab 5566-1 in Post Office Creek. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was a male, 9.78 cm CW that was tracked for 6 days. It traveled a total distance of 196.4 m before molting in *Spartina* grass habitat.

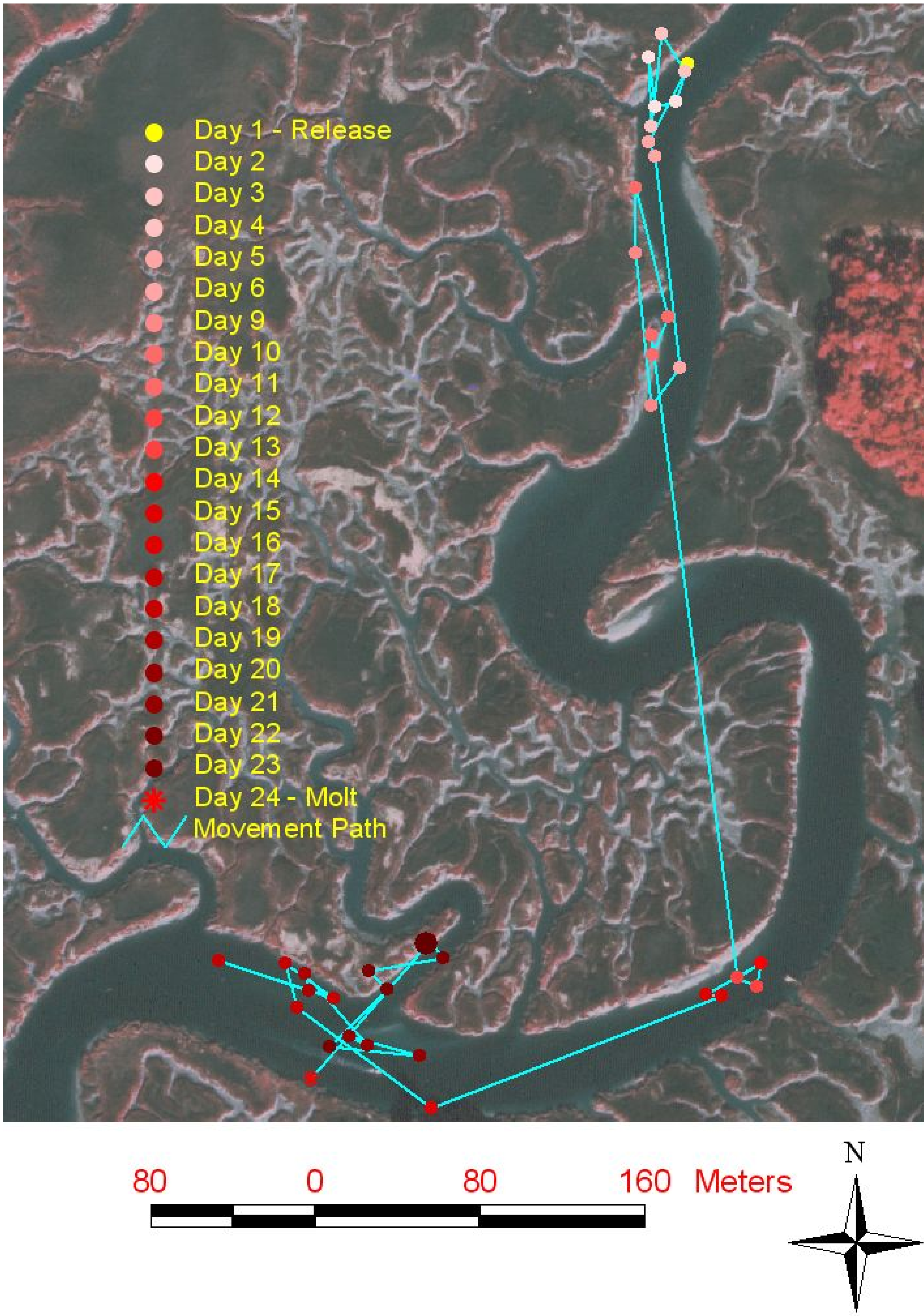


Figure 3.18. Pinger-molt crab 339 in the upper Duplin River. Movement path is not actual movement path but the shortest straight line distance between successive points. This crab was an immature female, 8.48 cm CW that was tracked for 24 days. It traveled a total distance of 2378 m before molting in *Spartina* grass habitat.

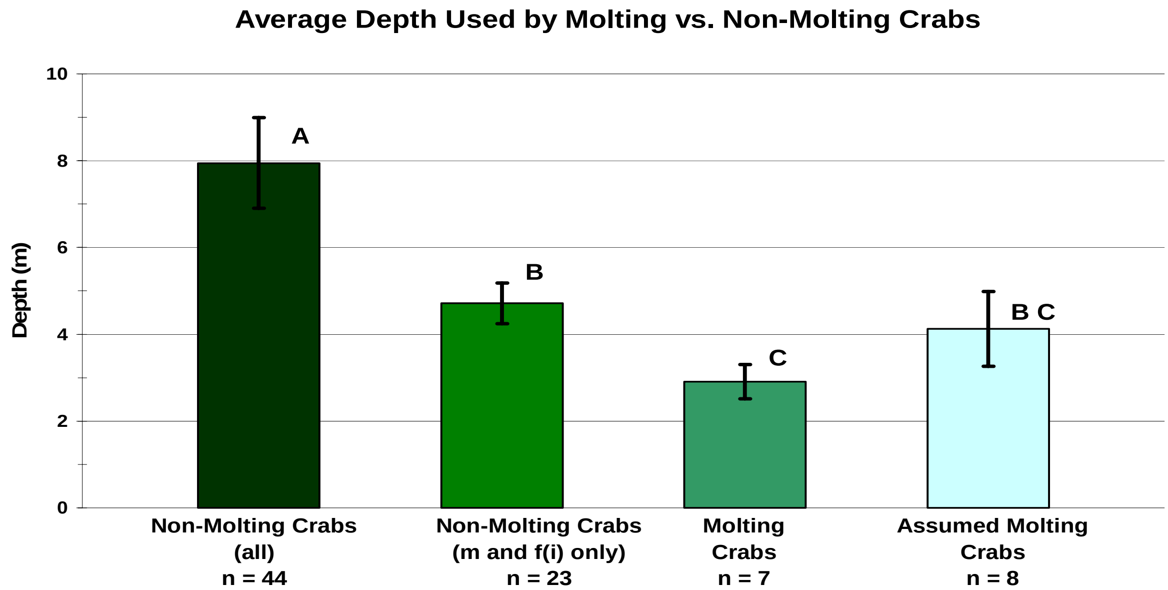


Figure 3.19. Mean depth utilized for non-molting ‘pinger’ transmitters (all sexes combined), ‘pinger’ transmitters (male (m) and immature female f(i) only), ‘pinger-molt’ crabs that were assumed to have molted (data from chapter 2), and crabs tagged with molting transmitters. Means with different letter values (A, B, or C) represent significant differences at the p<.05 value. Black bars represent standard error around the means.

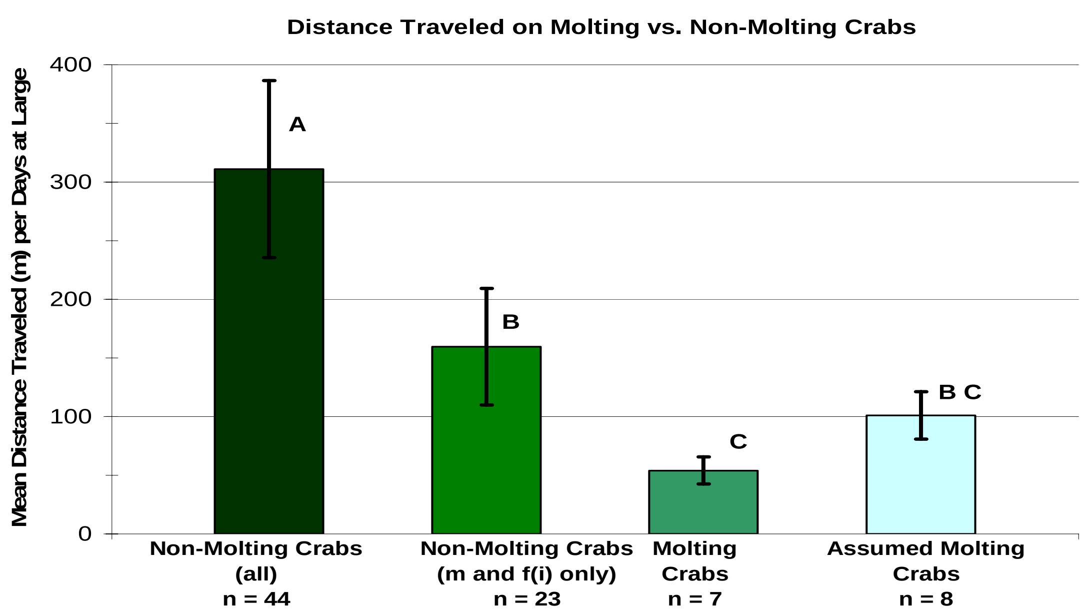


Figure 3.20. Mean distance traveled per day tracked for non-molting ‘pinger’ transmitters (all sexes combined), ‘pinger’ transmitters (male (m) and immature female f(i) only), ‘pinger-molt’ crabs that were assumed to have molted (data from chapter 2), and crabs tagged with molting transmitters. Means with different letter values (A, B, or C) represent significant differences at the p<.05 value. Black bars represent standard error around the means.

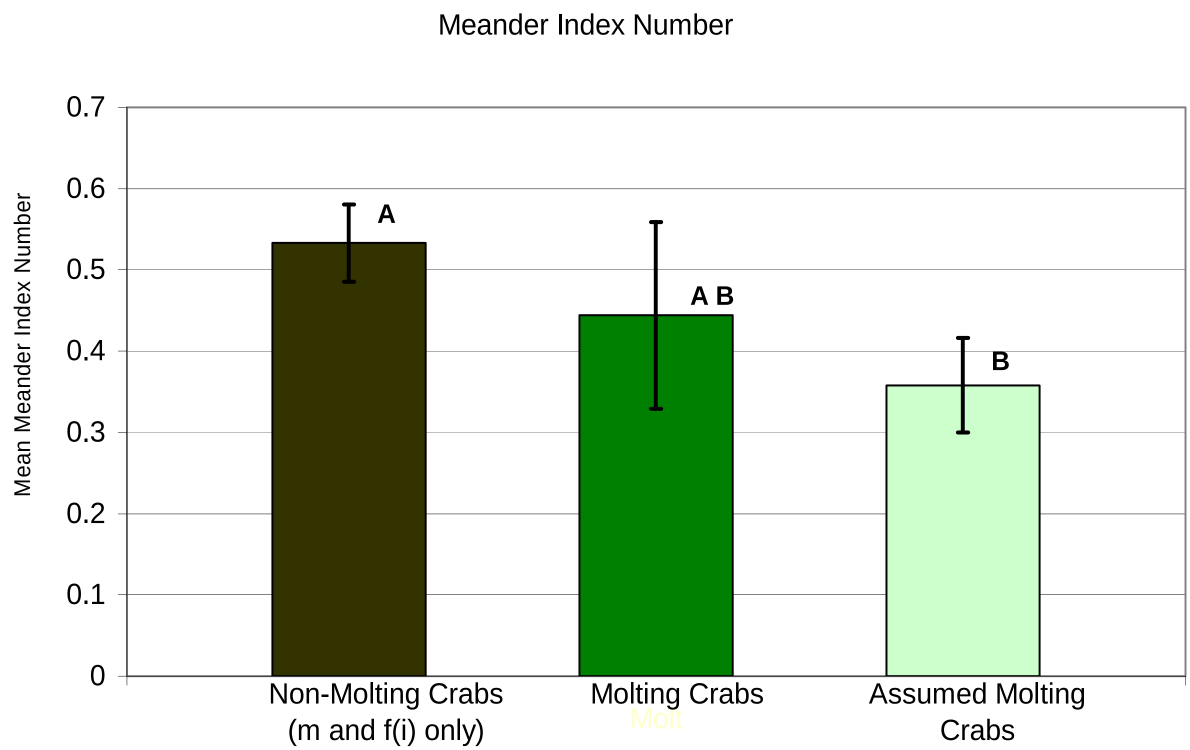


Figure 3.21. Comparison of mean meander index numbers for non-molting crabs, crabs that were tagged with molting transmitters, and crabs that were assumed to have molted (data from chapter 2). The meander index is the ratio of net to total distance traveled, varying from 0.0 for random movement to 1.0 for straight-line movement. Means with different letter values (A or B) represent significant differences at the $p<.01$ value. Black bars represent standard error around the means.

CHAPTER 4

DEFINING AREA REQUIREMENTS AND ESSENTIAL HABITAT OF BLUE CRABS (*CALLINECTES SAPIDUS*) USING A GEOGRAPHIC INFORMATION SYSTEM (GIS)

Introduction

The conservation of habitat is an important component of building and maintaining sustainable fisheries. Salt marshes represent some of the most productive habitats on the planet and this high production supports a wide array of invertebrate and vertebrate animals important to commercial and recreation fisheries. Due to high production rates and the high quality of protein they contain, harvests of animals from estuaries are higher than those from unmanaged terrestrial systems including temperate freshwater lakes (Nixon, 1988).The saltmarsh supplies such ecological functions as nursery habitats for juvenile crabs and fishes and migrational feeding grounds for larger commercial fishes. Coastal salt marshes are dissected by complex tidal creek networks, which create heterogeneous habitats in terms of depth and tidal regime (Desmond, et al., 2000) while the subtidal habitat within this area is a “patchwork” of different habitat types including shallow water creek edge, deep water tidal creeks or rivers, oyster reefs, and non-vegetated sandy or muddy bottom (Micheli and Peterson, 1999).

In Georgia, the marshes are essential habitat for maintaining Penaeid shrimp populations for the multimillion dollar shrimp industry, for blue crabs, and for many anadromous fish that support a growing recreational fishery (Wiegert and Freeman, 1990). Georgia Salt marshes are prolific habitats for blue crabs. Densities of blue crabs in the Duplin River estuary were estimated at .01 per m^2 (Fitz, 1990).

Recent studies in marine seagrass systems suggest that many small seagrass patches may increase overall probability of encounter by larvae or other immigrants, thereby increasing overall colonization of the patch (Eggleston et al., 1998). Hovel et al., (2001) found that fragmented seagrass landscapes serve as significant refuge for juvenile blue crabs and that overall crab survival increased with habitat complexity (shoot density) regardless of patch size.

Anthropogenic fragmentation of habitat is the destruction of contiguous habitat due to human effects such as boat scars on sea grass beds or coral reefs and development of marsh hammocks. This type of habitat loss is rapidly becoming a central issue in conservation policy, promoting legislative and regulatory action aimed at mitigating its impacts on biotic diversity as well as promoting long term research on its effects.

Scientist and natural resources managers worldwide are faced with the challenge of predicting the consequences of habitat loss and fragmentation to the function of marine ecosystems and of adopting appropriate strategies for protecting and restoring marine habitats (Micheli and Peterson, 1999). The Georgia coastline, only 160 km in length, holds 33% of the total area of estuarine marshes on the Atlantic east coast (Wiegert and Freeman, 1990). The Georgia coastline has also sustained much less disturbance due to human activity such as dredging, filling, and pollution, than other coastlines of the Atlantic states. This trend, however, is not predicted to continue (Wiegert and Freeman, 1990). The coastal rate of development in Georgia will exceed the national average over the next 20 years (Wiegert and Freeman, 1990). This coupled with the fact that Georgia's coastal counties are the fastest growing in the state could mean a loss of saltmarsh habitat.

In rapidly growing areas, developers often drain or fill wetlands to create property suitable for development and can file for a permit to do so with the state. Disturbing wetlands through drainage or fill is prohibited unless there is "no practicable alternative." Practicable alternatives can consider cost, existing technology and logistics and can include the acquisition of other suitable property. This provision is outlined in Title 40, Part 230, Section 404(b)(1) Subpart B. During the July 2000 – June 2003 period, the Coastal Marshlands Protection Committee has issued 75 permits, including 36 new community docks. In the past three years the Committee has issued 13 marina leases. This indicates that very little of Georgia's coastline may actually be permanently protected either because it is owned by state or federal park or reserve systems, or preserved with conservation easements.

Despite the global use of marine protected areas, only 1% of the world's marine area is protected. In a paper by Boersma et al., (1999) the definition and management implications of marine protected areas (MPAs) are summarized and reviewed. A MPAs is defined as ‘any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, and historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment’ (Kelleher and Kenchington, 1992). Within the past few decades MPAs have become a widely used form of marine conservation and management. Although the reserves can be helpful in protecting habitat- specific species from over exploitation, highly mobile species do not benefit from MPAs (Boersma et al., 1999).

Currently, the state government of Georgia claims title to all coastal marshlands except those that have been granted by the Crown or the State. In 1970, the Georgia legislature enacted the Coastal Marshlands Protection Act (CMPA) to aid in the protection coastal marshlands. The CMPA created the Coastal Marshlands Protection Committee and provides that “no person shall remove, fill, dredge, drain, or otherwise alter any marshlands in this state within the estuarine area thereof without first obtaining a permit from the committee." To receive a permit, an applicant must demonstrate that a proposed alteration is not contrary to “public interest" and that “no feasible alternative sites exist." The “public interest" is deemed by the statute to include the following consideration: “Whether or not the granting of a permit and the completion of the applicant's proposal will unreasonably interfere with the conservation of fish, shrimp, oysters, crabs, clams, or other marine life, wildlife, or other resources, including but not limited to water and oxygen supply."

Recognizing the importance of habitat to the productivity and sustainability of marine fisheries, the U.S. Congress added habitat conservation provisions to existing legislature. The federal Magnuson-Stevens Act (1996) calls for direct action to stop or reverse the continued loss of fish habitats and may be legislation that can be used to protect estuary habitat in Georgia. Through this federal act, congress has mandated the identification of habitats essential to managed species and measures to conserve and enhance this habitat. The Act requires “cooperation among federal and state agencies, the fishermen, and others in achieving the essential fish habitat (EFH) goals of habitat protection, conservation, and enhancement”. Congress defined essential fish habitat for federally managed fish species as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity." Essential fish habitat may include “aquatic areas historically used by fish where appropriate; substrate includes sediment, hard bottom, structures underlying the waters, and associated biological communities; necessary means the habitat required to support a sustainable fishery and the managed species’ contribution to a healthy ecosystem; and spawning, breeding, feeding, or growth to maturity covers a species’ full life cycle” (EFH Interim Final Rule, 62 FR 66531).

Currently the blue crab is not a federally managed species. It is, however, a state managed and commercially important species within its range along the Atlantic and Gulf coasts of the U.S. The Georgia Department of Natural Resources is currently considering the construction of such a plan in which identification of essential habitat for blue crabs will need to be identified (GADNR per comm.) and results from this study could be used to answer questions about species-area and habitat requirements for blue crabs in Georgia.

According to Micheli and Peterson (1999), effective management, restoration, and preservation of estuarine habitats should take into account interconnections between habitats and with other ecosystem components mediated through animal movements. Traditional catch and release tagging studies give information about general locations of individuals but not about movement patterns of an animal, or its habitat use. Methods used elsewhere to determine habitat use of blue crabs (block nets, suction samplers, etc.) cannot be used in Georgia because of large tidal amplitudes and fast flowing currents. Ultrasonic telemetry has recently been used with blue crabs to assess foraging behavior, agonistic behavior, migration, and habitat choice of molting blue crabs in systems other than Georgia (NC: Carr et al., 2003; VA: Clarke et. al, 1998; Hines et.al., 1995). Results of the use of telemetry in the determination of movement and habitat use in Georgia are discussed in Chapters 2 and 3.

Positional data sets generated during telemetry studies can be large, and may contain spatial patterns difficult to discern patterns without spatial analysis tools. A Geographic Information System (GIS) is a tool specifically designed to manage and analyze spatial data. Using GIS can show locations of crabs by mapping them in their habitat and can be used to answer the questions of: how much and what types of habitats do blue crabs they use, and how are crabs distributed throughout the estuary with regard to size, sex, and seasonality. The scale of habitat use of a species can be determined by the lifetime home-range of the individual (Eggleston et al., 1998). There is a considerable amount of data that can be collected and used to analyze home-range size, shape, and internal configuration (Harris et al., 1990). Various analysis techniques used to define home-range have been reviewed by Macdonald et al., (1980), Jaremovic and Croft (1987) and Worton (1987).

The operational definition of an animal's home range is quite variable, but a simple definition is the area of an animal's normal travels (Kenward, 1987). The most widely published method of home-range calculation is the minimum convex polygon or MCP (Mohr,1947; Harris et al., 1990). The MCP is the smallest polygon that will enclose all of the location observations (fixes) of an organism. It can be considered as the space that an animal uses and traverses. It is the only technique that is strictly comparable between studies and is more robust when the number of fixes is low. This technique, however, suffers from sample size effects, is greatly affected by outliers and since the polygon boundary includes all the fixes, the range size is strongly biased by peripheral fixes and the resulting range may include large areas that are never visited by the organism (White and Garrott, 1990). The MCP method gives no indication of the intensity of range use.

Probalistic methods of home-range analysis attempt to asses an animal's probability of occurrence at each point in space. These are often called utilization distributions; each cell within a probalitstic home range has an associated probability that the animal is at that location (Worton, 1989). The kernel home-range method is a form of moving average analysis and represents the internal structure of an animal’s home range (Worton, 1989). The technique examines the innermost areas of an individual’s home range by selecting 50% of locations and creating a core area of greatest activity. Contours can be drawn at any stage that relate to the percentage of fixes enclosed by clusters present at that time. Because of the method of calculation, it is possible to have more than one center of activity, and the technique is useful for calculating core areas when the contour lines are used for defining areas of high and low usage within the home range. One disadvantage of this technique is that it can be difficult to compare between studies because of the use of different sets of algorithms (Harris et al., 1990). This chapter attempts to use both MCP and kernel home range methods of analysis to determine species-area requirements of blue crabs in a Georgia estuary in an attempt to define essential fish habitat.

Methods

GIS Analysis

All data, positional fixes, depth, substrate type, and molting locations of crabs were taken from Chapters 2 and 3 and mapped using ARCINFO (ERSI, 1983). An ArcView® GIS analysis tool called the Animal Movement Analysis Extension (Hodge et al., 1999) was used to determine MCP and kernel home ranges of all crabs tracked. A minimum convex polygon (MCP) was determined from the location points in order to estimate total areas used by crabs during tracking. The MCP’s were separated based on molting vs. non-molting crabs, and by sex and ontogenetic stage (male, mature female, and immature female).

The MCPs that were created for both molting and non-molting crabs were used as a clipping feature with ArcView's X-tool in order to determine the total amount of habitat found within the MCPs that were used by these crabs. A Kernel cluster analysis was performed to compare size of area use with MCPs.

These parameters were used to determine possible differences in the area extent of habitat use between crabs of varying sex, ontogenetic stage, and size. The dependent variable mean area of MCPs did not pass tests for normality or homoskedasticity. Because the data were not normally distributed, the test was run on the ranked values. A Proc GLM analysis of variance was used to test the hypothesis that there was no difference in the size of area used by molting vs. non-molting crabs and between crabs of different ontogenetic stages. A Proc GLM analysis of variance was performed to test if area use was different between ontogenetic stages within non-molting crabs only.

Results

Area Utilization Analysis

Minimum Convex Polygon (MCP) home range analyses were done on crabs of varying sex and ontogenetic stages to determine how much area they use and what types of habitats exist within those areas. A total of 40 non-molting crabs were considered for use in the MCP and kernel home-range analysis (table 4.1). Five crabs that were located less than three times were excluded from analysis. Out of the crabs that did molt, 18 were included in analysis (table 4.2). There were significant differences between MCP calculated areas between molting crabs (mean area = 0.367 hectares) and non-molting crabs (all sexes combined, mean area = 49.081) hectares and non-molting crabs excluding mature females (mean area = 11.981 hectares; $p<.0002$; table 4.3) and those differences were significant between sexes ($p<.02$; table 4.3).

There were significant differences between mean MCP calculated areas use between crabs that were molting, all crabs that were non-molting, and non-molting male and immature female crabs only (figure 4.1). Non-molting mature female crabs used the largest areas averaging 111.8 hectares, immature females used on average 21.5 hectares, and non molting males 8.4 hectares. These averages were significant at the $p<.0004$ level (figure 4.2). Molting immature female crabs used a larger average area (1.03 hectares) when compared with molting male crabs (0.17) and the difference between the means was significant at the $p = .001$ level (figure 4.3).

Figures 4.4 - 4.6 are plots of crab's MCPs that were near the average for their sex class. The MCP of one immature female crab (crab number 339) that was tracked through an entire ecdysis cycle is mapped in figure 4.7.

Kernel home range analysis ranges showed that mature female crabs used the largest areas (the 95% frequency of occurrence area was 1157 hectares; figure 4.8). Male crabs used smaller areas (95% frequency area = 431 hectares; figure 4.9) and immature females the smallest areas (95% frequency area = 264 hectares; figure 4.10).

The kernel home-range of the immature crab that was tracked during one entire ecdysis cycle (crab 339) is mapped in figure 4.11.

Habitat Use

When all of the MPCs for molting crabs were combined, the 18 crabs home ranges included a total area of 2.33 hectares of mud habitat and 7.13 hectares of grass habitat and 0.06 hectares of oyster reef habitat (figure 4.12). Most of the molting crabs were located within Post Office Creek where oyster reefs have not been mapped. For all non-molting crabs combined (35 crabs), the home ranges included a total area of 487.1 hectares of mud habitat, 7.1 hectares of grass, and 3.8 hectares of oyster reef habitat (figure 4.13).

Discussion

With the use of GIS, I was able to organize a large data set of georeferenced positions and habitat parameters in a simple way that facilitated easy retrieval for analysis. The Animal Movement extension extended the capabilities of ArcView GIS in order to analyze movement patterns and habitat use of blue crabs measured by the use of ultrasonic telemetry.

Home range analysis is an important method of investigating behavioral and ecological questions. Collecting telemetry data on blue crabs to use in home-range analysis was a time-consuming and expensive process which is reflected in the small numbers of crabs tracked in this study. Home-range estimates are seldom complete representations of area use for an entire population, especially in this case where few individuals were tracked and data points were not collected over long time periods or over all seasons.

Therefore, even though analysis is useful, conclusions about entire populations must be made cautiously.

The differences in home range sizes between molting and non-molting crabs, although significant, were probably due to the relatively short amount of time that the molting crabs were tracked. A home range determined by only 1 day of tracking is most-likely meaningless and may only give an indication of area use prior to molting.

The use of minimum convex polygons overestimates area used by blue crabs by incorporating habitats not surveyed, such as upland maritime forests. In the example of the mature female mapped in figure 4.4, the MCP boundary is forced through upland forest where that crab was unable to travel. The bounding boxes don't follow the available habitat boundaries. Kernel analysis run through the animal movement extension allowed good visualization of use where probability ellipses are centered on clusters of activities and tend to identify the actual habitat that was used by the crabs.

The MCP habitat analysis showed that non-molting crab's home ranges were mostly made up of mud, grass and oyster reef habitat in similar proportion to what was available in the Duplin River. Molting crabs MCP's are also comprised of habitat similar to that available in the areas that they were found. The areas where molting crabs were found had a higher proportion of grass available, and since they use marsh grass as molting refuge. This may indicate their reason for remaining in these areas to molt. The MCPs used for habitat analysis probably over-estimated the amount of marsh or grass habitat used by the crabs at times other than high tides. At high tide the marsh is covered with water and habitat becomes interconnected and grass area use estimates are probably closer to the ones given here.

The use of telemetry in this system was successful and has generated the only data available that could be used to generate a home-range estimate of blue crabs in this Georgia estuary. Future data collection using ultrasonic telemetry could focus on tracking mature female crabs to measure the full extent of their home range, and whether or not they return to the estuary after they release their eggs.

Species-Habitat Relationship of Blue Crabs

Blue crabs are a very mobile species and use a large array of habitats depending on sex and ontogenetic stage. Several models examining marine reserve areas as fishery management tools have suggested that determining an effective reserve size is highly sensitive to a species' mobility (Boersma, 1999). Clarke (1996) and Lauck et al., (1998) suggest that reserve size needs to be 50-90% of total habitat for species that are sensitive to overexploitation. Kenchington, et al., (1990) examined the relationship between the degree of protection of a MPA as a function of site fidelity and dispersal distance of the species of interest. Species with high site fidelity and low dispersal abilities are protectable even by small reserves, while species that have low site fidelity and high dispersal abilities are un-enclosable and could not be protected by a MPA. Only molting blue crabs in this system had some degree of site fidelity and could be categorized as a species stage that may be protectable by MPAs but only at this certain ontogenetic stage.

Sustained exploitation depends on sustaining a maximal yield without depleting the resource,which is the optimal size at which a population can be harvested where the population's rate of re-growth is positive and remains maximal. In theory, maximal yields can be obtained from populations by removing those individuals that are least likely to contribute to the population. A MPA for blue crabs should then focus on protecting those members of the population that are most likely to contribute to the population.

Populations of blue crabs are usually found in very stochastic environments where disturbance occurs frequently. They are considered 'opportunistic' species and are very quick to reproduce (at a very young age) and produce many offspring. One male can reproduce with several females but each female has only one opportunity to contribute to the future population, only mating once.

One of the most important management tactics in fisheries is to protect the individuals that spawn, and in the case of blue crabs this would mean the sponge females. Georgia (along with the rest of the Atlantic coast) blue crab populations appear to be recruitment-limited (see Orth et al., 1990). Settlement of megalopae appears to be low. Therefore increasing the reproductive output of the population would hopefully increase the amount of megalopae surviving and thereby increase the population. Protecting the number of spawners is one good management objective that could clearly help population numbers when environmental conditions are unfavorable or variable (such as drought years or years of high crab disease).

Females that are in the process of brooding their eggs (sponge females) are especially vulnerable to fishing since the egg mass is fragile and easily damaged or removed in crab pots or trawl nets. Sponge females are usually found in Georgia estuaries in early spring (March through May). Many female sponge crabs are pulled up as bycatch in shrimp nets during this part of the shrimp season. Although the females are returned, there may be significant mortality associated with this type of disturbance, and definite damage to the egg mass that the female is carrying.

As early as 1996 the taking of sponge crabs was identified as a concern of commercial crabbers in a sociological study of the blue crab fishery in Georgia (McIntosh, 1996). This issue was looked at by the Coastal Resources Division of DNR who concluded that there was no scientific evidence to indicate that restricting or limiting the harvest of sponge females would increase stock abundance (see Clarke, 1998). However, the taking of sponge females was banned in 2003. Perhaps the protection of the sponge females could be enhanced by creating MPAs in regions where they are known to migrate through and to for larval release. This is the first year in Georgia that the state has banned the taking of all females from January-April during the time that they may have the greatest chance for reproductive success. Since so many crabbers did harvest female crabs (both the adult and immature peeler females), simply banning their take may be forcing crab fishermen to increase fishing pressure on males. Creating a MPA for blue crabs could help preserve the population by creating areas of favorable habitat for crabs, free from exploitation or the disturbances associated with fishing.

The effects of harvest on peeler crabs, or immature crabs preparing for their terminal/mature molt has not been studied in Georgia. The fishery itself has gone unregulated, and the amount of peeler crab fishermen has yet to be determined. Only one crab identified as a peeler crab was tracked with success and so little conclusions can be made about its area requirements. More tracking studies done on this type of immature female crab could help identify if these crab have special area requirements different that other blue crabs which might be essential in determining a MPA.

Based on the area use of females in this study, a large nature reserve or MPA could benefit blue crab populations in Georgia. This area would have to be considerably large, perhaps even the entire size of the Duplin River Estuary. The Duplin River Estuary is part of the Sapelo Island National Estuary Research Reserve and so in this author's opinion it would only make sense for the State of Georgia to designate the Duplin River Estuary as off-limits to fishing. Since the exact location of crab larvae dispersal is unknown, it is unclear which estuary would benefit from protecting spawners within the Duplin system. Ballantine (1997) summarized some basic constraints of a marine reserve to include representation of habitats, replication of habitats, and a network of multiple reserves that function as a metacommunity. Only one MPA may not benefit the population of blue crabs in Georgia but rather a network of designated MPAs, representing all habitat types needed would be desirable.

Essential Fish Habitat for Georgia Blue Crabs

Essential habitat for blue crabs in Georgia is an extensive area of water and multiple substrates depending on sex, age, and reproductive stage of the crabs. A typical life cycle includes megalopal recruitment into the estuary from the coastal shelf region where the larvae develop. Once inside the estuary the megalopae settle onto a substrate where they molt into first stage crabs. The crabs spend their immature period in the nursery habitat of tidal creeks and rivers, and the marsh surface feeding and growing until they are sexually mature. At sexual maturity females mate with male crabs and then migrate out to higher salinities found in bays, sounds, or along barrier island beaches. Males remain in the creeks and rivers continuing to feed, grow, and mate with other females until they migrate out to deeper water during colder water months. Once the females are in higher salinity waters they can hatch several batches of eggs, the eggs hatch as zoea, and the zoea are transported out to the shelf waters where they develop into megalopae.

Each of these life history stages can be impacted by environmental change and human activity and add a level of habitat complexity to the definition of essential habitat for blue crabs. In the larval stage (zoea and megalopae) the crabs are vulnerable to water quality. Nutrient loading of estuaries that discharge water out the shelf could produce HAB whose toxins or high oxygen demand could adversely affect the developing and feeding crab plankton. Once inside the estuary the megalopae need specific substrates to settle on, but these substrates in Georgia are unknown.

In the juvenile stage crabs could be affected by loss of nursery habitat and the degradation of water quality due to human activities. Juveniles need adequate physical habitat and SAV, oyster beds, and shallow waters have all been shown to be important in juvenile growth by providing food sources and refuge from predation.

Even though blue crabs are excellent osmoregulators, it has been shown that their optimal growth rates occur in salinities of 25 psu and salinity changes in the estuary could have indirect effects on crabs (increasing predation, reduction in food, or increase in disease). Changes in salinity can be due to either natural causes (such as drought conditions) or anthropogenic (the alteration of riverine freshwater flows or loss of underground seepage into the estuary). Growth and survival of juvenile crabs is also dependent on D.O. in the water which could be altered by input of nutrients, increases in temperature, or HABs.

In the adult stage (or for this example, legal size) the crabs are most vulnerable to mortalities due to fishing, water quality (changes in D.O. and salinity), and disease (which is probably related to the previous variables). Females that are in the process of brooding their eggs (sponge females) are especially vulnerable to fishing since the egg mass they carry is fragile and easily damaged or removed in shaken crab pots or trawl nets. Changes in salinity could also affect their migration patters, which would affect the number of larvae that make it out to the shelf.

Within the Duplin River saltmarsh, shallow water habitats are essential for small and large sized, male and reproductively immature crabs. Reproductively mature female crabs utilize deeper habitats as they migrate to higher salinity waters utilizing both the river and its edges along the way. The importance of the marsh surface to blue crabs is evident especially for crabs going through the molting process and should be included in the description of essential fish habitat for all crabs in Georgia.

Marsh grass in this system is essential to blue crab as habitat for both non-molting and molting crabs. Non-molting crabs utilize the marsh surface to feed (Fitz and Wiegert, 1991) while molting blue crabs may come up into the grass in search of molting refuge.   Other habitat types such as oyster reefs were also frequently used by blue crabs and should be included in a definition of essential fish habitat. Implications about habitat choice and habitats that are critical to survival and reproduction can be made only by experimentation and should be further studied in this system to help built the definition of EFH for blue crabs.

Habitat mapping is crucial in a project of this kind. It is important to look at habitat use based on the availability of those habitats. The Duplin has not been extensively surveyed and this basic analysis represents the best scientific data available to date.   Further refined mapping of the Duplin River estuary, including mapping of the benthos, would add to a more complete understanding of blue crab habitat use within this system.

Blue crabs are considered to spend the larger proportion of their life cycle with the saltmarsh. There is, however, a considerable amount of habitat that is used outside of the saltmarsh system that should be included in a complete definition of essential habitat. Mature females migrate out into deeper sounds and sandy beaches to release their larvae, while larvae drift offshore in the coastal shelf waters to develop. Other areas and habitats that crabs use over winter months in Georgia are unknown and should also be considered. Indeed the definition of essential fish habitat becomes complex and very large scale when considering all of the life stages of this important species. The designation of blue crabs as a federally managed species could result in an additional means to protecting a wide variety of habitats and large areas of coastal habitats that currently remain unprotected in Georgia.

Table 4.1 Results of minimum convex polygon areas of non-molting crabs tracked in the Duplin River Estuary.

Crab	Sex	Area use (hectares)
246	f(i)	0.63
337	f(i)	95.58
339	f(i)	15.34
355	f(i)	0.28
456-2	f(i)	1.34
5566-2	f(i)	15.74
234-02	f(m)	40.49
256	f(m)	0.6189
258-2	f(m)	143.19
267	f(m)	334.13
285	f(m)	121.91
294-1	f(m)	82.93
294-2	f(m)	265.83
336	f(m)	24.94
336-2	f(m)	141.55
444	f(m)	15.44
447-1	f(m)	165.84
4555	f(m)	55.32
555	f(m)	62.08
1	m	73.38
234	m	1.77
249	m	4.93
276	m	0.23
3	m	0.11
333	m	0.74
335	m	0.87
345-2	m	2.65
348-3	m	17.33
357	m	1.56
384	m	2.68
4	m	24.49
447-2	m	0.88
7	m	1.34
8	m	0.43
2	m	1.25

Table 4.2 Results of minimum convex polygon areas of molting crabs tracked in the Duplin River Estuary.

Crab	**Sex**	**Area use (hectares)**
258-1	f(i)	0.67
348-1	f(i)	0.01
339	f(i)	1.53
5677-2	f(i)	1.92
348-2	m	0.35
5566-1	m	0.01
366-1	m	0.80
1	m	0.20
2	m	0.17
3	m	0.12
4	m	0.01
5	m	0.01
6	m	0.69
7	m	0.01
8	m	0.01
9	m	0.13
10	m	0.01
11	m	0.01

Table 4.3. Proc GLM analysis of variance on ranked values was used to test for significant differences in crab area use between molting and non-molting crabs and between sexes.

Source	***F value***	***P<***
Molt vs. Non-Molt	11.52	0.0002
Sex	4.83	0.028

Table 4.3. Proc GLM analysis of variance on ranked values was used to test for significant differences in crab area use between sexes of non-molting crabs.

Source	***F value***	***P<***
Sex	10.04	0.004

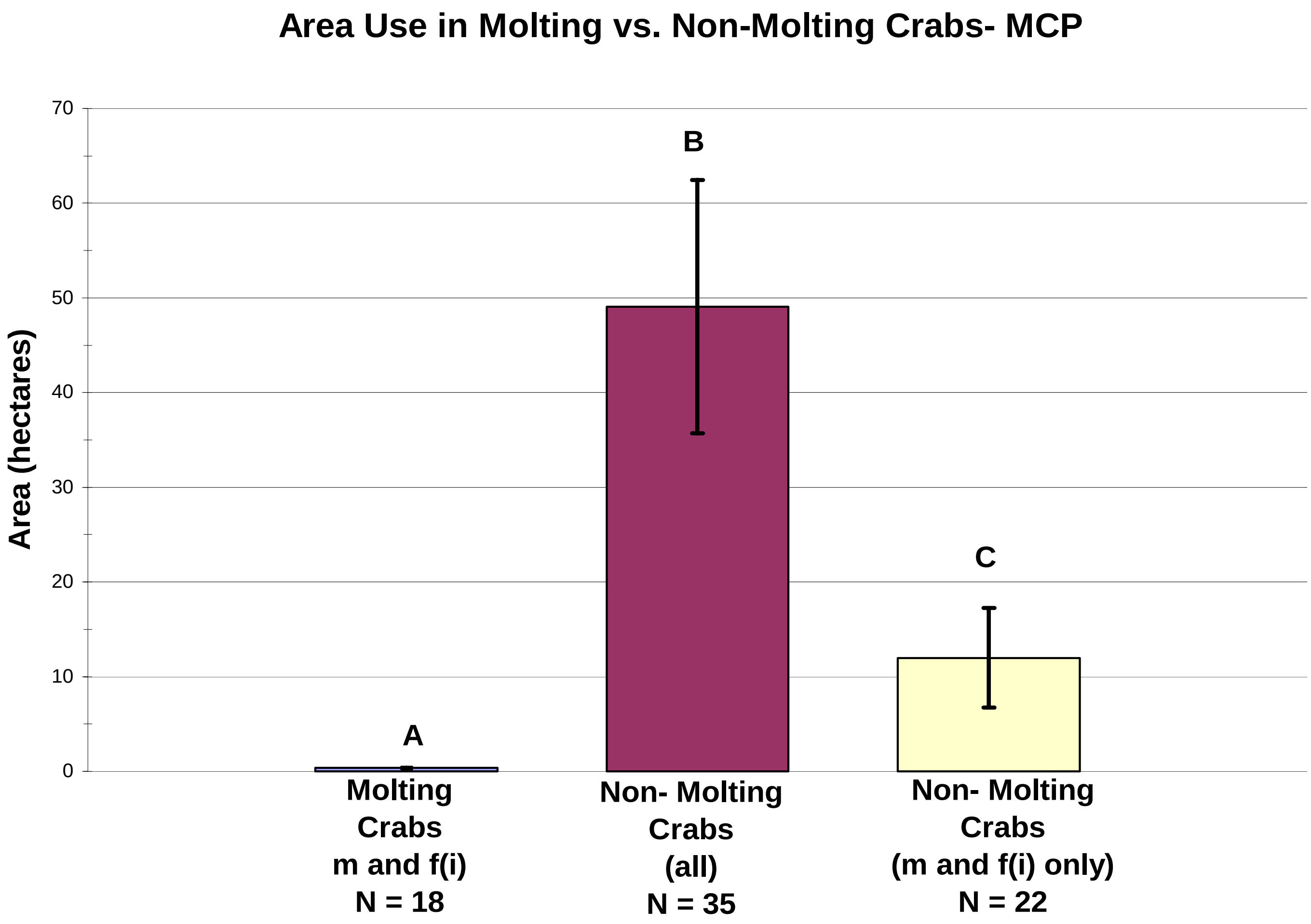


Figure 4.1 Area use differences between molting and non-molting crabs based on mean area determined by MCP analysis. Means are reported with standard error bars. Differing letters represent significant differences at the p<.001 level.

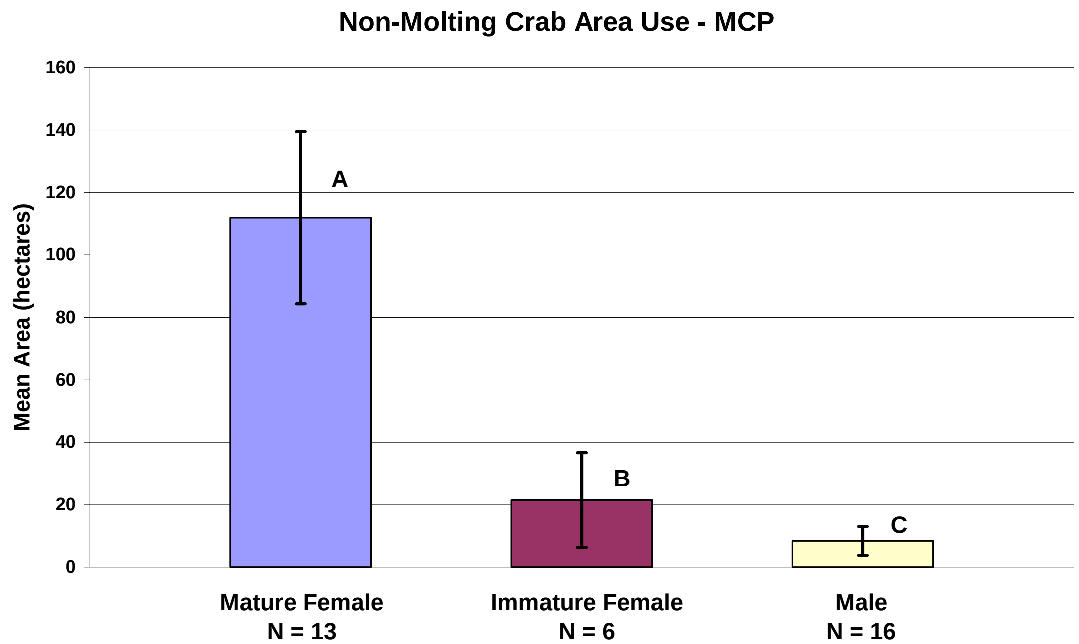


Figure 4.2. Area use differences between mature female, immature female, and male crabs based on mean area determined by MCP analysis. Means are reported with standard error bars. Differing letters represent significant differences at the p<.001 level.

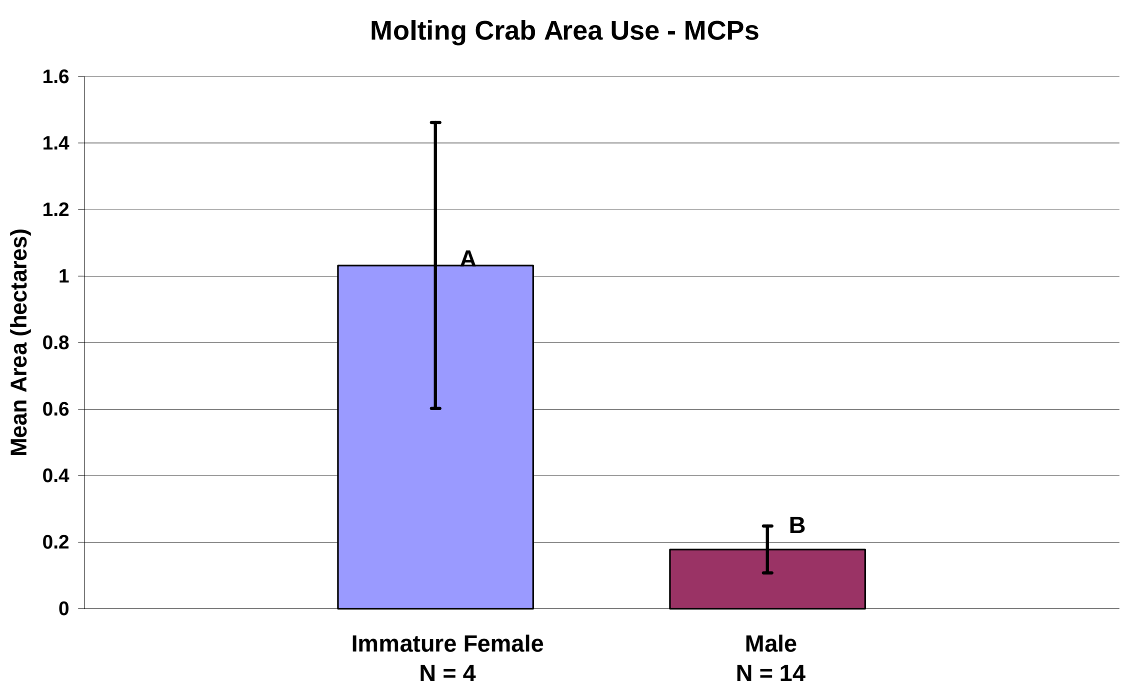


Figure 4.3. Area use differences between immature female and male crabs that had molted based on mean area determined by MCP analysis. Means are reported with standard error bars. Differing letters represent significant differences at the p<.001 level.

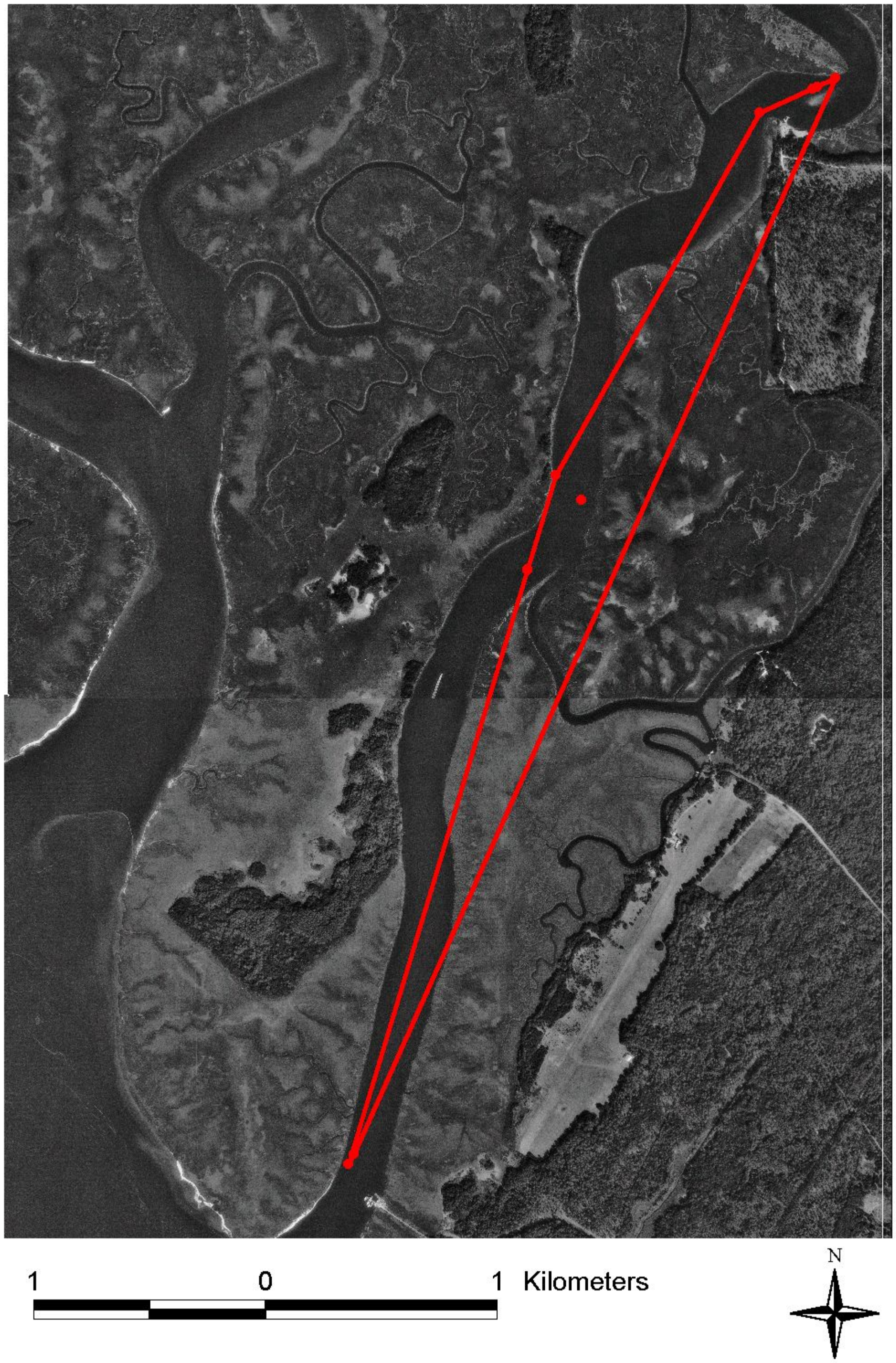


Figure 4.4 Minimum convex polygon of a mature female crab. Dots represent actual location fixes. Lines represent outer perimeter of MCP. Area = 121.906 hectares.

Figure 4.5 Minimum convex polygon of an immature female crab. Dots represent actual location fixes. Lines represent outer perimeter of MCP. Area = 15.748 hectares.

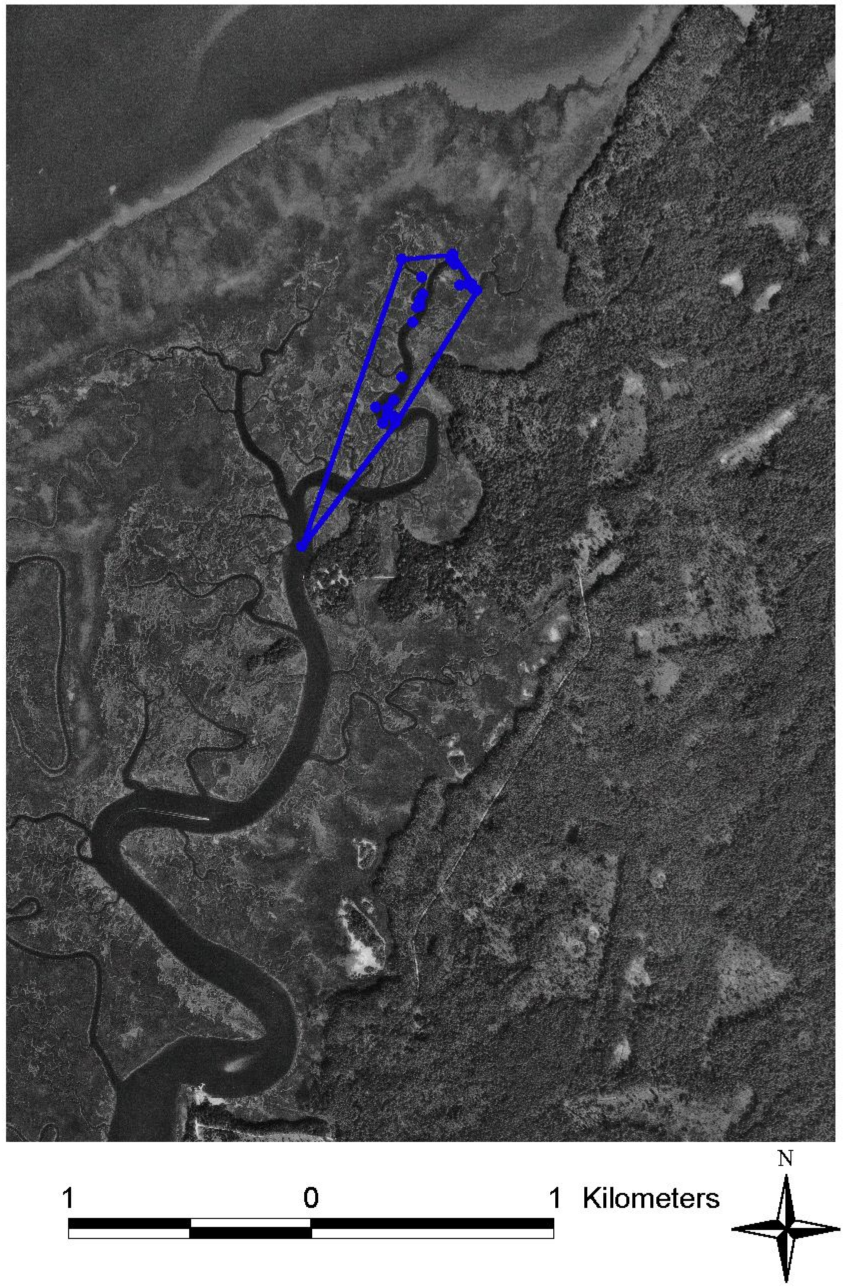


Figure 4.6 Minimum convex polygon of a male crab. Dots represent actual location fixes. Lines represent outer perimeter of MCP. Area = 17.3 hectares.

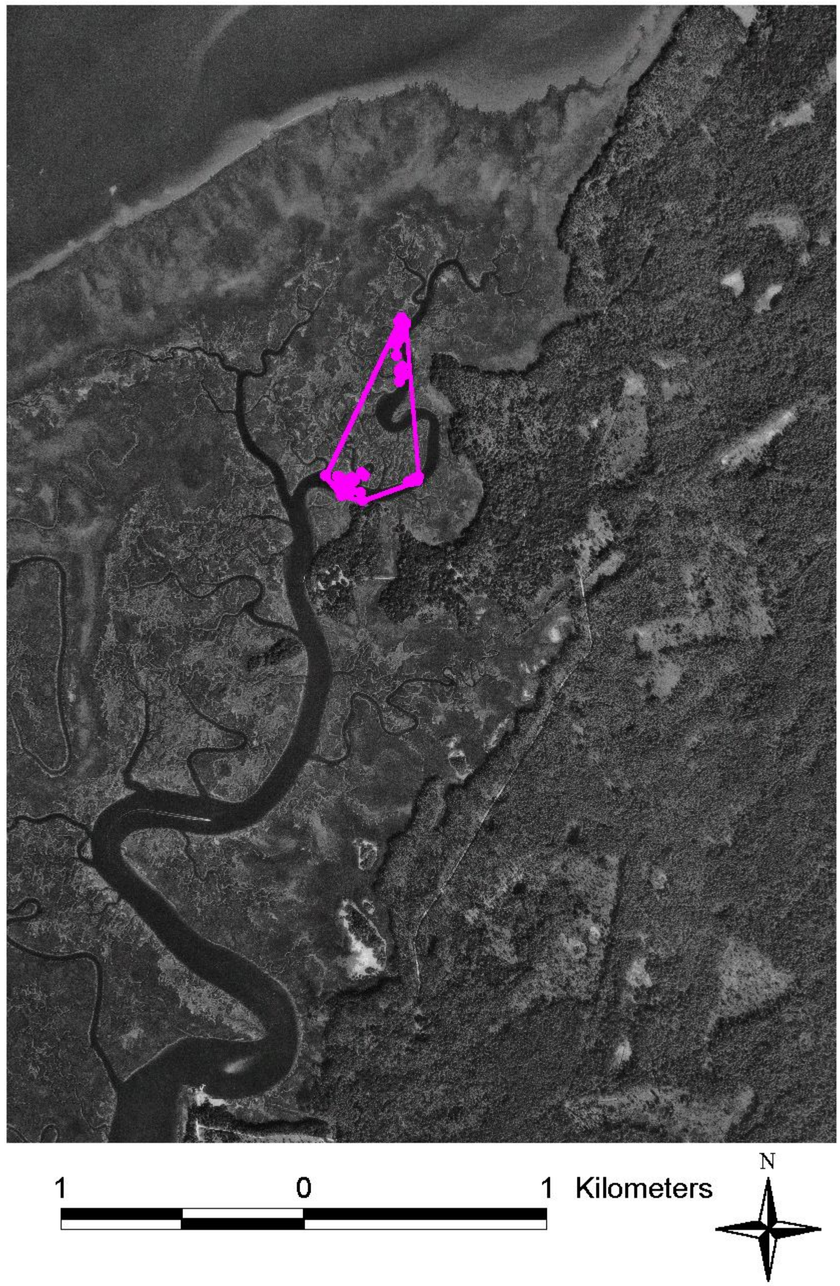


Figure 4.7 Minimum convex polygon of an immature crab that was tracked through one complete ecdysis cycle. Dots represent actual location fixes. Lines represent outer perimeter of MCP.

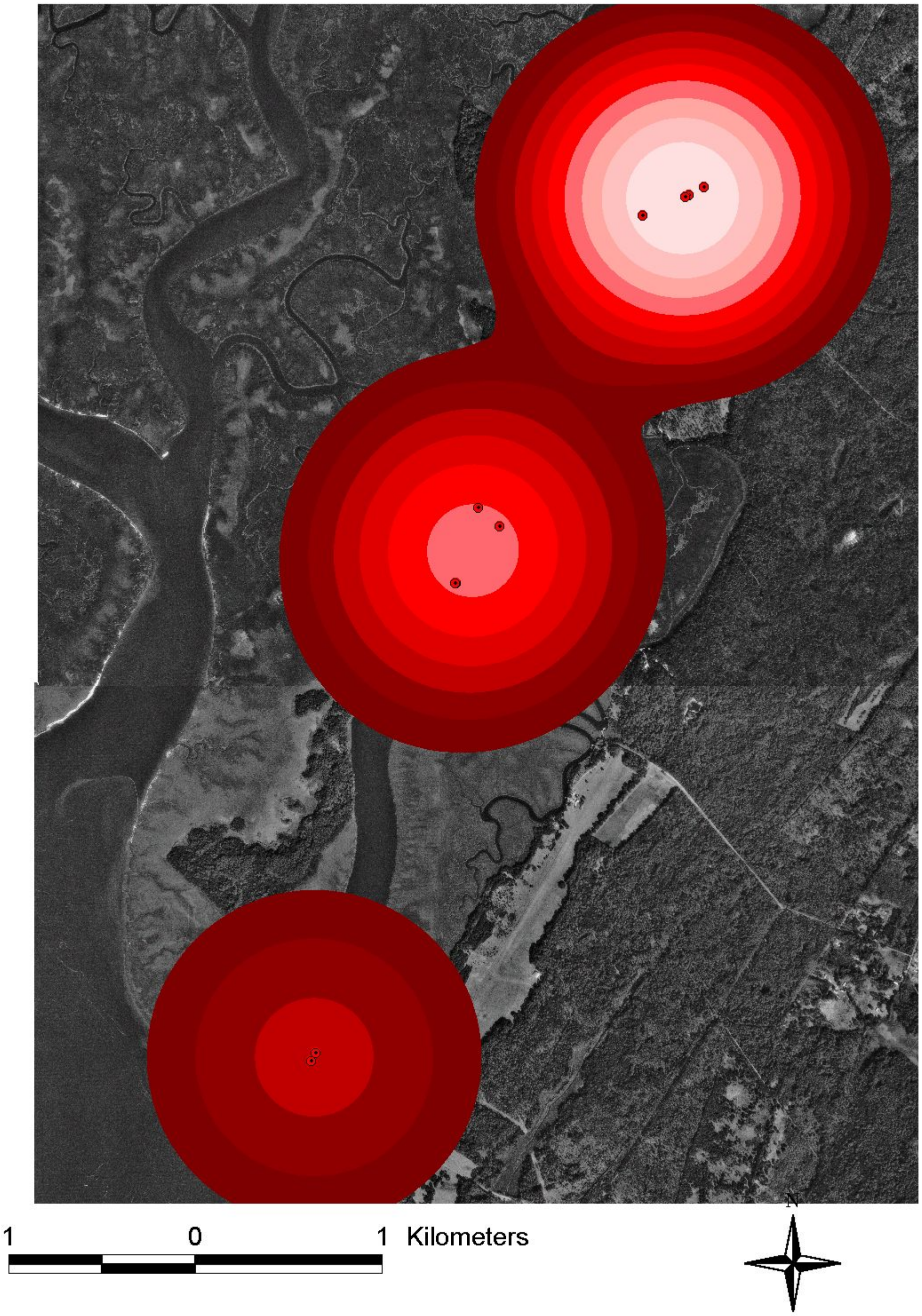


Figure 4.8. Reproductively mature female (10.5 cm CW) tracked July 1999, for 4 days. Dots with black centers represent actual positional fixes. Circles represent the Kernel utilization distribution with 10% probability contours. 95% area = 115.7 hectares.

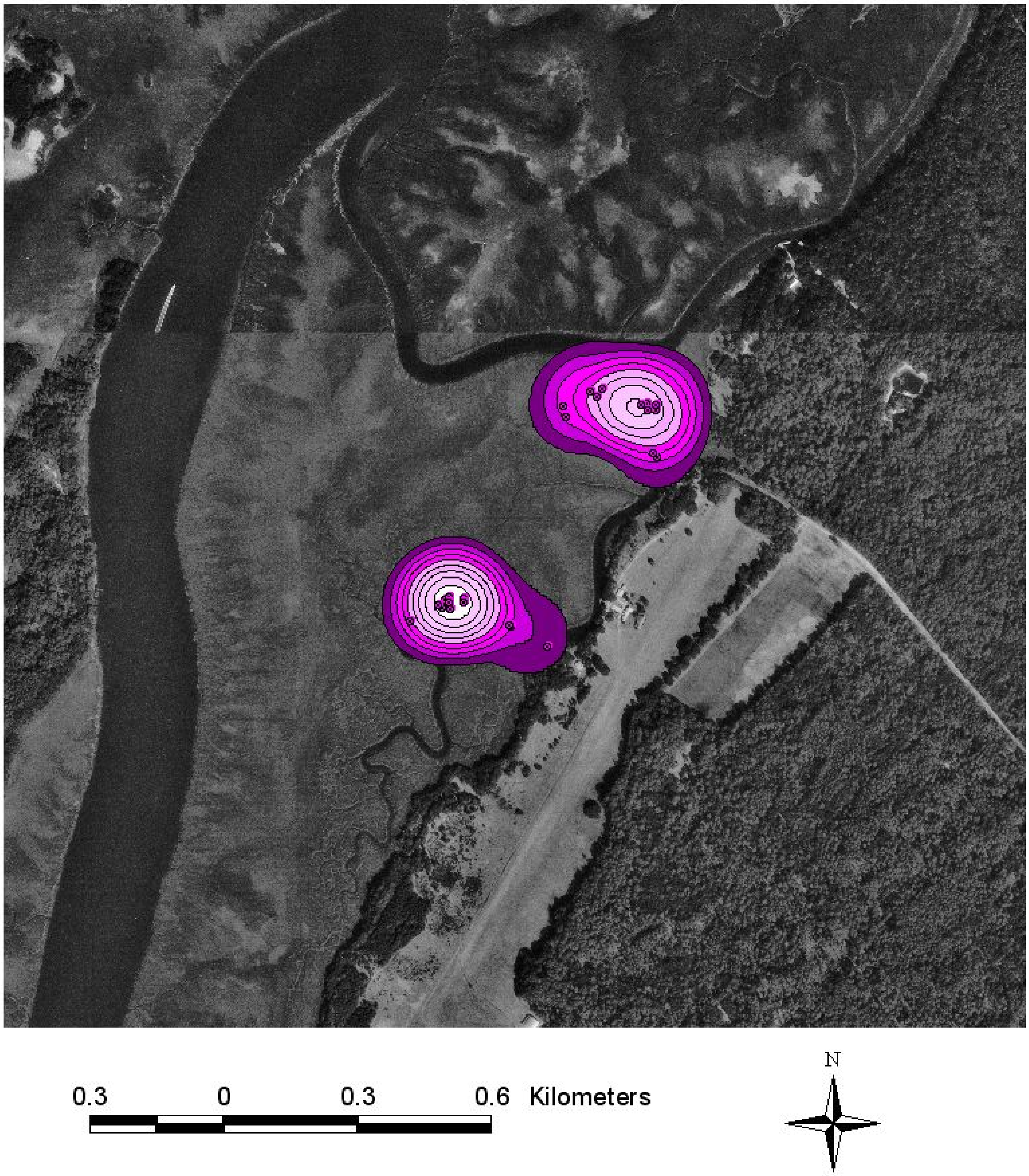


Figure 4.9. Reproductively immature female (9 cm CW) tracked July 1999, for 24 days. Dots with black centers represent actual positional fixes. Circles represent the Kernel utilization distribution with 10% probability contours. 95% area = 26.4 hectares.

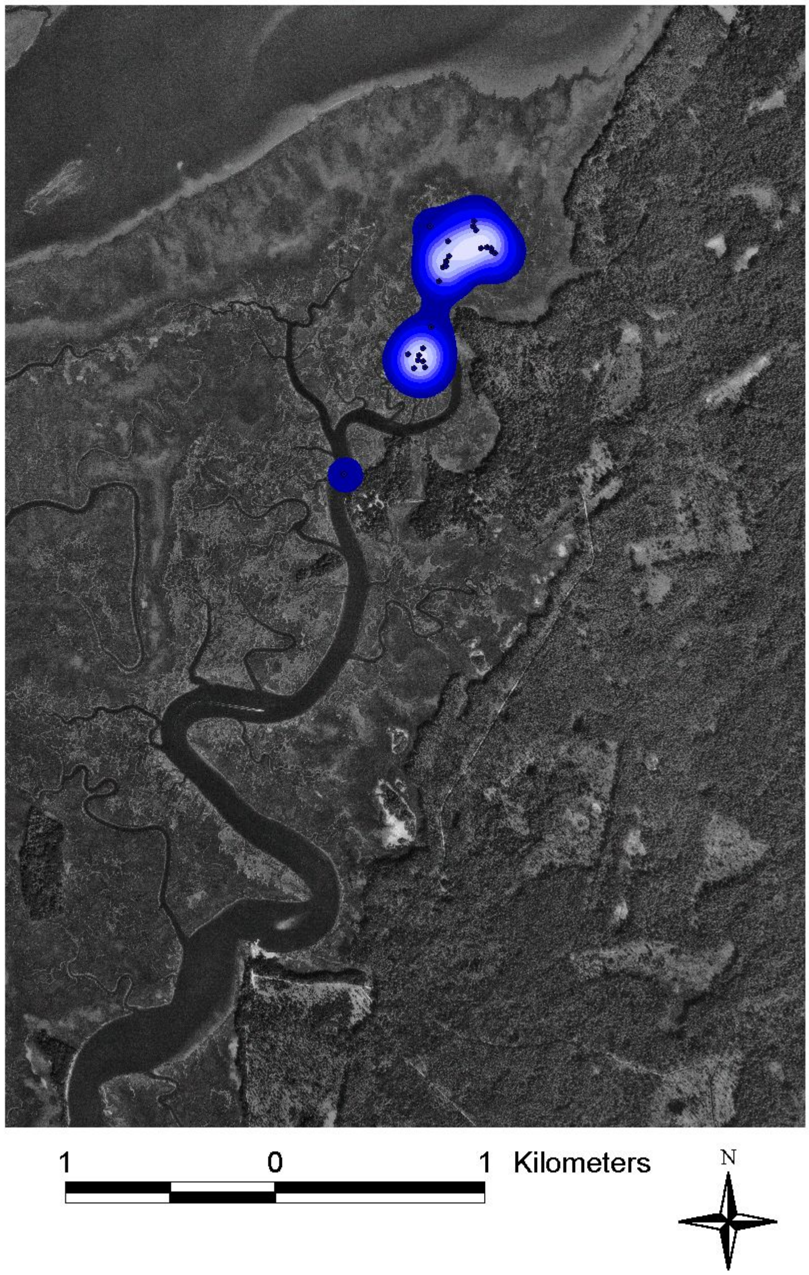


Figure 4.10. Male crab (10.2 cm CW) tracked July 1999, for 16 days. Dots with black centers represent actual positional fixes. Circles represent the Kernel utilization distribution with 10% probability contours. 95% area = 43.1 hectares.

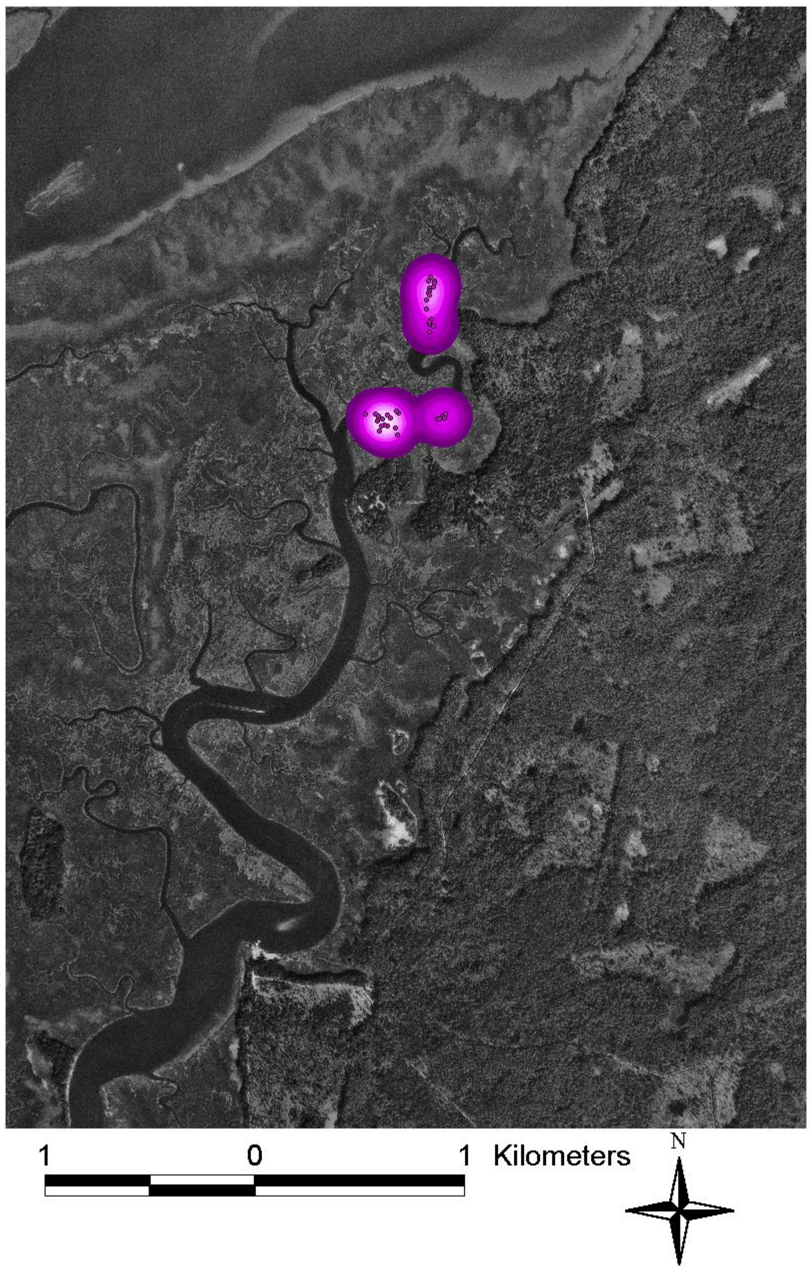


Figure 4.11. Immature Female peeler crab that was tracked throughout one complete cycle of ecdysis. Dots with black centers represent actual positional fixes. Circles represent the Kernel utilization distribution with 10% probability contours. 95% area = 43.1 hectares.

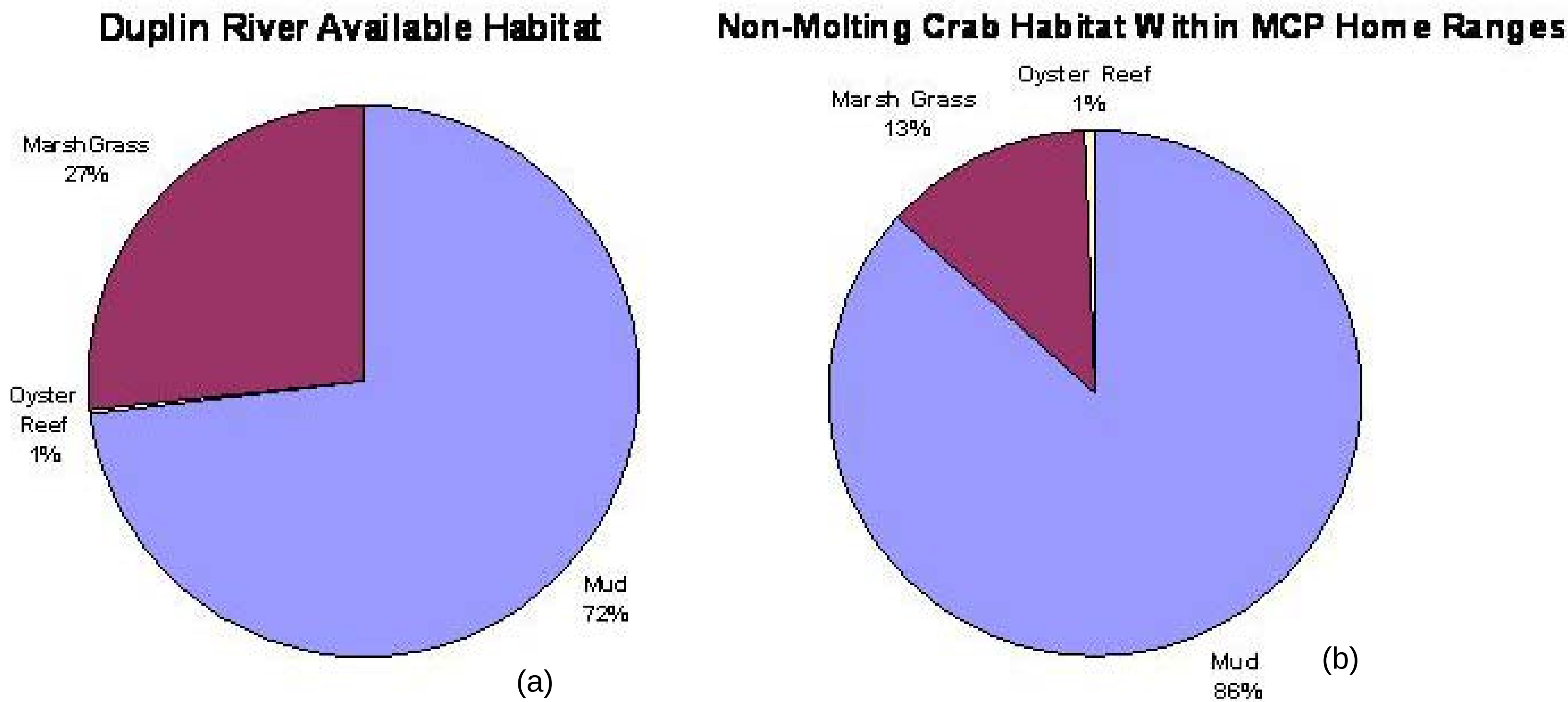
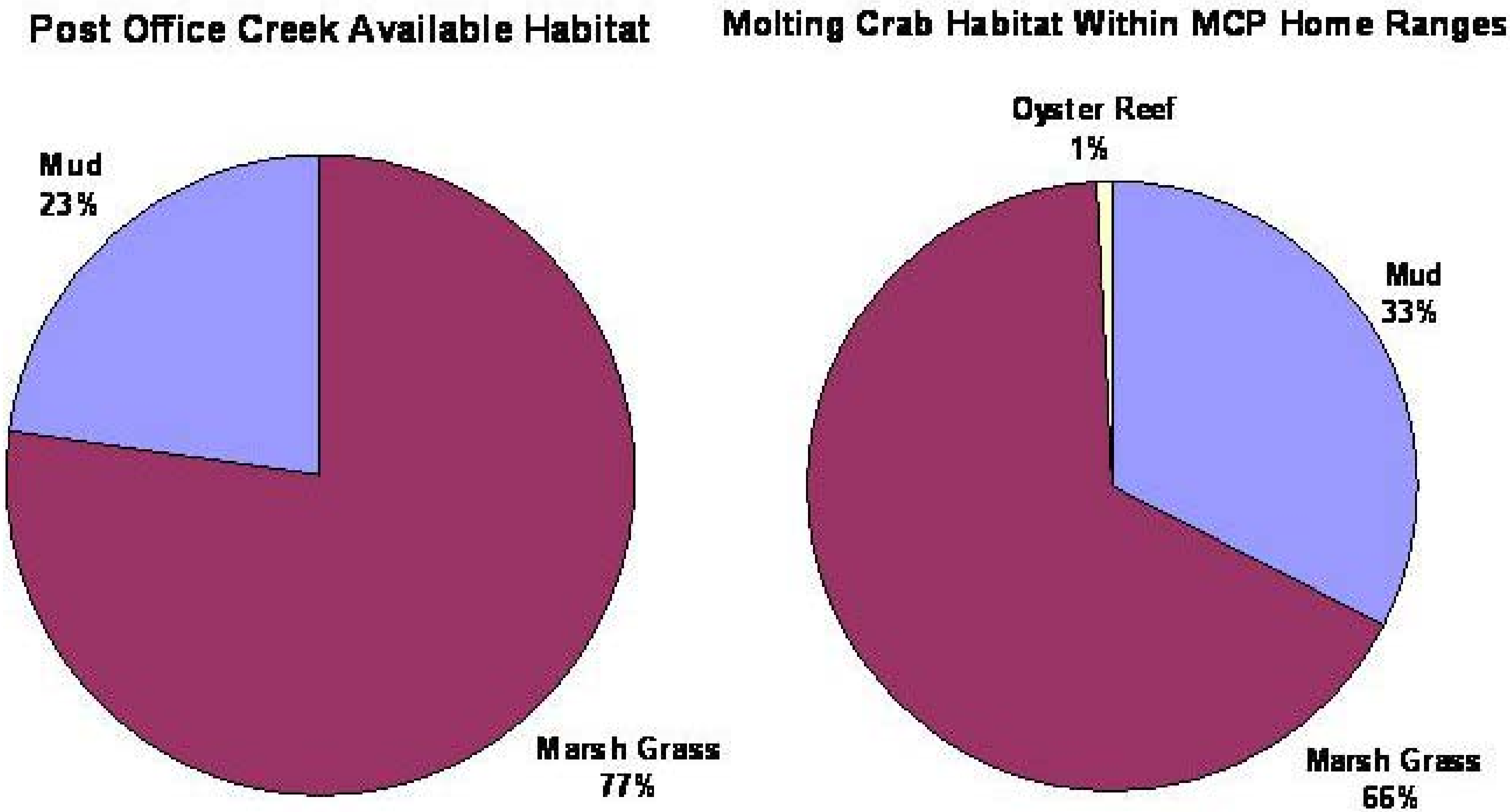


Figure 4.12. Available habitat in the Duplin River Estuary (a) and habitat proportion within non-molting blue crab MCP home ranges, all crabs combined (b).



(a) (b)

Figure 4.13. Available habitat in Post Office Creek (a) and habitat proportion within molting blue crab MCP home ranges, all crabs combined (b).

CHAPTER 5

CONCLUSIONS

This research adds to the understanding of the complex life history strategies of a commercially and ecologically important estuarine species. The blue crab has been studied extensively in other estuaries along the Atlantic and Gulf of Mexico coasts, but these habitats are different than Georgia's estuaries in many ways. This study reviews data about blue crabs in Georgia and other estuaries, identifies what information is lacking about blue crabs in Georgia, and describes the use of ultrasonic telemetry as a tool to test several hypotheses about blue crab behavior in the Duplin River estuary in Georgia. Georgia blue crab landings are currently the lowest on record and more data is needed about blue crab life history for managers to make scientifically based, best practice decisions to manage the fishery in a sustainable way. The information gained from this study can now be incorporated into the larger scale information network about blue crabs in order to make better informed fishery management decisions about blue crab populations in Georgia.

Ultrasonic Telemetry

Ultrasonic telemetry has proven to be a useful research tool to examine movement patterns and habitat use of blue crabs within this Georgia estuary. In an area with high tidal amplitude and low visibility and a very mobile organism like the blue crab, data obtained with ultrasonic telemetry has given insight into blue crab behaviors that may not have been measured with other sampling techniques.

Ultrasonic transmitters are light weight, are easily attached to crabs in the field and have little to no adverse effects on crab behavior. The equipment is relatively expensive and the manual tracking method used in this study was time-consuming, therefore resulting in small numbers of tagged individuals. Extrapolation of conclusions from this study to populations must be made with caution. The data that were gathered, however, are very detailed and much can be deduced from it.

GIS Analysis of Telemetry Data

The many positional fixes taken in an almost featureless environment within this study required the use of a handheld global positioning unit and a GIS to map the locations. Upon the location of each crab, many other variables were collected and noted including dates, times, depths and locations of crabs , substrates and time between fixes. These data point were easily incorporated into a GIS which was used to plot the data, classify habitats, and calculate parameters on georeferenced maps. Distance per day traveled, habitat use, home range analysis, etc. can all be described and calculated and tested for differences among sexes and sizes of blue crabs.

Crab Movement

The movement patterns of blue crabs are heavily influenced by their ontogenetic stage. Mature female crabs tagged with transmitters moved sometimes surprising distances over short periods of time as they migrated out of the estuary with an average speed of 675 meters/day. When a female is reproductively mature she is most likely already fertilized, and must move out of the nursery habitats in tidal creeks and rivers to the higher salinities of the ocean sounds and beaches for the survival of zoea that will hatch from her eggs. Movement of immature females could best be described as semi-directional, moving medium distance over short periods of time, out of tidal creeks and into the larger tidal rivers at an average of 150 meters/day. Male crab movement could best be described as non-directional in nature, moving short distances over long periods of time, with no clear indication of direction and averaged 82 meters/day.

All crab movement (males, immature females, and mature females) peaked in July and decreased with decreasing water temperatures. Male and immature female crabs were distributed similarly with depth. They were more often found in shallow water habitats ranging from 0.5 to 10 m. Mature female crabs were found at all depths but were the only crabs found at depths greater than 23 meters (range 0.5 to 45 m).

All habitats within the study site (oyster reef, marsh grass, and non-vegetated subtidal habitat) were used by all crabs in the study, but use differed between sex and ontogenetic stage. All crabs (male, mature female, and immature female) used oyster reef habitat in greater proportion than was available, indicating selection of this habitat type, possibly for foraging. The use of marsh grass habitat in this system has been previously documented as crabs migrate onto and off of the marsh surface at high tides when the marsh is inundated to feed. Immature female and male crabs used this habitat more often than mature females. During this study several crab transmitters were found within marsh grass habitat and it was hypothesized that crabs were going onto the marsh surface to molt.

Molting Habitat

With Georgia’s lack of SAV and high amplitude tides that flood the marsh regularly, blue crabs use marsh grass as molting habitat. A special molting transmitter (originally designed by Tom Wolcott at North Carolina State University) was a successful too to use to determine where crabs molt in this Georgia estuary.

Seven out of 11 tagged male crabs were successfully tracked to molting habitat which consisted of vegetated levees of the creek banks that were inundated at high tide but completely dry soon after. At this point, other non-molting transmitters that were found on the marsh surface were assumed to have been deposited on the marsh surface during molting. Four immature females and 4 more males were assumed to have molted and were all found in similar molting habitat to those crabs tagged with molting transmitters. Molting crabs used shallow water habitats more frequently than non-molting crabs, and exhibited more meandering behavior within their movement patterns.

Essential Fish Habitat and Area Requirements of Blue Crabs

Defining essential fish habitat for blue crabs is a useful concept for proactive sustainable fisheries management of blue crabs. Telemetry data collected in this study (movement patters, habitat use, molting habitat) was analyzed with a GIS to determine area and habitat requirements of blue crabs in the Duplin River, GA.

Minimum Convex Polygon (MCP) home range analyses were done on crabs of varying sex and ontogenetic stages to determine how much area they use and what types of habitats exist within those areas. There were significant differences between area and habitat use of crabs that were molting (mean area = 0.4 hectares) vs. non-molting crabs (area = 12.0 hectares). Molting crabs used less total area but areas that consisted of more grass habitat than non-molting crabs. There were also significant area requirements between different ontogenetic stages of crabs. Mature females used the largest areas averaging 111.8 hectares, followed by immature females averaging 21.5 hectares and male crabs averaging 8.4 hectares.

These large areas used by such a highly mobile species could not be protected by marine protected areas that are commonly used in conservation ecology. Protecting essential fish habitat would be a more likely successful conservation tool for blue crab populations.

Georgia’s estuaries are noticeably different from estuaries to the north and south. These large scale differences appear to contribute to the difference in blue crab behaviors and life history strategies between estuaries. Information about Georgia’s blue crab populations is not complete and research should focus on movement of mature females once they leave the estuary, habitat use of juvenile blue crabs, as well as what physiologic factors (such as D.O., temperature, or salinity) that may significantly influence blue crab behavior in Georgia. Management decisions about Georgia’s blue crabs population should focus on proactive and not reactive management decisions such as defining and protecting essential fish habitat for blue crabs in Georgia.

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