Mortality of Diamondback Terrapins in Blue Crab Traps: Population Changes and Conservation in Southeastern Virginia

Megan Ann Rook

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Mortality of Diamondback Terrapins in Blue Crab Traps: Population Changes and Conservation in Southeastern Virginia

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A Thesis presented to the Graduate Faculty of the College of William and Mary in Candidacy for the Degree of Master of Science

Department of Biology

The College of William and Mary
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This Thesis is submitted in partial fulfillment of the requirements for the degree of

Master of Science

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Bycatch and mortality of non-target species in fisheries is a well-documented conservation concern. The diamondback terrapin (Malaclemys terrapin) of Virginia is a common bycatch species in blue crab traps. Terrapins are easily caught in these traps and frequently drown. Due to the sexual size dimorphism exhibited by this species, crab trap mortality affects males and females differently. At maturity, females are larger than the gape in a crab trap and cannot enter the trap. Males of any age are small enough to become entrapped. Size-selective bycatch mortality in crab traps has been shown to cause an increase in the average age of terrapin populations and a concomitant increase in the average size of the individuals in a population. Crab trap mortality also has the potential to quickly extirpate local terrapin populations. Bycatch Reduction Devices (BRDs) are required on selected crab traps in Maryland, Delaware, and New Jersey to help mitigate these threats.

I investigated the effects of size-selective bycatch mortality on terrapin populations in lower Chesapeake Bay by comparing demographic data from sites with and without crabbing. Terrapins were captured, measured, weighed, and tagged at three locations, two with and one without crab traps, throughout the summers of 2007 and 2008. At all sites, no males older than age nine were found, nor was there a difference in age structure among sites. Average female age was greater at sites with crabbing than sites without. At the crabbed sites, females were much larger overall and slightly larger in each age class than at the crab trap free sites. No such apparent size differential was found for males among sites. The results are not inconsistent with hypothesis that the blue crab industry may be selecting for fast-growing, large females while substantially decreasing the number of males in the population, but significantly more data are needed to determine if crab traps are the mechanism causing the differences among populations.

I also investigated a possible mechanism for reducing bycatch of diamondback terrapin, in blue crab traps without affecting crab catch, which would assist terrapin recovery. Over 23 sampling dates during summer 2008, I compared terrapin captures at two sites typical of recreational crabbing, using 10 paired sets of an un-baited crab trap fitted with BRDs and a trap without BRDs at each site on each sampling date. Traps were also baited and fished four times during the summer, and the number, carapace width, and condition of crabs captured in each trap were recorded. Of 48 terrapin captures in crab traps, only two were from traps fitted with BRDs. Crab catch, including number, size and biomass of crabs, was equivalent between traps with and without BRDs. Because BRDs are effective in excluding all but the smallest terrapins from entering crab traps and had no effect on the crab catch, BRDs are recommended for all recreational crab traps throughout shallow estuarine waters. Combined with bycatch reduction policies in other North American estuaries, a comprehensive and effective strategy for the conservation of diamondback terrapin threatened by recreational or commercial fisheries is emerging.
COMPLIANCE PAGE

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DEDICATION

For the terrapins. May your silly faces be around for my great-grandchildren to enjoy.
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I would like to thank my advisor, Dr. Randy Chambers and committee member, Dr. Rom Lipcius for their guidance, advice, patience, and support during my work on this project. I would also like to thank my committee members Dr. Martha Case and Dr. George Gilchrist for their valuable input and critiques.

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CHAPTER 1

INTRODUCTION: BYCATCH, THE DIAMONDBACK TERRAPIN, AND STUDY AIMS

Bycatch

Bycatch of non-target species in commercial fisheries is a well-known and well-documented conservation concern. In 1998, the National Marine Fisheries Service defined bycatch as, “Discarded catch of any living marine resource plus retained incidental catch and unobserved mortality due to a direct encounter with fishing gear” (www.nmfs.noaa.gov/bycatchplanonline.pdf). Especially susceptible to bycatch are large vertebrates because they are often preying on the target species (Davoren 2006), are attracted to fishing gear by the same mechanisms as the target species (Wang et al. 2007), are used in finding the target species (Gosliner 1999), or simply inhabit the same microhabitat as the target species (Rogan & Mackey 2007). The problem in many fisheries is that fishing gear tends to be non-selective and bycatch of large vertebrates often results in mortality.

High rates of mortality due to bycatch can be particularly devastating to large vertebrates with a long life span, late sexual maturity, and low fecundity. These particular life-history traits inhibit a population from replenishing itself and coping with increased adult mortality. Models show that animals with such a life history strategy cannot sustain harvest of sub-adults and mature adults (Heppel 1998, Tucker et al. 2001, Mitro 2004). If bycatch mortality is not eliminated, the population may rapidly decline (Sarti et al. 1996, Eckert 1997) and extinction is likely to result with mortality rates as low as 10-20% of the population (Musick 1999). Further, recovery is uncertain after bycatch is eliminated.
(Gerrodette & Forcada 2005, Loder 2005, Martin et al. 2009), especially if the initial removal has created a shift in the ecosystem to an alternate stable state (Cassini et al. 2009).

In the Chesapeake Bay and elsewhere, the diamondback terrapin (*Malaclemys terrapin*), a long-lived vertebrate, is suffering high rates of bycatch mortality in crab traps from the blue crab (*Callinectes sapidus*) industry (Garber 1990, Roosenburg 1991, Burger & Garber 1995, Gibbons et al. 2001, Roosenburg 2004, Baldwin et al. 2005, Butler & Heinrich 2007, Dorcas et al. 2007). Terrapins, for unknown reasons, enter crab traps where they become entrapped and either drown if the trap is submerged or die of exposure if left in the trap for more than 48 hours in shallow tidal areas.

Crab trap mortality selectively removes juvenile and adult males and immature females from the population (Wolak 2006, Roosenburg et al. 1997, Wood 1997, MA Rook pers. obs.). Hatchling and very young terrapins are small enough to exit a crab trap should they enter, and most are not found in the habitat where crab traps are set. Adult females, however, are too large to fit through the gape in a standard crab trap. Functionally equivalent to size-selective fishing mortality, the selective removal of large numbers of males and pre-reproductive females has the potential to rapidly cause local extinctions (Roosenburg et al. 1997, Tucker et al. 2001).

Steps to alleviate bycatch mortality in crab traps have been implemented in some states, but not yet in Virginia. The overall goal of my thesis was two-fold: to characterize the extent of the threat that bycatch poses to local terrapin populations, and to develop a data set that could be used to inform terrapin conservation policy. This is the first study of its kind in Virginia.
The Diamondback Terrapin

Classification and Physical Description

The diamondback terrapin (Figure 1.1) is a small estuarine turtle of the order Chelonia, infraorder Chryptodira. Terrapins belong to the family Emydidae, the youngest and most species-rich family of the Chelonian order (Bonin 2006). They are the sole members of the genus *Malaclemys* and are most closely related to freshwater turtles of the genera *Graptemys* spp., *Trachemys* spp., and *Chrysemys* spp., commonly known as map turtles, sliders, and painted turtles, respectively (Carr 1952, Garber 1990). Scientists have had a difficult time settling on a species and subspecies classification scheme, due to the terrapin’s extreme phenotypic and behavioral variability (Hay 1892, Hay 1904, Coker 1906, Hildebrand & Hastel 1926, Coker 1931, Cagle 1952). Though terrapins were once considered four different species with one subspecies (Coker 1920), they are currently classified as one single species, *Malaclemys terrapin*, with seven different subspecies (Fritz & Havas 2006).

Phenotypically, terrapin size, growth rate, skin color and patterning, shell coloring and patterning, scute sculpting, egg size, clutch size, and prominence of carapacial annuli and ridges can exhibit a wide range of morphologies (Coker 1931, Roosenburg 1996, Roosenburg & Dunham 1997, Butler et al. 2006, MA Rook pers. obs.). Fully-grown males usually range from 10-14 cm in carapace length while females range from 15-23 cm (Ernst et al. 1994). The skin can be anywhere from almost entirely black to white with black spots to almost entirely white, and some terrapins have a distinct color patch on the upper jaw that gives them a mustachioed appearance. Plastron coloration ranges from
dark brown to light yellow and the carapace may be black, green, light brown with black markings or anything in between. Midline carapace ridges may be quite prominent or nearly non-existent.

The sexes are difficult to distinguish until about three years of age at which time secondary sex characteristics begin to develop. Terrapins exhibit extreme sexual size dimorphism that Carr (1952) considered the most pronounced of any North American turtle. At their maximum growth, females are about half again as long and as deep as males, and three times as massive (Simoes and Chambers 1999, Baldwin et al. 2005, MA Rook pers. obs.). In addition to overall size, terrapins are sexually dimorphic in that females have proportionally larger heads and shorter, thinner tails, and the cloacal opening is much closer to the body (Ernst et al. 1994).

Life History

Emydid turtles are quite diverse and abundant throughout the Americas, with the greatest diversity occurring in North America (Bonin et al. 2006). However, the diamondback terrapin is unique among Emydids and all other turtles in that it lives exclusively in an estuarine environment (Ernst et al. 1994, Baldwin et al. 2005,). Among freshwater species, snapping turtles of the family Chelydridae and mud turtles of the family Kinosternidae, occasionally reside in tidal marshes, but they occupy distinct niches from terrapins, feeding in the fresher parts of the marsh and spending much of their time buried in the mud (Moll & Moll 2004). In contrast, the terrapin’s range is restricted to the Atlantic and Gulf coast tidal marshes from Massachusetts to Texas, including the Florida Keys, and the terrapin has recently been discovered to be a native

This distinction makes the terrapin an important component of the marsh ecosystem as it feeds on a number of invertebrates including: salt marsh periwinkles (*Littorina littorea* and *Littoraria irrorata*), blue crabs (*Callinectes sapidus*), fiddler crabs (*Uca spp.*), mud crabs, shrimp, polychaetes, clams, barnacles; and the mussel, *Mytilus edulis* (Tucker et al. 1995, Bels et al. 1998, Silliman & Bertness 2002). By far the most abundant and most commonly preyed upon food item is the salt marsh periwinkle, comprising as much as 79% of the total food intake by mass in some areas (Coker 1920, Tucker et al. 1995). Silliman and Bertness (2002) showed that, when unchecked by keystone predators like the terrapin, *Littoraria* can defoliate a marsh in as little as 8 months.

Food abundance may have an interesting and important effect on the growth rate of terrapins. Early terrapin studies showed growth rate was directly correlated with the amount of prey consumed (Barney 1922, Hildebrand 1932). The claim has not been reevaluated but could have potentially important reproductive consequences. Sexual maturity is reached when a terrapin attains the requisite size, rather than age (Roosenburg & Green 2000). Therefore, a female may lay her first nest anywhere between six and thirteen years of age depending upon the food availability in her environment. Males grow to a much smaller size at maturity than females and so typically reach sexual maturity between five and seven years of age (Coker 1920, Barney 1922, Cagle 1952, Lovich & Gibbons 1990, Roosenburg 1991, Roosenburg & Green 2000).
Average clutch size is usually between 8 and 13 but clutches can vary from 5 to 25, depending on the age and condition of the female (Barney 1922, Roosenburg & Dunham 1997, Feinburg & Burke 2003, Roosenburg et al. 2003, Feinburg 2004, Herlands et al. 2004, Baldwin et al. 2005). If a female is disturbed while nesting and has laid fewer than four eggs, she will abandon the nest and finish laying elsewhere within two hours, a behavior that sometimes confounds clutch size measurements (Burger 1977). Roosenburg (1991) estimates maximum yearly egg output at 39, similar to the maximum of 35 observed by Barney in 1922.

After hatching, hatchlings (Figure 1.2) may immediately emerge, remain in the nest for several months until they emerge, or overwinter in the nest and emerge the following spring. After emergence a hatchling will crawl into the nearest vegetation and “disappear” until they are about three or four years of age. (Hay 1904, Coker 1906, Coker 1920, Hurd et al. 1979, Yearicks et al. 1981, Lovich et al. 1991, Gibbons et al. 2001, Butler et al. 2004, Draud et al. 2004). They likely remain in the marsh until they are large enough to avoid predation on the beach and in the water, though this has not been documented.

Once they reappear in the population, terrapins tend to spend the rest of their 40 or more years in the same general area of the marsh. They have been shown to have extremely limited home ranges and migration distances, though the occasional terrapin will travel a great distance for reasons not entirely clear (Tucker et al. 2001, Baldwin et al. 2005, Harden et al. 2007, Szerlag-Egger and McRobert 2007). Adult females tend to travel farther than males in order to nest and to find different, larger prey items (Roosenburg et al. 1999, Tucker et al. 2001). Females also show strong nest site fidelity,
coming back to the exact same creek or beach year after year (Tucker et al. 1995, Gibbons et al. 2001, Avissar 2006).

**Human Related History**

Diamondback terrapins have been an important part of human existence on the East Coast of the United States since Europeans settled in America. Moll and Moll (2004) report that Native Americans and settlers hunted terrapin for food. Upon the advent of slavery, terrapins were so cheap and so abundant that they were nearly the only food fed to slaves (Coker 1920). Terrapin stew became a favorite dish among early Americans and such was the demand for terrapin meat that populations throughout the eastern seaboard suffered heavy declines. In the late 1800s terrapins had already experienced two centuries of exploitation and the northern fisheries had been depleted for many decades (Coker 1931). Hay states that, in 1904, in areas where a person once could find hundreds of terrapins in a single day, only one or two terrapins could be found in an entire season. By 1906, it was no longer profitable to hunt terrapin in North Carolina and populations were thought to be locally extinct in Connecticut, Rhode Island, and Massachusetts by the mid-1930s (Coker 1906, Garber 1990).

To keep terrapin harvests profitable, captive breeding and artificial selection programs, farming operations, and harvest restrictions began in the early 1900s, particularly in North Carolina (Hay 1904, Barney 1922, Hildebrand & Hastel 1926, Garber 1990). Due to these restoration efforts, incidental release of terrapins from fish shops, and decline in demand for terrapin meat, populations began to rebound (Finneran 1948, Cagle 1952, Yearicks et al. 1981, Garber 1990). However, at about the same time...
terrapins were rebounding, the blue crab industry developed the crab trap (Van Engle 1962). Mortality in crab traps is currently the greatest threat to terrapins and has combined with other increased anthropogenic threats over the past 60 years to once again render the terrapin a potential candidate for extinction.

Status

Population declines are being documented throughout its range, but the diamondback terrapin has no federal protection. As of April 2009, the diamondback terrapin was listed as a near threatened species on the IUCN red list of threatened species. This listing has not been updated since 1996. Because they are not federally endangered, terrapins are not listed as a CITES species (UNEP_WCMC 2009) despite the recent terrapin fishery and probable illegal trade in the Asian market. Status listings by state, if present, range from “Species of Concern” to “Endangered” (Gray & Watters 2004, Mitro 2004). In Virginia terrapins are listed as “Apparently Secure” (Hackney & Baldwin, submitted). However, previous studies (Ruzicka 2006, Wolak 2006), as well as the present study and anecdotes from local watermen indicate that populations are declining. There is no legal terrapin harvest in Virginia (www.dgif.virginia.gov).

Research Aims

Only two prior studies of terrapins have been completed in Virginia, both by William and Mary students. A Master’s thesis by Victoria Ruzicka (2006) examined the life history traits of diamondback terrapins in Virginia with an emphasis on nesting ecology at the Goodwin Islands complex in the mouth of the York River. An
undergraduate honors project by Matthew Wolak (2006), also conducted at the Goodwin Islands, examined the effects of high rates of mortality in crab traps on terrapin populations. No males older than eight years of age were found throughout the entire study despite the ability of terrapins to survive in excess of forty years. Many older females were found. Wolak concluded that high rates of crab trap mortality prohibited males from surviving beyond eight years and that crab trap mortality was selecting for fast-growing, large female terrapins, thus creating a population demographically different from a prior state.

However, geographic and temporal discrepancies weaken comparisons in this study and call into question whether terrapin populations in the York River are demographically different than in the past. However, it is clear that crab traps are imposing selective pressure against all males and small, slow-growing females, and it has been shown that crab trap mortality can cause dramatic changes to terrapin population demography in as little as 20 years (Dorcas et al. 2007). Therefore, I framed Wolak’s (2006) conclusions as hypotheses and used a different experimental design to determine the extent to which crab trap mortality was having an impact on the diamondback terrapins of Southeastern Virginia. I hypothesized that (1) Crab trap mortality is truncating the maximum age attained by male terrapins, such that by age 9 survival probability has dropped to zero, and that (2) Size selective mortality results in a population of female terrapins that are faster-growing and larger than in the past. These experiments are the subject of Chapter 2.

As I began to conduct my research, it quickly became apparent that crab traps either were or could potentially exact a detrimental toll on the terrapin populations of
Virginia. Bycatch Reduction Devices (BRDs) are required on certain crab traps in Maryland, Delaware, and New Jersey, and several studies have demonstrated their effectiveness at reducing terrapin bycatch. However, few studies have examined the effect of BRDs on the crab catch. Therefore, I conducted a study examining the effectiveness of BRDs at reducing the terrapin bycatch as well as the effect of BRDs on the crab catch. This study is presented in Chapter 3.
FIGURE 1.1. The diamondback terrapin: male (a) and female (b).
FIGURE 1.2. Hatchling terrapin captured immediately after emergence.
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CHAPTER 2

DEMOGRAPHIC DIFFERENCES AMONG TERRAPIN POULATIONS
INHABITING SITES WITH AND WITHOUT CRAB TRAPS

Introduction

Relatively few studies of bycatch mortality have focused on population level changes beyond decreases in population size. However, long-term, size-selective bycatch is essentially the same process as long-term, size-selective fishing, so one can look at changes in fished populations over time to understand what the potential long-term consequences of bycatch may be. Fished populations tend to show decreases in the overall size, biomass, physical condition, growth rate, and age at first reproduction (e.g.: Sattar et al. 2008, Shackell & Frank 2007, Ricker 1981), though increases in size, biomass and growth rate have been reported (Hillborn & Munte-Vera 2008). In addition, if the species being harvested is a top predator, an entire ecosystem may shift to an entirely different, less productive stable state (Cassini et al. 2009, Dulvy et al. 2004).

In 2005, Wolak (2006) investigated the potential population effects of crab trap mortality on a population of diamondback terrapins in the York River, Virginia. Due to the extreme sexual size dimorphism exhibited by terrapins, crab traps affect the sexes differently. At their maximum size, males remain small enough to fit through the gape in a crab trap whereas females are large enough to be excluded. Very young terrapins, both male and female, do not inhabit the waters where crab traps are found. Therefore, after three or four years of age, males are subject to crabbing pressure for the remainder of their lifetime, while females face a window of crabbing pressure from about four to eight years of age. Increased mortality of males of all ages should lead to a population in which
the average age of males is younger than from areas without crab traps. Additionally, size selection against the slowest-growing, smallest females could lead to a population in which the average female terrapin is faster growing and larger than from areas without crab traps.

Wolak found no difference in the size structure of males subjected to crabbing pressure when compared to males inhabiting sites without crab traps. He also found no males older than age eight in his crabbed population, despite their estimated longevity of more than forty years (see Chapter 1). He concluded that crab traps were truncating the maximum age attained by males but having no effect on male size.

For females, he found that terrapins from the York River appear to reach a larger maximum size than terrapins from Connecticut. This is curious when one considers Bergmann's Rule. The rule, as defined by Mayr (1956), states that, “Races of warm-blooded vertebrates from cooler climates tend to be larger than races of the same species from warmer climates.” Though the definition was originally developed for endothermic vertebrates it has been shown to be applicable for some Emydid turtles (Ashton & Feldman 2003). Wolak hypothesized that crabbing was selecting against smaller, slower growing females, thus leaving a population of terrapins that grew more rapidly and attained a larger average size at maturity relative to areas without crab traps.

The results are based on three data sets: (1) data collected by the author at the Goodwin Islands complex in the mouth of the York River, an area surrounded by crab traps, (2) size data from a prior recent study of terrapins in Connecticut, an area with no crab traps, and (3) size data from preserved terrapins and terrapin shells from the Smithsonian that were collected in the Chesapeake Bay before 1940, a time before crab
traps began having an effect on terrapin survival. All data were plotted on the same graph and fitted with a Gompertz equation to model growth rate (Figure 2.1).

The results are intriguing but equivocal. First, the data set from the Smithsonian is small and equations like the Gompertz equation tend to be heavily point driven, i.e. a few outliers can greatly skew the shape of the curve. The small sample size limits confidence in the fit of the curve for the Smithsonian data. Similarly, the apparent rapid growth of females from the Goodwin Islands between ages 4 and 6 is based on very few points. More measurements of females in this age class are needed to better describe this growth. Finally, the data do not control for time and geographic location. Terrapins are so phenotypically variable (see Chapter 1) that differences among populations that are latitudinally and temporally separated cannot be directly attributed to any one of many potential environmental differences among sites. The geographic and temporal disparity in samples must be accounted for to yield a more compelling test of the crab trap hypothesis.

The study by Wolak, however, does raise interesting questions and focuses on a crucial area of study in bycatch that seems to be neglected in the literature. To accurately assess the effects of crab traps on terrapin populations, one ideally would track a population of terrapins from a few years before initiation of crabbing pressure until sufficient time had passed to evaluate any changes that may have occurred. This type of study is now impossible in Virginia since commercial crabbing began some 70 years ago. However, if several populations from the same geographic region are sampled and some are subject to crabbing pressure while others are not, one could test whether any differences in populations could be attributed to crab trap mortality.
The goal of my study was to sample terrapins from several locations in the lower Chesapeake Bay, some in crabbed areas and some in “pristine” sites, i.e. areas without crabbing, in order to see what long-term effects crab trap mortality may be having on terrapin populations. I hypothesized that (1) crab trap mortality is truncating the maximum age attained by male terrapins, such that by age 9 survival probability has dropped to zero, and (2) size-selective mortality results in a population in which the female terrapins are faster-growing and larger than those from areas without crabbing. For comparison, I also looked at the age structure of females and the size structure of males. I expected proportionally older females in crabbed sites due to decreased survival of the younger females. I expected no change in the size structure of the male portion of the population.

Methods

Study Sites

A total of four sample sites were used during the study: The Goodwin Islands, Felgate’s Creek, Queen’s Creek, and Fort Eustis. Goodwin and Felgate’s were sampled in the 2007 field season and all four sites we sampled in the 2008 field season. The sites were chosen due to accessibility and span the Lower Peninsula of Virginia (Figure 2.2).

Goodwin Islands. The Goodwin Islands Complex is a 127-hectare (Ruzicka 2006) chain of three islands stretching from west to east at the junction of the York River and the Chesapeake Bay. Goodwin was considered one of the experimental sites because the waters surrounding the islands are full of commercial crab traps and ghost traps. The islands are informally named “West Island,” “Middle Island,” and “East Island,” and
each island is separated from the mainland or its neighbor(s) by small channels. Habitats for the East and Middle islands are almost entirely open beach and tidal marsh comprised of the marsh grasses *Spartina alterniflora*, *Spartina patens*, *Juncus* spp. and *Phragmites australis*. On the West Island, the intertidal marsh grades into upland pine/oak forests, which is the dominant habitat. Abundant beds of submerged aquatic vegetation (SAV), used by terrapins for feeding and mating, surround the islands. The availability of nesting habitat, and considerable amounts of food resources such as salt marsh periwinkles, blue crabs, mussels, and small fish associated with the healthy salt marsh and surrounding eelgrass beds, make the Goodwin Islands prime habitat for hatchling and breeding terrapins.

Using the Schnabel Mark-Recapture Method (Krebs 1989), I estimated the Goodwin terrapin population to be 995 individuals with a 95% confidence interval of 555-3070 for the 2008 season. Using the same method, Wolak estimated the population at Goodwin to be 717 with a 95% confidence interval of 534-1014 for the 2006 field season. The broad and overlapping confidence intervals preclude me from concluding that there has been an increase in the population at Goodwin.

**Felgate’s Creek.** Felgate’s Creek was considered a pristine site. It is a large tidal creek off of the York River located inside the Yorktown Naval Weapons Station and has been free from crab traps for at least fifty years. The sampling area was located 2.1 km within the Weapons Station from the York River. It is assumed that there is no gene flow among Felgate’s terrapins and other York River terrapins due to the strong nest site philopatry and limited movements by terrapins described in Chapter One, and by the
observed lack of movement of Felgate’s terrapins (RM Chambers, pers. com.). By the same logic, the effect of crab traps on Felgate’s terrapins should be extremely limited.

The creek experiences strong tidal fluctuations of up to 1.2 m per day. At low tide, all but the very center of the main channel is a mud flat. The part of the creek used as our sampling site is surrounded by a healthy salt marsh mainly composed of *Spartina* spp. The marsh grades upland into pine and mixed-hardwood forest. Open terrapin nesting area appears to be limited to a small band of dirt along a road that passes through the creek and narrow strips of beach at the mouth of the creek as it enters the York River. The marsh supports abundant stocks of salt marsh periwinkles, fiddler crabs, and mussels, among other terrapin prey species. There was no evidence of submerged aquatic vegetation in the area.

Using the Schnabel Mark-Recapture method, I estimated the terrapin population to be 143 terrapins with a 95% confidence interval of 118-178 in 2007 and 167 terrapins with a 95% confidence interval of 113-299 in 2008. Unfortunately, the 95% confidence intervals in these estimates overlap and are quite broad. Several more years of mark-recapture data will be needed to determine if the Felgate’s and Goodwin populations are changing. The observed increase in estimated population sizes may be normal stochastic fluctuation, inherent problems with the estimating method, or actual increases.

**New Quarter.** Queen’s Creek was considered a second experimental site. It is a large tidal creek off of the York River, just over 4.1 kilometers upriver from Felgate’s Creek. Queen’s Creek experiences similar tidal fluctuations to Felgate’s and there is commercial crabbing through the center of the creek. Queens Creek is surrounded by an intertidal marsh dominated by *Spartina* spp., which grades into upland mixed-hardwood
forest. The creek is bordered to the north by Camp Perry and to the south by New Quarter Park, part of York County Parks and Recreation. My sampling area was confined to the tidal inlets on the south side of the creek in New Quarter Park because access to Camp Perry property was unattainable. Thus, the site was named “New Quarter.” Open beach nesting habitat was limited to a small strip of beach at the mouth of Queen’s Creek as it entered the York River. There was no evidence of submerged aquatic vegetation in the area. Periwinkles and blue crabs appeared to be less abundant than at the two previous sites, but fiddler crabs were quite abundant.

Using the Schnabel Mark-Recapture method I estimated the 2008 terrapin population to be 65 individuals with a 95% confidence interval of 44-113. The total population size may be grossly underestimated, since very few female terrapins were captured.

**Fort Eustis.** Fort Eustis is on the James River, Virginia and encompasses many tidal creeks that superficially looked as though they would be occupied by terrapins. A boat survey in October 2007 documented the presence of terrapins in one tidal creek (RM Chambers, pers. obs.). This site was identified as a second pristine site because commercial crabbing is prohibited on the property. Due to accessibility restrictions however, I could only sample an adjacent, unnamed creek that was not surveyed for terrapins. This tidal marsh was somewhat fresher than the other three sites. The fresher environment could easily be seen in the dominant vegetation of *Juncus* spp. and *Spartina cynosuroides* and the increased presence of sliders (*Trachemys* spp.) and mud turtles (*Kinosternon subrubrum*). However, standard terrapin prey items such as periwinkles and blue crabs were abundant and it has been reported that terrapin occurrence is affected by
prey abundance rather than salinity (Coker 1906, Coker 1931). There was no evidence of submerged aquatic vegetation in the area. Though the habitat looked promising, no terrapins were trapped at this site and it had to be abandoned for the present study but was used for the study discussed in Chapter 3.

**Sampling Technique**

In 2007 the Goodwin Islands and Felgate’s Creek sites were sampled. In 2008, my attempt to add one additional pristine site and one additional crabbed site was largely unsuccessful. Ft. Eustis, our pristine site, had no terrapins, and at New Quarter, our crabbed site, only six females were captured. Due to the small sample size of females at New Quarter this data set was eliminated from the population analyses.

**2007.** At Goodwin, beaches were monitored daily for nesting females. Males were not trapped because my lab already had a good data set for males at Goodwin. At Felgate’s, 20 crab traps with specially constructed chimneys that allowed terrapins to swim up and breathe at high tide (Figure 2.3) were placed throughout the creek in small tidal inlets (Figure 2.4a). Unbaited traps were checked daily for male and female terrapins. The banks of the road passing over Felgate’s were also checked daily for nesting females.

When a new terrapin was captured it underwent the following processing: sex was determined by examining the length and width of the tail; females were checked for gravidity by palpating the body cavity just in front of the rear limbs; each terrapin was given a unique number using a notching method developed by my lab predecessors described below; carapace length (CL), carapace width (CW), and shell depth (D) were
measured to the nearest millimeter with field calipers; terrapins were placed into a bag
attached to a spring scale and weighed (M); the age of the turtle was determined by
counting the carapacial rings; the carapace and plastron were photographed. At Goodwin,
the plastron length (PL) and plastron width (PW) were also measured. Each measurement
was taken at the longest/widest point. This measurement was different from
measurements used throughout the literature (e.g.: Baldwin et al. 2005, Avissar 2006,
Butler & Heinrich 2007) but was used in my study so as to keep consistent records with
my lab and document changes over time. Wolak used the measurement technique
because maximum size determines whether a terrapin can fit through a crab trap gape or
not. All terrapins were released after processing. If a terrapin was recaptured, the number,
sex, and age were noted.

2008. In 2008 Goodwin, Felgate’s and New Quarter were sampled. At each site
20 crab traps with chimneys were placed throughout the study area (Figure 2.4 b-d) in
order to standardize sampling methods. Ten additional traps with Bycatch Reduction
Devices were placed throughout Felgate’s Creek for my study in Chapter 3. Any terrapins
captured in these traps were also included in the data for this study. Trap 18 at Goodwin
was relocated a few weeks into the study after several terrapins died in this trap. It is
believed that the water quality in this one location had something to do with the deaths,
but the cause of death was not determined. This trap location was no shallower than any
other, so overheating was not suspected. After the trap was moved, no additional
terrapins were killed. Traps 1-4 at New Quarter were relocated about half way through
the study season because, after the first few weeks, no terrapins were captured in these
traps. The move was successful as we captured several terrapins in the new location.
Males and females were sampled at all sites. Beaches at Goodwin were again monitored for nesting activity, as well as the roadside at Felgate’s. A beach at the mouth of New Quarter was checked infrequently for nesting females. All terrapins, new or recaptured, underwent the same processing as all initial captures in 2007 with the addition of plastron length (PL) and plastron width (PW) measurements. All terrapins were released after processing.

**A note on mass measurements:** Different scales were used in 2007 and 2008, presenting some problems. First, 2007 measurements were not as precise as those in 2008 since the scale gradations went by 50 grams whereas the scales that were used in 2008 went by 20 grams. Also, the scales used in 2008 broke easily and gave several inaccurate readings before the problem was realized. I was able to identify and throw out some, but not all, of the days when data were inaccurate and unusable.

**Scute notching method.** Since I was working in the same area as my lab predecessors, I followed their marking system, which was a modification of Cagle’s (1939), in order to be consistent. Cagle notched deep marks on the left side on the turtle, using each scute as one number. He started from the front and went backwards. His marks were deep and sometimes made the terrapins bleed. My lab’s method made shallower marks and the scutes of the bridge were not used. Marks were made on the right side and went from back to front. Wolak (2006) and Ruzicka (2006) used a binary system to enable more numbers (Figure 2.5). After all 255 possible numbers had been used at Goodwin, we began using two notches per scute to signify that that scute should be counted twice. If the turtle was male, a mark was made in the rear scute just to the left of the midline.
**Statistical Analyses**

All data were analyzed using the Frequentist approach of determining statistical significance at $p < 0.05$. Due to the limited number of study sites and lack of replication, more intensive statistical interpretation was not possible. Pair-wise t-tests were used to compare Age, CL, CW, Depth, and Mass among all sites. Conclusions are strictly limited to determining if there is a difference among sites. Even these conclusions are limited in their power because of logistical difficulties resulted in trapping different portions of the population at Goodwin than at the other two sites.

**Results**

*Age structure*

**Males.** Of the 254 male terrapins captured throughout the entire study, only one was older than eight years of age. The lone nine-year old was found at the Goodwin Islands in 2008. In 2007, four year olds were the dominant year class at Felgate’s (Figure 2.6a). At all sites, five and six year olds dominated the population in 2008 (Figure 2.6 b-d). Though the range of ages was similar at all sites, Goodwin and New Quarter males were, on average, older than males at Felgate’s in both years, with the Goodwin males being significantly older than the Felgate’s males in both years (pair-wise t-test: $p < 0.01$). Goodwin males were on average 0.84 years older than 2007 Felgate’s males and 0.64 years older than 2008 Felgate’s males.

**Females.** A total of 143 female terrapins were sampled throughout the study. In 2007, Goodwin females averaged about one year older than Felgate’s females. This was not significant, but nearly so (pair-wise t-test, $p = 0.09$). The difference between sites
might have been due to the different sampling techniques so, in 2008 sampling was standardized, but the age discrepancy widened. In 2008, females at Goodwin were significantly older than females at Felgate’s (pair-wise t-test, p= 0.0002) and nearly significantly older than they were in 2007 (pair-wise t-test, p = 0.1). In 2008, Goodwin females averaged almost two years older than females at Felgate’s and about one year older than 2007 Goodwin females. In 2007, seven year olds dominate the population at Goodwin and they appear as eight year olds the following year (Figure 2.7 c,d). Also, for unknown reasons, I caught far fewer terrapins at Felgate’s in 2008 as in 2007. This resulted in six year olds dominating the population as they had the previous year because in 2008 there was a complete lack of seven, eight, ten and eleven year olds (Figure 2.7 a,b).

Size Structure

**Females.** In both years, females at Goodwin were four to five cm longer, three to three and a half cm wider, about one and a half cm deeper, and about 375 g more massive than Felgate’s females (Table 2.1). This was a significant difference in size between sites (Table 2.2). Additionally, average female size at Goodwin in 2007 was significantly larger than in 2008 (Table 2.2), as expected once sampling techniques had been standardized, but contradictory to expectations when 2008 females were significantly older than 2007 females. In 2007, Goodwin females were about two cm longer, one to one and a half cm wider, 0.7 cm deeper, and about 150 g more massive than in 2008 (Table 2.1).
However, when size metrics are plotted by age, there appears to be a much smaller difference in the size structure between sites (Figure 2.8). Females at Goodwin may be slightly longer but they are no wider than females at Felgate’s. Interestingly, when only six year olds are considered the range of lengths and widths at both sites are the same but at Goodwin the points tend to be clustered towards the high end of the range and at Felgate’s the points tend to be clustered towards the low end of the range. This is consistent with my expected results. Similarly, female terrapins from Goodwin seem to be larger than Felgate’s females after they have fully matured. The largest female sampled throughout the entire study was found at Felgate’s, showing that females at this site at least have the potential to reach the same ultimate size as Goodwin females.

Males. There was very little difference in the size structure of males among sites, with a few exceptions. Goodwin males were on average 0.3-0.8 cm longer, 0-0.3 cm wider, and 0-0.2 cm deeper than males at all other sites (Table 2.3). This made 2008 Goodwin males significantly longer and deeper than 2008 Felgate’s males (Table 2.4). 2007 Felgate’s males were significantly more massive than all 2008 males, and 2008 males at Goodwin were significantly more massive than 2008 males at Felgate’s (Table 2.4). However, when size is plotted by age, there is no apparent difference in size structure (Figure 2.9).

Discussion

Age Structure

The lack of male terrapins older than eight years at Goodwin and New Quarter was expected, but the same trend at Felgate’s is puzzling. I hypothesized that crab traps
would result in 100% mortality of male terrapins by age nine. Since Felgate’s was considered a pristine site with regards to crab trapping I expected to find many older males at the site and did not. One potential reason for the unexpected result is the aging method of counting scute rings. Counting carapacial annuli has been shown to be accurate for some turtles but not all (Litzgus & Brooks 1998), and the validity of this method has never been tested for terrapins. Some say that it is accurate (Cagle 1952, Gibbons et al. 2001) while some say that it is only accurate for young terrapins (Hay 1904, Hildebrand & Hastel 1926, Roosenburg 1991). When painted turtles reach maturity their growth rate slows so much that new annuli are too close together and too thin to be counted (Sexton 1959). It is likely that the same phenomenon occurs for terrapins. Therefore, counting rings is probably accurate for males up to age eight and females up to age 13, and some terrapins were probably inaccurately aged in my study. However, several terrapins captured in 2008 that had been marked in 2007 were aged as one year older upon recapture than they had been upon initial capture. Additionally, I did not get many terrapins that were clearly too old to age, nor did I get a disproportionately large number of eight year old males at Felgate’s. In fact, I trapped a disproportionately large number of young males at Felgate’s. In 2007, four year olds were the dominant year class. They appear as five year olds in 2008, which would explain the slight increase in the average age at Felgate’s from 2007 to 2008. Very few four-year olds were found at Goodwin and New Quarter, and a larger proportion of seven and eight-year olds were found at Goodwin than at any other site.

It is possible that the preponderance of younger males at Felgate’s is due to better recruitment at Felgate’s. Nest predation rates were similarly high between Felgate’s and
Goodwin (Ruzicka 2006, MA Rook unpublished data) but hatchlings may have higher survivorship at Felgate’s, though there is no data to support this claim. Raccoons and known avian predators appeared to be far more abundant at Goodwin. A study tracking hatchlings from emergence to recruitment would give data to support or refute this claim, as well as give information about the whereabouts and behavior of hatchlings during that three-year period when they seem to be missing.

Another possibility for the preponderance of young males is that Felgate’s acts as both nursery and breeding habitat while Goodwin is only breeding habitat. The absence of 1-3 year old terrapins in a marsh is well documented. At Goodwin though, four year old males and four and five year old females were also absent. In a 1979 study, Hurd et al. suggest that it is unlikely that small terrapins inhabit the main tidal creek because they are not strong enough to swim with the current. Additionally, Roosenburg et al. (1999) showed that terrapins in the Patuxent River, MD used different parts of the river during different life stages. Given that the Goodwin Islands are right at the intersection of the York River and the Chesapeake Bay, and are subject to heavy wave action, it is possible that young terrapins do not inhabit the Goodwin Islands until they are fully capable of entering the breeding population. The islands are only 0.5 kilometers from the mainland which has a series of protected coves, fringed with marsh. This area has never been sampled for terrapins but many have been seen there (RN Lipcius, pers. com.). It is very likely that terrapins at the mouth of the York River are using the nearby coves as nursery habitat and the Goodwin Islands as breeding habitat, while the entirety of Felgate’s Creek is used for both.
This is also a possible explanation reason for significantly older females at Goodwin than at Felgate’s. I was expecting older females at Goodwin if crab traps were affecting the population but since I trapped only six females at New Quarter and no terrapins at all at Fort Eustis sites, the results cannot be attributed specifically to crab trap mortality. Additionally, my inability to find terrapins at Felgate’s in 2008 and my inability to find nesting females at Felgate’s in both years likely skewed the data. A large population decline at Felgate’s is not likely. The absence of terrapins at Felgate’s in 2008 may have been caused by an extremely warm, dry summer. Due to the intense heat in June of 2008 and the complete lack of rainfall throughout most of the summer, the water in which I placed traps was very warm the entire summer. Capture rates throughout the entire 2008 season were similar to capture rates during the hottest part of the 2007 season. My population estimates showed that the Felgate’s population increased from 2007 to 2008, though the confidence intervals overlapped. Additionally, it is not believed that nesting females were absent from the Felgate’s population. Rather, nesting areas except for the roadside near the sampling area could not to be accessed due to restrictions associated with working on a military base.

Size Structure

Females at Goodwin were, on average, much larger than females at Felgate’s, both overall and in each age class. Though this was expected, the difference in size cannot be directly attributed to the presence or absence of crab traps. Again, I was unable to incorporate data from New Quarter into my analysis, and I had no data at all from Fort Eustis. Having only one “control” site and one “treatment” site precludes me from testing
any hypotheses regarding differences between sites. However, I believe the difference in size most probably reflects the difference in my ability to trap different portions of the population at different sites. The sample size of mature females at Felgate’s is very small. If I had a larger sample size of old females at Felgate’s, it is quite possible that there would be no difference in the maximum size attained by females at both sites.

However, female terrapins at Goodwin are larger than females at Felgate’s in each year class, so sampling differences cannot be the only cause for differences between sites. Habitat differences may have also played a role. It has been found that changes in food availability in an ecosystem, rather than fishing pressure, are far more likely to have an affect on growth and age at weight for Atlantic cod (Brander 2007). If females at Felgate’s have the potential to grow as large as females at Goodwin but are not, a difference in food availability, rather than crab trap mortality may be the cause. Goodwin appears to be much more rich in food resources than Felgate’s. Qualitatively, the marsh at Goodwin seems much more extensive and harbors a much denser invertebrate population, particularly salt marsh periwinkles. Additionally, there are extensive beds of sea grass around the Goodwin Islands and there is no sea grass at Felgate’s, and terrapins are known to feed in sea grass beds (RN Lipcius pers. com.). Since terrapin growth rate is dependent upon the amount of food consumed (Hildebrand 1932, Barney 1922) one would expect terrapins of both sexes inhabiting a site with more abundant food to be larger, both maximally and in each age class, than those in an area with fewer resources.

If crab traps were causing an increase in the average size of females, I would expect that the older females in both populations would be the same in size, there would just be more of the older females in the affected population to drive up the average. With
regards to younger females, I would expect that females in a crabbed population would be maturing earlier and would be larger than their age cohorts at a pristine site, also driving up the average. I would expect no difference in males. I did see earlier maturing females at Goodwin, but the older females at Goodwin were larger than females at Felgate’s, despite a demonstrated ability for Felgate’s females to reach the same size as those at Goodwin. There was no significant difference in male size except for mass, but I believe this reflects the difference in type of scale used from one year to the next and the likely possibility that the broken scale was used more often at Felgate’s in 2008. Average male mass in 2008 was 282 g and the broken scale consistently read around 280 g unless a large female was being measured. However, 2007 males from Felgate’s were significantly deeper than Felgate’s males in 2008, so the difference in mass may be correct.

It is also possible that both habitat differences and crab trap mortality are affecting the populations differently. Unfortunately, there is no way to distinguish between mechanisms with the data I collected. A more appropriate experiment to distinguish between factors might be a common garden experiment. One could collect eggs from both sites and incubate them between 28.5 and 29.5°C to get a mix of male and female terrapins. Then, mark and separate all hatchlings into several ponds, placing an equal number of terrapins from both sites into each pond. In half of the ponds, terrapins would be fed a diet comparable to what they would receive at Felgate’s and in the other five ponds terrapins would be fed a diet comparable to what they would receive at Goodwin. If terrapins in “Goodwin” ponds mature earlier and are maximally larger than terrapins from “Felgate’s” ponds, then food is most likely the factor affecting size. If
Goodwin terrapins are larger than Felgate’s terrapins at six years old, and all terrapins reach the same maximum size range, despite the amount of food received, then changes caused by crab trap mortality is the likely explanation.

An important point to remember is that the actual extent to which the crabbing industry actually affects terrapins in Virginia is not quantified. There is plenty of anecdotal evidence suggesting that crab trap mortality is a problem but the scope and scale of the problem remains to be determined. Differences among sites may have nothing to do with crab trap mortality because crabbing may have little to no effect on the terrapins of Virginia. One way to make a good guess as to the extent of the problem is to compare the differences among my sites to demographic changes that have occurred in a population under known crabbing pressure. Dorcas et al. (2007) sampled terrapins from a site affected by crab traps for nearly 20 years. Terrapin numbers declined significantly across this time and population changes were clearly noted. The modal age of terrapins increased from five to eight years, the proportion of older, large females trapped increased dramatically, and the modal size of male terrapin plastron length increased by about 0.5 cm. In my study, the modal age increased from five to six from Felgate’s to Goodwin and did not increase from Felgate’s to New Quarter. Many more older, larger females were trapped at Goodwin than at Felgate’s, and male plastron length increased by 0.6 cm from Felgate’s to Goodwin and 0.3 cm from Felgate’s to New Quarter. So, my crabbed populations show some signs of being affected by crabbing pressure but not as heavily as other populations. Further, crabbing may not be the mechanism for differences among my populations because changes were not as dramatic as would be expected.
However, bycatch in blue crab traps is very likely having some effect on the diamondback terrapin populations in the Virginia portion of the Chesapeake Bay. It is clear that, at least in my study areas, crab trap mortality is not a strong enough threat to cause immediate extirpation of the species in this state, but the potential for local extinctions is very real. Given that terrapin populations are declining across the entire east coast, and given that terrapins in southeastern Virginia seem to be less heavily affected by crab trapping than in other states, Virginia may be in a unique position to take a leadership role in pro-active conservation. Implementing conservation measures before populations are in dire straights is far more time and cost efficient, will have more effective results, and will have fewer detrimental effects to people whose livelihoods may be affected by conservation regulations. In the next chapter I explore the use of Bycatch Reduction Devices (BRDs) to protect terrapins from crab trap mortality, and the effects of BRDs on the crab catch. If effective, this conservation strategy may help keep the blue crab fishery from being shut down, a possible scenario should the diamondback terrapin become federally endangered.
TABLE 2.1. Mean sizes and standard errors (se) of female diamondback terrapins, including carapace length (CL), carapace width (CW), plastron length (PL), plastron width (PW), shell depth (D) and mass (M). Mass measurements likely include much more error than is represented by the standard error estimates.

<table>
<thead>
<tr>
<th></th>
<th>CL Mean</th>
<th>CL se</th>
<th>CW Mean</th>
<th>CW se</th>
<th>PL Mean</th>
<th>PL se</th>
<th>PW Mean</th>
<th>PW se</th>
<th>Depth Mean</th>
<th>Depth se</th>
<th>Mass Mean</th>
<th>Mass se</th>
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<td>Felgate’s 2007</td>
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<td>0.583</td>
<td>12.5</td>
<td>0.458</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.8</td>
<td>0.270</td>
<td>970</td>
<td>99.4</td>
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<tr>
<td>Felgate’s 2008</td>
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<td>0.810</td>
<td>11.3</td>
<td>0.453</td>
<td>12.2</td>
<td>0.463</td>
<td>6.6</td>
<td>0.235</td>
<td>5.9</td>
<td>0.250</td>
<td>476</td>
<td>71.6</td>
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<td>Goodwin 2007</td>
<td>20.6</td>
<td>0.282</td>
<td>15.5</td>
<td>0.209</td>
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<td>14.0</td>
<td>0.394</td>
<td>17.1</td>
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<td>9.1</td>
<td>0.248</td>
<td>7.8</td>
<td>0.243</td>
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TABLE 2.2. P-values from all pair-wise t-test results for mean female size. Shaded boxes indicate significant differences of p < 0.05

<table>
<thead>
<tr>
<th></th>
<th>Felgate’s 07</th>
<th>Felgate’s 08</th>
<th>Goodwin 07</th>
</tr>
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<tbody>
<tr>
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<td>-</td>
</tr>
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<td>-</td>
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<tr>
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TABLE 2.3. P-values from all pair-wise t-test results for mean male size. Shaded boxes indicate significant differences of p < 0.05.

<table>
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<th>Felgate’s 07</th>
<th>Felgate’s 08</th>
<th>Goodwin 08</th>
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<tr>
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<tr>
<td>New Quarter 08</td>
<td>0.998</td>
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<td>0.930</td>
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<td>Goodwin 08</td>
<td>0.011</td>
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<tr>
<td>New Quarter 08</td>
<td>0.0004</td>
<td>0.477</td>
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TABLE 2.4. Mean sizes and standard errors (se) of female diamondback terrapins, including carapace length (CL), carapace width (CW), plastron length (PL), plastron width (PW), shell depth (D) and mass (M). Mass measurements likely include much more error than is represented by the standard error estimates.

<table>
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<tr>
<th></th>
<th>CL</th>
<th>CW</th>
<th>PL</th>
<th>PW</th>
<th>D</th>
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<td></td>
<td>Mean</td>
<td>se</td>
<td>Mean</td>
<td>se</td>
<td>Mean</td>
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<tr>
<td>Felgate's 2007</td>
<td>12.6</td>
<td>0.139</td>
<td>9.7</td>
<td>0.103</td>
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<td>Felgate's 2008</td>
<td>12.2</td>
<td>0.165</td>
<td>9.4</td>
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<td>10.6</td>
<td>0.142</td>
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<td>9.7</td>
<td>0.075</td>
<td>11.2</td>
<td>0.100</td>
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<tr>
<td>Queen's Creek 2008</td>
<td>12.6</td>
<td>0.221</td>
<td>9.5</td>
<td>0.144</td>
<td>10.9</td>
<td>0.173</td>
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</table>


FIGURE 2.1. From Wolak, 2006. Multiple regression of (a) female Carapace Width (CW) and (b) male Carapace Width by age. A Gompertz Equation was used to fit a more biologically relevant line to the data. Red circles and line represent Goodwin terrapins, blue squares and line represents Connecticut terrapins, and black triangles and line represent Smithsonian terrapins. The dashed horizontal line indicates the opening gape size of a crab pot (117mm).
FIGURE 2.2. Map of the Chesapeake Bay indicating the four study locations.
FIGURE 2.3. Crab trap with chimney attached to the top.
FIGURE 2.4. Study sites showing trap placement: (a) Felgate’s 2007, (b) Felgate’s 2008, (c) Goodwin Islands, (d) Queen’s Creek. Each point represents one pot.
FIGURE 2.5. Terrapin marking method. Each scute on the right side of the shell that was not on the bridge corresponded to a number. If that scute was marked the number was added to any additional marked scutes. This terrapin shows marks on scutes 4, 8, and 16 and therefore is turtle #28. It has been identified as a male and the scute to the left of the 1 scute has been marked accordingly.
Male Age Distribution

FIGURE 2.6. Age distribution for males at (a) Felgate’s Creek in 2007, (b) Felgate’s Creek in 2008, (c) the Goodwin Islands in 2008, and (d) Queen’s Creek in 2008.
FIGURE 2.7. Age distribution of females at (a) Felgate’s Creek in 2007, (b) Felgate’s Creek in 2008, (c) the Goodwin Islands in 2007, and (d) the Goodwin Islands
FIGURE 2.8. Scatter plots of female (a) carapace lengths and (b) carapace widths by age representing data from 2007 and 2008 combined. The black line represents 11.7 cm, the maximum width of the gape in a crab trap.
FIGURE 2.9. Male (a) carapace lengths and (b) carapace widths plotted by age for each site. Felgate's data includes 2007 and 2008 data. The black line represents 11.7 cm, the maximum width of the gape in a crab trap.
Literature Cited


Hildebrand SF, Hastel C (1926) Diamondback terrapin culture at Beaufort North Carolina. Department of Commerce, Bureau of Fisheries Economic Circular No. 60.


CHAPTER 3
EFFECTIVENESS OF BYCATCH REDUCTION DEVICES (BRDs) AT REDUCING DIAMONDBACK TERRAPIN MORTALITY WHILE NOT REDUCING CATCH IN BLUE CRAB TRAPS

Introduction

A major threat to organisms in coastal environments arises from the overexploitation of non-target species as intentional catch or unintentional take as bycatch (Lewison et al. 2004). Significant bycatch can result in rapid depletion of the non-target population or a demographic shift in body size, sex ratio, and age structure, all of which may lead to severe population depletion. Frequently, the outcome of severe bycatch is a smaller size and younger age at maturity, or at worst, local extinction. Smaller body size may mean a decrease in fecundity (Conover & Munch 2002, Lipcius & Stockhausen 2002) or decreased fertilization rates (Jamieson et al. 1998).

Attempts to reduce bycatch are typically met with resistance from the fishing community. Conservation goals are often in direct conflict with proximate fisheries goals (Heppell et al. 2004), and gear modifications are perceived to be detrimental to catch of target species in the short-term, though few rigorous studies have actually examined the effects of gear modifications on catch. However, as Preikshot and Pauly (2004) state, “Sustainable management of fisheries cannot be achieved without an acceptance that the long-term goals of fisheries management are the same as those of environmental conservation.” For conservation to be successful and for fisheries to persist, both
conservation measures and fisheries management need to move away from single-species focus and move toward an integrated ecosystem- and economic-based approach.

A candidate model system in which to test this proactive approach is that of the interaction of the diamondback terrapin and the blue crab fishery. The diamondback terrapin (*Malaclemys terrapin*) is the only turtle in North America to inhabit estuarine environments exclusively (Ernst et al. 1994). Terrapins are potentially keystone predators in estuarine ecosystems, feeding on prey such as crabs, mussels, salt marsh periwinkles, barnacles, and clams (Tucker et al. 1995, Silliman & Bertness 2002). The most abundant and common prey is the salt marsh periwinkle *Littoraria irrorata*, which comprises as much as 79% of the total food intake by mass in some areas (Coker 1920, Tucker et al. 1995). When unchecked by predators, *L. irrorata* can defoliate a marsh in as little as 8 months (Silliman & Bertness 2002). Adult terrapins in turn are prey of bald eagles (Clark 1982) and may be eaten by toadfish and crabs (Cecala et al. 2008).

Terrapins have a long history of overexploitation, having been hunted to commercial extinction in the early 1900s (Coker 1906). Soon thereafter, a captive breeding program, a moratorium on terrapin harvest, and a dwindling demand for terrapin meat helped some populations to recover (Garber 1990, Yearicks et al. 1981). By the late 20th century, populations had been making a steady comeback until numerous anthropogenic changes to coastal environments combined to threaten populations anew (Butler et al. 2006).

Among all threats to terrapins, mortality in crab traps is the most serious in North America (Butler et al. 2006). Throughout much of the terrapin’s range, estuarine waters
are replete with blue crab traps, and terrapins enter baited or un-baited traps where they become entrapped and drown. Detrimental effects of crab traps include decreases in population size and demographic shifts in size structure, age structure, and sex ratio (Bishop 1983, Roosenburg et al. 1997, Wood 1997, Hoyle & Gibbons 2000, Tucker et al. 2001, Dorcas et al. 2007). As a result, the diamondback terrapin is listed as 'endangered' in one state (RI), 'threatened' in one (MA), and as 'vulnerable' or 'imperiled' in eight other states (NC, LA, AL, MS, GA, TX, CT, and NY) (Hackney & Baldwin, submitted).

The threat from crab traps differs by use. Standard commercial crab traps are constantly submerged and typically checked daily. The constant submersion poses a major threat but drowning is limited due to the high frequency with which the traps are checked and because commercial traps are most often placed in deeper water outside of the terrapin’s normal range (Roosenburg et al. 2008). The predominant threat from commercial traps comes in the form of ghost traps, which are traps that have been lost or abandoned and remain in the estuary, continuously trapping all animals that enter. For example, Bishop (1983) found one ghost trap with 28 dead terrapins and Roosenburg (1991) found one trap with 49 terrapin shells, among other animal remains.

Recreational crab traps are identical in structure to commercial traps but are used for private, recreational crabbing. Though fewer in number, recreational traps potentially pose a more serious threat because private crabbers tend to place traps in shallow-water habitats where terrapins are more common and traps are checked less frequently (Hoyle & Gibbons 2000). Even if a trap is only submerged at high tide, a trapped terrapin may die from exposure rather than drowning if left in a trap for more than 48 hours (M. Rook,
pers. obs.). Moreover, recreational traps may also become ghost traps.

Because gape size in traps restricts entrance by large terrapins, crab traps selectively capture immature males and females, as well as mature males, which are smaller than mature females (Roosenburg et al. 1997, Wood 1997, M. E. Wolak unpublished data). Hatchling and very young terrapins are small enough to exit a crab trap, and most are not found in the same habitat as crab traps. In contrast, mature females grow too large to fit through the gape in a standard crab trap. The selective removal of males and pre-reproductive females has the potential to shift terrapin population demographics (Dorcas et al. 2007) and cause local extinctions (Roosenburg et al. 1997, Tucker et al. 2001).

In lower Chesapeake Bay, diamondback terrapins are likely suffering high rates of mortality as bycatch (Ruzicka 2006, M. E. Wolak unpublished data). In upper Chesapeake Bay and in Delaware Bay, bycatch reduction devices (BRDs) are required on all recreational crab traps, while in Delaware Bay, BRDs are required on any trap set in tidal creeks < 50 m wide at mean low water (http://dnr.maryland.gov, http://www.fw.delaware.gov, http://www.state.nj.us).

Several studies have examined the effects of BRDs on reducing the terrapin bycatch but few have examined the effect of BRDs on the crab catch. The effects of BRDs on terrapin bycatch and crab catch vary by site and results from one site cannot be applied to other localities (Wood 1997, Roosenburg & Green 2000, Butler & Heinrich 2007). Consequently, we sought to (1) determine the effects of BRDs in crab traps upon terrapin mortality and blue crab catch in lower Chesapeake Bay, and (2) devise a conservation
strategy that could be implemented with the least resistance, as a model for a win-win strategy in marine conservation.

Methods

Study Sites

The experiments were conducted at Felgate's Creek, part of the Yorktown Naval Weapons Station on the York River, Virginia, and at an unnamed creek in Fort Eustis on the James River, Virginia (Figure 3.1). For complete site descriptions, see Chapter II.

Sampling design

During summer 2008, 10 pairs of crab traps were placed throughout each of the two creeks (Figure 3.2). Each pair consisted of one crab trap without BRDs (“non-BRD trap”) and one crab trap fitted with a 4.5 x 12 cm plastic BRD (Figure 3.3) on each of its four entrances (“BRD trap”). Trap pairs were placed side by side in the entrances of small marsh creeks. Crabs were sampled for a single trapping interval once a week for four weeks. Traps were baited at the beginning of the week and checked after 48 hours. The total number of crabs per trap was recorded at both sites. Tip to tip carapace width was measured using field calipers and the sex of each crab was recorded. Carapace width (CW) was converted to biomass using the following equations (Smith & Chang 2008):

\[
\text{Biomass} = 0.000355 \times \text{CW}^{1.571} \quad \text{for females, and}
\]

\[
\text{Biomass} = 0.00027 \times \text{CW}^{1.662} \quad \text{for males.}
\]
Terrapins trapped in crab traps were sampled and released continuously throughout the summer. The total number of terrapins per trap was recorded along with sex, age, carapace length and width, plastron length and width, shell depth, and mass of each terrapin.

*Crab Trap Modifications*

Aside from BRDs, crab traps were modified to eliminate terrapin mortality by cutting a hole in the top of each trap and securing a closed "chimney" of chicken wire extending 60 cm above the hole (Figure 3.3). The chimney allowed captured terrapins to swim up and breathe during high tide but kept them from escaping. Also, 2-m wooden stakes were driven into the mud and chimneys were tied to the stakes to help prevent the traps from tipping over during times of high wave action or storms. Finally, 15-cm wooden props were attached with plastic zip ties to the standard opening in the top of the trap. Props were used to keep the traps open when the research team could not get out to sample. Modifications for terrapin survival were assumed to have no effect on the crab catch since no trap was ever filled to capacity. Any error associated with the modifications should have affected non-BRD traps and BRD traps similarly.

*Hypothesis Testing and Models*

All data were analyzed using the information-theoretic (I-T) approach of maximum-likelihood multi-model comparisons (Burnham and Anderson 2002, Anderson 2008). For terrapins in Felgate's Creek, we hypothesized that the total number of terrapins caught per
trap would be lower in BRD traps, with a possible Date effect; the BRD x Date interaction was also tested, though the effect was hypothesized to be negligible (Table 3.1).

For crab catch, we tested the effects of BRD, Site, and Date on total number of crabs, number of legal crabs, number of sublegal crabs, size of total crabs, size of legal crabs, size of sublegal crabs, biomass of total crabs, biomass of legal crabs, and biomass of sublegal crabs. For each of the abundance and biomass response variables we used the difference in abundance and biomass between normal traps and traps with BRDs on a trap \(^{-1}\) day \(^{-1}\) basis. We compared four possible models considering each of the main effects independently and possible interaction effects (Table 3.2). For each of the size response variables we examined the average carapace width of each crab captured in a standard trap and a normal BRD trap. We compared eight possible models (Table 3.3). AIC values and parameter estimates were obtained using the Generalized Linear Model (GLM) function in the R statistics package (www.r-project.org). For analyses involving the total number of terrapins or crabs, the Poisson option was used with the GLM analysis because of the low numbers caught per trap.

Results

Terrapin bycatch

Forty-eight terrapins were captured over 23 trapping days. Of these, 46 were caught in non-BRD traps, and two in BRD traps. The mean catch was 0.20 terrapins trap \(^{-1}\) day \(^{-1}\) in non-BRD traps and 0.01 terrapins trap \(^{-1}\) day \(^{-1}\) in BRD traps (Figure 3.4). Mean shell
depth of terrapins captured in non-BRD traps was 5.1 cm, while the smallest terrapin captured in non-BRD traps had a shell depth of 4.3 cm. The two terrapins captured in BRD traps had a shell depth of 4.1 cm. Since only two terrapins were captured in BRD traps, placing 100% of the data on only 2 of 23 dates, the BRD x Date interaction model was eliminated from the analysis. The model including the effects of BRD and Date was the most probable model with a weighted probability of 0.986 (Table 3.4a). However, the Date effect was trivial, such that the BRD effect was the only significant effect (Table 3.4b).

Crab catch

Abundance. Over the four crab-trapping intervals we captured 348 crabs, with 137 caught at Fort Eustis and 211 caught at Felgate's. In all analyses, Site was the only factor that had a noticeable effect, with crabs being more abundant at Felgate's. For total number and legal number, the Site effect model (\( g_2 \)) had the greatest weighted probability and was used to estimate the BRD effect. For sublegal number, both the Date effect model and the Site effect model had the highest probabilities (Table 3.5a) but neither was a strong candidate for best model because of the low effect sizes and high variances (Table 3.4b). Therefore, the null model, a BRD effect, was considered the most probable, though the estimated BRD effect was very low and not reliable due to the relatively high variance. This assumption was consistent with the data. We averaged 1.19 crabs trap\(^{-1}\) day\(^{-1}\) in traps without BRDs and 1.31 crabs trap\(^{-1}\) day\(^{-1}\) in traps with BRDs (Figure 3.5b). For legal number of crabs, the estimated BRD effect was an increase of 0.3 crabs trap\(^{-1}\).
day$^{-1}$ with a difference of about 0.5 crabs trap$^{-1}$ day$^{-1}$ between sites (Table 3.5b). For legal-size crabs we averaged 0.88 crabs trap$^{-1}$ day$^{-1}$ in traps without BRDs and 0.94 crabs trap$^{-1}$ day$^{-1}$ in traps with BRDs (Figure 3.5a), attesting to the small effect of BRDs on crab catch.

**Carapace width.** In all analyses, Site had the greatest effect, Date had no effect, and BRD had a small effect compared to Site. For total and sublegal size, the model with the effects of Site, Date, and BRD ($g_5$) was the most likely model. For legal size, the model with the effects of Site and Date ($g_4$) had the highest probability (Table 3.5a), but parameter estimates changed only slightly from $g_4$ to $g_5$, so $g_5$ was used to obtain the BRD effect estimate. Site had a non-trivial effect for all size estimates, with Fort Eustis having slightly larger crabs. Legal-size crabs averaged about 130 mm in carapace width at Felgate's and 137 mm at Ft. Eustis (Figure 3.6a). Legal-size crabs caught in traps with BRDs were on average 2.0 mm larger in carapace width than crabs caught in traps without BRDs. This was consistent with the model estimate for the BRD effect of a 2.2 mm increase in carapace width (Table 3.5b). Sublegal-size crabs caught in traps with BRDs were on average 1.5 - 2.0 mm larger in carapace width than crabs caught in traps without BRDs (Figure 3.6b). This too was consistent with the model estimated BRD effect of a 1.7 mm increase in carapace width (Table 3.5b).

**Biomass.** Site had the strongest effect in all analyses. For total and legal biomass, the Site effect model ($g_2$) was the best. For sublegal biomass, the Site plus Date effect model
(g₃) was the best (Table 3.5a). Crabs were heavier at Fort Eustis than at Felgate's. Legal-size crabs averaged 112 g at Felgate's and 134 g at Ft. Eustis. Crabs caught in BRD traps were 5-6.5 g heavier than crabs caught in non-BRD traps (Figure 3.7a). For legal biomass, BRD traps caught 55 grams trap⁻¹ day⁻¹ more than non-BRD traps (Table 3.5b). Sublegal crabs were also heavier in traps with BRDs than in traps without by 2.5–3.0 g (Figure 3.7b). For sublegal biomass, BRD traps caught 13 grams trap⁻¹ day⁻¹ more than non-BRD traps (Table 3.5b).

**Discussion**

Bycatch reduction devices (BRDs) reduced terrapin bycatch in crab traps by 95.7%. The 46 terrapins captured in traps without BRDs represented 27.5% of the estimated population at Felgate's (see Chapter 2). This potential mortality rate could not be sustained by diamondback terrapin due to its K-selected life-history traits (Gibbons et al. 2001), including a long life span, late sexual maturity, and low fecundity. In contrast, the two terrapins captured in BRD traps represented only 0.6% of the estimated population, a loss that should be sustainable.

In contrast to the substantial effect on terrapins, BRDs had little to no effect on crab catch. Traps with BRDs had slight increases in the number, size, and biomass of both legal and sublegal crabs caught. These increases did not differ from zero, such that the overall effect of BRDs on the crab catch was considered negligible.

The collective findings of our study and previous studies (Wood 1997, Roosenburg & Green 2000, Butler & Heinrich 2007) support the contention that survival of
diamondback terrapin populations in North American estuaries is severely reduced by crab traps, but also that fishery catches of blue crab are not significantly affected. In coastal marsh habitats and seaside lagoons of the northwestern Atlantic, Wood (1997) tested three types of BRDs, with the 4.5 x 10 cm BRD the closest in size to that used in our study. Traps without BRDs captured 0.17 terrapins and 1.67 crabs trap\(^{-1}\) day\(^{-1}\), whereas traps with BRDs captured no terrapins and 0.80 crabs trap\(^{-1}\) day\(^{-1}\). In upper Chesapeake Bay, Roosenburg and Green (2000) saw a decrease in the number of crabs trapped per day when they used 4 x 10 cm BRDs and 5 x 10 cm BRDs on normal crab traps and specially constructed “tall” crab traps that prevented terrapins from drowning. However, when they used 4.5 x 12 cm BRDs, the same as in our study, they saw a slight increase in catch. Crab catch in normal sized non-BRD traps was 2.55 crabs trap\(^{-1}\) day\(^{-1}\) and increased to 2.69 crabs trap\(^{-1}\) day\(^{-1}\), while crab size did not differ between BRD and non-BRD traps. In tall pots, crab catch was 1.0 crabs trap\(^{-1}\) day\(^{-1}\) in non-BRD pots and increased to 1.14 crabs trap\(^{-1}\) day\(^{-1}\) in BRD pots with no difference in size of crabs between pots. All sizes of BRDs reduced terrapin bycatch. The 4 x 10 cm BRD completely eliminated bycatch, the 4.5 x 12 cm BRD reduced bycatch by 62%, and the 5 x 10 cm BRD reduced bycatch by 53%. At eight sites along coastal habitats of the Gulf of Mexico and Atlantic Ocean in Florida (USA), Butler and Heinrich (2007) compared traps fitted with a 4.5 x 12 cm BRD and without a BRD. Traps without BRDs captured 37 terrapins, whereas traps with BRDs caught only four terrapins, one of which was due to BRD failure. Crab catch in traps with BRDs was higher than that in non-BRD traps at three sites, lower at two sites, and similar at three sites, resulting in an overall increase in
crab catch in BRD traps. Since height of a BRD affects the ability of terrapins to enter a trap and width of a BRD affects the ability of a crab to enter a trap, the 4.5 x 12 cm BRD appears to be a good compromise between reducing bycatch and not adversely affecting the crab catch.

As in other studies, traps with BRDs also reduced other bycatch in our experiments. Whereas the only bycatch in BRD traps consisted of two small terrapins, non-BRD traps captured several species of fish, a Virginia rail, a muskrat, a nutria, and several mud and snapping turtles. In Wood's (1997) study, which was conducted in deeper waters, bycatch comprised spider crabs, conchs, and several species of fish. BRDs therefore also have a direct benefit to wildlife, and not just for diamondback terrapin. Moreover, individual BRDs are inexpensive (US$0.42 per BRD) and simple to attach to the entrances of crab traps, such that there are no obvious economic, environmental, or physical disadvantages to their use.

I therefore recommend the use of bycatch reduction devices on all crab traps placed in diamondback terrapin habitat of the North American coastline, particularly for crab traps in the shallow waters (< 2 m water depth) fringing coastal marshes, estuaries and lagoons. Conversely, bycatch reduction devices may not be necessary for crab traps set in deeper waters where terrapins are scarce. When bycatch reduction devices are used in shallow-water commercial crab traps, our findings suggest that commercial catch will not be affected. Consequently, the use of bycatch reduction devices in blue crab traps represents an excellent example of ecosystem-based fishery management whereby the goals of marine conservation and fishery harvest can be met simultaneously.
<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_1$</td>
<td>$y = \alpha + \beta_1 x_1 + e$</td>
</tr>
<tr>
<td>$g_2$</td>
<td>$y = \alpha + \beta_2 x_2 + e$</td>
</tr>
<tr>
<td>$g_3$</td>
<td>$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + e$</td>
</tr>
<tr>
<td>$g_4$</td>
<td>$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + e$</td>
</tr>
</tbody>
</table>

$\alpha$ = Intercept, $x_1$ = Date effect, $x_2$ = BRD effect

TABLE 3.1. Models for terrapin bycatch analysis.
TABLE 3.2. Models for crab abundance and biomass analyses.

<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_1$</td>
<td>$y = \alpha + \beta_1 x_1 + e$</td>
</tr>
<tr>
<td>$g_2$</td>
<td>$y = \alpha + \beta_2 x_2 + e$</td>
</tr>
<tr>
<td>$g_3$</td>
<td>$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + e$</td>
</tr>
<tr>
<td>$g_4$</td>
<td>$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 + e$</td>
</tr>
</tbody>
</table>

$\alpha = $ BRD effect, $x_1 =$ Date effect, $x_2 =$ Site effect
### Table 3.3. Models for crab size analyses.

<table>
<thead>
<tr>
<th>Model</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>g1</td>
<td>$y = \alpha + \beta_1 x_1 + e$</td>
</tr>
<tr>
<td>g2</td>
<td>$y = \alpha + \beta_2 x_2 + e$</td>
</tr>
<tr>
<td>g3</td>
<td>$y = \alpha + \beta_3 x_3 + e$</td>
</tr>
<tr>
<td>g4</td>
<td>$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + e$</td>
</tr>
<tr>
<td>g5</td>
<td>$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + e$</td>
</tr>
<tr>
<td>g6</td>
<td>$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1 x_2 + e$</td>
</tr>
<tr>
<td>g7</td>
<td>$y = \alpha + \beta_2 x_2 + \beta_3 x_3 + \beta_5 x_2 x_3 + e$</td>
</tr>
<tr>
<td>g8</td>
<td>$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_1 x_2 + \beta_5 x_2 x_3 + \beta_6 x_1 x_3 + \beta_7 x_1 x_2 x_3 + e$</td>
</tr>
</tbody>
</table>

$\alpha = \text{Intercept, } x_1 = \text{Date effect, } x_2 = \text{Site effect, } x_3 = \text{BRD effect}$
### TABLE 3.4a. AIC values, corrected AIC values, deltas, and model weights for terrapin bycatch analysis. The greatest model probability is highlighted.

<table>
<thead>
<tr>
<th>Model</th>
<th>AIC</th>
<th>AICc</th>
<th>ΔAICc</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>g_1</td>
<td>320.96</td>
<td>321.01</td>
<td>47.88</td>
<td>0.00</td>
</tr>
<tr>
<td>g_2</td>
<td>281.72</td>
<td>281.77</td>
<td>8.64</td>
<td>0.013</td>
</tr>
<tr>
<td>g_3</td>
<td>273.04</td>
<td>273.13</td>
<td>0.00</td>
<td>0.99</td>
</tr>
</tbody>
</table>

### TABLE 3.4b. Parameter estimates for terrapin bycatch models. Estimates from the best models are highlighted.

<table>
<thead>
<tr>
<th>Model</th>
<th>α</th>
<th>se</th>
<th>β_1</th>
<th>se</th>
<th>β_2</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td>g_1</td>
<td>-1.665</td>
<td>0.215</td>
<td>-0.027</td>
<td>0.009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g_2</td>
<td>-1.609</td>
<td>0.147</td>
<td></td>
<td></td>
<td>-3.136</td>
<td>0.722</td>
</tr>
<tr>
<td>g_3</td>
<td>-1.014</td>
<td>0.217</td>
<td>-0.027</td>
<td>0.009</td>
<td>-3.136</td>
<td>0.722</td>
</tr>
</tbody>
</table>

α = Intercept; β_1 = Date; β_2 = BRD
### Table 3.5a
Weighted probabilities for crab abundance and biomass analyses. Greatest model probabilities are highlighted.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$g_1$</th>
<th>$g_2$</th>
<th>$g_3$</th>
<th>$g_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Date ($D$)</td>
<td>Site ($S$)</td>
<td>$D + S$</td>
<td>$D + S + DxS$</td>
</tr>
<tr>
<td>Total Number</td>
<td>0.073</td>
<td><strong>0.594</strong></td>
<td>0.239</td>
<td>0.094</td>
</tr>
<tr>
<td>Legal Number</td>
<td>0.199</td>
<td><strong>0.501</strong></td>
<td>0.222</td>
<td>0.079</td>
</tr>
<tr>
<td>Sublegal Number</td>
<td><strong>0.418</strong></td>
<td><strong>0.398</strong></td>
<td>0.138</td>
<td>0.046</td>
</tr>
<tr>
<td>Total Biomass</td>
<td>0.115</td>
<td><strong>0.515</strong></td>
<td>0.280</td>
<td>0.090</td>
</tr>
<tr>
<td>Legal Biomass</td>
<td>0.115</td>
<td><strong>0.515</strong></td>
<td>0.280</td>
<td>0.090</td>
</tr>
<tr>
<td>Sublegal Biomass</td>
<td>0.114</td>
<td>0.188</td>
<td><strong>0.457</strong></td>
<td>0.241</td>
</tr>
</tbody>
</table>

### Table 3.5b
Parameter estimates from the most probable model for each crab abundance and biomass analysis.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\alpha$</th>
<th>se</th>
<th>$\beta$</th>
<th>se</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$BRD$</td>
<td></td>
<td>$Site$</td>
<td></td>
</tr>
<tr>
<td>Total Number</td>
<td>0.525</td>
<td>0.356</td>
<td>-1.075</td>
<td>0.504</td>
</tr>
<tr>
<td>Legal Number</td>
<td>0.300</td>
<td>0.240</td>
<td>-0.525</td>
<td>0.339</td>
</tr>
<tr>
<td>Sublegal Number</td>
<td>-0.350</td>
<td>0.234</td>
<td>0.050</td>
<td>0.334</td>
</tr>
<tr>
<td>Total Biomass</td>
<td>61.81</td>
<td>37.23</td>
<td>-100.02</td>
<td>52.65</td>
</tr>
<tr>
<td>Legal Biomass</td>
<td>55.26</td>
<td>28.90</td>
<td>-80.10</td>
<td>40.87</td>
</tr>
<tr>
<td>Sublegal Biomass</td>
<td>12.60</td>
<td>31.75</td>
<td>-35.42</td>
<td>30.59</td>
</tr>
<tr>
<td>Analysis</td>
<td>$g_1$</td>
<td>$g_2$</td>
<td>$g_3$</td>
<td>$g_4$</td>
</tr>
<tr>
<td>-----------------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>Date (D)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site (S)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BRD (B)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D + S$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D + S + B$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D + S + SxS$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$D + S + B + SxS$</td>
<td>0.000</td>
<td>0.140</td>
<td>0.000</td>
<td>0.137</td>
</tr>
<tr>
<td>Total CW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Legal CW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sublegal CW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE 3.6a. Weighted probabilities for all crab carapace width (CW) models. Greatest model probabilities are highlighted.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$\alpha$</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>$\beta_3$</th>
<th>$\beta_4$</th>
<th>$\beta_5$</th>
<th>$\beta_6$</th>
<th>$\beta_7$</th>
<th>$\beta_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Date</td>
<td>Site</td>
<td>BRD</td>
<td>Mean</td>
<td>Date</td>
<td>Site</td>
<td>BRD</td>
<td>Mean</td>
</tr>
<tr>
<td>Total Carapace Width</td>
<td>118.91</td>
<td>1.548</td>
<td>0.064</td>
<td>0.054</td>
<td>5.930</td>
<td>1.304</td>
<td>2.514</td>
<td>1.268</td>
<td></td>
</tr>
<tr>
<td>Legal Carapace Width</td>
<td>131.93</td>
<td>2.012</td>
<td>-0.109</td>
<td>0.069</td>
<td>6.610</td>
<td>1.643</td>
<td>2.210</td>
<td>1.625</td>
<td></td>
</tr>
<tr>
<td>Sublegal Carapace Width</td>
<td>111.15</td>
<td>1.143</td>
<td>0.174</td>
<td>0.040</td>
<td>2.954</td>
<td>0.988</td>
<td>1.668</td>
<td>0.947</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 3.6b. Parameter estimates from the most probable model for each crab carapace width analysis.
FIGURE 3.1. Map of the Chesapeake Bay showing study sites: Felgate’s Creek in the Yorktown Naval Weapons Station and Fort Eustis on the James River.
FIGURE 3.2. Aerial photographs of (a) Felgate's Creek and (b) the unnamed sampling creek in Fort Eustis showing trap locations. Each yellow point represents one trap.
FIGURE 3.3. Crab trap with chimney, prop, and Bycatch Reduction Devices
FIGURE 3.4. Average number of terrapins captured trap$^{-1}$ day$^{-1}$ in traps with and without BRDs. Error bars represent one standard error.
FIGURE 3.5. Average number of (a) legal sized and (b) sublegal sized crabs caught at each site by trap type. Error bars represent one standard error.
FIGURE 3.6. Average carapace width of (a) legal sized and (b) sublegal sized crabs caught at each site by trap type. Error bars represent one standard error.
FIGURE 3.7. Average biomass of (a) legal sized and (b) sublegal sized crabs caught at each site by trap type. Error bars represent one standard error.
Literature Cited


Hackney A, Baldwin R (Submitted) How the diamondback terrapin *(Malaclemys terrapin)* could save an ecosystem: enforcing existing laws with a policy hub species.


VITA

Megan Ann Rook

Megan Ann Rook received her B.A. in Zoology from Ohio Wesleyan University in 2006. She graduated Summa Cum Laude and with University Honors. During her time at Ohio Wesleyan she conducted minor research projects on the feeding behavior of manatees and the impacts of increased carbon dioxide concentrations on corals. She also worked as a summer intern for the Ohio Environmental Protection Agency in the Department of Air Pollution Control. She led Internet research projects on low sulfur diesel, participated in covert audits, and was the Ohio EPA representative for a phone conference on low sulfur diesel with the Federal EPA.

In the fall of 2006, she began her graduate studies in the Department of Biology at the College of William and Mary and in collaboration with faculty at the Virginia Institute of Marine Science. The research presented in this thesis was the subject of a feature article in the Richmond Times Dispatch and has been used to inform stewardship policy at the Goodwin Islands, part of the Chesapeake Bay National Estuarine Research Reserve System. Additionally, this research has been presented to the Virginia Marine Resources Commission (VMRC) in an attempt to raise awareness of bycatch mortality in crab traps and make Bycatch Reduction Devices a requirement on all recreational crab traps in the commonwealth of Virginia.

Megan defended the work presented in this thesis on June 5, 2009. She will soon be working in collaboration with Dr. Romuald Lipcius, the VMRC, and local watermen to conduct a Chesapeake Bay-wide study of the effects of BRDs on the blue crab catch.