

**Anthropogenic Impacts on the Reproductive Ecology of the  
Diamondback Terrapin, *Malaclemys terrapin***

A Thesis

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**ABSTRACT**

Anthropogenic Impacts on the Reproductive Ecology of the  
Diamondback Terrapin, *Malaclemys terrapin*

John P. Wnek

Harold W. Avery, Ph.D., Supervisor

Diamondback terrapins, *Malaclemys terrapin*, inhabit estuaries along the east and Gulf coasts of North America. One such estuary, Barnegat Bay, New Jersey, is considered one of the most anthropogenically altered estuaries in the United States. Barnegat Bay's marsh and shoreline habitats have been filled with anthropogenically impacted substrate dredged from the bay floor, called dredged sediment. Terrapins use anthropogenically impacted areas for nesting that can negatively impact hatching success of terrapins. The introduction of non-native plants and structures (i.e., fences) shade nest sites, reducing nest temperature which affects the incubation duration and gender of terrapin embryos. This study investigated population sizes, hatching success, incubation duration of terrapin embryos in nests in different soil treatments including dredged substrate; and nests exposed to shade at North Sedge Island, Barnegat Bay. Microhabitat nest factors including: temperature, soil conductivity (SC), water potential, and gas composition in different soil types were studied. Our results indicated that freshly dredged substrate had the lowest water potential (MPa) and highest soil conductivity (mS/cm) than all other soil treatments with a 100% embryo mortality with no embryonic development past the first stage of development. Nest temperatures at North Sedge Island were at the pivotal incubation temperature in non-shaded treatments and were below the pivotal temperature with 50% shade. Shading of nests caused significantly longer incubation durations and delayed emergence for terrapin embryos compared to

non-shaded nests. Terrapin population estimates at N. Sedge Island indicated that  $430 \pm 23$  female terrapins utilize the island for nesting, and the earliest reproductive age of females on the island was six years. Increased body size and earlier age of maturity at N. Sedge Island may be a result of the area being located within a marine conservation zone, which has a large expanse of marsh, limited commercial operations, and ample estuarine food resources.

This study showed that nest site conditions (i.e., soil texture, shading) are important for the success of diamondback terrapin populations. Effective management practices including the analysis of dredged substrate and washing it prior to its utilization to enhance or restore wildlife habitat are recommended based on the results of this study.



## CHAPTER 1: GENERAL INTRODUCTION

Reproductive biology in ectotherms incorporates genetic, maternal, and environmental effects as factors that lead to successful offspring (Ernst et al. 1994). In ectotherms, environmental conditions contribute to the survival and development of embryos, thus affecting the growth rate of some species (Roosenburg 1996; Wilson 1998). In aquatic turtles, temperature, soil composition and moisture have been linked to nest success (Brooks et al. 1991; Packard et al. 1993; Bobyn and Brooks 1994; Roosenburg 1996; Wilson 1998; Feinberg and Burke 2003; Butler et al. 2004) as well as hatchling survivorship (Packard et al. 1999; Nagle et al. 2000). Additionally, egg location within a clutch coupled with microenvironmental conditions within a nest affect embryo development (Wallace et al. 2004) and gender (Jeyasuria et al. 1994).

Habitat quality is important to the survival of local populations of vertebrate species (Hanski 1996). Today, turtles face human threats that impact their habitat including destruction and fragmentation of nesting areas (Joyal et al. 2001). Especially threatened are habitats located within coastal areas along the United States (Greenberg et al. 2006). Understanding the relationship of specific habitat types within coastal areas to the life history characteristics of species that inhabit those areas is important to the sustainability of those species. In estuarine systems, diamondback terrapins, *Malaclemys terrapin*, utilize impacted nesting locations as a result of destruction and fragmentation of existing natural nesting areas. One such estuary, Barnegat Bay (referred to as “the Bay”) in New Jersey, contains a mosaic of natural and artificial habitats with unknown impacts on nesting ecology of terrapins. Approximately 38% of the shoreline bordering Barnegat Bay has been altered using structures such as bulk-heading which has destroyed shoreline

nesting habitat for species (BBEP 2001). Barnegat Bay was designated as part of the National Estuary Program in 1996, which has enhanced scientific investigation and management of the Bay. Anthropogenic changes in the Bay are being studied to determine impacts from, and future management recommendations for, sea level rise and shoreline stabilization (Lathrop and Love 2007).

### **Terrapins: Distribution and Life History Characteristics**

The diamondback terrapin is a small, estuarine emydid turtle with a geographic range from Cape Cod, Massachusetts to the Gulf Coast of Texas (Ernst et al. 1994). Seven sub-species of terrapins are recognized across its range, and it is the only species of turtle endemic strictly to brackish coastal marshes, bays, lagoons, creeks, and estuaries in North America (Palmer and Cordes 1988; Lovich and Gibbons 1990; Gibbons et al. 2001). The northern-most subspecies, *M. terrapin terrapin*, is found from Cape Cod to North Carolina. Terrapins were extirpated in many locations across their range as they were a popular food source in the late 1800s to early 1900s (Cook 1989). Adult female terrapins reach sexual maturity later than male terrapins and are larger than male terrapins (Lovich and Gibbons 1990).

### **Reproductive Ecology and Nesting Habitat**

Clutch sizes, nest fidelity, clutch frequency and incubation time are known for terrapins across their range (Montevecchi and Burger 1975; Roosenburg 1996; Roosenburg and Kelley 1996; Gibbons et al. 2001; Butler et al. 2004). However, there may be latitudinal variations in clutch sizes and egg masses as is the case with *Chelydra serpentina* (Iverson et al. 1997). Differences in clutch size may be in response to

resource availability as a result of productivity in the ecosystem, metabolic costs of reproduction and latitudinal variations (reviewed in Miller and Dinkelacker 2008).

Morphometric egg variations in size and mass have also been well documented with a general increase in terrapin clutch sizes from the southern part of their range to the northern part of their range (Siegel 1980b; Tucker et al. 2001; Butler et al. 2004).

Terrapins demonstrate nest site fidelity based on mark-recapture studies across their range (Roosenburg 1996; Feinberg and Burke 2003; Szerlag and McRobert 2007).

Terrapins nest on barrier islands and high areas along shoreline and areas that accrete sand (Burger and Montevicchi 1975; Roosenburg 1994). In addition to barrier islands, terrapins nest on anthropogenically impacted areas including unpaved roadways, construction sites and backyards (pers. obs.). In an effort to keep navigational channels open, materials from the Bay floor have been moved to banks along the shoreline or to small “islands” (Miller 1994). The removed sediment, called “dredge material” was typically deposited in marsh areas. Dredge-filled areas serve as rookeries for birds such as herring gull (*Larus argentatus*; Burger and Shishler 1979) and nesting sites for terrapins (Roosenburg et al. 2003; Graham 2009). The composition of nesting substrate may have an effect on hatching success of turtles (in painted turtles, Wilson 1998). Soil textural compositions in terrapin nesting areas in New Jersey could vary from sand (Burger 1976b; 1977) to dredge soil (Wnek et al. in review). Dredge soil is an unconsolidated soil, rock and organic matter mixture that can be used to produce anthropogenic landforms (Shoeneberger and Wysocki 2005). Composition of sand is usually 80% or more in most sediment of Barnegat Bay, but silt and clay fractions can be as high as 50% in some areas (Miller 2004). If dredged material is used to fill areas that

serve as nesting sites, variations in particle type may ultimately affect hatching success and survival of turtle hatchlings which may result in changes in nest conditions including temperature and moisture (Roosenburg 1996; Packard and Packard 1997).

### **Human Impacts on Nesting Habitats**

Nest temperatures are important for incubation time and gender determination in many turtle species, including diamondback terrapins (Jeyasuria et al. 1994; Roosenburg and Kelley 1996). Terrapins demonstrate temperature-dependent sex determination (TSD, Jeyasuria et al. 1994; Roosenburg and Kelley 1996). Eggs incubated below 28°C produce a majority of male hatchlings and eggs incubated above 30°C produce a majority of female hatchlings (Jeyasuria et al. 1994). Nest conditions can vary according to geographical location of the species (Roosenburg 1996; Wilson 1998). Roosenburg (1996) found that smaller female terrapins tended to lay small eggs in cooler, male producing areas with greater vegetative cover; however, larger female terrapins deposited larger eggs in warm, female-producing environments. Anthropogenic impacts including the building of structures can cast shade on nesting areas, thus lower incubation temperatures resulting in a male gender bias in hatchlings (Roosenburg 1992). Vegetative cover on terrapin nests acts as shade and results in lower incubation temperatures (Roosenburg 1992). Lower incubation temperatures increase the incubation time of turtles (in sea turtles, Standora and Spotila 1985; in *Chelydra serpentina*, Packard et al. 1987; in sea turtles, Godfrey and Mrosovsky 2001). Incubation temperatures can also affect incubation time in terrapins (Roosenburg and Kelley 1996). In New Jersey, incubation time is dependent upon seasonal nest temperature (Burger 1976b; 1977).

Longer incubation time, coupled with later seasonal nesting, may produce clutches that delay their emergence from the nest (overwinter), thus reducing the risk of predation when there are limited resources for rapid growth (Baker et al. 2004). Nest depth was also found to influence the survivorship of eggs of diamondback terrapins in open, natural areas as a result of variations in incubation temperature, with higher temperatures (> 32°C) causing embryo mortality (Burger 1976b).

The goals of this study are to 1) determine differences in hatching success of terrapins in different soil texture types; 2) determine the effects of shade as an anthropogenic impact on nesting ecology of terrapins; 3) determine the mechanisms that affect hatching success of terrapins in different soil texture types; 4) determine reproductive characteristics (nesting female morphometrics and reproductive output) of female terrapins in Barnegat Bay, New Jersey; and 5) determine effective population sizes of terrapins at Spizzle Creek (southern Island Beach State Park) and North Sedge Island, Barnegat Bay, New Jersey.

This is the first study to address the use of new dredge substrate for enhancing diamondback terrapin nesting areas. Specifically, this study will provide a direct comparison between soil texture types and terrapin hatching success. We will identify the mechanisms involved in incubation including: temperature, soil conductivity, gases, and moisture between nesting substrate. Anthropogenic impacts of shade will also be studied between soil texture types, which will provide a better indication about the effect of shade and incubation temperatures. Reproductive output of terrapins will be determined at North Sedge Island and compared with other studies geographically. This study will contribute to understanding latitudinal and regional differences in the reproductive output

of terrapins. Terrapins are a model estuarine species; they are the only vertebrate species endemic to estuaries with a sub-aquatic and terrestrial requirement. Terrapin populations are good indicators of estuarine health and function. Since there is little known about populations of terrapins across New Jersey, we will provide new data about terrapin populations in Barnegat Bay, New Jersey. Management recommendations for developing or enhancing terrapin nesting areas will be a result of this study including: choice of nesting substrate, effective treatment of dredge sediment, and temporal use of dredge sediment as a nesting substrate.

**CHAPTER 2: EFFECTS OF NEST SUBSTRATE AND SHADING ON THE DEVELOPMENT AND SURVIVORSHIP OF DIAMONDBACK TERRAPIN EMBRYOS (*Malaclemys terrapin*)**

**ABSTRACT**

Diamondback terrapins, *Malaclemys terrapin*, live in estuarine ecosystems and may be adversely affected by anthropogenic impacts. Non-native plants and structures shade terrapin nesting sites reducing nest temperatures. Potential nesting areas have been partially or completely destroyed, causing terrapins to nest on roadsides and artificial islands made of materials dredged from the bottom of bays. In Barnegat Bay Estuary New Jersey, a mosaic of natural and degraded terrapin nesting habitats occurs. During June – September 2006 we constructed three experimental plots at a site that had been previously filled with dredge material in non-shaded (open) and shaded treatments. Nests in open loamy-sand had the highest hatching success (55.2%), while nests in the open and shaded dredge soil produced no hatchlings. In 2007, nests in open loamy-sand had 85.3% hatching success, while those in dredge soil that aged one year, had a 59.4% hatching success. Nests in open loamy-sand had higher mean temperatures ( $26.1 \pm 0.6^{\circ}\text{C}$ , SE) in 2006, while those in open dredge soil had the highest mean temperatures ( $25.8 \pm 0.4^{\circ}\text{C}$ , SE) in 2007. Our data indicate that although diamondback terrapins use nesting areas with dredged soil, the composition of the dredged soil may reduce hatching success, with important consequences for viability of terrapin populations.

## INTRODUCTION

Reproductive success in reptiles depends upon genetic, maternal, and environmental factors (Ernst et al. 1994). In aquatic turtles, temperature, soil composition and moisture affect hatching success (Brooks et al. 1991; Packard et al. 1993; Bobyne and Brooks 1994; Roosenburg 1996; Wilson 1998; Feinberg and Burke 2003; Butler et al. 2004) and hatchling survivorship (Packard et al. 1999; Nagle et al. 2000). Additionally, location of the egg within a clutch, coupled with microenvironmental conditions within a nest may affect an embryo's growth and development (sea turtles Wallace et al. 2004). Habitat quality is important to the survival of local populations of species (Hanski 1996; McKinney 2002). Turtles face human threats that impact their habitat (Gibbons et al. 2000; Hartig et al. 2002) including destruction and fragmentation of nesting areas (Joyal et al. 2001). Especially threatened are historic diamondback terrapin (*Malaclemys terrapin*) nesting habitats located within coastal areas along the eastern United States (Burger and Montevecchi 1975; Wood and Herlands 1997). Diamondback terrapins are estuarine emydid turtles with a geographic range from Cape Cod, Massachusetts to the Gulf Coast of Texas (Ernst et al. 1994). They utilize altered nesting locations due to the destruction and fragmentation of natural nesting areas. Understanding the relationship of specific habitat types within coastal areas to the life history characteristics of species that inhabit those areas is important to the conservation and management of those species.

Barnegat Bay Estuary in New Jersey contains a mosaic of natural nesting habitats including sand dunes and bay beach areas, as well as altered habitats that are filled with dredged sediment taken from the bottom of the bay. Approximately 36 % of the shoreline of Barnegat Bay is altered by structures such as bulk-heading (BBEP 2001)

(vertical walls constructed of metal, concrete or wood that reduces shoreline erosion) that destroyed historic terrapin nesting areas, forcing terrapins to nest in dredge-filled locations. Dredge soil is composed of unconsolidated, randomly mixed sediments composed of rock, soil, and/or shell materials extracted and deposited during dredging and dumping activities (Schoeneberger and Wysocki 2005). Dredge soil can contain a high concentration of organic solids (Newell et al. 1999), which could impact hatching production. Dredge-filled areas are also used by nesting female terrapins in the Patuxent River, Maryland (Roosenburg et al. 2003; Roosenburg and Kendall, 2004).

Changes in hydric soil conditions including high soil moisture content or salt water can impact hatchling production (Miller and Dinkelacker 2008). Historically, dredge material was removed from the bottom of the bay to maintain navigational channels. Throughout the past 50 years, dredge materials were dumped at designated locations within the estuary to build dredge-filled islands or to fill upland sites (Brown 2001). Dredge material contains a high organic content due to varying levels of total organic carbon in its silt-clay particles (Brown 2001). As many as 38 dredge depressions (holes created when large amounts of dredge material are taken) were created in New Jersey estuaries between Manasquan Inlet and Townsends Inlet, approximately 130 km, as shore development expanded in the mid-1900s (Fig. 1). Of the 38 dredge depressions, 21 are located within Barnegat Bay (Brown 2001).

Terrapins have temperature-dependent sex determination (TSD). Eggs incubated below 28°C develop as males, while eggs incubated at or above 30°C develop as females (Jeyasuria and Place 1997). Roosenburg (1996) found that smaller female terrapins lay small eggs in cooler, shaded nest areas, while larger female terrapins deposit larger eggs

in warmer, female-biased environments. Incubation temperature affects incubation time in terrapins (Jeyasuria et al. 1994; Roosenburg and Kelley 1996). Nests incubated above 31°C hatched in 45 days while those incubated below 27°C hatched in 60 to 104 days (Burger 1976b; 1977). Nest depth influences the survivorship of diamondback terrapins eggs in open areas due to variations in temperature, especially in eggs closer to the surface where higher temperatures can cause embryo mortality (Burger 1976b).

Composition of the soils in nesting areas varies and microenvironmental conditions (e.g., temperature, CO<sub>2</sub>, O<sub>2</sub>, soil moisture) within the nest chamber of different nests at the same location may vary considerably. Different nest substrates retain different amounts of available water, which affects water exchange between eggs and the soil (Packard et al. 1987; Packard and Packard 1988b; Cagle et al. 1993). Changes in microenvironmental nest conditions, including soil moisture and temperature can affect embryo development and impact incubation time (Packard et al. 1987; Godfrey and Mrosovsky 2001). Differences in soil composition can affect the hatching success and survival of hatchlings (sea turtles Foley et al. 2006) due to variations in temperature and moisture (Packard et al. 1987; Packard and Packard 1997).

Vegetation cover can play a significant role in the nesting ecology of terrapins. Vegetation can impede a female terrapin from digging a nest due to interference by roots (Burger and Montevecchi 1975). Cover also influences nest temperature. Nests in more open areas have warmer nest temperatures than areas that are under vegetative cover (Jeyasuria et al. 1994). Terrapins usually select nesting locations with less than 20 % cover (Burger and Montevecchi 1975). Cover greater than 75 % is unsuitable for nesting terrapins because it reduces incubation temperature of eggs, while cover between 25 and

75 % affects nesting suitability inversely (Palmer and Cordes 1988). As a result of reduced incubation temperatures from shading of nesting areas, sex ratios of developing embryos can be affected.

We studied hatching and emergence success of terrapin eggs incubated in shaded and non-shaded dredge soil, loamy-sand soil, and sand. The objective of this study was to determine if there was a difference in nest temperature, incubation time and egg survivorship between nests with different soil characteristics (sand, loamy-sand and dredge) with full sun exposure versus 50% cover, and whether the age of dredge soil affected these variables.

## **METHODS**

### **Study Area**

This study took place on North Sedge Island in Barnegat Bay, New Jersey, U.S.A. Latitude 39°47'48" N Latitude, 074°07'07" W Longitude (Fig. 1). North Sedge Island is managed by the New Jersey Division of Fish and Wildlife within the Marine Conservation Zone established in 2003. Female diamondback terrapins nest on the island during June and July. Island Beach State Park is a 16 km peninsula of undeveloped bay and ocean beach containing primary and secondary sand dunes. North Sedge Island is approximately one km west of the park. A portion of North Sedge Island was filled in with sediment from the Bay floor in the early 1900s to build hunting and fishing shacks (Miller 1994). The island consists predominantly of salt marsh with bay beach access on the north and east sides of the islands where female terrapins nest.

## Experimental Plots

We constructed three experimental plots on North Sedge Island with the same solar orientation and elevation on the highest part of the island. We filled plots with one of three different soil treatments including sand, loamy-sand from the island and dredge soil consisting of unsorted sediments. Sand was transported from a terrapin nesting location on Island Beach State Park. We collected fresh dredge soil from the bottom of the bay in 2005 from a fast moving channel on the east side of the island. Dredge material dried and aged until plots were prepared the following spring. We measured salt content of the soils prior to filling the plots. We filled plots with 45 cm of treatment soil and covered half of each plot with a 50% landscape shade cloth by Gempler®, 15 cm above the plot. We characterized the shade regime using a standard photometer to determine lux intensity ( $\pm 100$  lux) at midday which produced 49,200 lux in the shaded plots compared to 100,000 lux in the open treatments. Sides of the plots were open for ventilation. The other half of each plot was open for maximum light penetration. The following designations were used in the study: open dredge, shaded dredge, open loamy-sand, shaded loamy-sand, open sand, shaded sand, and natural reference nests. The reference nests were in full sun, but contained 25% vegetative cover or less. Borders (1 m) between experimental plots provided drainage and space between treatment types. We also separated nests  $\geq 0.25$  m to provide a boundary between nest chambers. We assumed that this boundary was sufficient to consider treatment effects as biologically and statistically independent. We collected clutches naturally laid on the island in areas where there was high human activity and randomly placed five clutches in each plot for each treatment. We dug experimental nests at the same egg depths and egg orientations

as those in the original nest. We marked and transported eggs no more than 100 m from their original nest location to the experimental plots in an insulated container in vermiculite without changing egg orientation (Packer and Packer 2000). We monitored five *in situ* nests on the island as natural reference nests. Predator excluder devices made of 12.7 mm hardware cloth covered all individual nests.

A Campbell CR-10x datalogger recorded temperatures ( $\pm 0.05^{\circ}\text{C}$ ) daily within each experimental plot treatment and within *in situ* nests using 24 gauge copper-constantan thermocouples set at the surface (1 cm above the ground), and depths of 8 cm (top of the nest), 12 cm (middle of the nest) and 16 cm (bottom of the nest). These nest depths were based on the mean depths of nests dug by female terrapins on the island in previous years. All temperatures were reported with  $\pm 1$  SE.

After terrapins emerged, we checked nests for undeveloped eggs, and recorded the stages of development. We measured length ( $\pm 0.1$  mm) and mass ( $\pm 0.1$  g) of all hatchlings and recorded the number of overwintering hatchlings. We used a one way analysis of variance (ANOVA) and Tukey's HSD post hoc test to compare arcsine-transformed percent hatched embryos between soil types and shading treatments. Due to the decomposition of some dead terrapin embryos within eggs, especially within the dredge treatments, we classified the embryos into early, middle and late development (Bell 2005).

### **Measuring Soil Types in Nests**

We analyzed soils for percent composition of sand, silt, and clay particles using the Bouyoucos soil texture method (Wilson 1998). We dried soils at  $100^{\circ}\text{C}$  for 24 hours (Theocharopoulos et al. 2004), then dry sieved and separated the soil. We used the dry

mass fragments remaining in each sieve to calculate the distribution of fragments, which we normalized with respect to the total dry mass (Diaz-Zorita et al. 2007).

Using the Soil Texture Triangle (USDA), we then classified soil types according to the U.S. Department of Agriculture soil texture system. Our soils were sand, loamy-sand, and the dredge soil was sandy-loam. We will refer to it as “dredge” soil in this study. All soils were analyzed for salt composition by washing the soil with equal volumes of distilled water and determining the electrical conductivity (Rhoades 1996) using a YSI 85 model meter ( $\pm 0.1$  dS/m).

## RESULTS

In 2006, soil electrical conductivity (SC) in sand and loamy-sand treatments measured 0.3 dS/m, while the new dredge soil had an electrical conductivity of 7.8 dS/m. In 2007, SC in the one year aged dredged soil treatment was 0.4 dS/m. The higher electrical conductivity in the bay where the new dredge was taken was 40.0 dS/m. There was no significant difference in clutch sizes between treatments in 2006 ( $F = 0.14$ ,  $P = 0.19$ ) or 2007 ( $F = 0.68$ ,  $P = 0.67$ ) using an ANOVA single factor test. The mean nest temperatures at the study area at each nest temperature reading (July through September) were 26.0°C in 2006 and 26.3°C in 2007, which were consistent with data from the National Oceanic and Atmospheric Administration (NOAA 2009).

### **Temperature variations 2006**

The mean open loamy-sand nest temperatures ( $26.4 \pm 0.6^\circ\text{C}$ ) were higher than all other mean nest temperatures (Table 1), while the shaded dredge plot had the lowest

mean nest temperatures ( $23.9 \pm 0.4^{\circ}\text{C}$ ). Nest temperatures were compared within plots at the same depths. Comparing mean temperatures at the 8 centimeter (top) depth, the open loamy-sand treatment ( $28.4 \pm 1.1^{\circ}\text{C}$ ) produced significantly higher mean temperatures than the shaded dredge ( $24.6 \pm 0.5^{\circ}\text{C}$ ; Tukey's HSD post hoc test,  $P = 0.003$ ) and shaded sand treatment ( $25.2 \pm 0.5^{\circ}\text{C}$ ; Tukey's HSD post hoc test,  $P = 0.04$ ). At the 12 centimeter (middle) depth, there was only a significant difference in mean temperatures between the open loamy-sand ( $26.1 \pm 0.6^{\circ}\text{C}$ ) and shaded dredge treatment ( $23.7 \pm 0.4^{\circ}\text{C}$ ; Tukey's HSD post hoc test,  $P = 0.01$ ). There were no significant mean temperature differences amongst treatments at the 16 cm (bottom) nest depths. There were no significant differences in mean nest temperatures when comparing all grouped shaded, open and natural reference nests at all depths.

### **Temperature variations 2007**

The open dredge treatment produced the highest mean temperatures ( $25.8^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ ), while the lowest mean temperatures were found in nests in the shaded dredge ( $23.3 \pm 0.4^{\circ}\text{C}$ ). Mean nest temperatures (Table 2) were significantly higher in the open dredge treatment than in shaded dredge (Tukey's HSD post hoc test,  $P = 0.01$ ) and shaded loamy-sand treatments ( $23.4 \pm 0.4^{\circ}\text{C}$ ; Tukey's HSD post hoc test,  $P = 0.02$ ). At the 8 cm depth (top), the open dredge treatment produced significantly higher temperatures ( $27.7 \pm 0.7^{\circ}\text{C}$ ) than the shaded dredge treatment ( $24.9 \pm 0.4^{\circ}\text{C}$ ; Tukey's HSD post hoc test,  $P < 0.01$ ) and shaded loamy-sand ( $24.3 \pm 0.4^{\circ}\text{C}$ ; Tukey's HSD post hoc test,  $P < 0.01$ ). The open loamy-sand treatment ( $26.6 \pm 0.6^{\circ}\text{C}$ ) also showed significantly higher temperatures than the shaded dredge (Tukey's HSD post hoc test,  $P = 0.03$ ) and shaded loamy-sand treatment (Tukey's HSD post hoc test,  $P = 0.02$ ). At the

12 cm depth (middle), the open dredge ( $25.4 \pm 0.6^{\circ}\text{C}$ ) produced significantly higher mean nest temperatures than the shaded dredge treatment, ( $23.5 \pm 0.4^{\circ}\text{C}$ ; ANOVA,  $F = 1.57$ ;  $P = 0.04$ ). At the 16 cm depth (bottom), the open dredge treatment produced significantly higher mean nest temperatures ( $24.3 \pm 0.4^{\circ}\text{C}$ ) than the dredge shaded treatment ( $22.4^{\circ}\text{C} \pm 0.4^{\circ}\text{C}$ ; Tukey's HSD post hoc test,  $P = 0.03$ ). Grouping all open, shade and natural reference, the open treatment produced significantly higher mean nest temperatures ( $24.6 \pm 0.2^{\circ}\text{C}$ ) than shaded treatments ( $23.5 \pm 0.2^{\circ}\text{C}$ ; ANOVA,  $F = 1.07$ ,  $P < 0.01$ ).

### **Hatching success 2006**

There was a 21.6% hatching and emergence success in 2006. Of 35 terrapin nests (30 experimental and five natural reference nests), only thirteen nests produced hatchlings and showed emergence. Three nests in the open sand treatment produced hatchlings, but no nests in the shaded sand treatment produced hatchlings. Embryos that died were in the final third stage of development in two nests in the shaded sand plot. None of the clutches in dredge soil produced hatchlings. Development of embryos in both dredge treatments ceased during the first third stage of development and a majority of eggs were desiccated. The open loamy-sand plot produced hatchlings in all five nests, while the shaded loamy-sand produced hatchlings in only two of five nests. In three of the five nests in the shaded loamy-sand treatment with no hatching, embryo development stopped in the middle third of development. Hatching percentage in the open loamy-sand plot (55.2%) was higher than hatching in all other treatments (Table 3). Using a single factor ANOVA and Tukey's HSD post hoc test to analyze the arcsine transformation of percent of eggs hatched between each plot, natural reference nests ( $\bar{x} = 53.6\%$ ) had significantly higher hatching percentages than nests in open dredge, shaded dredge and

shaded sand ( $\bar{x} = 0$ , ANOVA,  $F = 4.04$ ;  $P = 0.048$ ) treatments which produced no hatchlings. Comparing natural reference, all shaded, and all open treatments, there was a significantly higher hatching percentage in natural reference than in all shaded treatments (ANOVA,  $F = 5.80$ ;  $P = 0.01$ ).

There was no significant difference in the incubation time between nests from all experimental treatments (shade and open) and natural reference. The mean incubation time was 83.5 days in the open sand plot, 71.8 days in the open loamy-sand plot, 84.3 days in the shaded loamy-sand plot, and 81.3 days in the natural reference nests. The range of incubation was 67 days in the open loamy-sand plot to 102 days in the shaded loamy-sand plot.

### **Hatching success 2007**

There was a 67.0% hatching and emergence success in 2007. Of 44 terrapin nests (36 experimental and 8 natural reference nests), only three nests did not produce hatchlings throughout the study period. Two nests in the shaded sand plot and three in the shaded loamy-sand plot showed signs of predation and were not used in this study. Nests in all open treatments in loamy-sand, sand and dredge plots produced hatchlings in each of the six experimental nests. Hatching percentage in the open loamy-sand treatment (85.3%) was higher than all other treatments (Table 3), but was only significantly higher than hatching percentage in the shaded sand plot (41.4%) using a single factor ANOVA ( $F = 0.84$ ,  $P = 0.04$ ).

There was a significant difference in mean incubation time between the open loamy-sand ( $\bar{x} = 80.0$  days) and shaded dredge treatment ( $\bar{x} = 99.3$  days; ANOVA,  $F = 11.3$ ,  $P < 0.01$ ). There was also a significant difference in mean incubation time between

natural reference ( $\bar{x}$ =86.4 days) and shaded dredges treatments (ANOVA,  $F = 12.9$ ,  $P = 0.049$ ). The range of incubation time was 58 days in the open loamy-sand treatment to 106 days in the shaded dredge treatment. After light excavation, we determined that eggs in two nests in the dredge-shaded plot produced hatchlings, but exhibited delayed emergence with hatchlings remaining in the nest over three weeks. Comparing incubation time between all shade and open nest treatments (Table 3), open treatments had a significantly shorter incubation time ( $\bar{x} = 85.6$  days) than shaded nest treatments ( $\bar{x} = 92.2$  days; ANOVA,  $F = 6.57$ ,  $P = 0.03$ ).

## DISCUSSION

### Temperatures

In both study years, the shaded dredge treatment produced the lowest mean nest temperatures compared to other treatments. The shaded nest treatment showed a significantly longer incubation time than the reference nests in 2006 and open nests in 2007, likely due to low temperatures which are consistent with the same incubation effects in snapping turtles (Packard et al. 1987; Packard and Packard 1988a). In 2006, the open loamy-sand soil treatment had the highest mean nest temperatures, while the open dredge soil treatment had the highest mean nest temperatures in 2007 (Fig. 2). There was a greater difference in nest temperatures between treatments at the 8 cm depth with less variation between treatments at the bottom 16 cm nest depth (Fig 3. A-G). The open loamy-sand nest temperatures were higher than all other treatments at all depths and significantly higher than the shaded sand and shaded dredge at the 12 cm nest depth, and shaded sand at the 16 cm nest depth. In 2007, the aged open dredge mean nest

temperatures were significantly warmer than the shaded aged dredge nests at all depths. This was due to the darker color of the soil and ability of the soil to retain heat from full sun exposure. Maximum nest temperature in the center of the nest occurred during the mid-afternoon as expected given the lag in soil temperature with depth (Fig. 4; Spotila et al. 1987). Therefore, weather conditions coupled with soil characteristics are important factors in determining nest temperatures.

### **Hatching and emergence rates**

The experimental plots were kept free of vegetation, so that there were no effects of root growth on the nests. Natural reference nests were prone to root growth that may have reduced hatching success between the open loamy-sand treatment and natural reference nests in both 2006 and 2007. Natural reference nests generally contained 25% or less of vegetative cover throughout the study. Nests in shaded treatments produced fewer hatchlings than those in corresponding open treatments and natural reference nests in both years and significantly fewer hatchlings than natural reference nests in 2006. In the open loamy-sand treatment, hatching percentage was higher than in the loamy-sand shaded treatment in 2006 and 2007. This is consistent with Burger and Montevecchi's (1975) observations that terrapins nest in areas with less than 20 percent vegetative cover. Our data showed that 50% shade cover caused a significant reduction in the hatching success of terrapins. These data are consistent with Cordes and Palmer (1988) who suggest that nest sites with less than 25% cover are more suitable for terrapin nesting compared to sites with 25% to 75% cover. In 2006, three nests in the open sand treatment produced hatchlings, but eggs in nests in the shaded sand treatment produced no hatchlings. The developing embryos were drowned due to two major events which

produced an inundation of rainfall that flooded the entire Island in late July and mid-September. Eggs in the open sand, shaded loamy-sand, open loamy-sand and shaded loamy-sand treatments survived the July event, but embryos that did not hatch prior to the mid-September event, died after the second rainfall event. The open and shaded dredge treatments did not have embryo development continue past the first third stage of development (Bell 2005), and all eggs failed prior to the July rainfall event. In 2006, a majority of the eggs in the dredge soil treatments were desiccated because the salt in the dredge soil caused eggs to lose moisture. Differences in the nesting substrate (i.e., sand, silt, or clay composition) can affect the soil moisture gradient and available environmental water to incubating eggs (Packard et al. 1987; Packard and Packard 1988b). Temperature along with available substrate moisture can also affect incubation time with greater moisture causing an increase in incubation time (Packard et al. 1987; Godfrey and Mrosovsky 2001).

In 2006 and 2007, the open loamy-sand treatment had the shortest incubation period and the highest hatching percentage (Table 3) compared to all other treatments. Based on the low hatchling success in 2006, with only 13 nests producing hatchlings, incubation time was not as reliable a predictor as in 2007 when 41 nests produced hatchlings. In 2007, all open treatments and natural reference nests had shorter mean incubation times than shaded treatments. The shaded sand and dredge nests had longer mean incubation times and fewer hatchlings than the other treatments and natural reference nests. The open loamy-sand treatment had higher mean nest temperatures than the shaded loamy-sand treatment in both years (Tables 1 and 2). Using the loamy-sand treatments for comparison, there was an inverse relation between incubation time and

mean nest temperature, which has also been documented for snapping turtle embryos (Packard et al. 1987; Miller and Dinkelaker 2008). In 2007, the mean incubation time was greater in eggs in the shaded nest treatments than natural reference nests, and significantly greater than all open treatments. In 2007, the dredge material was aged one year, which probably accounted for the improved hatching success that occurred in both open and shaded treatments as compared to no emergence of hatchlings in 2006. Washing out of salt ions and a reduction of organic compounds made the dredge material more suitable for embryonic development.

## CONCLUSIONS

Our study shows that fresh dredge soil is not a suitable nesting substrate for terrapins. In 2006, no terrapin embryos developed past the first-third stage of development. Shaded sand treatment produced no hatchlings in 2006, although most terrapin embryos made it into the last stage of development. This mortality was related to an intense storm with over 15 cm of rainfall in a six hour period which produced flooding conditions. This suggests that stochastic weather events may play a major role in the viability of terrapin nests.

Due to the reduced nest temperature of the shaded sand nests in comparison to the open sand treatments, incubation time was extended, consistent with Jeyasuria et al. (1994). Aged dredge soils may be a viable nesting substrate, but the components of dredge substrate (i.e., soil organic composition, toxins, or smaller soil particle size) may contribute to nest failure in fresh dredge soils. Our data also suggest that non-shaded loamy-sand soil is the most suitable nesting substrate for hatchling development (i.e.,

highest survivorship). In both 2006 and 2007, the open loamy-sand plots produced the most hatchlings (2006, n = 55; 2007, n = 71). Soil moisture and temperature are key factors for water exchange by eggs (Packard et al. 1994) which were different in each treatment.

Shading of nests is an important factor in determining nest temperature, especially at the top and middle depths of the nest. Since terrapins exhibit temperature dependent sex determination, shading may impact male to female sex ratios, especially if nests are located in areas where the incubation temperatures are close to the pivotal temperature of 29°C (Jeyasuria et al. 1994). Vegetation acts as a shade cover, lowering mean nest temperatures, which can extend the incubation time of embryos. Our data indicate that the nest temperature affects incubation time of terrapin embryos, which was evident in the shaded dredge nest treatment in 2007. The shaded nest treatments consistently produced lower nest temperatures and longer incubation times than the open treatments.

Our study also show that anthropogenic impacts of dredge soil and introduction of invasive vegetation that increases shading at nest sites may significantly affect the reproductive success of the diamondback terrapin. Eggs may not hatch until late fall, which may cause hatchlings to overwinter underground, elevating their mortality (Costanzo et al. 2004). Because Barnegat Bay is prone to northeastern storm patterns which cause flooding of bay beach areas, delayed emergence may also result in increased mortality due to exposure to flooded soil conditions. Our findings have important implications to management of estuarine ecosystems both in the U.S. and world-wide. They agree with Leslie and Spotila (2001) who reported that invasive *Chromolaena odorata* bushes destroyed the nesting sites of Nile crocodiles in St. Lucia estuary in South

Africa by shading the sites. Dredged soils and invasive plant species may destroy the suitability of former nest sites for reptiles as well as possibly ground-nesting shore birds and are factors that should be addressed in estuarine protection plans in the U.S. and elsewhere.

**Table 1.** Comparison of 2006 plot types using mean nest temperatures ( $^{\circ}\text{C}$ ) at North Sedge Island, NJ at depths of 8 cm, 12 cm, 16 cm and mean temperature values for all depths recorded for each plot type. Temperature values ( $^{\circ}\text{C}$ ) are reported with standard errors values. The highest mean nest temperature value is the loamy-sand open plot while the dredge shaded produced the lowest mean nest temperature. At the 8 cm depth, mean nest temperatures in open loamy-sand (\*) were significantly higher ( $P < 0.05$ ) than mean nest temperatures in shaded sand (a) and shaded dredge (a) treatments. At the 12 cm depth, mean nest temperatures in open loamy-sand (\*\*) were significantly higher ( $P < 0.05$ ) than mean nest temperatures in the shaded dredge (b) treatment.

Treatment	Natural Reference ( $^{\circ}\text{C}$ )		Open Loamy-Sand ( $^{\circ}\text{C}$ )		Shaded Loamy-Sand ( $^{\circ}\text{C}$ )		Open Sand ( $^{\circ}\text{C}$ )		Shaded Sand ( $^{\circ}\text{C}$ )		Open Dredge ( $^{\circ}\text{C}$ )		Shaded Dredge ( $^{\circ}\text{C}$ )	
	8 cm	27.3	$\pm 0.6$	28.4	$\pm 1.1^*$	25.6	$\pm 0.5$	26.6	$\pm 0.7$	25.2	$\pm 0.6^a$	26.7	$\pm 0.6$	24.6
12 cm	25.5	$\pm 0.6$	26.1	$\pm 0.6^{**}$	24.9	$\pm 0.5$	25.5	$\pm 0.6$	24.6	$\pm 0.5$	25.1	$\pm 0.5$	23.7	$\pm 0.4^b$
16 cm	25.0	$\pm 0.5$	24.8	$\pm 0.5$	24.5	$\pm 0.5$	24.7	$\pm 0.6$	24.1	$\pm 0.5$	24.3	$\pm 0.5$	23.4	$\pm 0.4$
Mean	25.9	$\pm 0.6$	26.4	$\pm 0.7$	25.0	$\pm 0.5$	25.6	$\pm 0.6$	24.7	$\pm 0.5$	25.4	$\pm 0.5$	23.9	$\pm 0.4$

**Table 2.** Comparison of 2007 plot types using mean nest temperatures ( $^{\circ}\text{C}$ ) at North Sedge Island, NJ at depths of 8 cm, 12 cm, 16 cm and mean temperature values for all depths recorded for each plot type. Temperature values ( $^{\circ}\text{C}$ ) are reported with standard errors values. The highest mean nest temperature value is the dredge open plot while the dredge shaded produced the lowest mean nest temperature. There was a significant difference in mean nest temperatures at all depths between the open aged dredge treatment (\*, \*\*, \*\*\*) and the shaded aged dredge treatment (a, b, c) at all depths.

Treatment	Natural Reference ( $^{\circ}\text{C}$ )	Open Loamy-Sand ( $^{\circ}\text{C}$ )	Shaded Loamy-Sand ( $^{\circ}\text{C}$ )	Open Sand ( $^{\circ}\text{C}$ )	Shaded Sand ( $^{\circ}\text{C}$ )	Open Aged Dredge ( $^{\circ}\text{C}$ )	Shaded Aged Dredge ( $^{\circ}\text{C}$ )
8 cm	$25.9 \pm 0.6$	$26.6 \pm 0.6$	$24.3 \pm 0.4$	$25.2 \pm 0.4$	$24.5 \pm 0.5$	$27.7 \pm 0.7^*$	$24.9 \pm 0.4^a$
12 cm	$24.2 \pm 0.5$	$24.9 \pm 0.4$	$23.2 \pm 0.4$	$23.5 \pm 0.4$	$23.4 \pm 0.5$	$25.4 \pm 0.5^{**}$	$23.5 \pm 0.4^b$
16 cm	$23.2 \pm 0.5$	$23.1 \pm 0.5$	$22.5 \pm 0.5$	$22.8 \pm 0.5$	$22.9 \pm 0.5$	$24.3 \pm 0.4^{***}$	$22.4 \pm 0.4^c$
Mean	$24.4 \pm 0.5$	$24.9 \pm 0.4$	$23.4 \pm 0.4$	$23.8 \pm 0.4$	$23.6 \pm 0.5$	$25.8 \pm 0.5$	$23.3 \pm 0.4$

**Table 3.** Percentage of eggs that hatched and mean incubation time with standard error values for all treatments in 2006 and 2007 at North Sedge Island, Barnegat Bay, New Jersey. A comparison was made between all open and shaded treatments. All nest plot types were ranked using a single factor ANOVA ( $P < 0.05$ ) and Tukey's HSD post hoc test, and all nest plot types and treatments were ranked from highest to lowest percentage of hatching per study year.

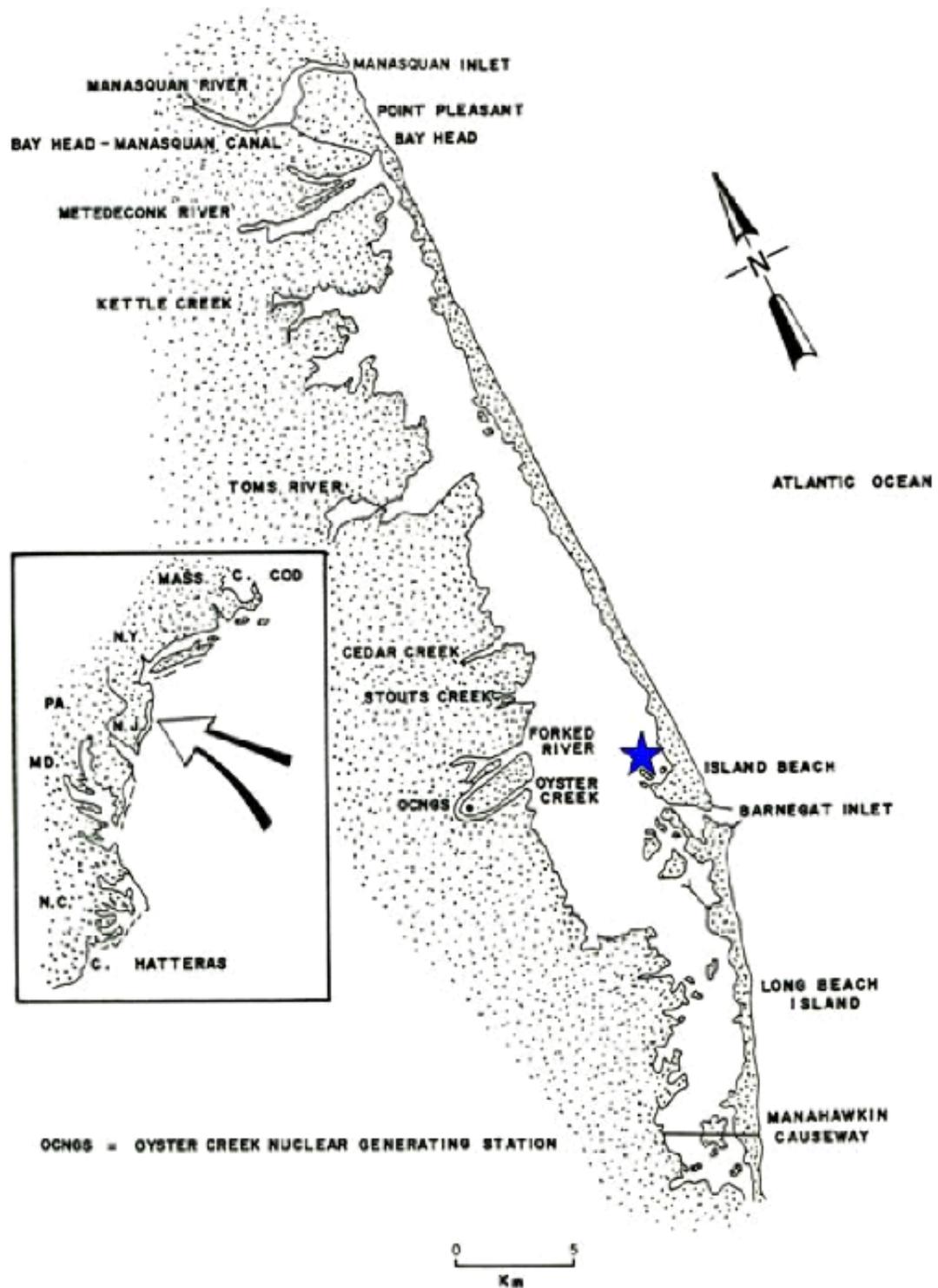
Nest plot type and treatment 2006	Percent eggs that hatched in each treatment	Incubation time in days	Nest plot type and treatment 2007	Percent eggs that hatched in each treatment	Incubation time in days
Open loamy-sand	55.2	71.8 ± 2.4	Open loamy-sand	85.3	80.0 ± 4.5
Natural reference nests	53.6*	81.3 ± 0.7	Natural reference nests	70.4	86.4 ± 3.1
Open sand	30.6	84.3 ± 8.8	Open sand	65.4	86.5 ± 2.7
Shaded loamy-sand	11.1	83.5 ± 15.5	Shaded loamy-sand	63.4	88.0 ± 1.7
Shaded sand	0	-	Open dredge (aged) †	59.4	90.3 ± 2.8
Open dredge	0 †	-	Shaded dredge (aged) †	41.6	99.3 ± 2.5
Shaded dredge	0 †	-	Shaded sand	41.4	88.6 ± 2.9
All open treatments	26.6	75.0 ± 5.1	All open treatments	70.1	85.6 ± 2.1**
All shaded treatments	3.4	84.3 ± 8.8	All shaded treatments	47.6	92.2 ± 1.8
Total for this study	21.6	78.9 ± 3.3	Total for this study	55.6	88.4 ± 1.3

† Both treatments produced no embryo development past the first third stage of development.

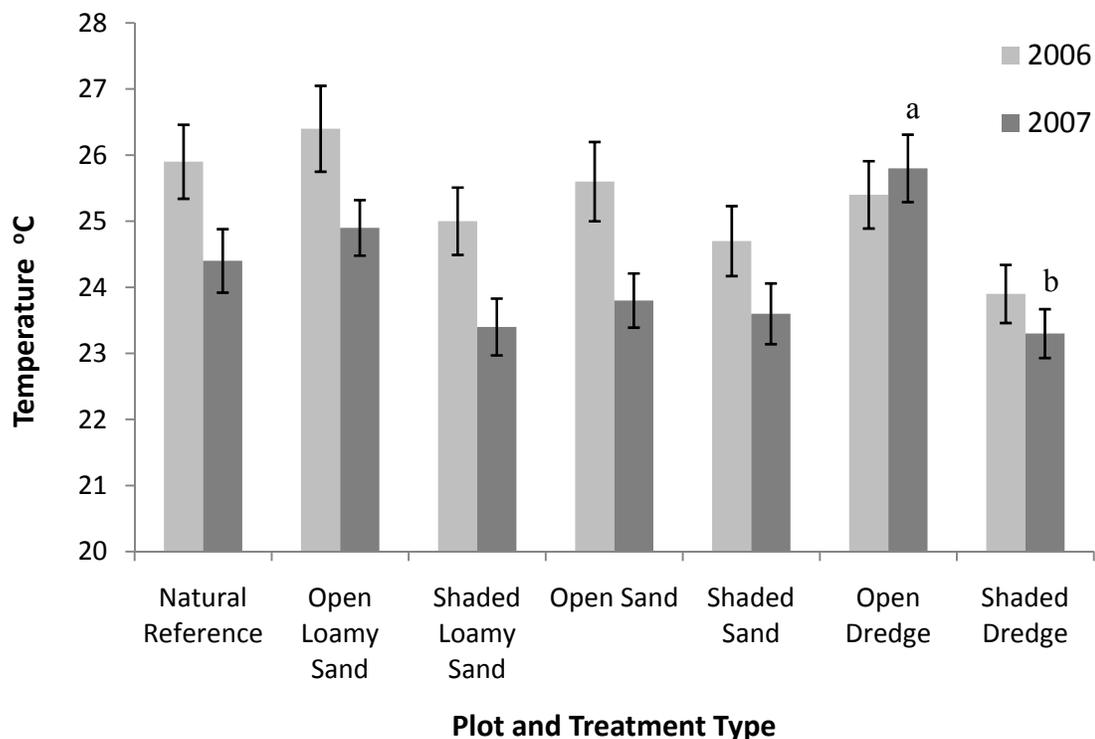
‡ Dredge material was aged one year at the study site and used in 2007.

\* Indicates a significantly higher hatching percentage in natural reference nests than in all shaded nests using Tukey's HSD post hoc test ( $P = 0.01$ ). Natural reference nests were also significantly higher than sand shaded, open dredge and shaded dredge (Tukey's HSD post hoc test,  $P = 0.048$ ).

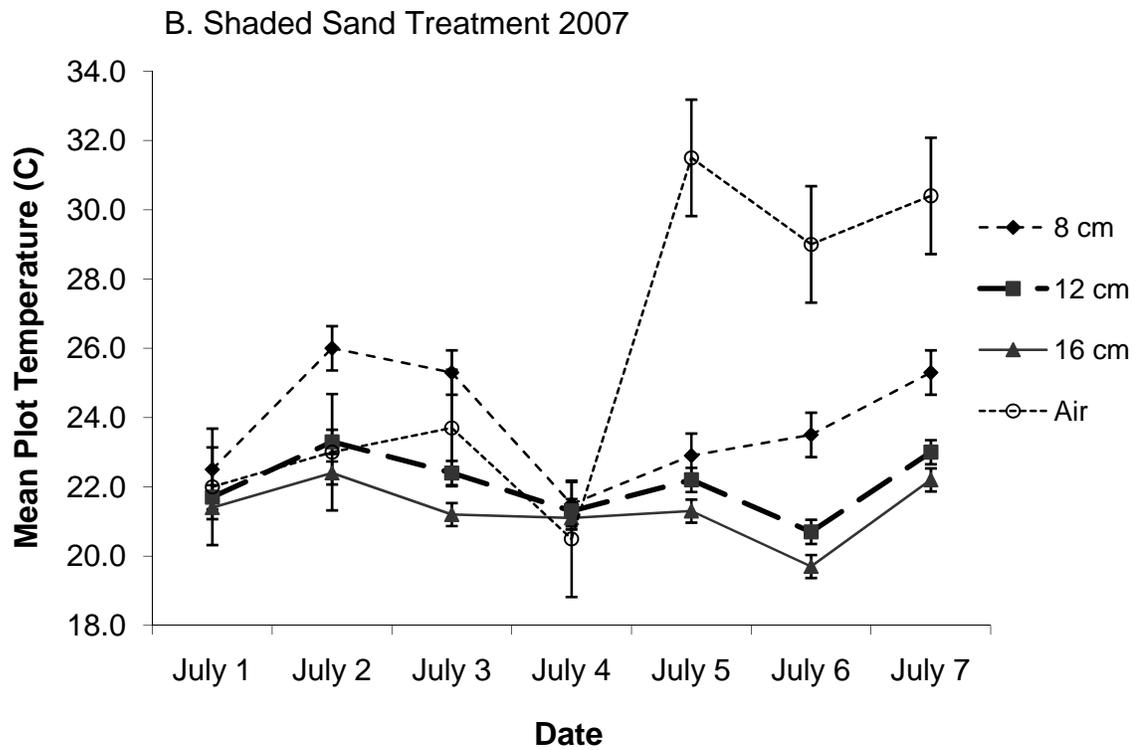
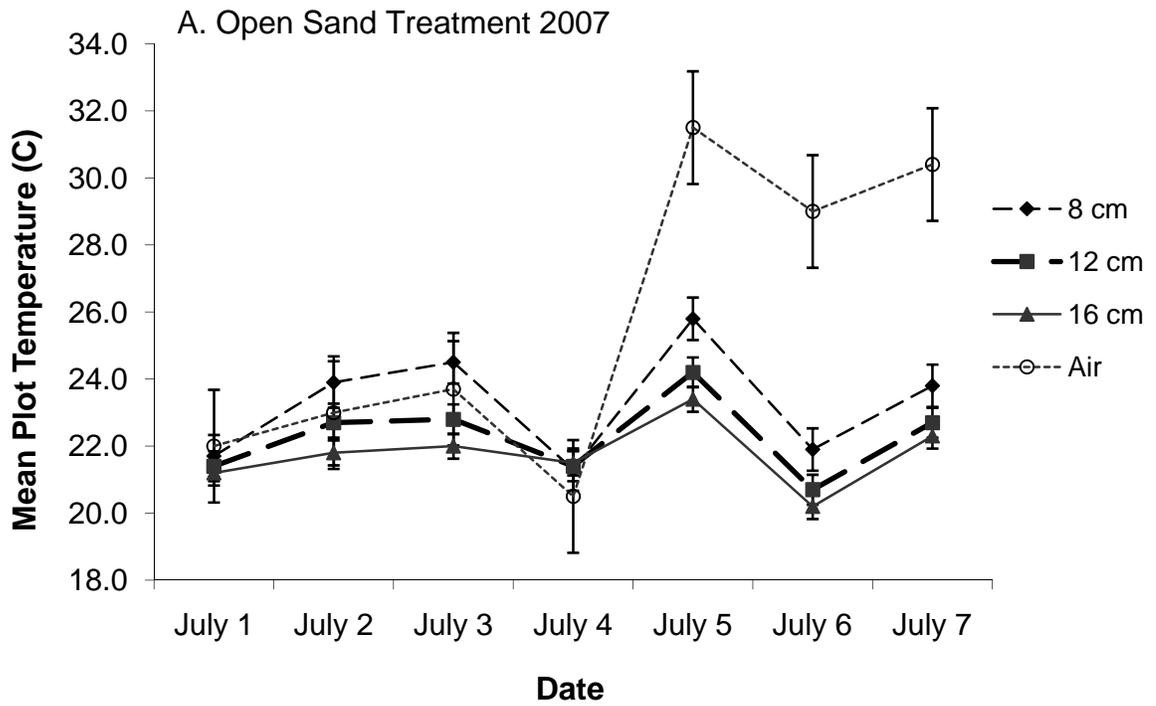
\*\* Indicates a significantly shorter incubation time (days) in all open treatment nests than in all shaded treatment nests (Tukey's HSD post hoc test,  $P=0.03$ ).

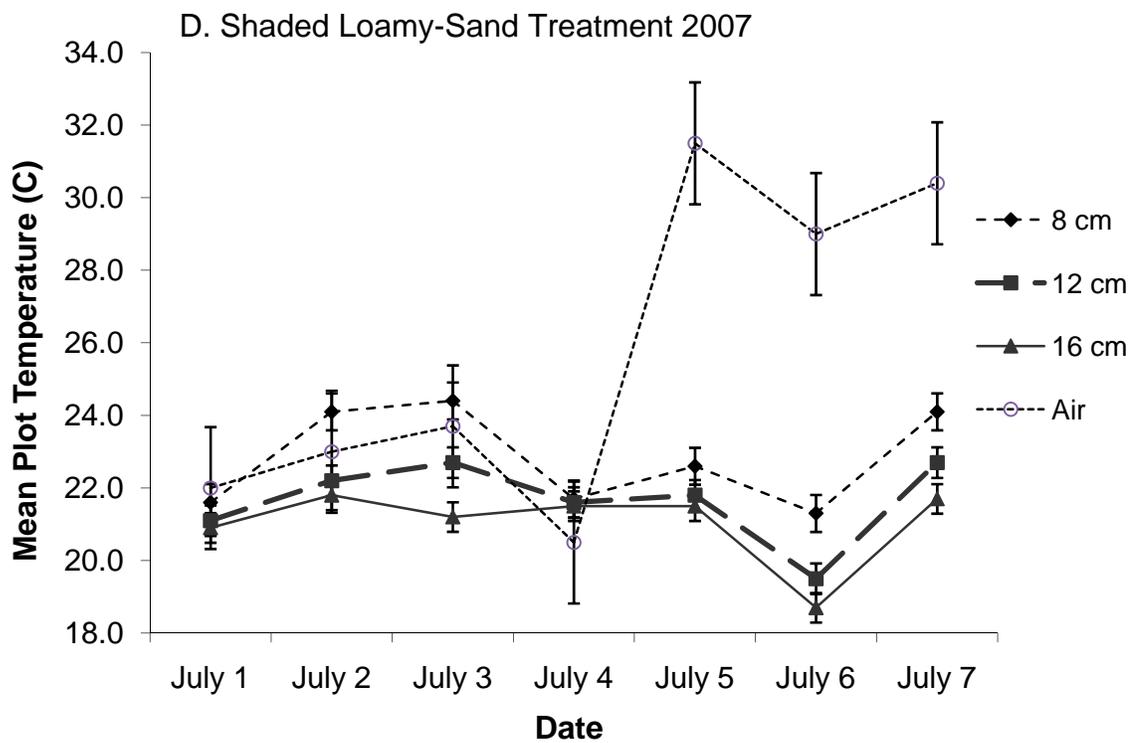
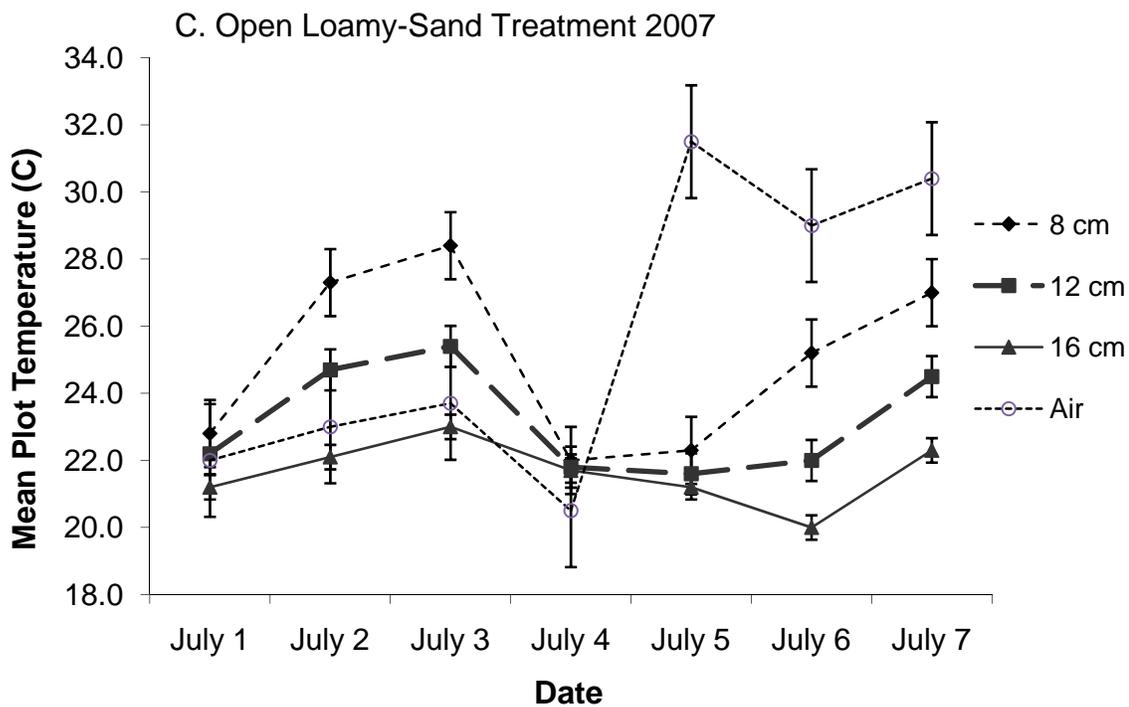


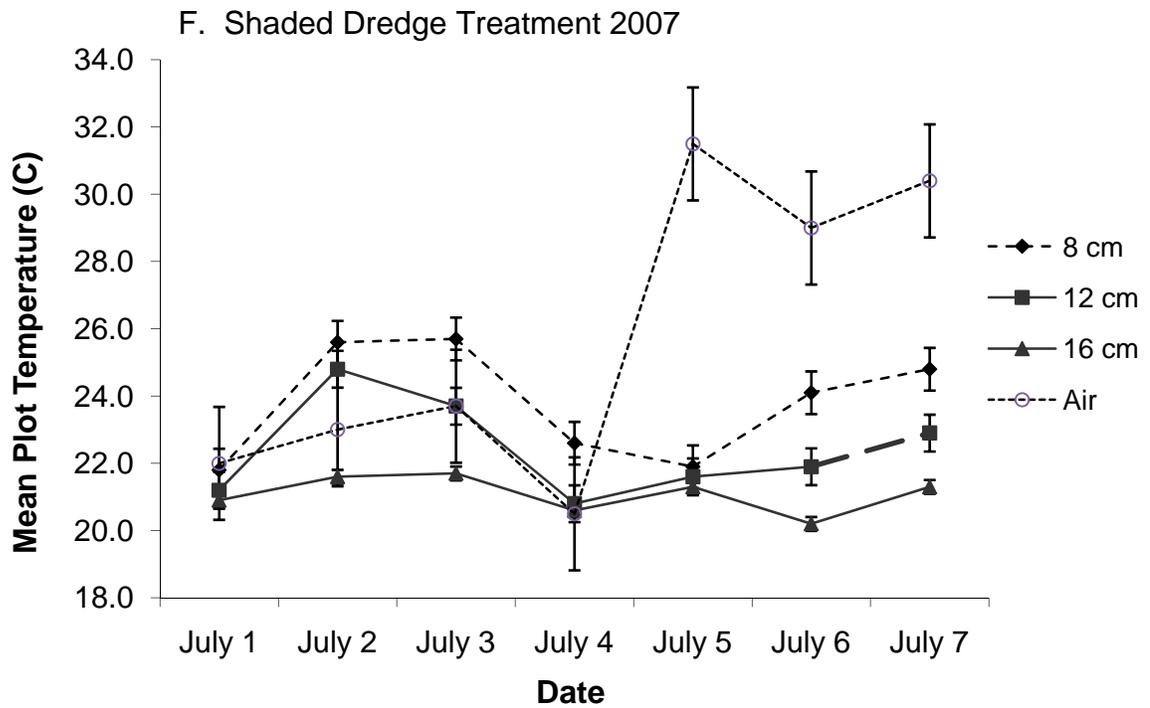
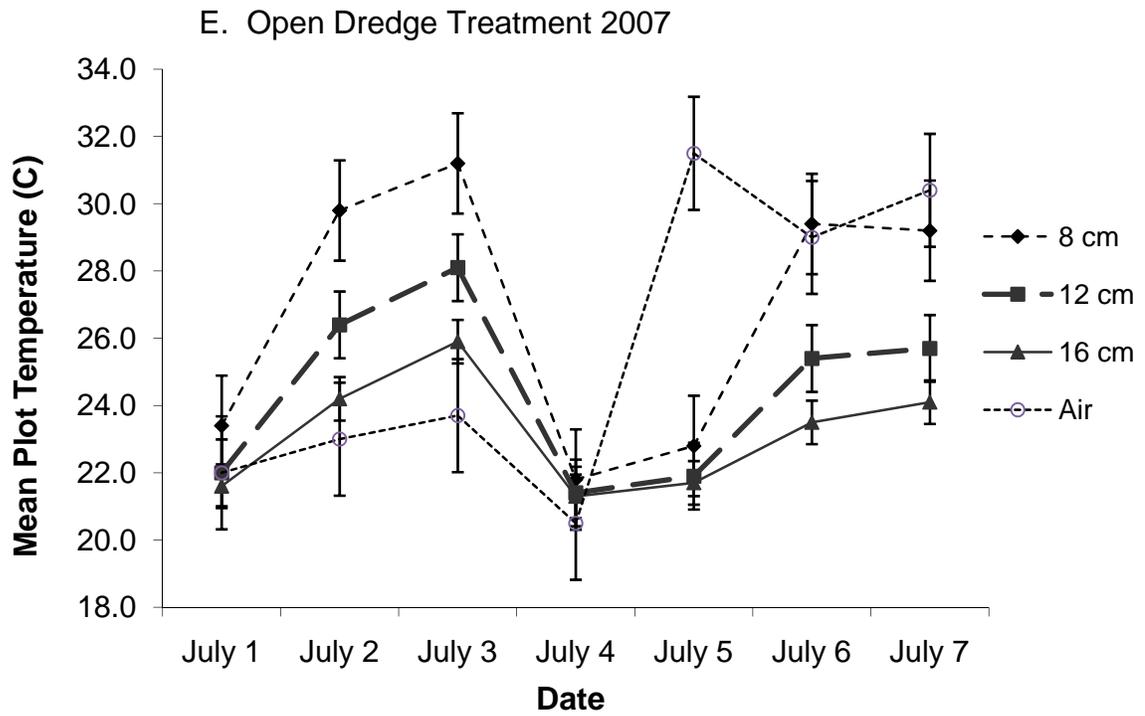
**Figure 1.** Barnegat Bay, New Jersey, USA showing our study area (marked) at North Sedge Island and Island Beach State Park. Map courtesy of Dr. Michael Kennish, Rutgers University, New Jersey, USA.

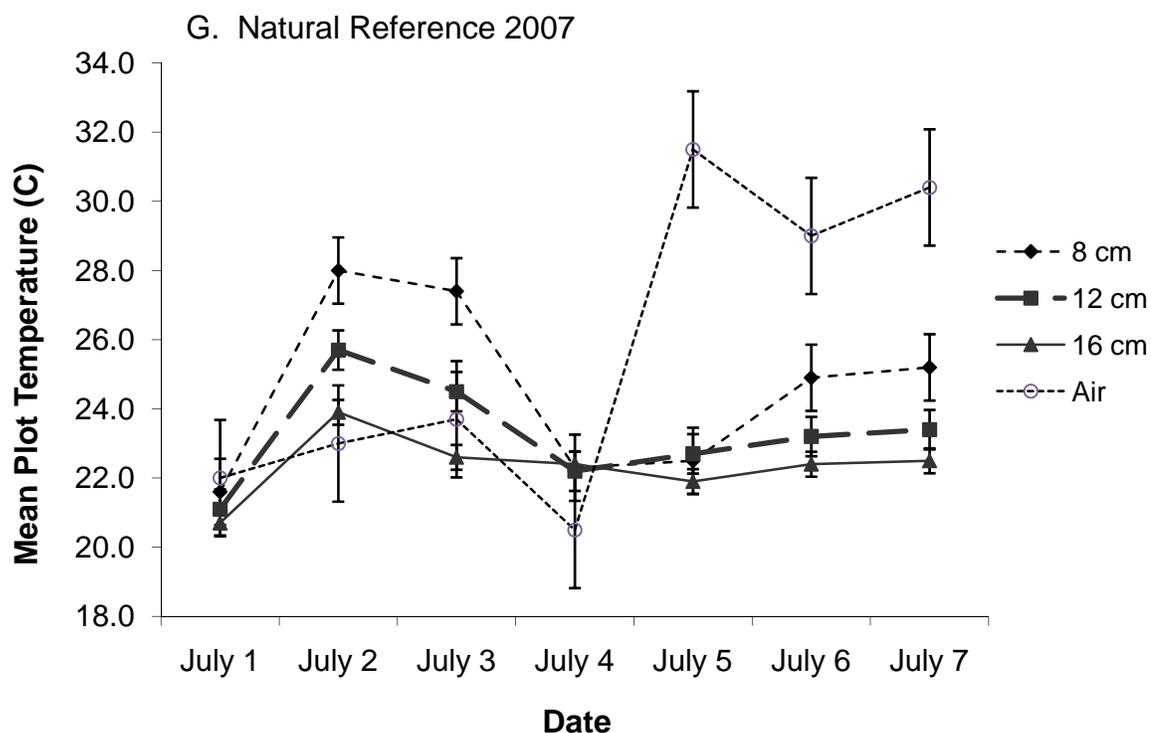


**Figure 2.** Comparison of all mean nest temperatures at North Sedge Island, NJ in all experimental and natural reference nests for 2006 and 2007. Temperatures were recorded at the top of the nest (8 cm), middle of the nest (12 cm), and bottom of the nest (16 cm). All temperatures were recorded at 1200 EST using a Campbell CR-10x datalogger ( $\pm 0.05^{\circ}\text{C}$ ) within each experimental plot treatment and within *in situ* nests using with 24 gauge copper-constantan thermocouples. In 2006 and 2007, the shaded dredge treatment produced the lowest mean temperatures. Bars indicate standard error values of the mean ( $\pm^{\circ}\text{C}$ ). In 2007, there was a significant difference between mean nest temperatures in open dredge treatment (a) versus nests in shaded dredge treatment (b; Tukey's HSD post hoc test,  $P < 0.05$ ).

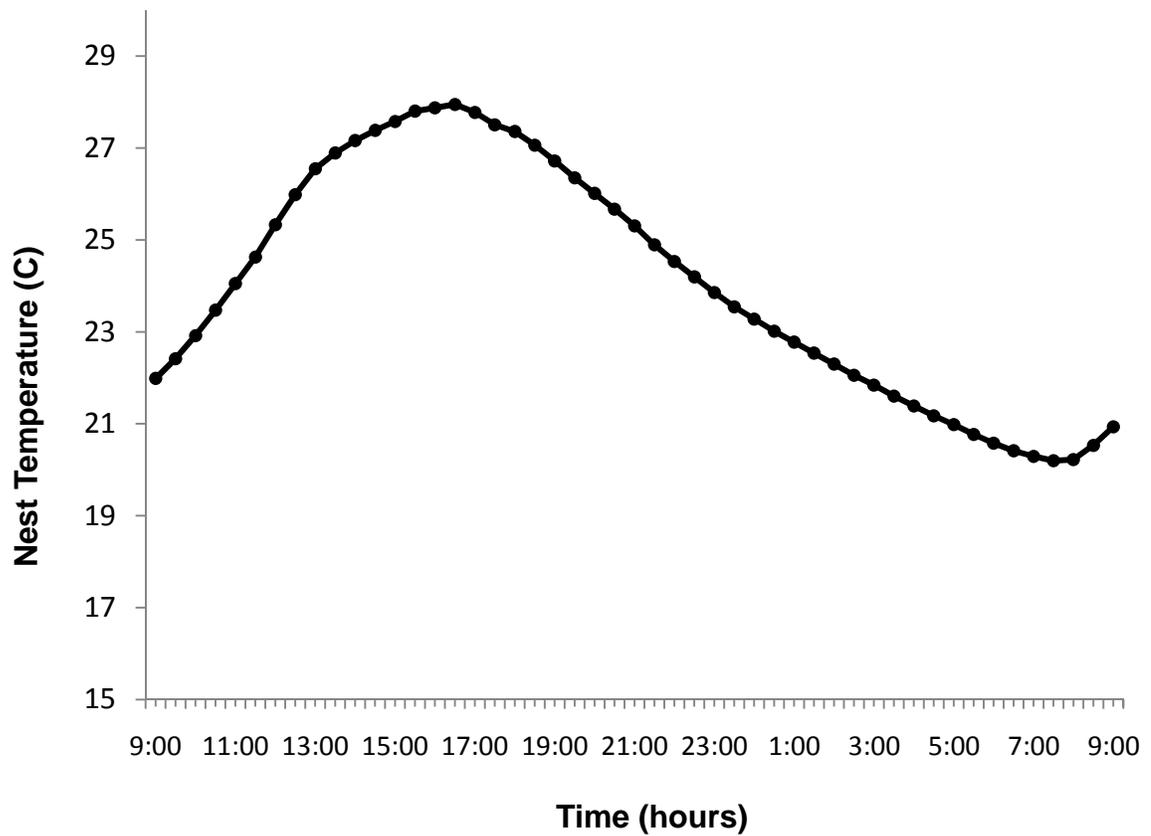








**Figures 3A-G.** One week (July 1- July 7, 2007) mean temperature profiles within nests in each experimental plot and natural reference nests at North Sedge Island, NJ. Air temperatures and nest temperatures were recorded at the top of the nest (8 cm), middle of the nest (12 cm), and bottom of the nest (16 cm) at 1200 EST. All temperatures were recorded at 1600 GMT using a Campbell CR-10x datalogger ( $\pm 0.05^{\circ}\text{C}$ ) within each experimental plot treatment and within *in situ* nests using with 24 gauge copper-constantan thermocouples. The temperature variation on July 4, 2007 was due to rain. Bars indicate standard error values of the mean ( $\pm^{\circ}\text{C}$ ).



**Figure 4.** Profile of middle nest (12 cm) temperatures in the open loamy-sand plot over a 24 hour period at North Sedge Island, NJ from 0900 EST July 1, 2007 through 0900 EST July 2, 2007. Temperatures were recorded using a Campbell CR-10x datalogger ( $\pm 0.05^{\circ}\text{C}$ ) with 24 gauge copper-constantan thermocouples.

**CHAPTER 3: EFFECTS OF SOIL TEXTURE AND MICROENVIRONMENTAL FACTORS ON THE HATCHING SUCCESS OF NORTHERN DIAMONDBACK TERRAPINS (*Malaclemys t. terrapin*)**

**ABSTRACT**

Diamondback terrapins (*Malaclemys terrapin*) inhabit estuaries along the East and Gulf coasts of North America. Barnegat Bay, New Jersey, is considered one of the most anthropogenically altered estuaries in the United States. Declines of sandy nesting areas have caused terrapins to nest in impacted areas composed of other soil types. Dredge soil is one such substrate used by terrapins. Dredge soil is collected from the bottom of the bay during the deepening of channels and is placed on land. Our research investigated the hatching success and development time of terrapin nests incubated in different soils at Barnegat Bay, NJ. We compared nest temperature, soil conductivity (SC), water potential, and gas composition (% O<sub>2</sub> and % CO<sub>2</sub>) of terrapin nests incubating in different soil types. Amongst soil treatments, there were significant differences in mean nest % CO<sub>2</sub> in the partially washed dredge treatment than nests in sand and loamy sand treatment differences in nest temperatures during the first 30 days of incubation. There were significant differences in mean nest % CO<sub>2</sub> in the partially washed dredge treatment than nests in all other treatments during the last 30 days of incubation. Nests in partially washed dredge had lower % O<sub>2</sub> than nests in sand and loamy sand for the first and last 30 days of incubation. New dredge soil had significantly lower water potentials (MPa) and conductivities (mS/cm) compared to all other soil treatments. These data indicate that elevated salt concentrations were the cause of reduced embryo development and survivorship by causing desiccation of terrapin eggs. Nests in new dredge soil showed 100% mortality with embryonic development ceasing prior to the second stage of

development. However when dredge soil was washed and drained hatchlings developed in 14.6% of eggs, indicating that dredge could be a viable nesting soil if salt was removed.

## INTRODUCTION

Loss of nesting habitat world-wide poses problems for reptile species across their ranges (Gibbons et al. 2000; Foley et al. 2006; Moore and Siegel 2006). Anthropogenic factors, including development and the effects of global climate change, are responsible for loss of nesting habitats (Gibbons et al. 2000). Coastal areas are particularly affected due to high densities of human populations and direct effects of rising sea levels (Foley et al. 2006). Environmental factors play an important role in the reproductive success in reptiles (Ernst et al. 1994). In aquatic turtles, temperature (Brooks et al. 1991; Packard et al. 1987; Packard et al. 1993; Bobyn and Brooks 1994; Roosenburg 1996; Feinberg and Burke 2003; Butler et al. 2004), soil composition (Wilson 1998) and moisture (Ackerman 1977) affect hatching success and hatchling survivorship (Packard et al. 1987; Packard et al. 1999; Nagle et al. 2000). Nest temperature and soil moisture conditions can also affect embryo development time and growth (Packard et al. 1987; Godfrey & Mrosovsky 2001; sea turtles Wallace et al. 2004). Nest site selection (Roosenburg 1996) and human impacts that degrade nesting habitat play a significant role in the future of turtle species (Hanski 1996; McKinney 2002). There are numerous threats that are impacting turtle habitats (Gibbons et al. 2000; Hartig et al. 2002) including both destruction and fragmentation of nesting areas (Joyal et al. 2001).

Habitat destruction is a major concern along coastal areas and estuaries where diamondback terrapins (*Malaclemys terrapin*) nest along the eastern and Gulf coasts of

United States (Burger and Montevecchi 1975; Siegel 1980b; Ernst et al. 1994; Wood and Herlands 1997; Greenberg et al. 2006). Diamondback terrapins are estuarine emydid turtles with a geographic range from Cape Cod, Massachusetts to the Gulf Coast of Texas (Ernst et al. 1994). Female terrapins can nest in areas composed of sand dunes and sand beaches (Burger and Montevecchi 1975; Burger 1976a, Burger 1977, Butler 2004), but they can also utilize anthropogenically altered nesting locations due to the destruction and fragmentation of natural nesting areas (Siegel 1980b; Roosenburg et al. 2003; Wnek et al., in review). Ehrenfeld (1979) noted that some species are highly selective about the choice of nest substrate, but other species like *Malaclemys terrapin macrospilota* nest in a variety of substrates.

Differences in soil composition affect hatching success of aquatic turtles (Wilson 1998) and survival of sea turtle hatchlings (Foley et al. 2006). Microenvironmental differences in nest conditions, including soil moisture and temperature can impact embryo development and incubation time (Packard et al. 1987; Godfrey and Mrosovsky 2001). Terrapins have temperature-dependent sex determination (TSD) with a pivotal temperature of 29°C; eggs incubated below 28°C develop as males, while eggs incubated at or above 30°C develop as females (Jeyasuria and Place 1997). Incubation temperature also inversely affects incubation time in turtles (snapping turtles Packard and Packard 1987) and terrapins (Jeyasuria et al. 1994; Roosenburg and Kelley 1996). Terrapin nests incubated in sand at mean temperatures above 31°C hatched in 45 days while those incubated below 27°C hatched in 60 to 104 days (Burger 1976b; 1977).

Variations in moisture also impact incubation time, hatching success (Packard et al. 1987, Packard and Packard 1997), and size of turtle hatchlings (Brooks et al. 1991;

Packard and Phillip 1994). Drier soils produce smaller sized hatchlings (*Chelydra serpentina* in sand; reviewed in Packard 1991; 1999). Different nest substrates retain varying amounts of water, which affects water exchange between eggs and the soil (Packard et al. 1987; Cagle et al. 1993; Packard and Packard 1988c). Increased soil moisture causes an increase in incubation time in snapping turtles incubated in sand (Packard and Packard 1987).

Another microenvironmental factor that can affect hatching success is the percent of CO<sub>2</sub> and O<sub>2</sub> in the nest. Gas exchange between the eggs and soil surrounding the clutch provides O<sub>2</sub> and dissipates CO<sub>2</sub> (Ackerman et al. 2008). Studies with sea turtles show that there are temporal variations in PCO<sub>2</sub> and PO<sub>2</sub> based upon the stage of development (sea turtles Wallace et al. 2004). Wallace et al. (2004) concluded that the greatest difference between ambient and nest PO<sub>2</sub> was during the second half of incubation (the last 30 days) in leatherback turtle (*Dermochelys coriacea*) embryos.

Dredge is a subaqueous soil that is taken from the bottom of a water body and deposited on land to drain (dewater; Shoeneberger and Wysocki 2005). As many as 38 dredge depressions (holes created when large amounts of dredged sediments are taken) were created in New Jersey estuaries (Barnegat Bay, New York-New Jersey Harbor, and Delaware Bay) as shore development expanded in the mid-1900s. Some of the dredged sediment was used to fill salt marsh to create dredge-filled islands (Brown 2001). Dredge soil is composed of unconsolidated, randomly mixed sediments containing rock, soil, and/or shell materials extracted and deposited during dredging and dumping activities of sediment (Schoeneberger and Wysocki 2005). Areas filled with dredge are used by nesting female terrapins in the Patuxent River, Maryland (Roosenburg et al. 2003;

Roosenburg and Kendall, 2004). Dredged sediments usually contain high organic content due to varying levels of total organic carbon in its silt-clay particle composition (Newell et al. 1999; Brown 2001). Adult female terrapins utilize these dredge-filled islands in Barnegat Bay, N.J. (Wnek et al., in review).

Very little is known about variations in microenvironmental factors in diamondback terrapin nests and how they affect developing embryos. Furthermore, there is little information about how these factors vary in different nesting substrates that terrapins use as nesting sites. With increased anthropogenic impacts along U.S. coastal areas, barrier island coastal features and marshes face the strongest threat to loss of habitat than other coastal features (i.e. rocky cliffs and cobble beaches; Pendleton et al. 2010). Estuarine marshes that serve as habitat for terrapins are also key nesting areas for shore birds (Ernst et al. 1994; Erwin et al. 2004). Loss of marshes and barrier islands make alternative nesting areas more important to the survival of species that utilize these areas to nest. Our study seeks to provide insight into the microenvironmental factors of nest soil textures that characterize human impacted areas, and to determine how these factors affect nesting success in the diamondback terrapin.

The objectives of this study were to: 1) determine whether there were differences in hatching success and incubation time of diamondback terrapin eggs in different soil treatments; and 2) determine the microenvironmental factors that affected hatching success of diamondback terrapins including: nest temperatures, gas concentrations ( $\text{PCO}_2$  and  $\text{PO}_2$ ), water potential and conductivity.

## METHODS

### Study Location

Barnegat Bay contains a mosaic of natural nesting habitats including sand dunes, bay beach areas and altered habitats filled with dredged sediment taken from the bottom of the bay. Approximately 36% of the shoreline of Barnegat Bay is altered by structures such as bulk-heading (vertical walls constructed of metal, concrete, plastic or wood that reduces shoreline erosion; BBEP 2001). Historically, dredged sediment was removed from the bottom of Barnegat Bay to maintain navigational channels. Throughout the past 50 years, dredged sediments were dumped at designated locations within the estuary to build dredge-filled islands or to fill upland sites (Brown 2001). Our research was conducted on North Sedge Island in the Barnegat Bay Estuary, New Jersey, U.S.A. (Latitude 39°47'48" N, Longitude 074°07'07" W) from June 1 through October 1, 2006 – 2008 as part of a long term study (Fig. 5). The island was 88,626 m<sup>2</sup> (21.9 acres) located one km west of Island Beach State Park, a 16 km peninsula of undeveloped bay and ocean beach containing primary and secondary sand dunes where female terrapins nest (Fig. 5). North Sedge Island is managed by the New Jersey Division of Fish and Wildlife within a designated Marine Conservation Zone.

A small portion of North Sedge Island (approximately 10,000 m<sup>2</sup>) was filled with dredged sediment in the early 1900s to build hunting and fishing retreats (Miller 1994). The island is predominantly salt marsh with bay beach access on its north and east sides that adult female terrapins use as an access to get to the filled area to nest (Wnek et al., in review).

## Experimental Design

We constructed six experimental treatment plots filled with different soil textures and dredge soil treatments. The plots were dug at ground level on the highest part of North Sedge Island in 2008 which had the highest density of naturally nesting diamondback terrapins. Each experimental plot was 1.75 m<sup>2</sup> and at the same solar orientation and elevation. Each plot was dug out and filled to a depth of 45 cm with different treatment soil treatments that included sand, loamy sand, new dredge soil, washed dredge soil, partially-washed dredge soil, and dredge soil aged two years. Sand was transported from a terrapin nesting location on adjacent Island Beach State Park and loamy sand was the predominant soil texture type found on the island (which was previously dredge material; Miller 1994).

We collected fresh dredged sediment from an area 50 m east of Sedge Island in April 2006 and 2008. The dredge sediment collection location was monitored by the N.J. Department of Environmental Protection. The salt content of the water body was 32 ppt and the location was adjacent to a channel that was regularly dredged. We also used dredge soil aged two years that was collected in 2006 as part of our initial study on the island. The dredged sediment collected in 2006 was considered “aged dredge” for this study. Since fresh dredged sediment could contain salt ions, we wanted to determine the effect of salt on the hatching success of eggs incubated in dredge soil. Therefore, we rinsed the salt out of fresh dredge sediment by using rainwater collected on the Island. Our fresh dredge experimental treatments included: 1) fully washed to saturation with rainwater collected at the study site; 2) partially washed with rainwater collected at the study site using half as much water as necessary for saturation; and 3) fresh dredge

sediment that was not washed. All of the dredge sediment collected in April 2006 and 2008 was spread out to a thickness of 20 cm and allowed to drain for two weeks. Dredge substrates were covered during periods of rainfall prior to placing it in the experimental plots to prevent additional rainwater from washing out ions or smaller particles. We used a YSI-85 conductivity meter to measure the soil electrical conductivity (SC) in mS/cm ( $\pm$  0.01 mS/cm) of experimental soil treatments and natural reference nests (Rhoades 1996). We mixed 100 cm<sup>3</sup> of soil sample with 200 cm<sup>3</sup> of distilled water (1:2) in the laboratory at 25°C (Rhoades 1996; Shorokova et al. 2000).

### **Soil Treatment Comparisons**

Eggs from known nesting female terrapins on North Sedge Island were randomly assigned to experimental treatment plots. In 2008, there were a total of 37 nests (31 experimental and six natural reference *in-situ* nests) used in this study. Experimental treatments were as follows: sand, loamy sand, aged dredge soil, fully saturated new dredge soil, partially saturated new dredge soil and new dredge soil (not saturated with rain water). Experimental plots were separated a distance of one meter from one another to provide drainage and reduce cross-contact of plots. We placed 12 eggs in each experimental nest. This number was based on the mean clutch size (12.5) at Sedge Island during the 2005 to 2007 nesting seasons (Wnek et al., in review). Eggs were positioned in each nest that simulated their natural orientation and depth. Eggs were buried between 6 cm and 16 cm below the surface. All eggs were marked and translocated less than 150 m from their original nest location to the experimental nests in an insulated container. Eggs were transported in vermiculite in their original orientation (Packard and Packard

2000). We separated nests  $\geq 0.25$  m from one another to provide a boundary between nest chambers. We assumed that this boundary was sufficient to consider treatment effects as biologically and statistically independent. We monitored temperatures in 6 *in situ* nests (natural reference nests) and measured gases in three of the *in situ* nests. Predator excluder devices made of 12 mm mesh galvanized hardware cloth covered all individual nests to protect eggs from predation. After 70 days, we excavated the soil around the nests to determine if any eggs were pipped to determine incubation time. Eggs that did not hatch were covered and we collected all hatchlings. We determined percent hatching success using the number of hatchlings (dead or alive) divided by the clutch size (modified from Wallace et al. 2004). We also determined if eggs were either desiccated or failed to develop. In 2006, we compared hatching success using 19 nests in new dredge soil, loamy sand, sand, and five reference *in-situ* nests. We compared the 2006 and 2008 hatching data to elucidate differences in hatching success between experimental treatments because new dredge was used as a treatment both years. To make a comparison between years and nest treatments for rainfall effects we recorded daily rainfall amounts (mm) taken from a weather station at the far northern end of Island Beach State Park (approximately 15 km north of our study site; Fig. 5). We included rainfall events (i.e., isolated thunderstorms) that infrequently contributed rainfall to North Sedge Island and not the Island Beach site as part of analyses. We compared rainfall amounts (mm) and mean nest temperatures ( $^{\circ}$ C) within and between nesting seasons.

## Soil Analysis

Soil for treatment plots and natural reference areas was collected at mean nest depth and the particle size measured. Soil samples were dried at 140°C for one day in a drying oven. Dry-sieving was performed with 11 sieves that ranged from course sand (1.41 mm) to fine silt screens (< 0.0625 mm). Dry mass fragments remaining in each sieve were used to calculate the distribution of fragments with respect to the total dry mass of the soil sample to determine composition of soil particle types (Diaz-Zorita et al. 2007). We also analyzed soils for percent composition of sand, silt and clay particles using the Bouyoucos soil texture method (Wilson 1998). Soil textures were separated using the Wentworth soil classification system (Wentworth 1922) and designated as sand, loamy sand, sandy-loam and sandy-clay using the U.S. Department of Agriculture Soil Texture Triangle (USDA 1993).

We compared water potential (MPa) with soil moisture content (%) for each soil texture treatment: sand, loamy sand, dredge soil (aged two years), new dredge, fully washed dredge and partially washed dredge. We tested dredge soil treatments including: fully washed dredge soil, partially washed dredge soil and new dredge soil aged two months. Water potentials were analyzed using the WP4 Dewpoint Water Potential Meter® ( $\pm 0.1$  MPa for 0 to -10 MPa, and  $\pm 1.0\%$  for samples from -10 to -60 MPa) and all results were reported in MPa (Campbell 2008). We used the water potential unit MPa instead of kPa for this study as a result of soil moisture percentages ranging from 0.25% to 15% for soils analyzed. Soil water potential was measured in a controlled laboratory environment after being dried overnight at 200°C. The WP4 meter was calibrated using 0.5 M KCl solution (water potential -2.19 MPa). Water potential calculations were made

by relating the sample water potential reading to the vapor pressure of air in equilibrium with the sample (Petry and Jiang 2004; Thakur et al. 2006). We plotted soil moisture potential curves for sand, loamy sand, aged dredge, and new dredge treatments (new dredge and fully washed dredge).

### **Temperature, Gas and Precipitation Measurements**

We recorded soil temperature profiles daily between 1600 and 1800 GMT in each experiment nest using a BAT 12 thermocouple meter (Physitemp) connected to 24 gauge copper-constantan thermocouples ( $\pm 0.05^{\circ}\text{C}$ ). Thermocouples were set at the mean middle nest depth (12 cm) in all experimental nests, control plot areas, and natural reference nests. We collected gas samples from at least three nests in each of the experimental groups, as well as natural reference nests, and three soil control locations within each treatment plot ( $n = 3$ ). Controls were used for comparative purposes for soil temperature and soil gas measurements between nests and non-nests within each soil treatment. We inserted a 35 mm film canister ( $34.6 \text{ cm}^3$ ) perforated with numerous small holes and fitted with 30 cm long Tygon® tubing (3 mm ID) at the 12 cm depth and buried eggs next to the film canister within the nest cavity. This method was a modification from gas collection methods used in sea turtle studies (Ackerman 1977; Wallace et al. 2004; Honarvar 2007) because aquatic turtles have smaller nest cavities and smaller clutch sizes than sea turtles. We estimated the mean volume of gas in terrapin nests by calculating the mean volume of nest cavities and mean volume of eggs within each clutch at North Sedge Island (Ackerman 1977; Roosenburg and Dennis 2005). For this study, we analyzed terrapin nests with clutch sizes of 12 and 13 eggs ( $n = 29$ ) because the mean clutch size at North Sedge Island was 12.5 (pers. obs.). A shut off-

valve was fitted on the end of each gas extraction tube to keep moisture, soil, and gases from directly entering the nest (Wallace et al. 2004; Honarvar 2007). Carbon dioxide was measured in percent CO<sub>2</sub> using an infrared analyzer and sensor (S151 CO<sub>2</sub> sensor, Qubit Systems, Kingston, Ontario). Oxygen was measured in percent O<sub>2</sub> using a flow through sensor (S103 O<sub>2</sub> sensor, Qubit Systems, Kingston, Ontario). As a result of smaller nest volumes in terrapin nests than in sea turtle nests (Ackerman 1977), we prevented gas deficits in nests by extracting only 10 mL of gas over a one minute period. Nest gases were extracted by a pump, moisture was removed using Drierite dessicant in a column, and O<sub>2</sub> was tested after CO<sub>2</sub> was scrubbed with Ascarite in a column (Wallace et al. 2004). Gases were measured every five days throughout the incubation period. Sensors were calibrated in the field prior to sampling using atmospheric air. All sensors were connected to a Vernier LabPro® interface and laptop computer to collect real time data. All gas data were analyzed using Logger Pro 3 software (Qubit Systems). We used a one minute calibration period between each nest sample which was sufficient to recalibrate all sensors (Wallace et al 2004). We calculated mean nest gas measurements for the first 30 days and last 30 days of incubation. We compared nest gas measurements with our control measurements to determine treatment effect.

### **Statistical Analysis**

We conducted all statistical analyses using SPSS-PAWS-17 software. We compared hatching success (%) between treatment types using ANOVA with significance being compared using a Bonferroni post hoc multiple comparisons test. We compared hatching success with rainfall events and mean temperatures in both 2006 and 2008 and

pooled years for statistical analysis using ANCOVA. We compared the relationship between hatching success (%), O<sub>2</sub> and CO<sub>2</sub> using ANOVA and used a MANOVA to compare hatching success with treatment and gas compositions. We compared environmental nest factors (soil conductivity, temperature and gases) using GLM univariant analysis (ANOVA) and used Tukey's HSD post hoc multiple comparison tests if significance was determined. We arcsine transformed all hatching percentages to normalize data and accepted an  $\alpha = 0.05$  significance level for all tests. All measurements were reported with standard errors of the mean ( $\pm$  SE).

## RESULTS

### Soil Treatment Comparisons

In 2008, nests in the new dredge soil and partially washed dredge soil treatments produced no hatchlings (Table 4). Comparing the hatchling percentages between experimental treatments (all categories of new dredge combined, loamy sand, two-year aged dredge, sand, and natural reference nests), there was a significant difference between treatments (ANOVA,  $F_{1,36} = 4.169$ ,  $P = 0.003$ ). There was a significantly higher hatching success in nests in the sand treatment ( $68.4\% \pm 11.5\%$ ; Bonferroni,  $P = 0.03$ ) and the loamy sand treatment ( $67.6 \pm 9.4\%$ ; Bonferroni,  $P = 0.02$ ) than nests in partially washed and new dredge treatments (no eggs hatched). There was a significant lower hatching success between all new dredge treatments combined (new, partially washed and fully washed) than in all other treatments (ANOVA,  $F_{4,33} = 6.516$ ,  $P = 0.001$ ). Nests in sand ( $68.4 \pm 8.4\%$ ; Bonferroni,  $P = 0.014$ ) and nests in loamy sand ( $67.6 \pm 11.1\%$ ; Bonferroni,  $P < 0.001$ ) had a significantly higher hatching success than all new dredge

treatments combined ( $4.9 \pm 4.2\%$ ). There were no significant differences in mean hatching success between natural reference nests ( $50.8 \pm 17.4\%$ ) and all new dredge treatments, and between natural reference nests and all aged and non-dredge treatments. Mean incubation times were significantly longer ( $94.0 \pm 6.0$  days) in nests in fully washed dredge than nests in sand ( $72.2 \pm 2.1$  days), loamy sand ( $71.4$  days  $\pm 1.2$  days), aged dredge ( $75.0 \pm 1.0$  days) and natural reference nests ( $70.7 \pm 3.2$  days; ANOVA,  $F_{4,15} = 10.64$ ,  $P < 0.001$ ; Table 4). Within the dredge treatments, desiccated eggs were more common than in other treatments. Desiccation was found in 16.7% ( $n = 8$ ) of eggs ( $n = 48$ ) in nests in fully washed dredge, 32.7% ( $n = 16$ ) of eggs ( $n = 49$ ) in partially washed dredge, and 66.0% ( $n = 33$ ) of eggs ( $n = 50$ ) in new dredge. In natural reference nests, 9.7% ( $n = 14$ ) of eggs ( $n = 145$ ) in nests were desiccated. There were no desiccated eggs in nests in aged dredge, loamy sand and sand treatments.

In 2006 and 2008, there were no significant differences in hatching success in nests among sand, loamy sand, new dredge, and natural reference (ANOVA,  $F_{4,51} = 8.03$ ,  $P < 0.001$ ). There was higher mean hatching success in sand ( $53.4 \pm 10.8\%$ ; Bonferroni,  $P = 0.044$ ), loamy sand ( $65.5 \pm 8.8\%$ ; Bonferroni,  $P = 0.001$ ), and natural reference nests ( $50.5 \pm 10.7\%$ ; Bonferroni,  $P = 0.037$ ) than nests in new dredge treatments (no eggs hatched; Table 5). However, dredge soil, aged two years ( $22.9 \pm 13.3\%$ ), was not significantly higher in hatching success than new dredge. There were no significant differences in mean incubation time among treatments ranging from  $71.1 \pm 0.9$  days in eggs incubated in loamy sand treatments to  $75.0 \pm 1.0$  days in eggs incubated in the aged dredge treatment (ANOVA,  $F_{3,25} = 0.496$ ,  $P = 0.689$ ).

## Soil Analysis

New dredge soils including fully washed and partially washed were classified as loamy sand with similar compositions despite the rainwater treatments (Table 6). The soil compositions were consistent in new dredge (80% sand, 4% silt, 16% clay), partially washed dredge (80% sand, 4.7% silt, 15.3% clay), and fully washed dredge (80% sand, 6.7% silt, 13.3% clay). Sand (2007; 96.6% sand, 1.7% silt, 1.7% clay) remained in a similar composition in 2008 (96.5% sand, 1.9% silt, 1.6% clay). There was a significant difference in soil conductivity among soil treatments (ANOVA,  $F_{8,18} = 2093$ ,  $P < 0.0001$ ) which ranged from  $0.04 \pm 0.01$  mS/cm to  $7.83 \text{ mS/cm} \pm 0.05$  mS/cm in new dredge (Fig. 6). Sand had significantly lower conductivity than all treatments (Tukey's HSD,  $P < 0.05$ ), except loamy sand ( $0.18 \pm 0.13$  mS/cm). New dredge had significantly higher mean soil conductivity than all other treatments (Tukey's HSD,  $P < 0.0001$ ). After four months, all new dredge treatments had significantly lower mean soil conductivities than original treatment conductivity measurements (Tukey's HSD,  $P < 0.0001$ ). Fully washed dredge had an initial mean conductivity of  $1.13 \pm 0.06$  mS/cm that decreased to  $0.45 \pm 0.01$  mS/cm after four months. In contrast, partially washed dredge had an initial mean conductivity of  $2.39 \pm 0.038$  mS/cm that decreased to  $0.49 \pm 0.04$  mS/cm after four months; and new dredge had an initial mean conductivity of  $7.83 \text{ mS/cm} \pm 0.05$  mS/cm that decreased to  $0.70 \text{ mS/cm} \pm 0.04$  mS/cm after four months, and  $0.32 \pm 0.01$  mS/cm after one year. We plotted two soil moisture tension curves which ranged from -54.0 MPa at 1% soil moisture for new dredge to -0.10 MPa at 1% for sand (Figs. 7 and 8). Partially washed dredge soil had a water potential of -26.4 MPa and fully washed dredge

had a water potential of -19.6 MPa at 1% soil moisture content, while both measured 0.0 MPa at 15% moisture content.

### **Temperature, Gas and Precipitation Measurements**

There were no significant differences in mean nest temperatures among treatments in 2006 (ANOVA,  $F_{3,44} = 0.626$ ,  $P = 0.602$ ), but there was a significant difference among treatments in mean temperatures in 2008 ( $F_{6,253} = 2.816$ ,  $P = 0.011$ ; Table 7). In 2006, mean nest temperatures among treatments ranged from  $25.4 \pm 0.5^{\circ}\text{C}$  in dredge to  $26.4^{\circ}\text{C}$  in loamy sand (Table 7). In 2008, the lowest mean nest temperature was in the partially washed dredge treatment ( $25.1 \pm 0.3^{\circ}\text{C}$ ) which was significantly lower than the mean nest temperature in the loamy sand treatment ( $26.4 \pm 0.3^{\circ}\text{C}$ ; Tukey's HSD,  $P = 0.037$ ). No other treatments showed a significant difference between mean nest temperatures in 2008. Mean nest temperatures in 2008 were not significantly different between treatments than those in 2006 (Table 7). There were no differences between mean control soil treatment temperatures and mean nest temperatures throughout this study.

The mean volume of nest cavities was  $153.6 \text{ cm}^3$  and the mean volume of eggs for a clutch of 12 or 13 eggs was  $95.2 \text{ cm}^3$ . The mean volume of gas was approximately 38.0% of the mean nest cavity volume. There were significant differences in the nest gases  $\text{CO}_2$  and  $\text{O}_2$  in the dredge treatments (Table 8). The  $\text{CO}_2$  in partially washed dredge ( $0.30 \pm 0.03\%$ ) was significantly higher than in loamy sand ( $0.17 \pm 0.02\%$ ;  $P = 0.006$ ) and sand ( $0.16 \pm 0.01\%$ ; Tukey's HSD,  $P = 0.025$ ). The  $\text{CO}_2$  in new dredge ( $0.33 \pm 0.05\%$ ) had significantly higher mean  $\text{CO}_2$  than loamy sand (Tukey's HSD,  $P = 0.003$ ),

natural reference nests ( $0.19 \pm 0.03\%$ ; Tukey's HSD,  $P = 0.019$ ), and sand (Tukey's HSD,  $P=0.0001$ ). Control in the sand treatment ( $0.10 \pm 0.01\%$ ) was the only treatment with a significantly lower  $\text{CO}_2$  than mean nest  $\text{CO}_2$  (ANOVA,  $F = 26.67$ ,  $P = 0.002$ ). During the last 30 days of incubation, the  $\text{CO}_2$  in partially washed dredge ( $0.48 \pm 0.10\%$ ) was significantly higher than all treatments (aged dredge, sand, loamy sand, natural reference nests, Tukey's HSD,  $P < 0.0001$ ; fully washed dredge, Tukey's HSD,  $P=0.03$ ; and new dredge, Tukey's HSD,  $P = 0.028$ ). During the last 30 days of incubation  $\text{CO}_2$  of partially washed dredge was significantly higher than the control ( $0.21 \pm 0.03\%$ ; Tukey's HSD,  $P = 0.019$ ). However, none of the  $\text{CO}_2$  levels were high enough to effect development of terrapin eggs.

For the first 30 days of incubation, the mean  $\text{O}_2$  in fully washed dredge ( $20.70 \pm 0.02\%$ ) was significantly lower than loamy sand ( $20.82 \pm 0.01\%$ ; Tukey's HSD,  $P = 0.022$ ). The mean  $\text{O}_2$  in partially washed dredge ( $20.68 \pm 0.03\%$ ) was significantly lower than loamy sand (Tukey's HSD,  $P = 0.008$ ) and sand ( $0.16 \pm 0.01\%$ ; Tukey's HSD,  $P = 0.034$ ). The mean  $\text{O}_2$  in new dredge ( $0.33 \pm 0.05\%$ ) was significantly lower than loamy sand (Tukey's HSD,  $P = 0.022$ ). For the last 30 days, the mean  $\text{O}_2$  in partially washed dredge ( $20.61 \pm 0.01\%$ ) was significantly lower than all treatments except new dredge ( $20.72 \pm 0.03\%$ ). Mean  $\text{O}_2$  in partially washed dredge was lower than that of sand  $0.79 \pm 0.01\%$ ; loamy sand  $20.82 \pm 0.02\%$ ; and aged dredge  $20.81 \pm 0.02\%$  (Tukey's HSD,  $P < 0.0001$ ); natural reference nests  $20.77 \pm 0.02\%$  (Tukey's HSD,  $P = 0.002$ ); and fully washed dredge  $20.75 \pm 0.02\%$  (Tukey's HSD,  $P = 0.013$ ). There were no significant differences in mean  $\text{O}_2$  between the first and last 30 days of incubation among soil treatments or between mean nest  $\text{O}_2$  and treatment controls. Rainfall events were greater

after the first 30 days of incubation in 2008 (Fig. 9).

## DISCUSSION

### Soil Treatment Comparisons

Microenvironmental factors are known to affect hatching success and development of embryos in turtles (Ackerman 1977; Packard and Packard 1988b; 1988c; Packard and Phillips 1994; Cagle 1993; Wilson 1998; Ackerman et al. 2008). Nests in new dredge and partially washed dredge treatments produced no hatchlings; with no embryos developing past the first stage (stages in *Chelydra serpentina*, Yntema 1968; Bell et al. 2004). This was probably the result of available soil moisture in the nests and not the result of toxins in dredge soil. Basile (2010) showed successful embryo development of terrapin eggs incubated in dredge soil containing high levels of polybrominated diphenyl ethers (PBDEs). Our results indicate that available water contributed to egg failure. Water is important for embryo development and growth in turtle and is provided through metabolic water; stored water in the egg; or acquired with environmental exchange (Ackerman et al. 2008). Cagle et al. (1993) reported that nest water potential is more important than temperature in determining embryo survivorship (in *Chelydra serpentina*). Our results clearly indicated that all new dredge treatments, with a more negative water potential than all other treatments, had a significantly lower embryo survivorship. Temperature was not a factor in embryo survivorship since there was no difference in mean nest temperature among treatments, which supported the findings in Cagle et al. 1993 (in *Chelydra serpentina*). Our fully washed treatment, which was not different in textural composition between new dredge and partially washed dredge treatments,

produced hatchlings in two of four nests (Table 4). Therefore; soil particle composition was not responsible for the hatching success in fully washed dredge versus partially washed and new dredge. However, lower soil conductivity in fully washed dredge nests accounted for the higher hatching success than new dredge and partially washed dredge nests because salts had a negative impact on hatching success of turtles (in sea turtles, Foley et al. 2006). Desiccation was a factor in all of the nests in dredge soil treatments. There were 33 desiccated eggs in new dredge treatment, 16 desiccated eggs in partially washed dredge treatment, and eight desiccated eggs in the fully washed dredge treatment. In natural reference nests where vegetation was present around most nests, 9.7% of the eggs were desiccated. This was the result of increased evapotranspiration and water intake by plant roots (Ackerman et al. 2008). However, desiccation of eggs in aquatic turtle nests is not well studied. Hewavisenthi and Parmenter (2001) concluded that *Natator depressus* eggs showed signs of desiccation (e.g. denting, cracking) when nesting substrate water potentials ranged from  $-650$  to  $-3500$  kPA. Desiccating conditions in nests were reported in other sea turtle species including *Caretta caretta* and *Chelonia mydas* (McGehee 1979; Mortimer 1990). Sand substrate in sea turtle nests is also the most reported nest substrate used by terrapins (Burger and Montevecchi 1975; Ernst et al. 1994; Roosenburg 1996). Changes in moisture regimes may result in changes in egg incubation time and affect hatchling size in turtles (Packard et al. 1987; Finkler 1999; Cagle et al. 2003).

There was a significantly higher hatching success in nests in sand (68.4%) and loamy sand (67.6%), as compared to all combined dredge treatment nests (4.9%; Table 4). When comparing treatment effects for both 2006 and 2008, nests in new dredge

produced no hatchlings (Table 5). Aged dredge (four nests) did not have a significantly higher hatching percentage (22.9%) than new dredge, but this may be a result of the high standard error (13.3%) and that only two of four nests produced hatchlings. Substrate moisture can also affect incubation time with greater moisture causing an increase in incubation time (Packard et al. 1987; Godfrey and Mrosovsky 2001). Embryos in the fully washed dredge treatment took significantly longer (94 days) to hatch than all other treatments. Despite more negative soil water potentials in nests in the fully washed dredge treatment than nests in sand and loamy sand treatments, smaller particle fractions (silt and clay) in fully washed dredge than in sand and loamy sand may account for higher moisture content retention (USDA 1993). However, moisture was most likely not available to terrapin eggs in new dredge treatments, especially when coupled with higher ion concentrations than the non-new dredge treatments. The wetter soil environment in fully-washed dredge may have resulted in a longer incubation period than in nests in the other non-dredge. Increased soil moisture can result in a longer incubation duration (Godfrey and Mrosovsky 2001; Cagle et al. 2003).

### **Soil Analysis**

After one year, there was a change in the dredge soil texture classification from sandy loam to loamy sand, with a noticeable reduction in smaller particles. Loamy sand soil is the predominant soil texture on North Sedge Island that was originally dredged over 80 years ago (Miller 1994). The clay fraction in loamy sand was 5% (2007) and 3% (2008). Small variations in soil texture percentages may be a result of differences in where soil samples were collected within plots. Although sample sites were randomized and soil samples taken within nest depth ranges, there may have been variations in

particle distribution, especially in new dredge which consisted of non-sorted particles. Soil water potential readings were consistent with the soil moisture potential differences based upon soil texture classifications in other studies (Campbell 2008). Based on a 5% water content, Campbell (2008) determined soil moisture potentials for soil textures (sand, -0.0034 MPa; loamy sand, -0.0045 MPa; sandy clay loam, -0.010 MPa; and sandy clay, -0.015 MPa). These measurements were consistent with our soil moisture curves (Figs. 7 and 8), except that new dredge had a higher soil moisture potential at a higher moisture percentage than fully washed dredge which was the same soil texture classification. The presence of solutes (dissolved ions) in soils can influence soil water energy (Campbell 2008). The high concentration of ions in new dredge soil may explain the more negative moisture potential (Figs. 6 and 7). Interestingly, regular rainfall patterns reduced soil conductivity in new dredge soil from 7.83 mS/cm to 0.70 mS/cm within four months. Sand had the least negative soil moisture potential than all other treatments (0.04 mS/cm) and had a lower water retention capacity than other soil textures with smaller particle sizes (Campbell 2008). Regular rainfall helps to maintain soil moisture (Ackerman et al. 2008) and can remove excess accretion of salts from tidal inundation or aerosol deposition on sand beaches that are used by nesting sea turtles (Ackerman 1997; Foley et al. 2006).

### **Temperature, Gas and Precipitation Measurements**

Within treatments, there were no differences in nest temperatures. However, in 2008, among treatments, mean nest temperatures in partially washed dredge ( $25.1 \pm 0.3^{\circ}\text{C}$ ) were lower than mean nest temperatures in loamy sand ( $26.4 \pm 0.3^{\circ}\text{C}$ ). There

were no other significant differences in mean nest temperatures among dredge and non-dredge treatments (Table 7). Nests in partially washed dredge may have contained more moisture which could affect incubation temperatures, thus a lower mean incubation temperature.

Unlike sea turtles that have large clutch sizes, eggs from turtles with smaller clutch sizes have more contact with the nesting substrate (Ackerman 1977; Miller and Dinkelacker 2008). In addition, nest location and location of eggs within clutches are important in terms of influencing metabolic conditions and sex determination (in sea turtles, Standora et al. 1982). The relationship between gas exchange and temperatures are complex in terms of O<sub>2</sub> and CO<sub>2</sub> (in sea turtles, Wallace et al. 2004). In our study, for the first 30 days of incubation, nests in partially washed dredge soil (0.30 %) and new dredge (0.33%) had significantly higher mean CO<sub>2</sub> (Table 8) than loamy sand (0.17%) and sand (0.16%), but not significantly higher than both controls, indicating that the decomposition of failed eggs within the first 30 days of incubation was not the only factor in the production of increased CO<sub>2</sub> within the substrate. The fully washed dredge treatment had lower CO<sub>2</sub> (0.25%) the first 30 days, but was not significantly lower than both partially washed and new dredge treatments. The mean CO<sub>2</sub> in nests in sand and aged dredge treatments was higher during the first 30 days of incubation than the last 30 days of incubation. This may have been due to increased precipitation after the first 30 days of incubation. During the last 30 days of incubation, partially washed dredge (0.48%) had significantly higher mean CO<sub>2</sub> than all other treatments (Table 8). During the last 30 days of incubation, the CO<sub>2</sub> in partially washed dredge was significantly higher than the control (0.21%). The mean partially washed CO<sub>2</sub> control during the last

30 days of incubation was lower than the mean partially washed control CO<sub>2</sub> during first 30 days of incubation (0.28%). This may be a result of organic material decomposition earlier in the summer in dredge soil. New dredge had a mean CO<sub>2</sub> control of 0.33% and fully washed dredge had a mean CO<sub>2</sub> control of 0.24% through the first 30 days of incubation. This indicated that some organic materials may have washed out of the dredge treatments during the water flushing treatment. The lower CO<sub>2</sub> values in new dredge nests versus partially washed dredge nests may have been due to the greater number of desiccated eggs in new dredge where there was less decomposition.

There were no differences in O<sub>2</sub> between nest soil treatments throughout the first and last 30 days of incubation. There were also no differences in nest O<sub>2</sub> between treatment controls and mean nest treatments during the last 30 days of incubation when there should be a higher metabolic demand. Terrapins dig relatively shallow nests (177 mm) compared with sea turtles (800 mm; Burger, 1976a; Ackerman 1977). The shallow terrapin nests show little variation in atmospheric O<sub>2</sub> measurements. Our O<sub>2</sub> results are consistent with Packard and Phillips (1994) who concluded that oxygen is usually not a constraint in the development of embryos in nests in small chelonians with relatively small clutches compared to sea turtles with deeper nest depths and larger clutch sizes (Ackerman 1977). The inverse relationship of mean nest CO<sub>2</sub> and O<sub>2</sub> in new dredge nests and control plots may be due to rainfall at least one day prior to gas sampling (Fig. 9; Figs. 10a and b). The first gas samples (day 13 of incubation) were taken after there was rainfall on 2008 Julian Days 179 (June 27) and 180 (June 28). Five days later, gas samples were taken after a morning rainfall event on 2008 Julian Day 186 (July 4). The lowest CO<sub>2</sub> values in new dredge nests were recorded on incubation day 29 which was in

a relatively dry period (Figs. 9 and 10b). The greatest recorded increase in CO<sub>2</sub> and decrease in O<sub>2</sub> in new dredge nests occurred on the 60<sup>th</sup> incubation day. A rainfall event started the previous day (2008 Julian Day 227, August 14) and continued into the morning prior to sampling. On incubation day 55 (2008 Julian Day 223, August 10), we sampled prior to start of the rainfall event that continued into 2008 Julian Day 224 (August 11). Nests in sand did not show the same variations in CO<sub>2</sub> and O<sub>2</sub>, especially towards the end of incubation (Figs. 10a and b). On incubation day 35, sand nest CO<sub>2</sub> and O<sub>2</sub> were a similar pattern to nests in the new dredge treatment. On incubation day 60, nests in sand had an inverse effect of gases than nests in new dredge (Figs. 10a and b). This was a result of diffusion of oxygen by rainfall because sand has a larger particle size composition than dredge. Rainfall may be a factor in gas exchange in turtle nests, although it is not considered a significant factor in gas exchange in sea turtle nests because eggs are in deeper nest cavities and the rainfall events may be sporadic and do not last long enough to be effective (Prange and Ackerman 1974).

With dredging of sediment continuing to occur within coastal regions, this research addresses the possible treatment of dredge sediment to enhance diamondback terrapin nesting areas. Dredge sediment should be analyzed for ions, particle composition and toxins prior to deposition on land for nesting area enhancement. If dredge sediment is disposed on nesting areas just prior to, and during, terrapin nesting season, then this will negatively impact the hatching success of terrapins. Therefore, the protection and enhancement of nesting areas is important to their survival. With proper temporal and spatial placement of dredge sediment, then dredge sediment can properly drain, displace salt ions, and be used as a viable nesting soil.

**Table 4.** Experimental treatment types during the summer 2008 on North Sedge Island at Barnegat Bay, New Jersey including mean hatching success (measured in percentage;  $\pm$  SE) and mean incubation time in days ( $\pm$  SE).

Treatment	Number of Nests	Mean Hatching Percentage	Mean Incubation Time (Days)	Combined Treatment Effects	Number of Nests	Mean Hatching Percentage
Natural Reference	6	50.8 $\pm$ 11.5	70.7 $\pm$ 3.2	Natural Reference	6	50.8 $\pm$ 17.4
Sand	6	68.4 $\pm$ 11.5 <sup>a</sup>	72.2 $\pm$ 2.1	Sand	6	68.4 $\pm$ 8.4 <sup>c</sup>
Loamy sand	9	67.6 $\pm$ 9.4 <sup>a</sup>	71.4 $\pm$ 1.2	Loamy sand	9	67.6 $\pm$ 11.1 <sup>c</sup>
Aged Dredge (2 Yr)	4	22.9 $\pm$ 13.9	75.0 $\pm$ 1.0	Aged Dredge (2 Yr)	4	22.9 $\pm$ 13.3
Fully Washed Dredge	4	14.6 $\pm$ 14.1	94.0 $\pm$ 6.0 <sup>b</sup>	All New Dredge Treatments 2008	12	4.9 $\pm$ 4.2
Partially Washed Dredge	4	0	*			
New Dredge	4	0	*			

<sup>a</sup> Significantly higher hatching percentage than both partially washed and new dredge treatments comparing the arcsine transformation of hatching percentage (sand, Bonferroni,  $P = 0.03$ ) and loamy sand, Bonferroni,  $P = 0.02$ )

<sup>b</sup> Fully washed dredge had significantly higher mean incubation times than all other treatments between all groups (Bonferroni,  $P < 0.001$ ).

<sup>c</sup> Sand and loamy sand hatching percentages were significantly higher than all new dredge treatments (sand, Bonferroni,  $P = 0.014$  ; loamy sand, Bonferroni,  $P < 0.001$ ).

\*No eggs developed past the first stage of incubation.

**Table 5.** Comparison of treatment types for mean hatching success (%;  $\pm$  1SE) and mean incubation time ( $\pm$  SE) for 2006 and 2008. Treatment types include sand, loamy sand, aged dredge and new dredge. Nests in the new dredge soil treatment produced no hatchlings and no embryos developed past the first third stage of development. New dredge soil from 2006 was aged 2 years and considered as the aged dredge treatment in 2008.

<b>Treatment</b>	<b>Number of Nests</b>	<b>Mean Hatching Percentage</b>	<b>Mean Incubation Time (Days)</b>
Natural Reference	13	50.5 $\pm$ 10.7 <sup>a</sup>	72.2 $\pm$ 2.3
Sand	10	53.4 $\pm$ 10.8 <sup>a</sup>	71.5 $\pm$ 2.1
Loamy Sand	12	65.5 $\pm$ 8.8 <sup>a</sup>	71.1 $\pm$ 0.9
Aged Dredge (2 yr)	4	22.9 $\pm$ 13.3	75.0 $\pm$ 1.0
New Dredge	9	0	-

<sup>a</sup> Indicates significantly higher hatching percentage among nests in all treatments and new dredge treatments using ANOVA ( $F_{4,43} = 7.16$ ,  $P < 0.0001$ ). Natural reference nests (Bonferroni,  $P = 0.037$ ) sand (Bonferroni,  $P = 0.044$ ), and loamy sand ( $P = 0.001$ ) treatment nests had a significantly higher hatching percentage than new dredge treatment nests.

**Table 6.** Composition of soil treatments types by using the Buoyancy method and dry-sieving. All percentages were used to determine the soil texture category using the U.S. Department of Agriculture Soil Texture Triangle. Soils were analyzed in 2008 and aged dredge, loamy sand, and sand samples were analyzed one year prior to this study (2007).

Treatment	Sand %	Silt %	Clay %	USDA Soil Texture Category
New Dredge 2008	80.0	4.0	16.0	Sandy Loam
Partially Washed Dredge 2008	80.0	4.7	15.3	Sandy Loam
Fully Washed Dredge 2008	80.0	6.7	13.3	Sandy Loam
Aged Dredge (1 Year, 2007)	86.0	2.7	11.3	Loamy Sand
Aged Dredge (2 Years, 2008)	85.0	4.7	10.3	Loamy Sand
Loamy Sand 2007	86.0	9.0	5.0	Loamy Sand
Loamy Sand 2008	84.0	13.0	3.0	Loamy Sand
Sand 2007	96.6	1.7	1.7	Sand
Sand 2008	96.5	1.9	1.6	Sand

**Table 7.** Comparison of mean nest temperatures ( $\pm 1$ SE) among treatments, and between years for 2006 and 2008. In 2008, there was a significant difference between the mean nest temperature in the loamy sand treatment (a) versus the mean nest temperature in the partially washed dredge treatment (b; Tukey's HSD post hoc test,  $P = 0.037$ ).

Treatment	# Nests 2007	Mean Nest Temperatures (°C)	# Nests 2008	Mean Nest Temperatures (°C)
Natural Reference	5	25.9 $\pm$ 0.6	3	25.3 $\pm$ 0.3
Sand	5	25.6 $\pm$ 0.6	4	25.6 $\pm$ 0.3
Loamy Sand	5	26.4 $\pm$ 0.7	3	26.4 $\pm$ 0.3 <sup>a</sup>
Aged Dredge	-	-	3	26.1 $\pm$ 0.3
Fully Washed Dredge	-	-	3	25.2 $\pm$ 0.2
Partially Washed Dredge	-	-	3	25.1 $\pm$ 0.3 <sup>b</sup>
New Dredge	5	25.4 $\pm$ 0.5	3	25.8 $\pm$ 0.3

**Table 8.** Mean CO<sub>2</sub> and O<sub>2</sub> percentages (mean  $\pm$  1SE) throughout the 2008 nesting season at North Sedge Island. Temperatures were recorded alternate days throughout the summer (n = 38). The mean nest data from the first 30 days of incubation and the last 30 days of incubation (%). All gas percentages were analyzed using a MANOVA to compare gas percentages and incubation period for all treatments. A Tukey's HSD post hoc test was used to compare treatments after significance was determined.

Treatment	# Nests	Mean CO <sub>2</sub> (%) 1 <sup>st</sup> 30 Incubation Days	Mean CO <sub>2</sub> (%) Last 30 Incubation Days	Mean O <sub>2</sub> (%) 1 <sup>st</sup> 30 Incubation Days	Mean O <sub>2</sub> (%) Last 30 Incubation Days
Reference	3	0.19 $\pm$ 0.03	0.21 $\pm$ 0.02	20.79 $\pm$ 0.01	20.77 $\pm$ 0.02
Sand	4	0.16 $\pm$ 0.01	0.12 $\pm$ 0.01	20.79 $\pm$ 0.02	20.82 $\pm$ 0.02
Loamy Sand	3	0.17 $\pm$ 0.02	0.17 $\pm$ 0.02	20.82 $\pm$ 0.01	20.79 $\pm$ 0.01
Aged Dredge (2 Yr)	3	0.21 $\pm$ 0.03	0.13 $\pm$ 0.01	20.78 $\pm$ 0.03	20.81 $\pm$ 0.02
Fully Washed Dredge	3	0.24 $\pm$ 0.02	0.25 $\pm$ 0.02	20.70 $\pm$ 0.02 <sup>d</sup>	20.75 $\pm$ 0.02
Partially Washed Dredge	3	0.30 $\pm$ 0.03 <sup>a</sup>	0.48 $\pm$ 0.10 <sup>c</sup>	20.68 $\pm$ 0.03 <sup>e</sup>	20.61 $\pm$ 0.01 <sup>g</sup>
New Dredge	3	0.33 $\pm$ 0.05 <sup>b</sup>	0.29 $\pm$ 0.02	20.69 $\pm$ 0.04 <sup>f</sup>	20.72 $\pm$ 0.03

<sup>a</sup> Partially washed dredge had significantly higher mean CO<sub>2</sub> values than loamy sand and sand (Tukey's HSD, P < 0.02).

<sup>b</sup> New dredge had significantly higher mean CO<sub>2</sub> values than loamy sand, natural reference nests and sand (Tukey's HSD, P < 0.02).

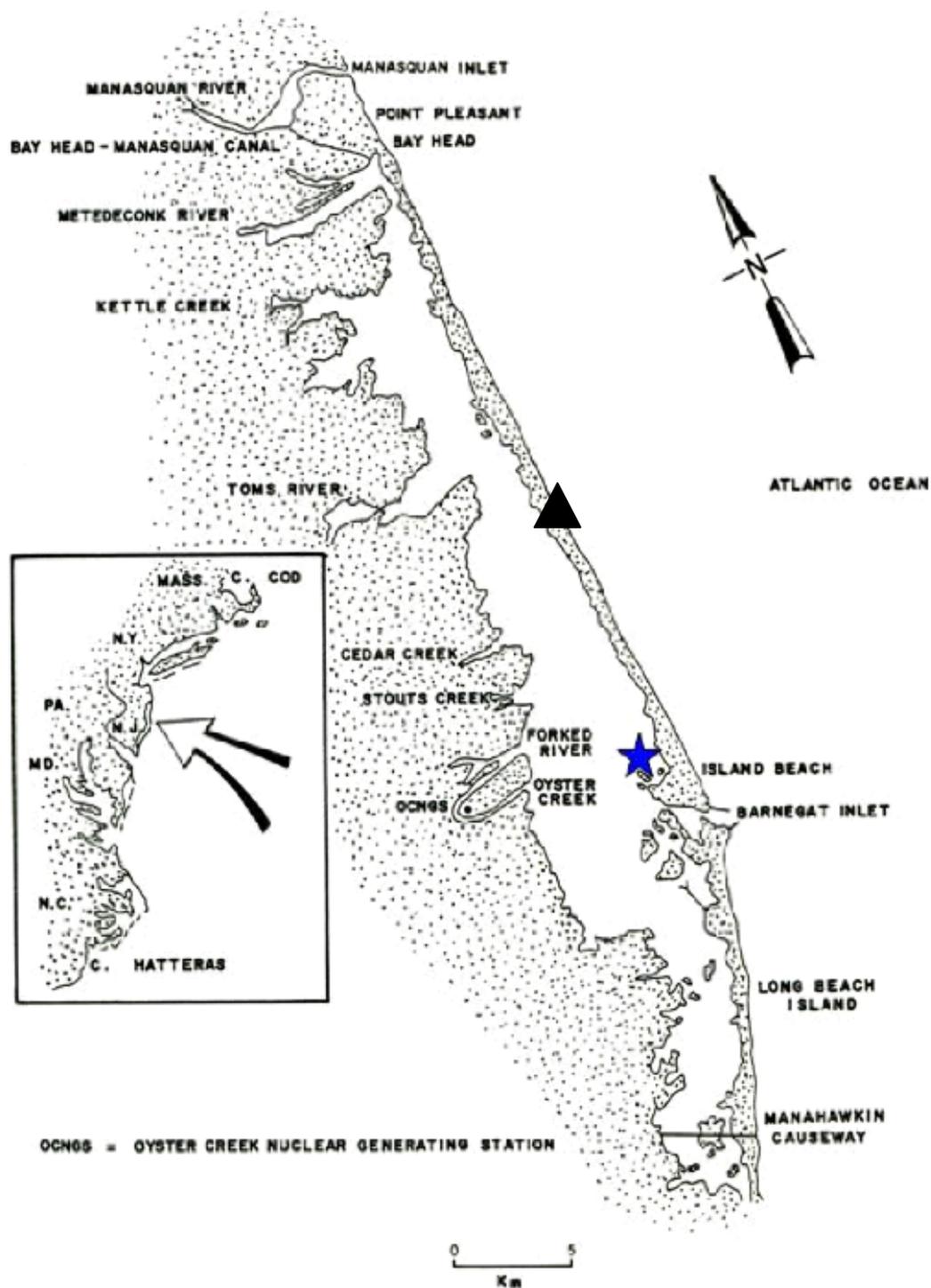
<sup>c</sup> Partially washed dredge had significantly higher mean CO<sub>2</sub> values than all treatments using ANOVA (aged dredge, sand, loamy sand, and natural reference nests (Tukey's HSD, P < 0.0001); fully washed dredge and new dredge (Tukey's HSD, P < 0.03).

<sup>d</sup> Fully washed dredge had significantly lower mean O<sub>2</sub> values than loamy sand (Tukey's HSD, P < 0.03).

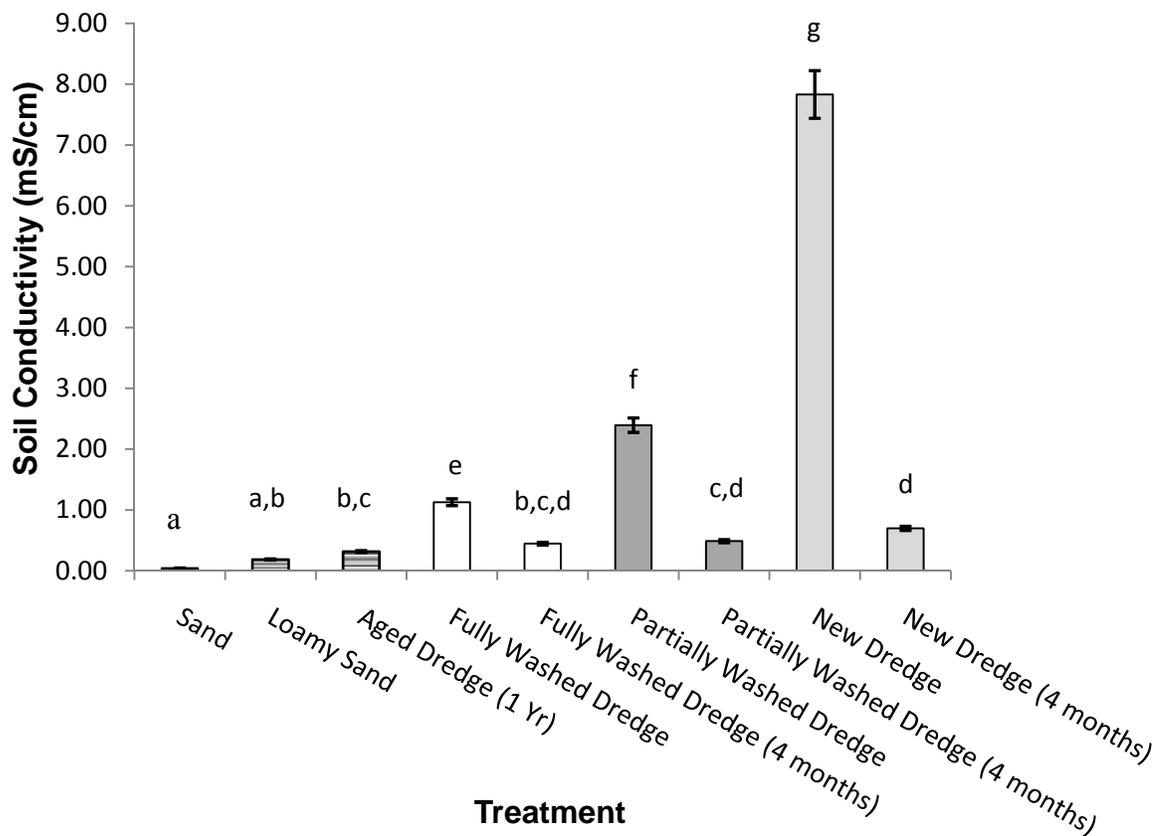
<sup>e</sup> Partially washed dredge had significantly lower mean O<sub>2</sub> values than loamy sand and sand (Tukey's HSD, P < 0.03).

<sup>f</sup> New dredge had significantly lower mean O<sub>2</sub> values than loamy sand (Tukey's HSD, P < 0.03).

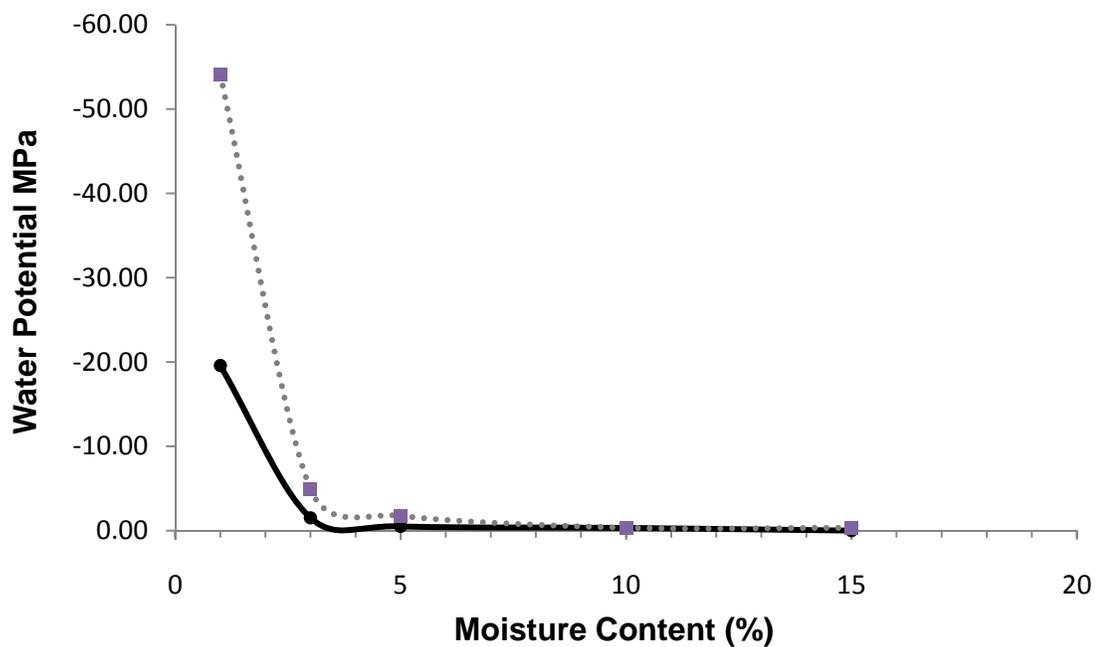
<sup>g</sup> Partially washed dredge had significantly lower mean O<sub>2</sub> values than all treatments except new dredge (Tukey's HSD, P < 0.01).



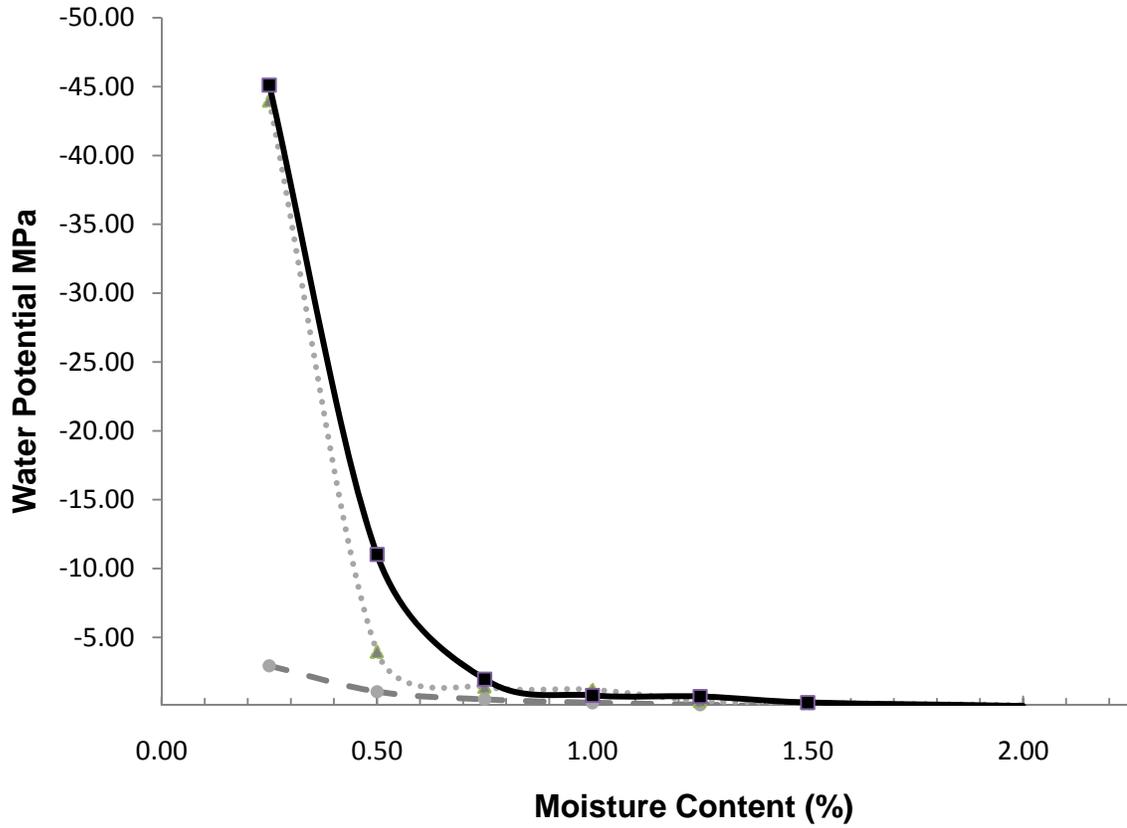
**Figure 5.** Map of North Sedge Island (star) at Barnegat Bay, N.J. USA (Latitude  $39^{\circ}47'48''$  N, Longitude  $074^{\circ}07'07''$  W). Map courtesy of Dr. Michael Kennish, Rutgers University, New Jersey, USA. Weather station (triangle) located at Seaside Park, N.J.



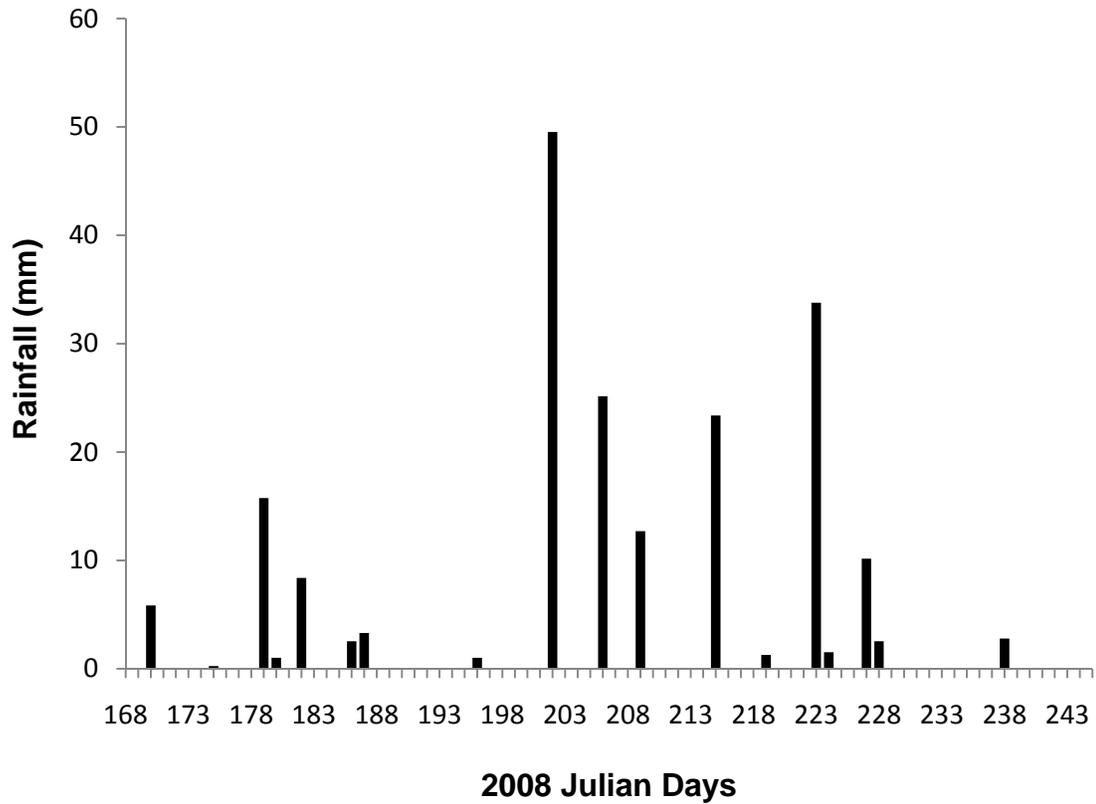
**Figure 6.** Mean soil conductivity (mS/cm  $\pm$  2SE) for nest treatments at North Sedge Island. There was a significant difference between treatments (ANOVA,  $F = 2093.05$ ,  $P < 0.0001$ ). The same letter designations indicate no significant difference among treatments and times for treatments (i.e., 4 months, 1 year) using Tukey's HSD post hoc test. Different letters indicate significantly different soil conductivity measurements. Sand (a) was significantly lower than all treatments (Tukey's HSD,  $P < 0.05$ ), except loamy sand. New dredge (g) had significantly higher soil conductivity (SC) than all treatments (Tukey's HSD,  $P < 0.001$ ). After 4 months, all new dredge treatments (d) had significantly lower SC than initial dredge treatments (Tukey's HSD,  $P < 0.0001$ ) and were not significantly different from each other.



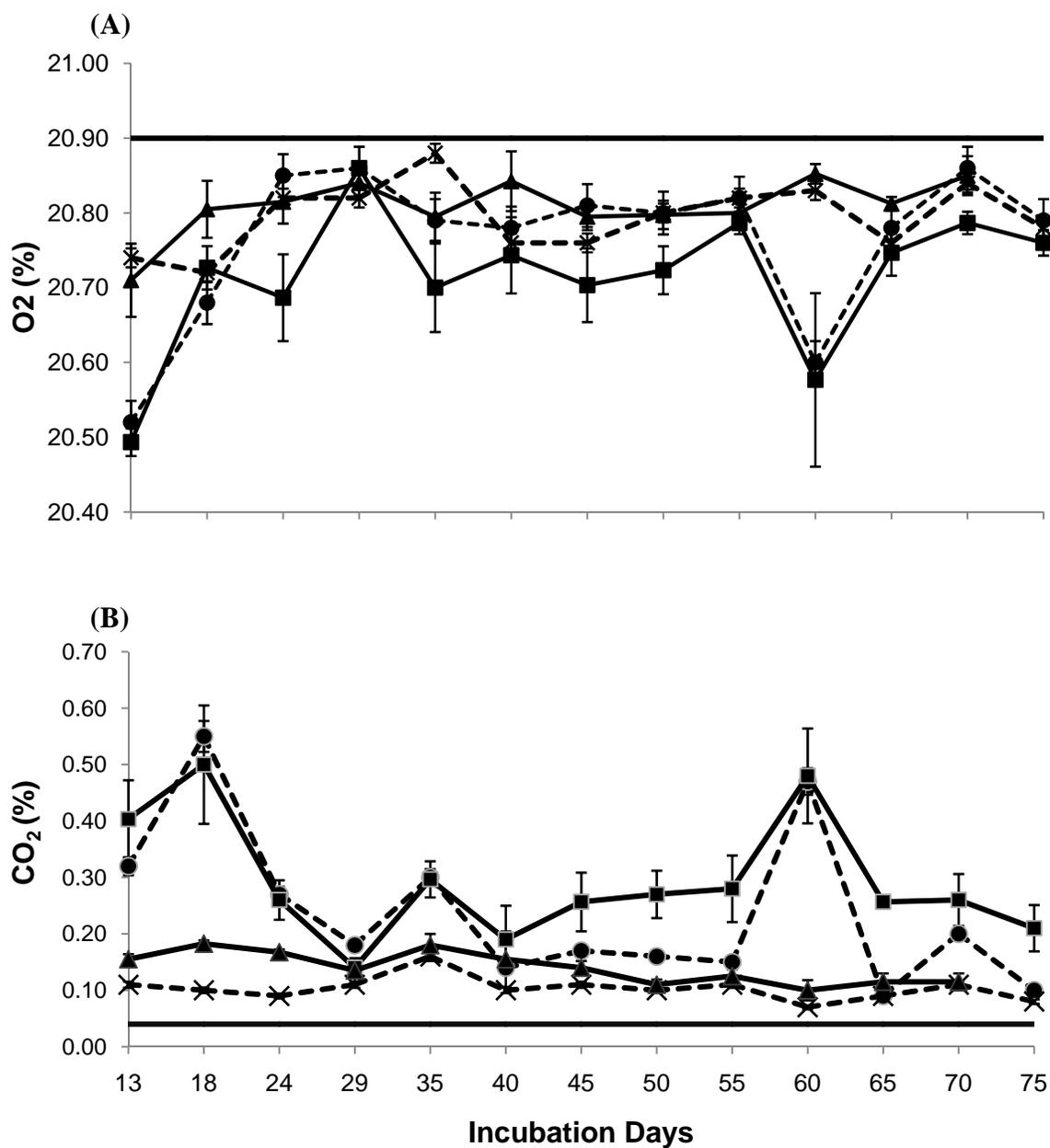
**Figure 7.** Water potential (MPa) of nest treatment soils at North Sedge Island at different soil moisture contents. New dredge (dashed line with squares) had a lower water potential at higher moisture content than fully washed dredge (solid line with circles). Partially washed dredge (not shown) had a water potential of -26.1 at 1% soil moisture.



**Figure 8.** Comparison of water potential and moisture content in three soil nest treatments at North Sedge Island during the summer of 2008. Sand (dashed line) had the highest water potential (MPa) at the lowest moisture content. Loamy sand (dotted line with triangles) and aged dredge (2 yr; solid line) had more negative water potentials (MPa) at 0.50% soil moisture content.



**Figure 9.** Rainfall (mm) at North Sedge Island during the 2008 nesting season (June 16 – Aug. 31). There was an increase in rainfall amounts after the first 30 days of incubation. The first 30 days of incubation started on Julian Day 168 (June 16); and the last 30 days of incubation ended on Julian Day 240 (August 27, for nests in sand and loamy sand treatments, and natural reference).



**Figure 10.** Gas measurements (%; mean  $\pm$  1SE) at North Sedge Island, New Jersey (solid lines with squares represent nests in new dredge; dashed lines with circles represent new dredge control; solid lines with triangles represent nests in sand; and dashed lines with “X” marks represent sand control). **A.** Indicates mean O<sub>2</sub> % for nests in sand (n = 4) and mean control samples (n = 3), solid dark line indicates ambient O<sub>2</sub> (20.90%). **B.** Indicates mean CO<sub>2</sub> % for nests in new dredge (n=3) and mean control samples (n = 3), solid dark line indicates ambient CO<sub>2</sub> (0.038%).

## CHAPTER 4: REPRODUCTIVE ECOLOGY OF THE DIAMONDBACK TERRAPIN IN BARNEGAT BAY, NEW JERSEY

### ABSTRACT

Variations in life history characteristics are exhibited by species of turtles across their range. One such emydid turtle, the diamondback terrapin, *Malaclemys terrapin*, exhibits latitudinal morphometric variations in body size and reproductive output. The northern-most subspecies, *Malaclemys t. terrapin* has larger body sizes and clutch sizes than *Malaclemys t. ornata* found in Florida. There are also morphometric and reproductive output variations within local geographical areas. We investigated the demography and life history characteristics of nesting female terrapins at North Sedge Island, Barnegat Bay, New Jersey from 2002 to 2009 and demography and life history characteristics of terrapin populations at Spizzle Creek, Barnegat Bay, New Jersey from 2005 to 2009. My results indicate that there is a 1.88:1 female-biased population captured at Spizzle Creek. At N. Sedge Island, we found that female terrapins nest up to three times per year with mean clutch size of  $12.6 \pm 0.8$ . There was variability in mean clutch size between years, but no significant difference was found between 2005 and 2009. Compared with nesting female terrapins 35 km south at Little Beach, Barnegat Bay, New Jersey, there was a significant difference in mean female plastron length with a greater mean clutch size and mean egg mass. Latitudinal clutch size variations in terrapins support the Optimal Egg Size (OES), however, there needs to be more studies in egg size variations. My results clearly indicate that reproductive output of *Malaclemys terrapin* can vary in local geographical regions. However, latitudinal differences over the broad

range for subspecies of *Malaclemys terrapin* should incorporate more local geographical variations in determining reproductive output and demography for each subspecies.

## INTRODUCTION

The diamondback terrapin, *Malaclemys terrapin*, is a small estuarine emydid turtle with a geographic range from Cape Cod, Massachusetts to the Gulf Coast of Texas (Ernst et al., 1994). Seven sub-species of terrapins are recognized across its range, and it is the only species of turtle endemic strictly to brackish coastal marshes, bays, lagoons, creeks, and estuaries in North America (Palmer et al. 1988; Lovich and Gibbons 1990; Gibbons et al. 2001). Despite many studies on habitat, resource requirements, reproductive aspects, and human impacts (Cook 1989; Roosenburg 1996; Roosenburg and Kelley 1996; Roosenburg and Dunham, 1997; Roosenburg et al. 1997; Wood and Herlands 1997; Gibbons et al. 2001; Whitelaw and Zajac 2002), there is still much uncertainty as to life history characteristics across its ranges (Mitro 2003). Diamondback terrapins are sexually dimorphic like other species of aquatic turtles (Lovich and Gibbons 1990). Adult terrapin females range from two to four times larger than males (Roosenburg and Kelley 1996). Lovich and Gibbons (1990) collected and measured terrapins from the Kiawah River, South Carolina. They reported that adult male terrapins had a mean straight-line plastron length (SPL) of 102 mm and mean mass of 242 grams. Adult female terrapins had mean SPL of 148 mm and mean masses of 705 grams (Lovich and Gibbons 1990). In the northern diamondback terrapin, *Malaclemys t. terrapin*, mean straight-line carapace length (SCL) ranges from 150 – 230 mm in adult female terrapins and ranged from 100 - 140 mm in adult male terrapins (Palmer and Cordes 1988). Female

terrapins reach sexual maturity between eight and thirteen years of age, and male terrapins reached sexual maturity between four and seven years of age (Roosenburg 1996).

### **Reproductive Ecology and Nesting Habitat**

Although several studies include terrapin reproductive characteristics of such as clutch size, nest fidelity, clutch frequency and incubation time across their range (Burger 1976a; Roosenburg 1996; Roosenburg and Kelley 1996; Gibbons et al. 2001; Butler et al. 2004), more studies are needed to determine reproductive variations geographically. Clutch sizes of diamondback terrapins differ from 10.9 in New York (Feinberg and Burke 2003), to 9.2 in New Jersey (Burger and Montevecchi 1975), 13.2 in Maryland (Roosenburg and Dunham 1997) and 6.7 in Florida (Seigel 1980b). Differences in clutch size may be due to variations in available resources and metabolic costs. In New Jersey, clutch sizes range from 4 to 18 eggs (Burger and Montevecchi 1975).

Among eggs, egg mass varies geographically from 7.70 g in New Jersey (Montevecchi and Burger 1975) to 9.80 g in Maryland (Roosenburg and Dunham 1997), 11.20 g in South Carolina (Zimmerman 1992), and 12.48 g in Florida (Seigel 1980b). Egg lengths vary from 32.1 mm in Rhode Island (Goodwin 1994) to 31.7 mm in New Jersey (Montevecchi and Burger 1975), 36.9 mm in South Carolina (Zimmerman 1992), and 39.0 mm in Florida (Seigel 1980b).

Terrapins nest on sandy shoreline areas along estuarine coasts (Burger and Montevecchi 1976; Burger 1977) and on high banks along tidal creeks that have been filled with bottom substrate (dredge sediment) dug out to keep channels open (pers. obs.). Terrapins demonstrate nest site fidelity across their ranges (Roosenburg 1996, Feinberg

and Burke 2003). In New Jersey, Szerlag-Egger and McRobert (2007) showed that female terrapins had a mean inter-nesting distance of 203 m in southern Barnegat Bay. Terrapin nesting seasons begin first at the southern end of the range and progress to the north. In Florida, terrapins nest from April through August (Butler et al. 2004) whereas in New Jersey, they nest in June and July (Burger 1977; Butler et al. 2004). The nesting season in New York is similar to that of New Jersey (Feinberg and Burke 2003).

Nest location is an important factor for the survival of embryos. Nests with 25% vegetative cover at 25% had greater hatching success than those incubated with less than 25% or more cover (Cordes and Palmer 1988). Location of terrapin eggs within nest cavities is also important to the hatching success. Burger (1976b) reported that terrapin eggs in shallow nests buried at the top of the nest cavity experienced incubation temperatures in excess of 35°C, causing higher embryo mortalities than those buried deeper in the nest that experienced lower temperatures. Incubation temperatures inversely affects incubation time of terrapin embryos with warmer incubation temperatures producing shorter incubation times (Roosenburg and Kelley, 1996). In New Jersey, incubation times, range from 61 to 104 days, dependent on seasonal temperatures (Burger 1976b; 1977). Besides nest depth and location, predation and catastrophic events cause high embryo mortality. Feinberg and Burke (2003) reported that only four of 77 nests survived predation and flooding in New York. Nest predation rates ranged from 41.3% to 88% in New Jersey (Burger 1977). In 1973 and 1974 terrapin nests on Little Beach, New Jersey had 39% and 18% hatching success rate respectively (Burger 1977).

## METHODS

### Study Area

Our research was conducted on North Sedge Island (Fig. 11) in the Barnegat Bay Estuary, New Jersey, U.S.A. (Latitude 39°47'48" N, Longitude 074°07'07" W) from 2002 through 2009. The island is approximately 88,626 m<sup>2</sup> (21.9 acres) located one km west of Island Beach State Park, a 16 km peninsula of undeveloped bay and ocean beach containing primary and secondary sand dunes where female terrapins nest.

Approximately 10,000 m<sup>2</sup> of the island was filled with dredged sediment in the early 1900s to build hunting and fishing retreats (Miller 1994). North Sedge Island, located within a designated Marine Conservation Zone, was predominantly salt marsh habitat with bay beach access on its north and east sides that adult female terrapins utilized to access the filled area to nest. North Sedge Island was managed by the New Jersey Division of Fish and Wildlife that operated a large residential education center, a caretaker's residence and boathouse on the island. Residential programs were scheduled throughout the late spring and summer months on the Island, with a majority of the programs in June and July which coincided with terrapin nesting season (Montevecchi and Burger 1975). Spizzle Creek was located along the Barnegat Bay shoreline of southern of Island Beach State Park (between access 19 and 20; Fig.11). Spizzle Creek was an open water area approximately 500 m in length by 100 m at its widest point surrounded by salt marsh with a mean depth of one meter at mean high water. The area was approximately 500 m from the main roadway access on Island Beach and was accessible by walking trail that featured native coastal flora and fauna. We collected

terrapins in the creek and adjacent channels in the marsh, as well as on the roadway during nesting season.

### **Nesting population: North Sedge Island**

We captured nesting female terrapins by hand at North Sedge Island between 2002 and 2009. We recorded dates, times (EDT) and landing locations for all female terrapins encountered. We palpated all female terrapins to determine if they were gravid at time of capture and injected them with 12 mm passive integrated transponder (PIT) tags that contained nine or ten alphanumeric characters (Buhlmann and Tuberville 1998). We scanned terrapins for PIT tags using a BioMark® portable reader, then all terrapins were weighed (g) using an Ohaus® digital balance (model 2100,  $\pm 1$ g), and all terrapins were measured with 400 mm tree calipers ( $\pm 1$  mm) to determine straight line carapace length (mm), carapace width (mm), carapace height (mm) and plastron length (mm; Gibbons et al. 2001). We aged females by counting annuli on the plastron scutes (Lovich and Gibbons 1990). In 2005, marginal scutes on all female terrapins were notched as an additional form of identification (Cagle 1939; Gibbons 1990). We used MARK (POPAN – Jolly Seber) to estimate effective female nesting population size at North Sedge Island based on our mark and recapture data from 2002 to 2009.

Terrapin nests that were oviposited in areas on the island with high human activity (i.e., walking areas, kayak launch locations, and around the caretaker's residence) were excavated and relocated to a hatchery on the northwest part of the island that was part of a comparative study on the effects of soil texture on terrapin hatching success from 2005 to 2009 (Wnek et al., in review). We marked and transported eggs from their original nest location to the experimental plots in an insulated container in vermiculite

without changing egg orientation (Packard and Packard 2000). For all excavated nests, we removed eggs, determined clutch size, and measured egg lengths (mm) and egg widths (mm) using a 150 mm Mituyo 700-126® digital caliper ( $\pm 0.02$  mm). All eggs were weighed using an Ohaus® portable digital pocket balance ( $\pm 0.1$  g). All nests were covered using predator excluder devices made of 12 mm mesh galvanized hardware cloth to protect eggs from predation. Nests were identified as either oviposited by known females or oviposited by unknown females. Upon hatching and emergence, hatchlings were measured (carapace length, carapace width, carapace height, plastron length) using the same digital caliper and portable pocket balance that was used to measure eggs. All hatchlings were released back to the original nest location of oviposition on the island. Dates, times and locations were recorded for all female terrapins on the island from 2002 through 2009. From 2005 through 2009, we determined clutch sizes, egg sizes and egg masses. We compared egg sizes and egg masses within and among clutches and years using ANOVA. We also correlated female plastron length (mm) with egg mass (Roosenburg and Dunham 1997). All body size and body mass relationships were transformed using the natural log to normalize data and then were regressed (Roosenburg 1992; Roosenburg and Dunham 1997). Clutch sizes and egg lengths (mm) were correlated with female plastron lengths (mm) using Pearson Correlation (significance,  $P=0.01$ ). Interclutch comparisons were made for egg size and egg length using a GLM univariate test and Bonferroni post hoc test for terrapins that oviposited at least two nests within years and among years. For three or more nests oviposited by the same female, an ANOVA was used within years and among years. Mean clutch egg masses and individual egg masses were analyzed and compared among years using ANOVA.

Significance among years was ranked using a Ryan-Einot Gabriel Welsch (REGW) post hoc test to group similar mean egg masses (g) and mean egg lengths (mm) among years. Incubation time was compared among years using ANOVA and a REGW post hoc test was used to group similar incubation times if significance was determined. ANOVA was also used to determine differences in arcsine transformed hatching percentage in reference nests among years; and was used to determine significance in hatchling morphometric comparisons of carapace length, carapace width, carapace height, plastron length and hatchling mass among years. We regressed mean clutch egg mass and mean clutch hatchling mass to determine the relationship (Giambanco 2002). An alpha of 0.05 was considered significant for all ANOVA, GLM univariant and post hoc tests.

### **Spizzle Creek population**

Baited hoop traps (1.2 m high x 1.5 m long with a 2.5 cm mesh) were set in Spizzle Creek periodically from 2005 to 2009 from May through October. Hoop traps were set parallel the shoreline with a 30 cm opening above the surface at high water to prevent terrapins from drowning. We set two to five traps in Spizzle Creek at any one time. We baited hoop traps with Atlantic Menhaden (bunker), but after our initial set in 2005, we captured over 25 terrapins in one trap, therefore, we did not use bait in the hoop traps anymore to prevent trap failure. We checked all hoop traps daily and removed them from Spizzle Creek on weekends to ensure safety of terrapins and prevent theft of traps and terrapins. Numbers of visitors to the New Jersey Shore, specifically, Island Beach State Park increased during weekends which included boaters accessing the park from bay beach access points adjacent to the creek.

We weighed all captured terrapins and measured them using the same protocol for nesting female terrapins at North Sedge Island. We marked terrapins by notching their marginal scutes (Cagle 1939; Gibbons 1988), and inserted PIT tags were into all female terrapins for additional identification, following the same marking protocol as at N. Sedge Island (Buhlmann and Tuberville 1998). All marked terrapins were immediately returned to Spizzle Creek adjacent to the trap location. Natural log transformation of terrapin plastron lengths (mm) and masses (g) were regressed for juveniles, females, and males. The MARK program (POPAN – Jolly-Seber) was used to estimate the population of terrapins (males, females and juveniles) at Spizzle Creek using mark and recapture data from 2005 through 2007. We also determined the ratio of female and male terrapins.

## RESULTS

### **Nesting population: North Sedge Island**

From 2002 to 2009, we captured and marked 334 individual nesting female terrapins at N. Sedge Island (Table 9). Mark-recapture data using a POPAN Jolly-Seber population estimate indicated that the nesting population was  $430 \pm 23$  (SE) with a 95% confidence level of 385 to 476 individuals (Table 10). Landing dates on N. Sedge Island ranged from late May (May 29, 2006) through late July (July 27, 2003; Fig. 12). Between 2006 and 2009, peak landing time on the island was 1200 h (Fig. 13). The earliest time that a female nested on the island was 0530 h and the latest time a female nested on the island was 2300 h. The landing times from 2002 through 2005 were not reported consistently, thus were not included in this study. Female terrapins nested up to three times within a season (Table 9). Interclutch intervals ranged from 12 to 33 days with a

mean interclutch interval of  $19.4 \pm 1.0$  days. The greatest frequency ( $n = 5$ ) of interclutch nesting occurred on day 16 (Fig. 14). Nesting female terrapins ( $n = 180$ ) had a mean straight-line carapace length (SCL) of  $190.3 \pm 1.0$  mm, a mean plastron length (PL) of  $172.7 \pm 0.8$  mm and a mean mass of  $1176.9 \pm 16.5$  g (Table 11). The smallest female that nested on N. Sedge Island, had a mean SCL of 154.0 mm, a mean PL of 142.0 mm and weighed 620.0 g (Fig. 15). She was captured in 2006 and was aged at eight years. The largest female terrapin had a mean SCL of 230.0 mm, mean PL of 196 mm, and weighed 1821.0 g. She was captured during the 2006 nesting season, but was too old to age. Of 49 age able female terrapins, a comparison of plastron lengths (mm) varied within age classes (Fig. 16). The youngest female to land on the island was age class six (two females) and the oldest age able terrapin was age class 13 (one female). At N. Sedge Island, 285 female terrapins either were not aged or could not be aged because there was low confidence reading the plastral scute annuli and a majority of the terrapins had no detectable annuli. For age-able females ( $n = 49$ ), ANOVA found that there was no significant difference in mean PL ( $164.7 \pm 1.3$  mm) among years ( $F_{1,47} = 0.891$ ,  $P = 0.511$ ). For all females ( $n = 180$ ), ANOVA found that there was no significant difference in PL of nesting female terrapins ( $172.7 \pm 0.8$ ;  $F_{4,124} = 1.679$ ,  $P = 0.159$ ) and no significant difference in SCL of nesting female terrapins ( $190.3 \pm 1.0$ ;  $F_{4,124} = 1.444$ ,  $P = 0.224$ ) among years. A regression analysis of the natural log transformation of PL and mass for nesting females ( $n = 180$ ) showed a similar relationship ( $P < 0.0001$ ,  $F_{1,178} = 447.86$ ,  $r^2 = 0.715$ ; Fig. 17A) as for SCL and mass ( $P < 0.0001$ ,  $F_{1,178} = 340.64$ ,  $r^2 = 0.679$ ; Fig. 17B).

### Clutch size and egg morphometrics

Mean clutch size at N. Sedge Island was  $12.6 \pm 0.2$  ( $n = 177$ ) from 2005 to 2009 (Table 12). Clutch sizes ranged from  $11.2 \pm 1.3$  ( $n = 11$ ) in 2005 to  $13.5 \pm 0.4$  in 2008 ( $n = 33$ ), with a minimum of two eggs in 2009 and maximum of 19 egg in 2008. The ANOVA found that there was no significant difference in mean clutch size among years ( $F_{4,172} = 1.893$ ,  $P = 0.114$ ; Table 12). There was a significant correlation between female plastron size and clutch size for 129 nests observed from 2005 to 2009 with a significance at  $P = 0.01$  ( $P < 0.001$ ,  $F_{1,127} = 13.38$ ,  $r^2 = 0.096$ ; Fig. 18). The mean clutch egg mass ( $n = 153$ ) was  $8.14 \pm 0.08$  g with no significance difference among years (ANOVA,  $F_{4,148} = 1.952$ ,  $P = 0.105$ ). The mean clutch egg length ( $n = 153$ ) was  $31.80 \pm 0.13$  mm with no significant difference among years (ANOVA,  $F_{4,148} = 1.632$ ,  $P = 0.169$ ; Table 13). However, the mean egg mass ( $n = 1907$ ),  $8.16 \pm 0.02$  g was significantly different among years (ANOVA,  $F_{4,1902} = 11.70$ ,  $P < 0.0001$ ) and the mean egg length,  $31.81 \pm 0.04$  mm was significantly different among years ( $F_{4,1902} = 22.75$ ,  $P < 0.0001$ ; Table 14). An REGW post hoc test showed that mean egg masses in 2007 and 2008 were more related than the other years of this study (Table 14). For mean egg length, 2006, 2007 and 2008 were more related than the other years of this study (Table 14). There was a significant correlation between egg length and egg mass for all eggs ( $n = 1907$ ;  $P < 0.0001$ ,  $F_{1,1905} = 2255.54$ ,  $r^2 = 0.542$ ; Fig. 19). From 2005 to 2009, there was no significant variation in mean clutch sizes among years (Fig. 20). Female plastron length showed a positive correlation with egg mass ( $n = 129$ ;  $P < 0.0001$ ,  $F_{1,127} = 27.96$ ,  $r^2 = 0.180$ ; Fig. 21) and egg length ( $P < 0.0001$ ,  $F_{1,127} = 13.20$ ,  $r^2 = 0.094$ ). There was a significant difference in egg mass (g; GLM univariant,  $F_{1,905} = 31.628$ ,  $P < 0.0001$ ) for

terrapins nesting within and between nesting seasons ( $n = 23$ ), and a significant difference in egg length (mm) for terrapins nesting within and between nesting seasons (GLM univariant,  $F_{1,905} = 22.420$ ,  $P < 0.0001$ ). Within seasons, only three of 14 terrapins had significantly different egg masses and two of 14 terrapins had significantly different egg lengths (Bonferroni,  $P < 0.05$ ; Table 15). Between seasons, only three of 21 terrapins had significantly different egg masses and four of 21 terrapins had significantly different egg lengths (Bonferroni,  $P < 0.05$ ; Table 15). Two individual nesting female terrapins were highlighted, terrapin codes AHPW and BCHW provided detailed information on reproductive output. Terrapin AHPW was marked in 2006 and returned to nest 6 times between 2006 and 2009. In 2008, she nested three times (June 16, July 2, and July 16) with no significant difference between mean egg mass ( $8.50 \pm 0.18$  g;  $8.40 \pm 0.07$  g;  $8.36 \pm 0.19$  g; ANOVA  $F_{2,45} = 0.229$ ,  $P = 0.796$ ) and mean egg length ( $30.96 \pm 0.23$  mm;  $31.48 \pm 0.33$  mm;  $31.02 \pm 0.33$  mm; ANOVA,  $F_{2,45} = 0.953$ ,  $P = 0.393$ ; Table 15; Fig. 22A). She produced clutch sizes of 16, 19 and 13 respectively. In 2009, female terrapin AHPW nested two times with a significant difference in mean egg mass ( $7.11 \pm 0.11$  g;  $8.56 \pm 0.19$  g; Bonferroni,  $P < 0.01$ ), but no significant difference in mean egg size ( $29.96 \pm 0.40$  mm;  $30.06 \pm 0.14$  mm; Bonferroni,  $P > 0.05$ ; Table 15; Fig. 22A). In 2009, she produced a significantly smaller clutch size ( $n = 9$ ; ANOVA,  $F_{5,81} = 12.659$ ,  $P < 0.05$ ) on June 13, then produced a clutch of 15 eggs when she oviposited a second nest on July 12. We may have missed observing a nesting cycle between the first oviposited and last oviposited nest in 2009. Terrapin BCHW was marked in 2006 and returned to nest five times between 2006 and 2009. In 2009, she nested two times (June 25 and July 17) with no significant difference within the year between mean egg mass ( $8.10 \pm 0.10$  g;  $8.44 \pm$

0.06 g; Bonferroni,  $P > 0.05$ ) and mean egg length ( $32.03 \pm 0.24$  mm;  $31.61 \pm 0.25$  mm; Bonferroni,  $P > 0.05$ ; Table 15; Fig. 22B). There was no significant difference between years in mean egg mass ( $8.14 \pm 0.06$  g; ANOVA,  $F_{4,64} = 6.981$ ,  $P = 0.06$ ) and mean egg length ( $31.73 \pm 0.10$  g; ANOVA,  $F_{4,64} = 1.215$ ,  $P = 0.317$  Table 15; Fig. 22B).

### **Hatching and hatchling morphometrics**

The mean incubation time was  $79.2 \pm 1.5$  days for all natural reference nests with known females ( $n = 33$ ) throughout the study period (Fig. 23). Incubation time for experimental plots and the open hatcheries were not included, but were used for shade comparisons (Chapter 2) and microenvironmental comparisons (Chapter 3). There was a significant difference among years in mean incubation time (ANOVA,  $F_{4,28} = 6.146$ ,  $P = 0.002$ ) with ranges in mean nest incubation time from  $72.2 \pm 3.2$  days in 2008 ( $n = 6$ ) to  $86.4 \pm 3.1$  days in 2007 ( $n = 8$ ).

There was no significant difference (ANOVA,  $F_{4,28} = 1.364$ ,  $P = 0.271$ ) in hatching success for all natural reference nests ( $55.7 \pm 5.8\%$ ;  $n = 33$ ) throughout the study (Fig. 24). There were significant differences in mean clutch hatchling carapace heights ( $14.28 \pm 0.10$  mm;  $n = 101$ ; ANOVA,  $F_{4,96} = 7.936$ ,  $P < 0.0001$ ) and mean clutch hatchling masses ( $5.80 \pm 0.08$  g;  $n = 101$ ; ANOVA,  $F_{4,96} = 3.130$ ,  $P = 0.018$ ) among years, but there were no differences in mean clutch carapace lengths ( $27.13 \pm 0.16$  mm), carapace widths ( $23.58 \pm 0.14$  mm) and plastron lengths ( $23.56 \pm 0.14$  mm) among years (Table 16). There was a significant regression of mean egg mass on mean hatchling mass ( $n = 89$ ;  $P < 0.0001$ ,  $F_{1,87} = 51.241$ ,  $r^2 = 0.376$ ).

### **Spizzle Creek Population**

Between 2005 and 2009, we captured 743 terrapins at Spizzle Creek. There were a greater number of female terrapins captured ( $n = 437$ ) compared to males ( $n = 236$ ) and juveniles ( $n = 70$ ; Table 17). There was a 1.88:1 female-bias in captures of terrapins for all five years. Of the total number of captures, genders were not determined for 13 terrapins, thus we did not include them in this study. Mark-recapture data using a POPAN Jolly-Seber population estimate indicated that the terrapin population at Spizzle Creek was  $1518 \pm 198$  (SE) with a 95% confidence level of 1216 to 2010 individuals (Table 10). Two terrapins captured at Spizzle Creek in 2007, were recaptured approximately 10 km from Spizzle Creek at the Edwin B. Forsythe Wildlife Refuge study site in 2009. In 2008, we captured only one terrapin using a trammel net early in the season. For all age-able terrapins ( $n = 481$ ), captures at Spizzle Creek included: juveniles ( $n = 70$ ); males ( $n = 147$ ) and females ( $n = 264$ ). The oldest age-able captured female terrapin was 15 years, and the oldest age-able captured male terrapin was 13 years. The youngest age-able captured female terrapins were four year sub-adults ( $n = 5$ ). The youngest age-able captured male terrapins were three year adult males ( $n = 7$ ). The greatest frequency of age-able captured male terrapins was five years ( $n = 40$ ) and the greatest frequency of age-able captured female terrapins was seven years ( $n = 59$ ; Fig. 25). There were 174 female terrapins and 88 male terrapins that we could not age. The mean plastron length for female terrapins ( $n = 440$ ) was  $156.3 \pm 1.2$  mm (range 82 – 196 mm); the mean plastron length for male terrapins ( $n = 233$ ) was  $99.5 \pm 0.6$  mm (range 82 – 124 mm); and the mean plastron length for juvenile terrapins ( $n = 70$ ) was  $94.9 \pm 1.5$  mm (range 62 – 119; Fig. 26). Mean mass for female terrapins was  $952 \pm 17.6$  g; the

mean mass for male terrapins was  $236 \pm 4.1$  g; and  $234 \pm 8.9$  g for juveniles. A regression of natural log of plastron length (mm) and natural log of mass (g) showed a significant relationship for juveniles ( $n = 70$ ;  $P < 0.0001$ ,  $F_{1,68} = 637.57$ ,  $r^2 = 0.904$ ), males ( $n = 233$ ;  $P < 0.0001$ ,  $F_{1,231} = 1312.91$ ,  $r^2 = 0.850$ ) and females ( $n = 440$ ;  $P < 0.0001$ ,  $F_{1,438} = 10906.74$ ,  $r^2 = 0.961$ ; Figs. 27A,B,C).

## DISCUSSION

### **Nesting population: North Sedge Island**

The nesting female population at N. Sedge Island was estimated at  $430 \pm 23$  female terrapins (Table 10). The parameters of capture effort and time were used to determine population estimates using POPAN Jolly-Seber model. The most likely model excluded time interval parameters and capture effort because all female terrapins were captured the same way, by hand, upon return to the water. Our 2005 female capture effort was approximately 60% of the capture effort for all other years, thus resulting in decreased captures (Table 9). There were declines in captures on the Island after the first two years (2002 and 2003) of the study (105 and 111 individuals respectively). The decline may be attributed to increased human activity on the Island since 2001 with more residential programming offered through the New Jersey Division of Fish and Wildlife (K. Leskie, personal communication). Female terrapins nested from late May through late July and nesting peaked in late June which was similar to nesting times at New Jersey (Fig. 12; Montevecchi and Burger 1975; Wood and Herlands 1997) and Maryland (Roosenburg 1991). We had one female terrapin land on the Island on May 29, 2008; however, no terrapins landed on the Island until June all other years. Peak nesting

frequency was in late June, which was consistent with terrapins in Maryland (Roosenburg 1992). Peak nesting frequency at 1200 h was consistent with Roosenburg (1994) in Maryland who had the most captures per hour between 1100 h and 1200h with peak activity between 1100 h to 1300 h. Our data indicated peak activity ranging from 1030 h to 1230 h, and 1330 h to 1500 h (Fig. 13). There was a decrease in nesting frequency at 1300 h, which may have been a result of increased human activity on the island during the early afternoon hours (pers. obs.). There has been an increase in the number of residential programs on the Island since 2001 with new groups reporting to the Island in the early afternoon, which may have accounted for the late morning nesting activity (J. Merritt, personal communication). Residential groups conduct an activity their second day at the Island which resulted in a day-long kayaking activity from 0900 h to 1500 h (J. Kelsey, personal communication). After 1600 h, groups regularly conducted a field collection activity along the shoreline where terrapins accessed nesting areas on the northwest part of the Island (J. Kelsey, personal communication). Residential groups departed the Island during the morning of their last day. Human activity may explain nesting frequency activity on the Island from 1030 h to 1500 h, which has been observed in other turtle species. Changes in time of nesting in *Graptemys flavimaculata* were correlated with human disturbance in Mississippi (Moore and Seigel 2006). Moll (1974) reported changes in nesting behavior in painted turtles, *Chrysemys picta belli*, in response to human interactions.

Clutch frequencies of up to three nests per year for terrapins at N. Sedge Island were similar to clutch frequencies for terrapins in Maryland and Florida (Siegel 1980b, Roosenburg 1992; Table 18). One terrapin, AHPW, oviposited eggs three times in 2008

(Fig. 22A). This was the only terrapin with three observed nests, but we captured numerous terrapins landing on the Island three times within the nesting season. Mean interclutch interval on the Island ( $19.4 \pm 1.0$  days) was approximately two days longer than the mean interclutch interval reported in Jamaica Bay, New York ( $17.5 \pm 1.39$  days; Feinberg and Burke 2003). The highest interclutch nest frequency ( $n = 5$ ) at N. Sedge Island occurred on day 16, which was similar to the highest interclutch frequency (15 days) that Roosenburg (1992) observed in the Patuxent River, Maryland (Fig. 14). Interclutch nesting ranged from 12 days ( $n = 2$ ) to 32 days ( $n = 1$ ) at N. Sedge Island, however it is not known if a nesting female oviposited eggs in another location (e.g., Island Beach State Park) between the first clutch and 32 days. There was variability in multiple clutches within a nesting season for terrapins, which may be a result of available food resources, energy acquisition and stored energy (in painted turtles, Congdon and Tinkle 1982; in freshwater turtles, Gibbons 1982; reviewed in Miller and Dinkelacker 2008).

Our data suggested that there are latitudinal geographical variations in mean plastron length (mm) in adult female terrapins with an increased mean plastron length in higher latitudes, which was found in *Chelydra serpentina* (Iverson 1992). The mean plastron length in Nuckum Hill, Rhode Island ( $41^{\circ} 46' N$ ,  $70^{\circ} 18' W$ ) was  $199.8 \pm 10.9$  mm SD ( $n = 85$ ), the mean plastron length in Jamaica Bay, New York ( $40^{\circ} 37' N$ ,  $73^{\circ} 50' W$ ) was  $172.9 \pm 8.6$  SD ( $n = 124$ ), which were greater than N. Sedge Island ( $172.7 \pm 0.8$  mm SE;  $n = 180$ ; Goodwin 1994; Feinberg 2000). N. Sedge Island ( $39^{\circ} 47' N$ ,  $74^{\circ} 07' W$ ) had a greater mean plastron length than Little Beach, New Jersey ( $39^{\circ} 29' N$ ,  $74^{\circ} 21' W$ ;  $154.4 \pm 9.9$  mm SD;  $n = 221$ ; Montevecchi and Burger 1975). The mean plastron

length of female terrapins at N. Sedge Island were smaller than adult female terrapins in the Patuxent River, Maryland (38° 30' N, 76° 41' W; 192.0 mm), but larger than female terrapins at Kiawah Island, South Carolina (32° 35' N, 80° 08' W; 157.0 ± 12.1 mm SD; n = 40) and Merrit Island, Florida (28° 35' N, 80° 40' W; 162.2 ± 8.7 mm SD; n = 378; Roosenburg 1990; Zimmerman 1992; Goodwin 1994; Butler 2002). The minimum plastron length for a nesting female on N. Sedge Island was 142 mm which was consistent with minimum mature female terrapin plastron length in South Carolina (138 mm; Lovich and Gibbons 1990). Plastron length varied regionally at Barnegat Bay with smaller nesting female terrapins captured at Little Beach compared to those at N. Sedge Island (one way ANOVA,  $F_{2,177} = 491.95$ ,  $P < 0.0001$ ). Little Beach is adjacent to the U.S. Fish and Wildlife Edwin B. Forsythe Refuge at Holgate, N.J., 35 km south of N. Sedge Island. Female terrapins in Maryland had a larger mean plastron length than female terrapins found at Little Beach, N. Sedge Island, and New York, which was different from the increase in body size with latitude in snapping turtles (Iverson 1992). Although the Maryland population is within the range of the northern-most sub-species of terrapin, *Malaclemys t. terrapin*, it is in the Chesapeake metapopulation (Hart 2005). The high productivity of the eutrophic Chesapeake Bay may support greater growth as seen in slider turtles in the Savannah River Plant in South Carolina (Gibbons 1990).

Female terrapins matured in Maryland at 1100 g between the ages of seven and 13 (Roosenburg 1996). At N. Sedge Island, an eight year old female, weighing 620 g reached sexual maturity, and two female terrapins aged six years were also sexually mature. We determined age using annual growth rings, which has been debated for accuracy in some studies (reviewed in Belzer and Seibert 2007). However, it remains an

effective practice used in determining age of turtles in the field (Germano 1998). Both plastron size and age class were similar to the minimum plastron length for mature female terrapins and the age class of new adult female terrapins (between ages six and seven) at the Kiawah River, South Carolina (Lovich and Gibbons 1990).

### **Clutch size and egg morphometrics**

Geographic clutch and egg morphometric comparisons were made for terrapin eggs from Rhode Island to Florida (Table 18). There was a general decrease in mean clutch size from the north to the south, but there were geographic variations in clutch size in New York ( $10.9 \pm 3.9$  SD) and Maryland ( $12.3 \pm 0.1$  SE; Roosenburg and Dunham 1996; Feinberg and Burke 2003; Fig.28). Among geographic regions, there could be variations in clutch size in turtles (reviewed in Miller and Dinkelacker 2008). In New York, mean clutch sizes were 11.6 (Giovanni 2002) and 10.9 (Feinberg and Burke 2003). At N. Sedge Island, there was a mean clutch size of  $12.9 \pm 0.8$  (SE) which differed from  $9.7 \pm 2.6$  (SD) at Little Beach, New Jersey (Montevecchi and Burger 1975). Although the study at Little Beach took place in 1973 and 1974, temporal variations may not account for the change in clutch size. Larger turtles tend to produce larger clutch sizes than smaller turtles within the same species (reviewed in Miller and Dinkelacker 2008). The smaller mean plastron body size of female terrapins at Little Beach ( $154.5 \pm 9.9$  SD) compared with the larger mean plastron body size of female terrapins at N. Sedge Island ( $172.7 \pm 0.8$  SE) may have resulted in lower clutch sizes at Little Beach (Montevecchi and Burger 1975). At Barnegat Bay, NJ, mean clutch size variations were observed in a landscape study of terrapins captured in different geographical locations within the Bay (Sheridan, personal communication). Mean clutch size variations were also observed in

the Patuxent River, Maryland (Roosenburg 1990). Among geographical locations, a regression of mean female plastron length (mm) and mean clutch size showed a significant correlation from Florida to Rhode Island ( $P = 0.015$ ;  $F_{1,5} = 13.288$ ,  $r^2 = 0.728$ ; Fig. 29). This supported Moll (1979) who found that clutch size increases with body size within turtle species (reviewed in Miller and Dinkelacker 2008). This may account for the mean female plastron size and mean clutch size in the Patuxent, Maryland population and may explain variations in clutch size between this study and Little Beach. Iverson et al. (1997) found variations in female body size and egg sizes locally and regionally for *Chelydra serpentina*, however there was a positive latitudinal correlation for reproductive traits.

There is a general decrease in terrapin egg mass and egg length from the south to the north, which is also reported in snapping turtles (Iverson et al. 1993). Terrapin egg masses and egg lengths in the south (Florida,  $12.5 \pm 0.7$  g SD,  $39.0 \pm 1.3$  mm SD; Seigel 1980b) were greater than terrapin egg masses and egg lengths in the north (this study,  $8.1 \pm 0.1$  g SE,  $31.8 \pm 0.1$  mm SE; Table 18). Although our data compared with Florida show this, there still needs to be more research on reproductive output in the northern range of terrapins. Also, with geographic variations in clutch size and egg size, some components of the Optimal Egg Size (OES) Theory may be supported by female terrapin reproductive output. First, larger eggs are produced with smaller clutch sizes in lower latitudes, which is a tradeoff between egg size and amount. Second, the amount of available resources provides a greater variation in clutch size than variation in egg mass in female terrapins (Roosenburg and Dunham 1997). This may be the case with nesting terrapin populations in both Maryland and this study. There is a balance in reproductive

output with fitness of the female (Smith and Fretwell 1974). The assumption is that changes in reproductive investment result in changes in clutch size, rather than changes in egg size (Hendry et al. 2001). There are geographical variations in clutch sizes in terrapins and there is a strong correlation between egg mass and female body sizes across their range.

### **Hatching and hatchling morphometrics**

There was a significant difference in mean incubation time in reference nests among years (Fig. 23). Mean incubation time in 2007 ( $86.4 \pm 2.9$  days) was significantly higher than the mean incubation time in 2008 ( $72.2 \pm 2.3$  days) and 2005 ( $74.0 \pm 0.6$  days). In 2005 and 2008, mean monthly air temperatures were warmer than those of 2007 in both June and July, which accounts for the longer incubation period in 2007 (Fig. 30). Prior studies show that cooler temperatures may result in longer incubation times for turtles (snapping turtles Packard and Packard 1987; Jeyasuria et al. 1994; Roosenburg and Kelley 1996). In 2009, mean summer monthly temperatures were lower than those in 2007 and there was a shorter incubation time ( $80.3 \pm 2.2$  days) than in 2007. However, temperatures in August 2009 were higher than those in August 2007, which may account for the shorter incubation time in 2009. In 2006, the nesting season started later in June than in other years and may account for the similar incubation time in 2009. This coupled with cooler temperatures in September may have caused a similar incubation time for 2006 ( $81.3 \pm 0.7$  days) and 2009. Despite a significant difference in incubation time among years, there was no significant difference in the hatching success in reference nests among years ( $n = 33$ ;  $55.7 \pm 5.8\%$ ; Fig. 24). All reference nests had protective

covers to prevent mammalian and avian predation to determine hatching success for a manipulative study (Chapter 2, Chapter 3). However, compared to non-predated nests in northern Florida (1997, 28.6%, n = 26; 2000, 16.1%, n = 18) we had a higher hatch success, although hatching success in Florida may have been reduced by microenvironmental nest conditions (e.g., nest temperatures, moisture) that were not reported in the Florida study (Butler 2002).

Hatchling morphometric data from N. Sedge Island indicated a significant correlation between egg mass and hatchling mass, which indicated that maternal effects played a strong role in terrapin hatchling mass. Larger eggs produce larger hatchlings (Brook et al. 1991; Spotila et al. 1992; Roosenburg and Kelley 1996).

### **Spizzle Creek Population**

Population estimates of all terrapins captured between 2005 and 2007 were 1518 terrapins with a 95% confidence between 1216 and 2010. In comparison, Roosenburg (1990) conducted a Jolly-Seber population estimate in the Patuxent River, Maryland, in a larger study area, where he determined that there were 2293 individuals with 95% confidence between 1717 and 2895. Roosenburg (1990) concluded that error in his population estimates may have been a result of increased trapping effort each year of his study. The Jolly-Seber model is recognized for open populations assuming a similar spatial and temporal trapping effort for all individuals in the population (Schwarz 2000). We only used the first three years of capture data as a result of a decreased capture effort in 2008 and 2009 (Table 17). The capture effort from 2005 to 2007 was consistent, employing the same method of capture within Spizzle Creek. Butler (2002) only included capture methods that discounted sex-biased captures when calculating

populations in Florida (e.g., hand captures that were female biased). Gibbons et al. (2001) captured terrapins using seine nets and trammel nets in South Carolina. Our attempts to capture terrapins using seine nets and a trammel net at Spizzle Creek were not successful (one capture in several attempts). Therefore, the use of hoop traps proved most successful. However, additional trapping seasons should improve population estimates since three years is a minimal amount of time to conduct a population estimate (Roosenburg 1990). The Spizzle Creek population had a 1.88:1 female-biased population. Female-bias was also observed in Maryland (2:1; Roosenburg et al. 1997), but there was male-bias in Florida (1:1.39; Butler 2002) and South Carolina (1:1.78; Lovich and Gibbons). Regional differences may be attributed to gender mortality bias. In Maryland, male terrapins showed a greater mortality as a result of crab fisheries (Roosenburg 1990; Roosenburg et al. 1997). In New Jersey, female-biased mortality is a result of road mortality during nesting season and drowning in crab pots (Wood 1997; Wood and Herlands 1997; Szerlag and McRobert 2006). The female terrapin capture bias at Spizzle Creek may be a result of the capture area being adjacent to Island Beach State Park, which is a nesting area for terrapins (pers. obs.). Spizzle Creek and North Sedge Island fall within a Marine Conservation Zone (MCZ) designated in 2001 that limits human activities (NJSJR 2001). As a MCZ, there is limited commercial activity including no commercial-style crab pots. Prior to the designation as a MCZ, the area was difficult to access by boat because of frequent shoals, and access from Island Beach State Park was infrequent as result of a long walk (500 m) through maritime forest with a high density of seasonal insects. Spizzle Creek had a high density of terrapins during nesting season, but there was a reduced density after nesting season ended in mid-July. Female

terrapins may be using Spizzle Creek as a mating aggregation area. Although we marked 437 females at Spizzle Creek, we recaptured only five marked animals at N. Sedge Island. Therefore, females in Spizzle Creek may be nesting on Island Beach State Park in open areas that have warmer nest temperatures ( $> 29^{\circ}\text{C}$ ) that favor female gender development (Burger 1977; Roosenburg 1992; Roosenburg 1996).

Our results indicate that there are regional variations in terrapin body sizes, terrapin egg sizes and clutch sizes in New Jersey. We also determined that female terrapins can reach sexual maturity at age six. Resources within N. Sedge Island and Spizzle Creek may be greater as a result of the area being within a marine conservation zone. This study also suggests that human activity at N. Sedge Island has a negative impact on nesting of female terrapins. Female terrapins nest more frequently during times on the island when there is less human activity. Our results indicate that mean clutch sizes are most similar to Patuxent River, Maryland than are similar to other regional locations. Barnegat Bay is a highly eutrophic estuarine ecosystem, which may be more like the Patuxent River, thus higher available resources for terrapins in both locations. Resource availability in the Sedge Island- Island Beach State Park Marine Conservation Zone may be to the reason why female terrapin body sizes are larger and clutch sizes are larger than at Little Beach, New Jersey.

**Table 9.** Mark and recapture data of female terrapins landing on N. Sedge Island, Barnegat Bay, New Jersey from 2002 through 2009.

Year	No. New Females Captured Nesting	No. Females Recaptured Nesting Same Season	No. Nesting Females Recaptured from Previous Year(s)	Total No. Nesting Females Observed
2002	104	1	—	105
2003	67	6	38	111
2004	40	0	59	99
2005	16	1	39	55
2006	42	7	40	82
2007	27	8	69	86
2008	17	4*	50	67
2009	21	9	58	79

\*denotes one female terrapin (notch code AHPW) returned to nest two additional times within the same season

**Table 10.** Results of the POPAN Jolly-Seber population model for the mark-recapture study at N. Sedge Island (2002 - 2009) and Spizzle Creek (2005 – 2007). Highlighted rows produced the most likely population estimates. N. Sedge Island data included results for a  $\hat{c}$ -hat=2.48 for female terrapins captured by hand. Both time and capture effort parameters did not affect the population estimate thus  $p(\cdot)\text{phi}(\cdot)$  was the best fit. Spizzle Creek data were run for the first three years of the study. Captured terrapins during 2008 and 2009 were not included in the model due to the limited trapping effort compared with the first three years of the study (one week and two weeks respectively). Capture effort and time  $p(0)\text{phi}(0)$  produced the best population estimate.

Sedge Island Population Estimate						95 % Confidence			
Model	QAICc	Delta QAICc	QAICc Weight	Model Likelihood	No. Para.	Estimate	SE	Lower Case	Upper Case
$p(\cdot)\text{phi}(\cdot)$	615.767	0.000	0.765	1.000	10	430.483	23.368	384.681	476.285
$p(\cdot)\text{phi}(t)$	618.208	2.440	0.226	0.295	16	398.860	17.955	363.669	434.051
$p(0)\text{phi}(\cdot)$	625.555	9.788	0.005	0.008	15	431.738	24.101	384.502	478.975
$p(t)\text{phi}(t)$	626.908	11.141	0.003	0.004	22	387.615	18.310	351.727	423.503
Spizzle Creek Population Estimate						95 % Confidence			
Model	AICc	Delta AICc	AICc Weight	Model Likelihood	No. Para.	Estimate	SE	Lower Case	Upper Case
$p(t)\text{phi}(t)$	377.102	0.000	0.988	1.000	7	1518.232	197.884	1215.528	2009.658
$p(\cdot)\text{phi}(t)$	385.986	8.884	0.012	0.012	6	3119.546	516.613	2301.746	4362.859
$p(t)\text{phi}(\cdot)$	393.598	16.497	0.000	0.000	5	3496.028	529.932	2636.526	4743.012
$p(\cdot)\text{phi}(\cdot)$	433.197	56.096	0.000	0.000	4	2758.495	363.325	2161.904	3603.651

**Table 11.** Nesting female morphometric data from N. Sedge Island for 2005 to 2009 (n = 180). All data are reported as mean  $\pm$  1SE.

Measurement	Mean	Minimum	Maximum
Straight Carapace Length (mm)	190.3 $\pm$ 1.0	154.0	230.0
Plastron Length (mm)	172.7 $\pm$ 0.8	142.0	196.0
Carapace Width (mm)	148.1 $\pm$ 0.9	68.0	97.0
Carapace Height (mm)	80.2 $\pm$ 0.6	125.0	185.0
Mass (g)	1176.9 $\pm$ 16.5	610.0	1821.0

**Table 12.** Overall statistics of *in situ* clutch size variation among five years of the study that clutch assessments were conducted. ANOVA found no significant differences in clutch size among the five years of the study.

Year	N	Mean $\pm$ S.E.	Minimum #Eggs	Maximum #Eggs
2005	11	11.2 $\pm$ 1.3	3	16
2006	35	12.2 $\pm$ 0.5	7	17
2007	41	12.5 $\pm$ 0.4	5	16
2008	33	13.5 $\pm$ 0.4	8	19
2009	57	12.5 $\pm$ 0.4	2	18
Total	177	12.6 $\pm$ 0.2	2	19

**Table 13.** Comparison of mean clutch egg mass and mean clutch egg length (mean  $\pm$  1 SE) among years at N. Sedge Island. ANOVA found no significant difference amongst years for mean clutch egg mass and mean clutch egg length.

Year	No. clutches	Mean clutch egg mass (g)	Mean egg mass range (g)	Mean clutch egg length (mm)	Mean egg length range (g)
2005	9	8.29 $\pm$ 0.39	6.36 – 9.80	32.49 $\pm$ 0.53	29.69 – 35.08
2006	28	8.25 $\pm$ 0.18	6.45 – 10.00	31.49 $\pm$ 0.31	28.77 – 34.99
2007	37	7.84 $\pm$ 0.17	6.13 – 9.83	31.56 $\pm$ 0.24	28.81 – 35.30
2008	32	8.00 $\pm$ 0.17	6.18 – 10.17	31.61 $\pm$ 0.26	29.13 – 34.47
2009	47	8.38 $\pm$ 0.12	6.50 – 10.02	32.15 $\pm$ 0.25	28.79 – 36.05
Total	153	8.14 $\pm$ 0.08	6.13 – 10.17	31.80 $\pm$ 0.13	28.77 – 36.05

**Table 14.** Comparison of mean egg masses and mean egg lengths among years at N. Sedge Island found a significant difference among years for mean egg mass ( $F_{4,1902}=11.70$ ,  $P < 0.0001$ ) and mean egg length ( $F_{4,1902}=22.75$ ,  $P < 0.0001$ ). A Ryan-Einot Gabriel Welsch post hoc test was used to group similar mean egg masses and mean egg length among years (A) or (B).

Year	No. Eggs	Mean egg mass (g)	Range (g)	Mean egg length (mm)	Range (mm)
2005	58	8.33 ± 0.14( <b>B</b> )	5.90 – 11.00	32.70 ± 0.23( <b>B</b> )	28.80 – 36.62
2006	354	8.31 ± 0.06( <b>B</b> )	6.00 – 10.50	31.64 ± 0.08( <b>A</b> )	27.24 – 36.70
2007	475	7.85 ± 0.05( <b>A</b> )	4.40 – 10.70	31.55 ± 0.08( <b>A</b> )	24.98 – 37.24
2008	440	8.01 ± 0.05( <b>A</b> )	5.70 – 12.50	31.68 ± 0.09( <b>A</b> )	26.70 – 40.26
2009	580	8.42 ± 0.04( <b>B</b> )	5.30 – 15.30	32.14 ± 0.09( <b>B</b> )	25.00 – 45.50
Total	1907	8.16 ± 0.02	4.40 – 15.30	31.81 ± 0.04	24.98 – 45.50

**Table 15.** Comparison of differences in egg mass and egg length for returning female terrapins within and between nesting seasons terrapins at N. Sedge Island using a Bonferroni post hoc analysis ( $P < 0.05$ ). Encounters are the number of landings within years and number of years a female terrapin came up to nest between years. NS indicates no-significant difference (numbers in parentheses indicate number of times significance was measured for that measurement).

Female Code	Encounters		Within Years		Between Years	
	Within Year	Between Years	Egg Mass	Egg Length	Egg Mass	Egg Length
ABHW	2(2008)	2(2008-2009)	NS	NS	NS	NS
ACIW	2(2007)	2(2007-2008)	P<0.0001	NS	P<0.0001	NS
AHPW	3(2008) 2(2009)	3(2007-2009)	NS P<0.0001	NS NS	P<0.05	P<0.0001
AIPW	2(2008)	3(2007-2009)	NS	NS	NS	P<0.05
AIPW2	2(2008)	2(2008-2009)	NS	NS	NS	NS
AJNW	2(2009)	-	NS	P<0.0001	-	-
AKOW	2(2009)	3(2006-2009)	NS	NS	NS	NS
AKQW	2(2009)	3(2006-2009)	NS	NS	NS	NS
AKVW	-	2(2006-2009)	-	-	NS	NS
AOVW	-	2(2007-2009)	-	-	NS	NS
APQW	-	3(2006-2008)	-	-	NS	NS
AQVW	2(2008) 2(2009)	2(2008-2009)	P<0.001	NS	NS	P<0.05(2)
BCHO	-	2(2007-2008)	-	-	P<0.0001	NS
BCHW	2(2009)	4(2006-2009)	NS	NS	NS	NS
BCIO	-	2(2008-2009)	-	-	NS	NS
BCPW	-	2(2006-2007)	-	-	NS	NS
BCPWX	-	2(2008-2009)	-	-	NS	NS
BCQW	2(2009)	2(2007-2009)	NS	NS	NS	NS
BHIO	2(2007)	3(2007-2009)	NS	NS	NS	P<0.01(2)
BIJN	2(2009)	-	NS	NS	-	-
BIKO	2(2009)	-	P<0.05	P<0.001	-	-
CHNO	-	2(2007-2008)	-	-	NS	NS
HPX	-	2(2006-2007)	-	-	NS	NS
JKW	-	2(2008-2009)	-	-	NS	NS

**Table 16.** Mean clutch hatchling morphometrics for carapace length, carapace width, carapace height, plastron length and mass ( $\pm$  1SE) among years at N. Sedge Island (n = 101). ANOVA found a significant difference among years in hatchling carapace height ( $F_{4,96} = 7.936$ ,  $P < 0.0001$ ) and mass ( $F_{4,96} = 3.130$ ,  $P = 0.018$ ). A Bonferroni post hoc analysis ( $P < 0.05$ ) was used to determine significant differences between years indicated by the letters. The same letters indicate no significant difference ( $P > 0.05$ ) between years. Carapace length, carapace width and plastron length had no significant measurement differences.

Year	N	Carapace length (mm)	Carapace width (mm)	Carapace height (mm)	Plastron length (mm)	Mass (g)
2005	4	28.02 $\pm$ 1.10	23.89 $\pm$ 0.97	15.54 $\pm$ 0.58 (A)	24.18 $\pm$ 1.11	5.82 $\pm$ 0.47 (D,E)
2006	9	26.53 $\pm$ 0.34	23.07 $\pm$ 0.26	15.15 $\pm$ 0.15 (A)	22.74 $\pm$ 0.29	5.15 $\pm$ 0.15 (E)
2007	34	26.61 $\pm$ 0.31	23.16 $\pm$ 0.26	13.79 $\pm$ 0.13 (B,C)	23.04 $\pm$ 0.26	5.62 $\pm$ 0.15 (D,E)
2008	21	27.83 $\pm$ 0.33	24.48 $\pm$ 0.24	14.59 $\pm$ 0.12 (A,C)	24.02 $\pm$ 0.28	6.01 $\pm$ 0.18 (D,E)
2009	33	27.28 $\pm$ 0.23	23.53 $\pm$ 0.22	14.20 $\pm$ 0.19 (B,C)	23.95 $\pm$ 0.20	6.02 $\pm$ 0.12 (D)
Total	101	27.13 $\pm$ 0.16 (21.21-30.92)	23.58 $\pm$ 0.14 (19.47-27.00)	14.28 $\pm$ 0.10 (9.71-17.07)	23.56 $\pm$ 0.14 (19.49-27.05)	5.80 $\pm$ 0.08 (3.93-7.45)

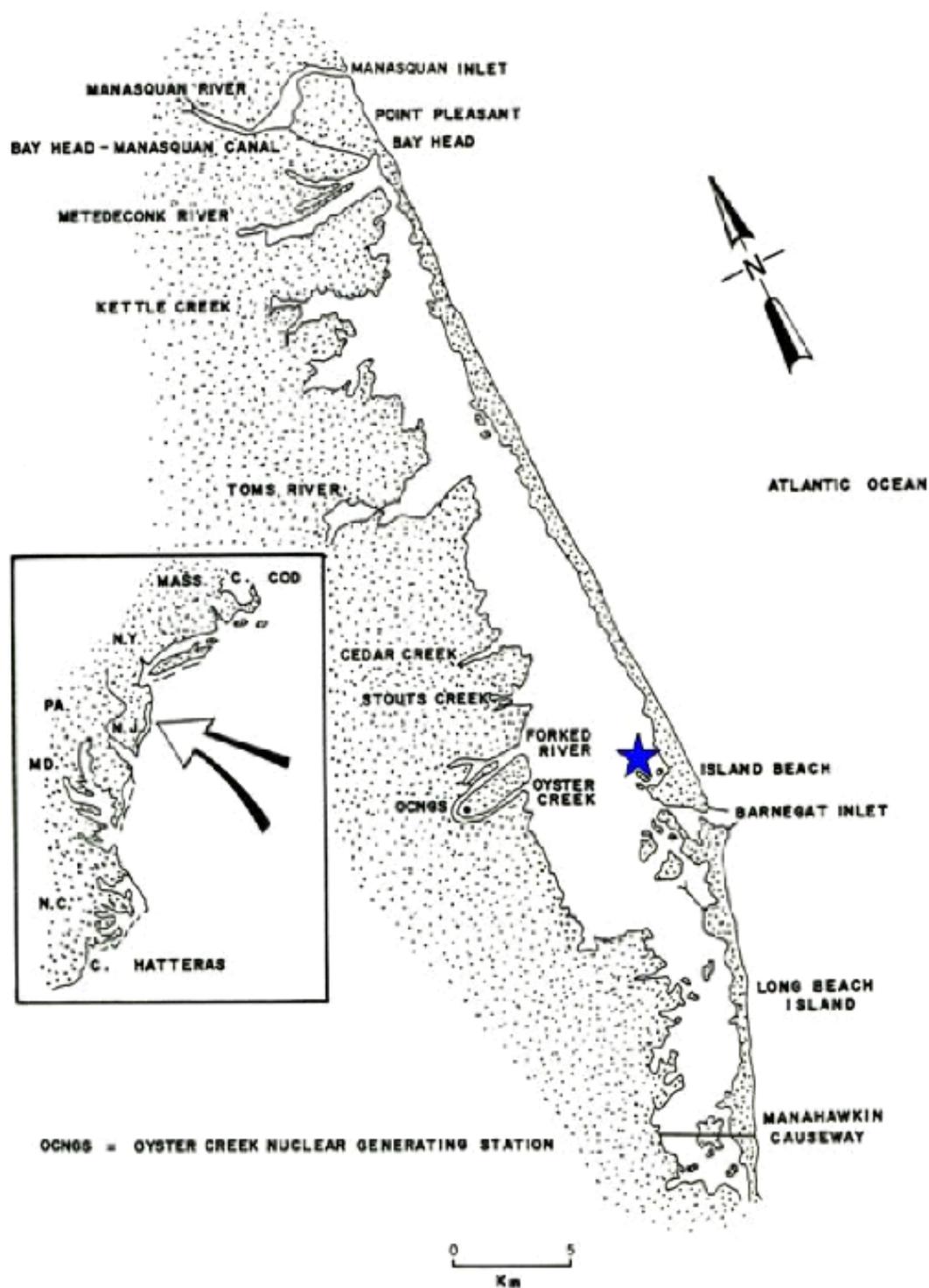
**Table 17.** Spizzle Creek capture data from 2005 to 2009 for all terrapin captures (n = 743). There were 13 terrapins captured at Spizzle Creek without a sex determination, thus not included. Data are reported in number of terrapins captured. A ratio of female to male capture was included. The 2008 and 2009 data were included, but the capture effort was significantly less than that from 2005 to 2007.

Year	New Captures				F:M	Recaptures			
	Males	Females	Juv.	Total		Males	Females	Juv.	Total
2005	130	251	46	427	1.93	0	1*	0	1
2006	46	54	3	103	1.17	4	1	1	6
2007	57	120	20	197	2.11	10	0	3	13
2008	0	1	1	2	-	0	27	1	28
2009	3	11	0	14	3.67	1	3	1	5
Total	236	437	70	743	1.85	15	32	6	53

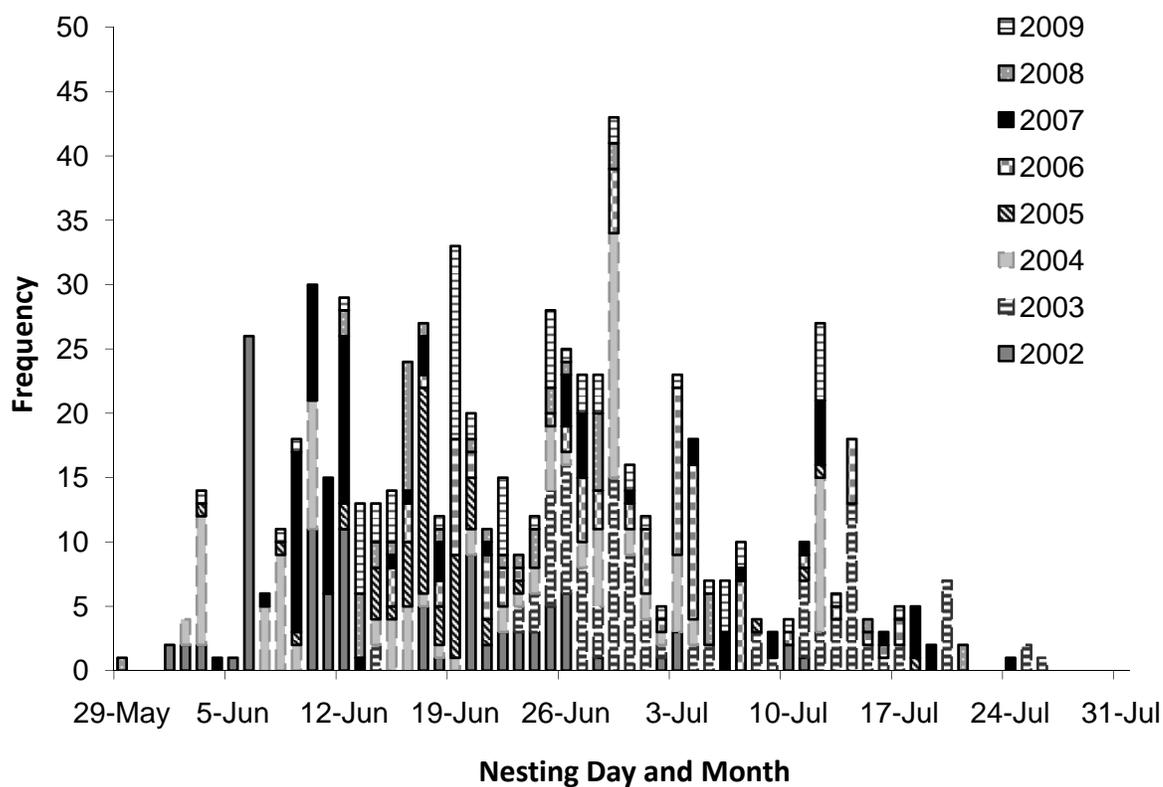
\* Female terrapin captured at N. Sedge Island and recaptured at Spizzle Creek.

**Table 18.** Geographical nest morphometric analyses representative of terrapins from their southern to northern distribution including latitude and longitude. Mean egg mass ( $\pm 0.1$  g) and mean egg length ( $\pm 0.1$  mm) were determined by using the mean egg clutch mass and mean egg clutch length over the five years of our study at N. Sedge Island. N is the clutch number assessed.

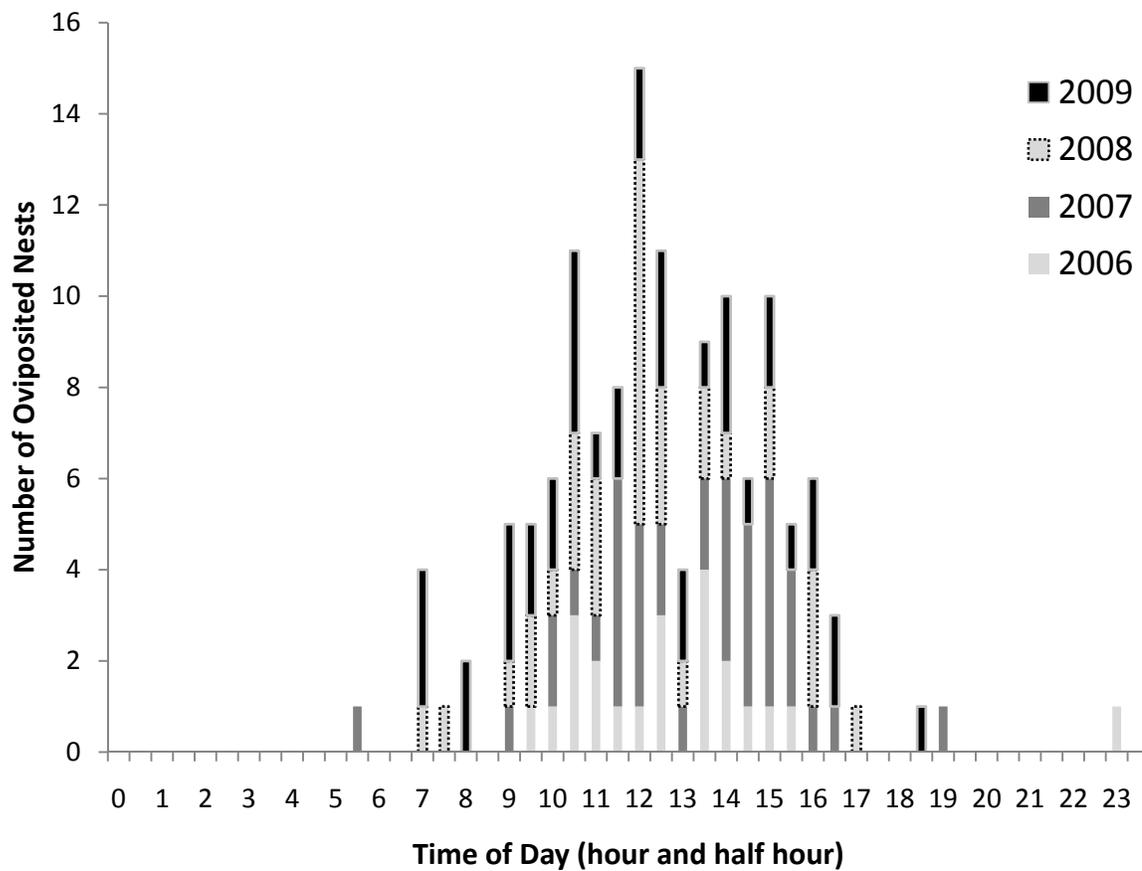
Location	N	Clutch Size (range)	Mean Egg Mass (g)	Mean Egg Length (mm)	Reference
Florida Lat. 28° 35' N Long. 80° 40' W	14	6.7 $\pm$ 1.4 SD (5 - 10)	12.5 $\pm$ 0.7 SD (n=31 eggs)	39.0 $\pm$ 1.3 SD	Seigel 1980b
South Carolina Lat. 32° 35' N Long. 80° 08' W	14	6.5 $\pm$ 1.5 SD (4 - 9)	11.2 $\pm$ 0.8 SD (n=48 eggs)	36.9 $\pm$ 2.3 SD	Zimmerman 1992
Maryland Lat. 38° 30' N Long. 76° 41' W	504	12.3 $\pm$ 0.1 SE (5 - 22)	9.8 $\pm$ 0.04 SE (n=270 clutch)	-	Roosenburg & Dunham 1997
New Jersey (Little Beach) Lat. 39° 29' N Long. 74° 21' W	40	9.7 $\pm$ 2.6 SD (4 - 18)	7.7 $\pm$ 1.1 SD (n=300 eggs)	31.7 $\pm$ 1.8 SD	Montevecchi & Burger 1975, Burger 1977
<b>New Jersey (N. Sedge Island)</b> Lat. 39° 47' N Long. 74° 07' W	<b>177</b>	<b>12.6 <math>\pm</math> 0.2 SE (2 - 19)</b>	<b>8.1 <math>\pm</math> 0.1 SE (n=1907 eggs)</b>	<b>31.8 <math>\pm</math> 0.1 SE</b>	<b>This Study</b>
New York Lat. 40° 37' N Long. 73° 50' W	45	10.9 $\pm$ 3.9 SD (3 - 18)	NR	NR	Feinberg & Burke 2003
Rhode Island Lat. 41° 46' N Long. 70° 18' W	20	15.8 $\pm$ 3.6 SD (2 - 21)	NR	32.1 $\pm$ 0.19 SD (n=36 eggs)	Goodwin 1994



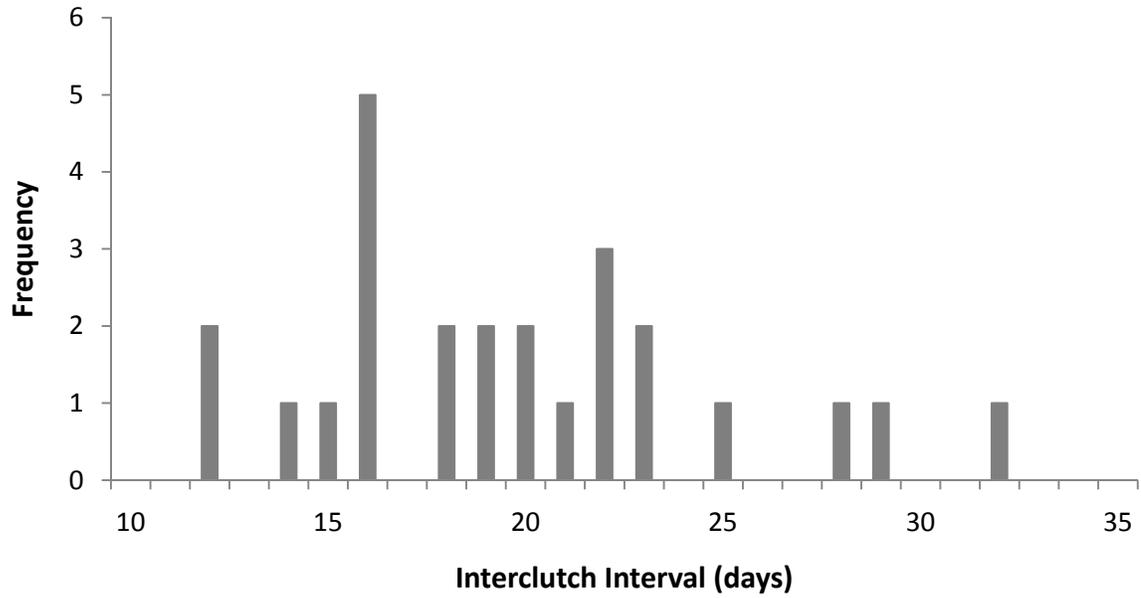
**Figure 11.** Map of North Sedge Island and Island Beach State Park at Barnegat Bay, N.J. USA (Latitude  $39^{\circ}47'48''$  N, Longitude  $074^{\circ}07'07''$  W). Map courtesy of Dr. Michael Kennish, Rutgers University, New Jersey, USA.



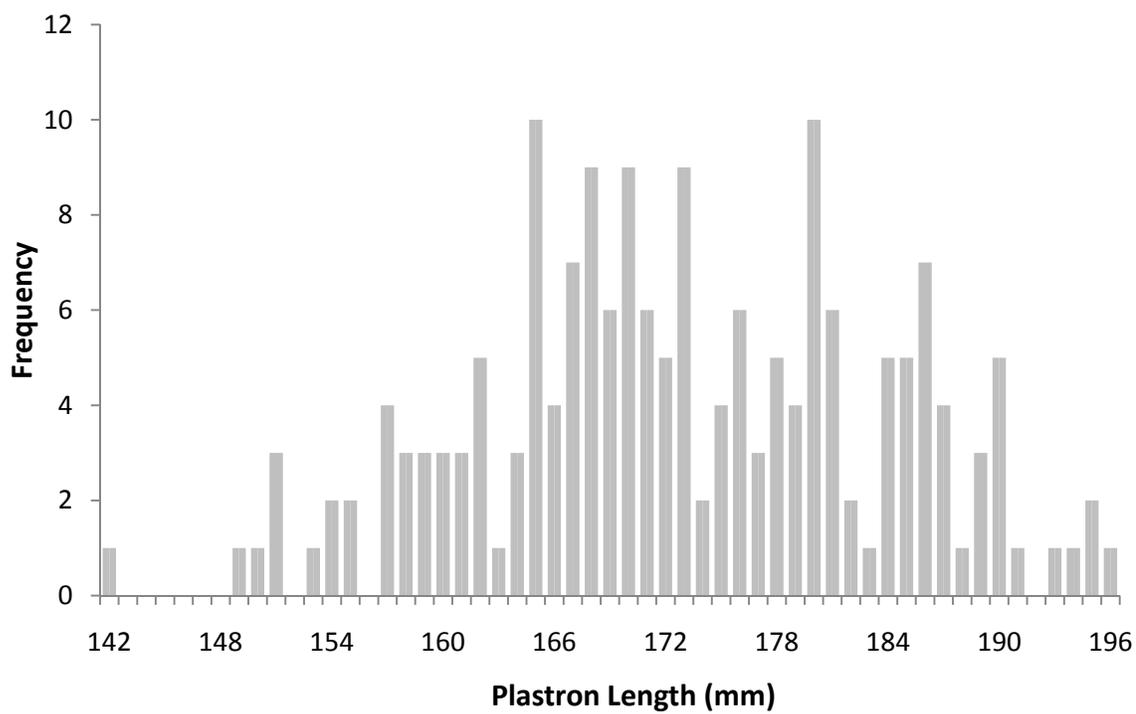
**Figure 12.** Day and month for the frequency of nesting female terrapins at N. Sedge Island throughout the eight years of mark and recapture efforts. The earliest day of an oviposited nest was on 29-May and the latest day of an oviposited nest was on 27-July. The highest frequency of nesting was on 29-June.



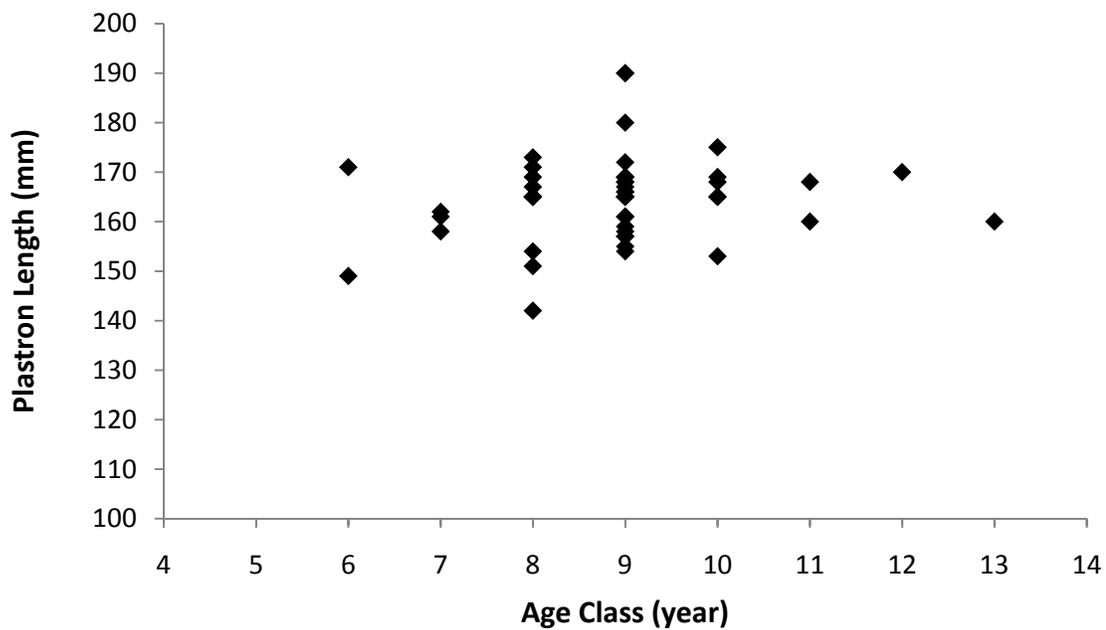
**Figure 13.** Time of nesting (hour and half hour increments) EDT at North Sedge Island from 2006 to 2009.



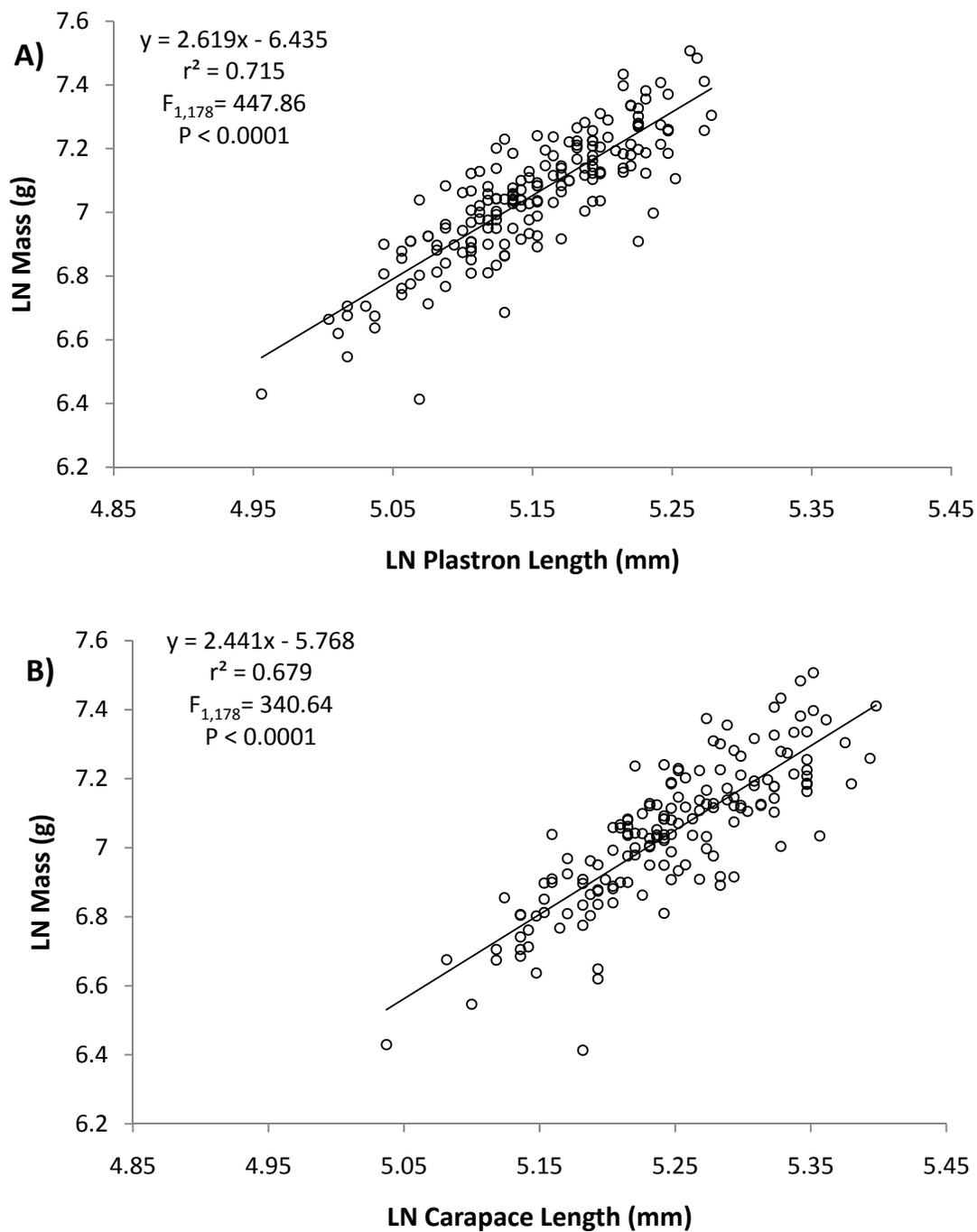
**Figure 14.** Frequency of nesting females ( $n = 25$ ) and interclutch intervals (days) for five years of the study at North Sedge Island. Interclutch nesting frequencies ranged from 12 days to 33 days. Our data were collected for returning females with known nests.



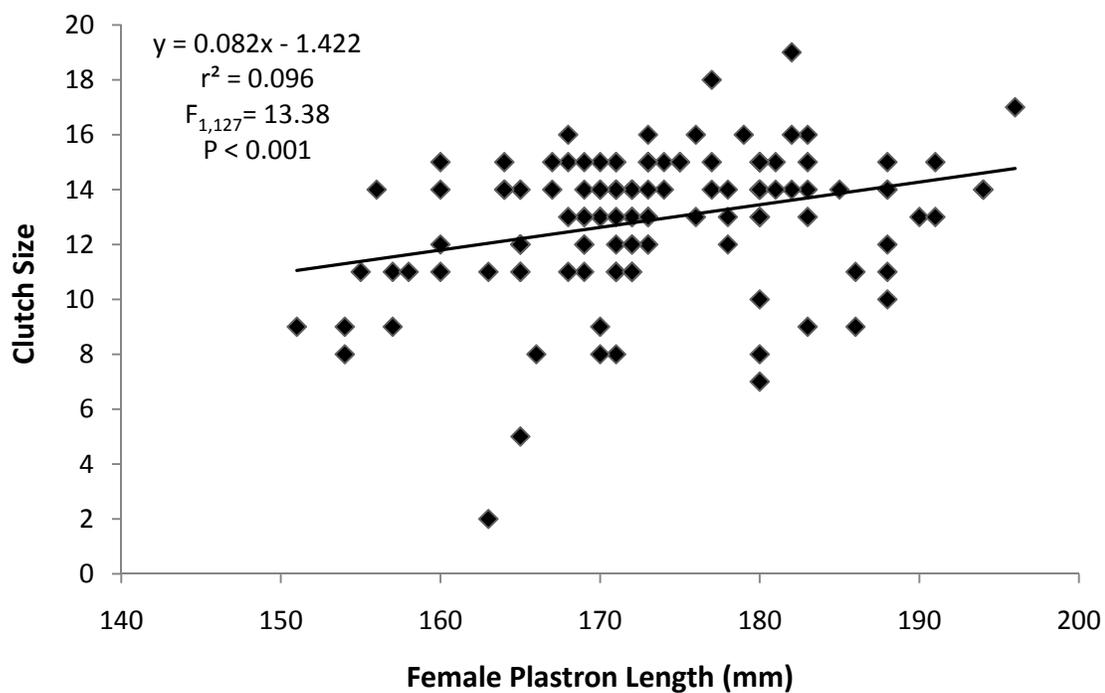
**Figure 15.** Plastron length (mm) distribution of nesting female terrapins at N. Sedge Island (n=180) from 2005 – 2009. The mean plastron length of female terrapins was  $172.7 \pm 0.81$  mm.



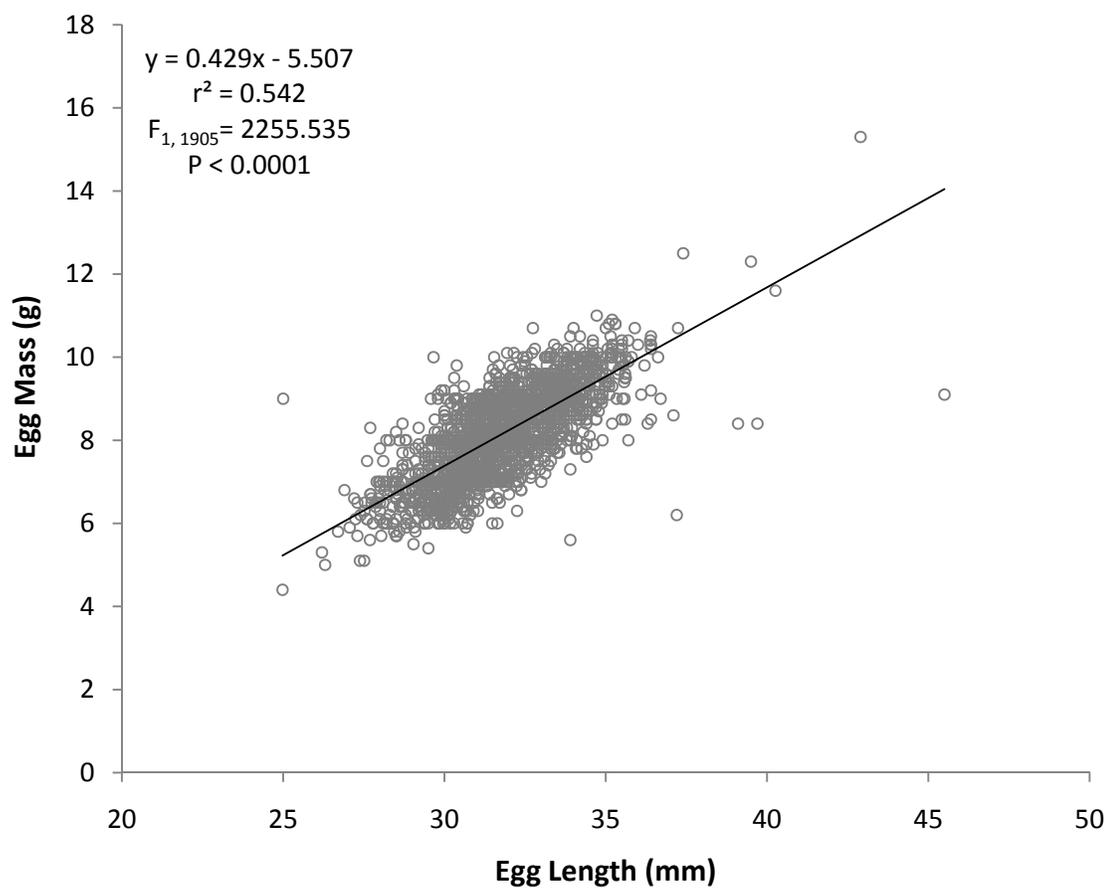
**Figure 16.** Nesting female plastron length (mm) designation by age class at N. Sedge Island for all aged females (n = 49) throughout the study period (2002-2009).



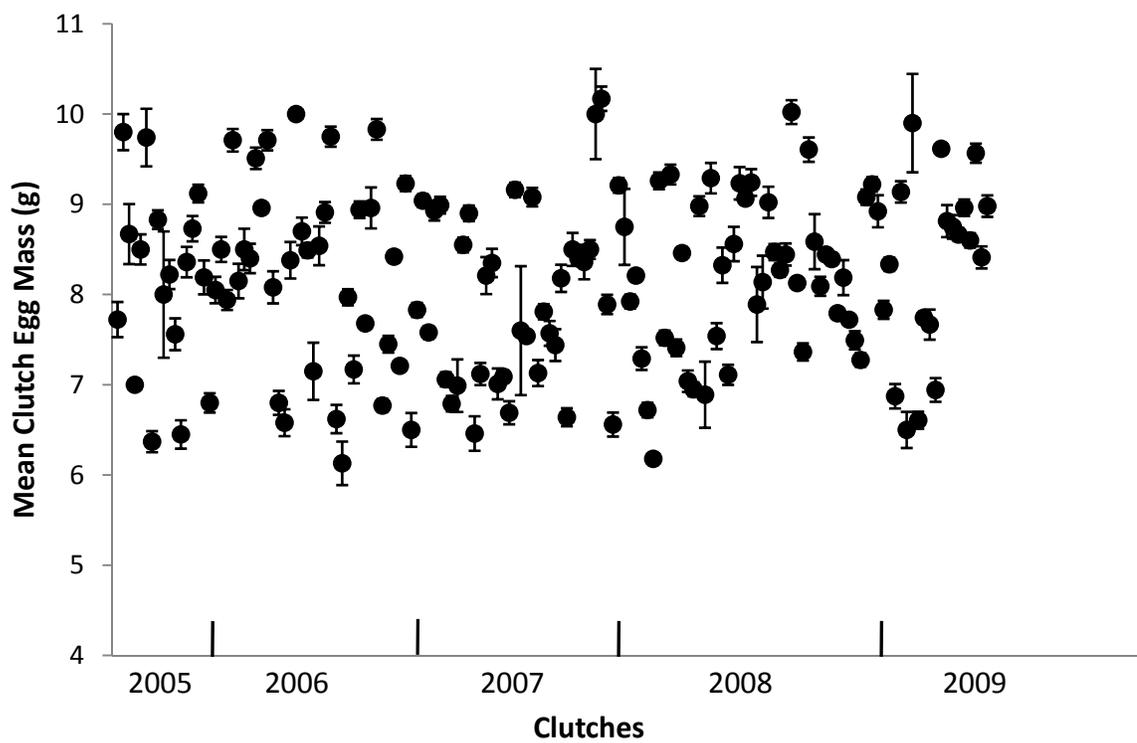
**Figure 17.** **A)** Regression of (LN) plastron length (mm) versus (LN) mass (g) at N. Sedge Island from 2002 – 2009; and **B)** Linear regression of the natural log (LN) transformation of straight-line carapace length (mm) versus LN mass (g) for nesting females ( $n = 180$ ).



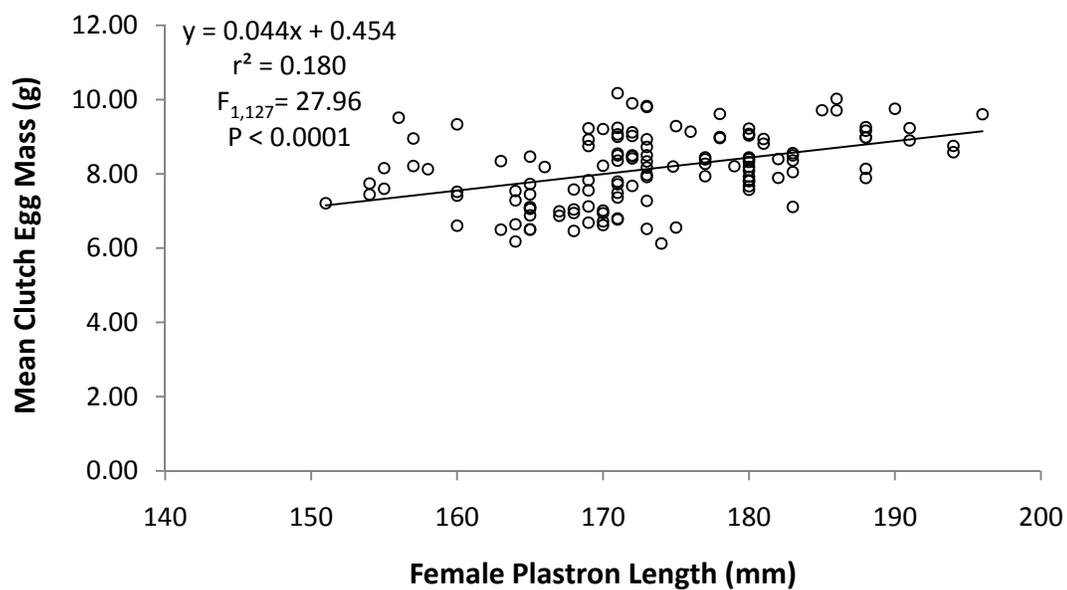
**Figure 18.** Regression of female plastron length (mm) and clutch size for nesting females at N. Sedge Island (n = 129) using linear regression ( $P < 0.001$ ;  $r^2 = 0.096$ ). Clutch sizes ranged from 2 to 19 eggs from 2005 to 2009.



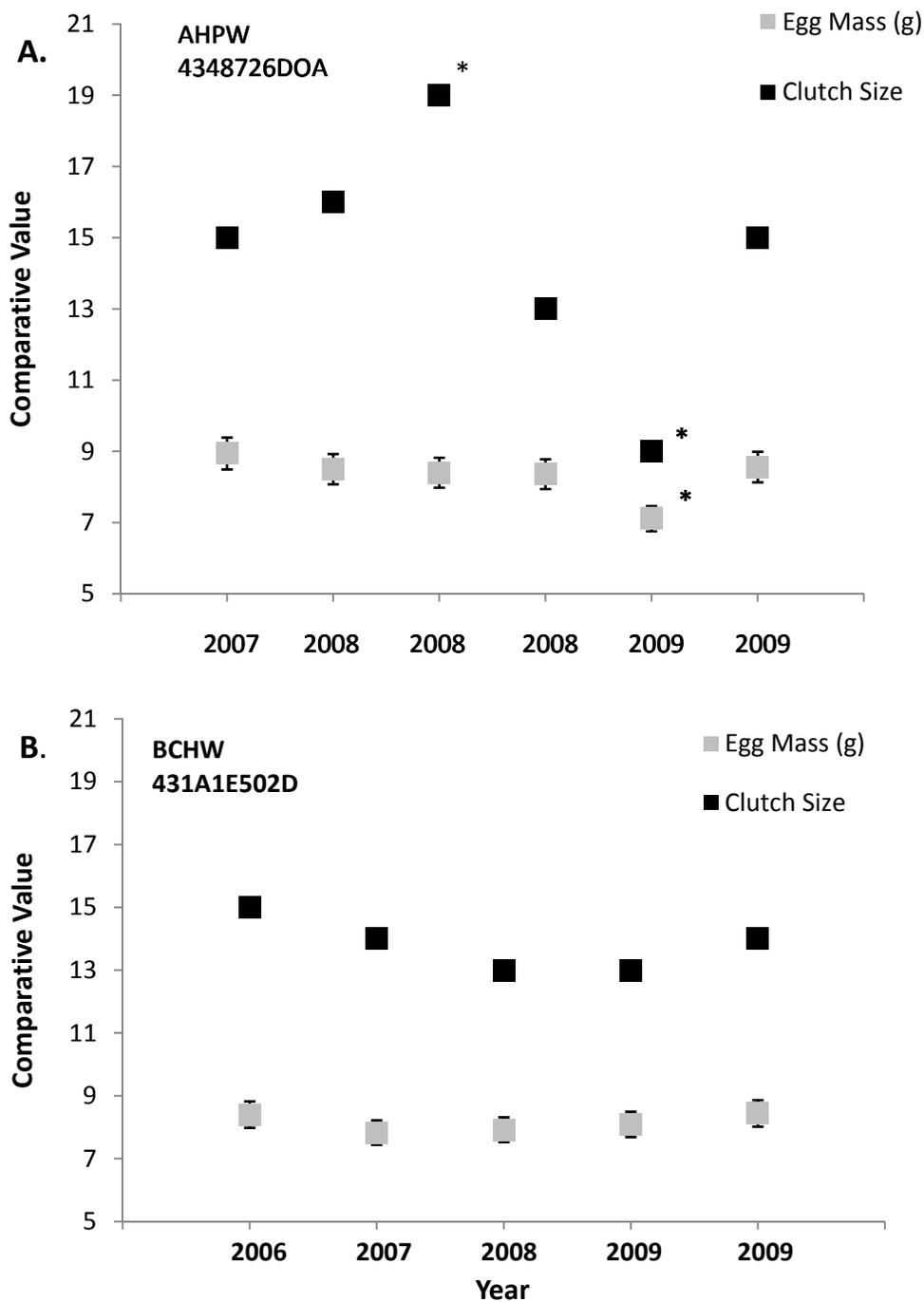
**Figure 19.** Regression of egg length (mm) and egg mass (g) for all eggs measured ( $n = 1907$ ) throughout the five year study period at N. North Sedge Island.



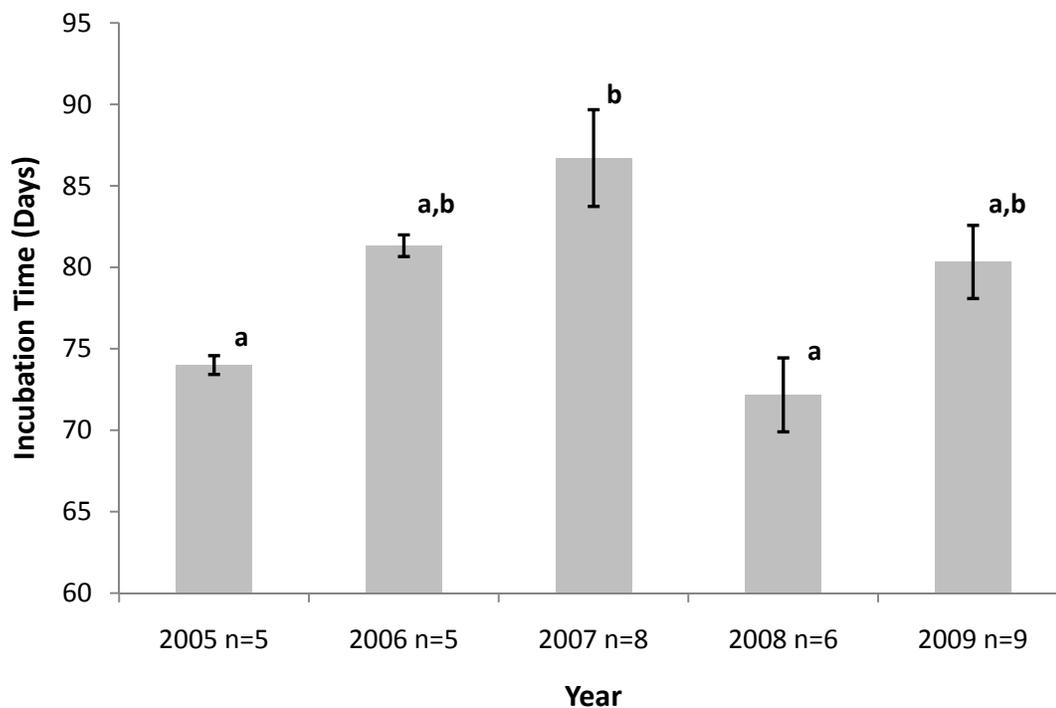
**Figure 20.** Mean egg clutch mass ( $\text{g}; \pm 1\text{SE}$ ) of 153 clutches collected at N. Sedge Island during the five years of the study. Mean clutch egg masses ranged from 6.13 g to 10.17 g.



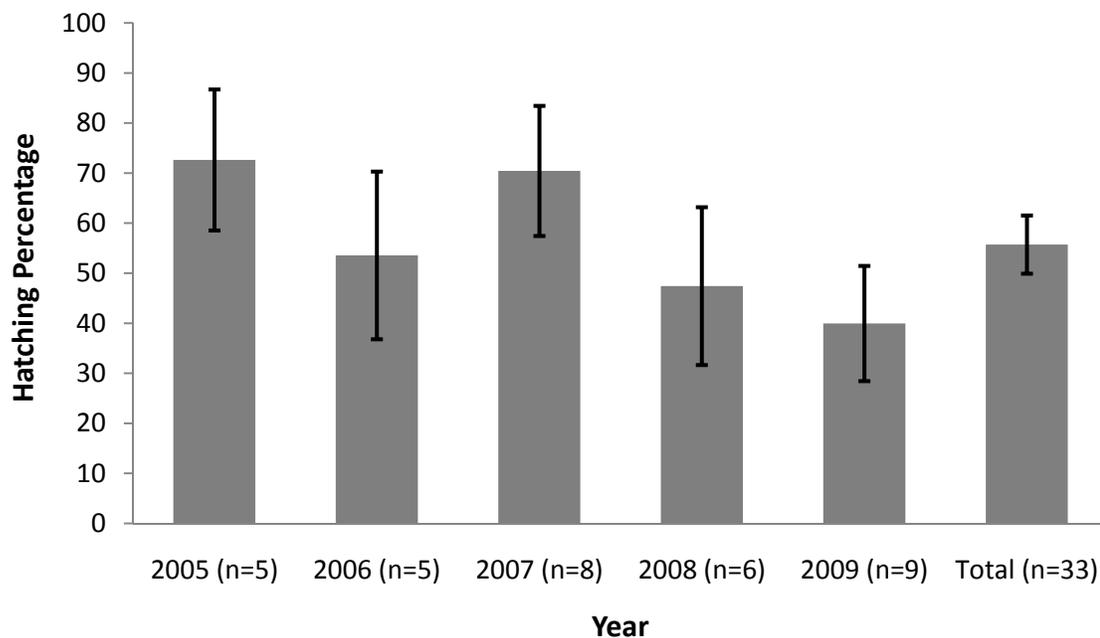
**Figure 21.** Regression of female plastron length (mm) versus mean clutch egg mass (g) at N. Sedge Island from 2005 – 2009 ( $n = 129$ ). There was a significant correlation between mean clutch egg mass (g) and female plastron length (mm;  $P < 0.0001$ ,  $r^2 = 0.180$ ).



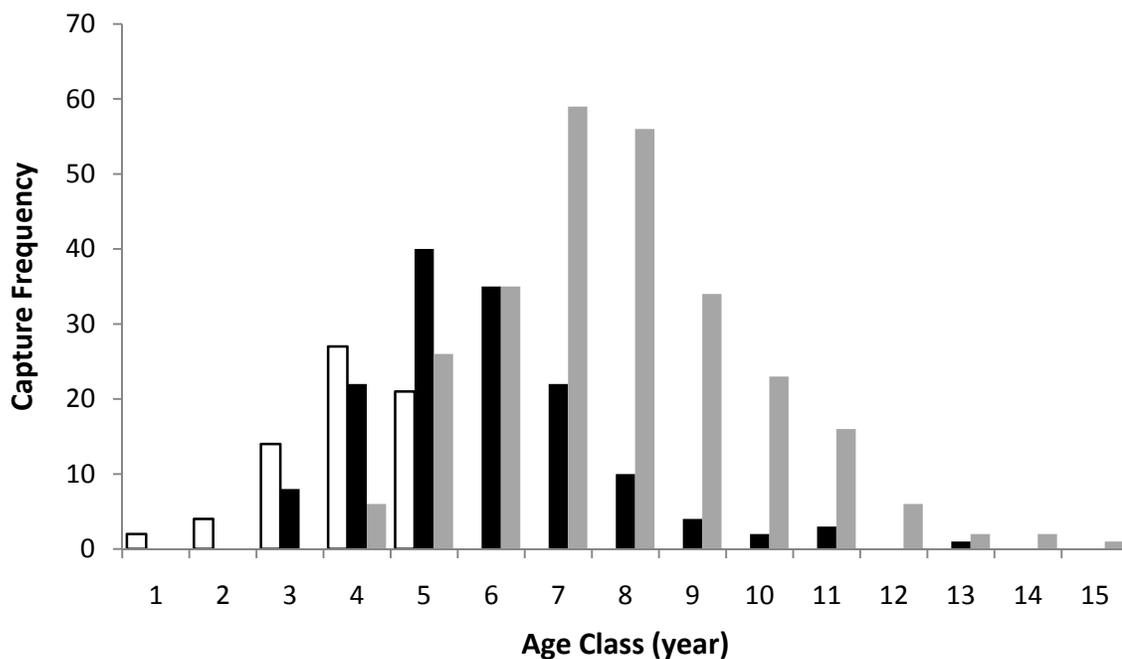
**Figure 22.** Selected nesting female comparison of mean clutch egg mass (g) and clutch size among and within nesting seasons at N. Sedge Island. All clutch and egg mass data were presented in order of nesting. A) Terrapin AHPW nested 3 times in 2008 and two times in 2009. There was a significant difference in both mean clutch egg mass (g; ANOVA,  $F_{2,84} = 10.25$ ,  $P < 0.01$ ) and clutch size ( $F_{5,81} = 4.50$ ,  $P = 0.001$ ) among and within seasons. B) Terrapin BCHW had no significant difference in mean clutch egg mass (g) and clutch sizes among years.



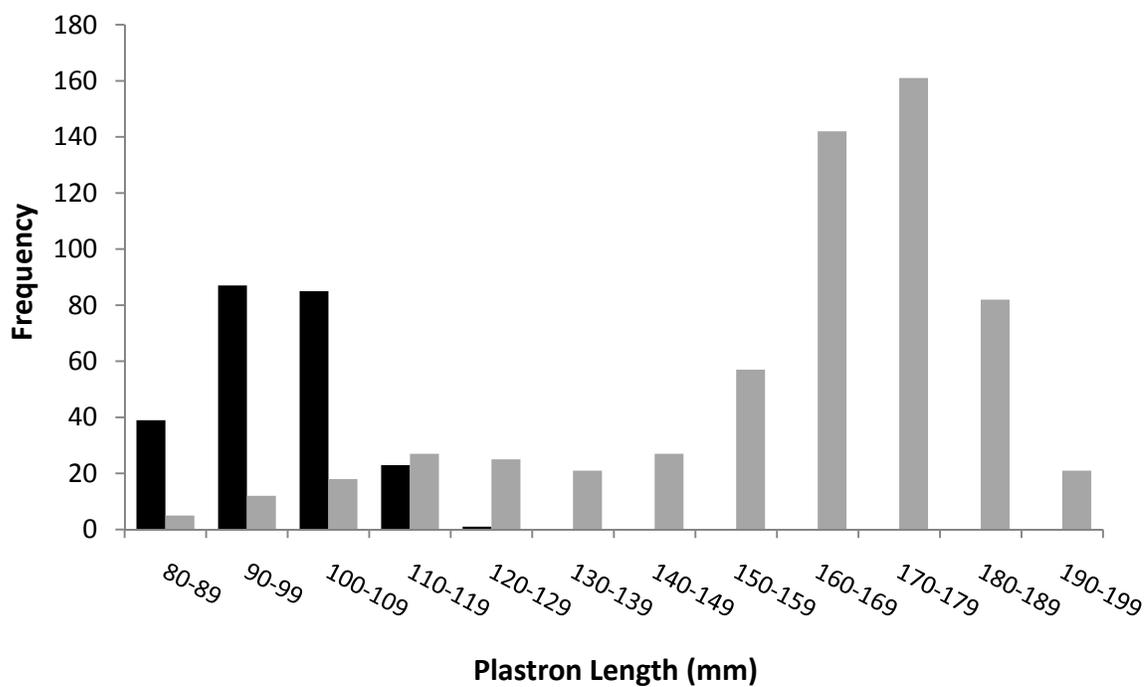
**Figure 23.** Incubation times (mean days  $\pm$  1 SE) for reference nests (n = 33) at N. Sedge Island. ANOVA found a significant difference among years ( $F_{4,28} = 6.146$ ,  $P = 0.002$ ). The range of incubation times were from  $72.2 \pm 2.3$  days in 2008 to  $86.4 \pm 2.9$  days in 2007. A REGW post hoc test was used to group incubation times (a, b) that were not significantly different.



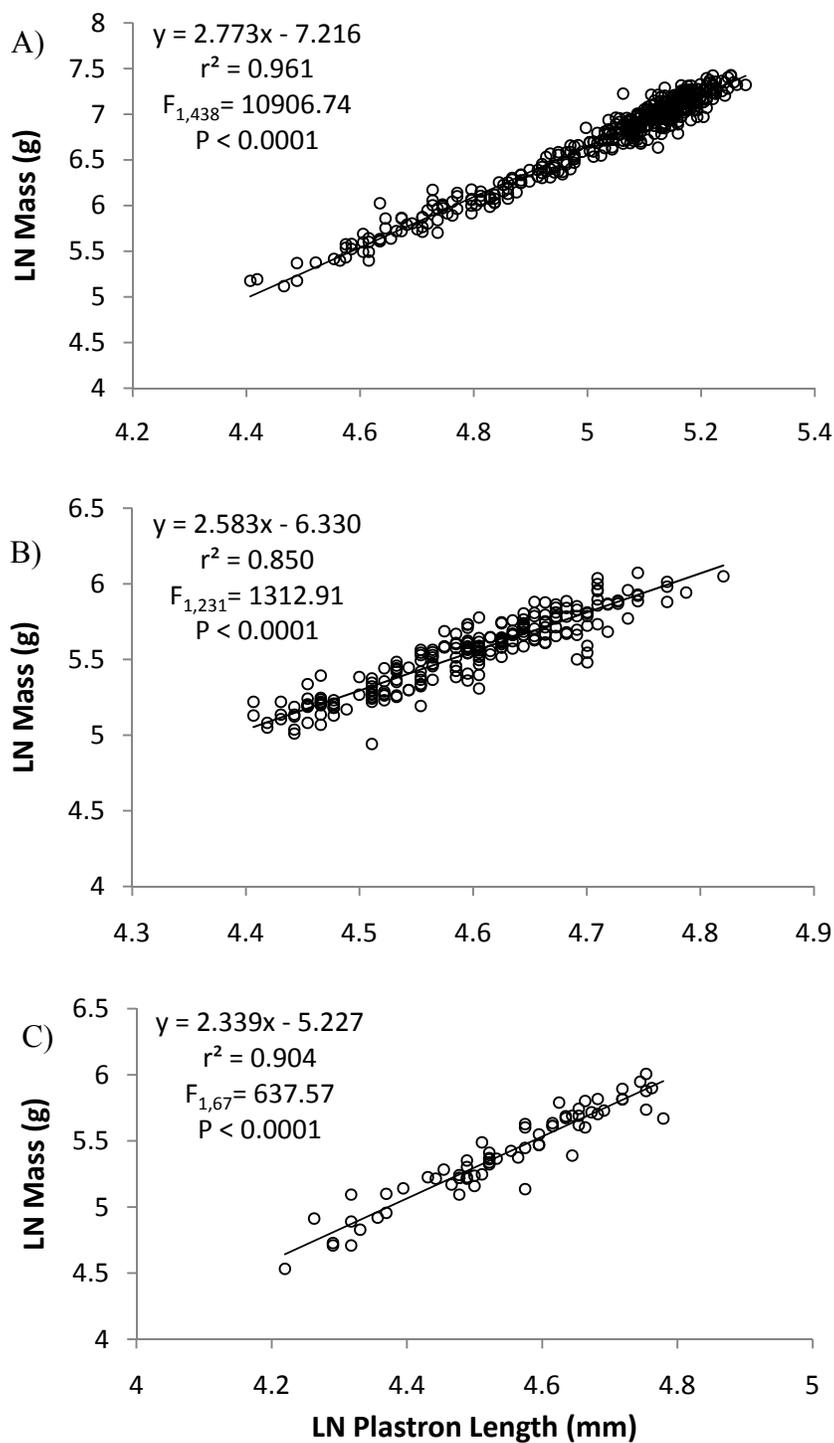
**Figure 24.** Hatching percentage (mean  $\pm$  1 SE) of reference nests at N. Sedge Island for the five years of the study ( $55.7 \pm 5.8\%$ ;  $n = 33$ ). All nests were protected with predator exclusion devices throughout the study. ANOVA found no significant difference in hatching percentage among years ( $F_{4,28} = 1.364$ ,  $P = 0.271$ ).



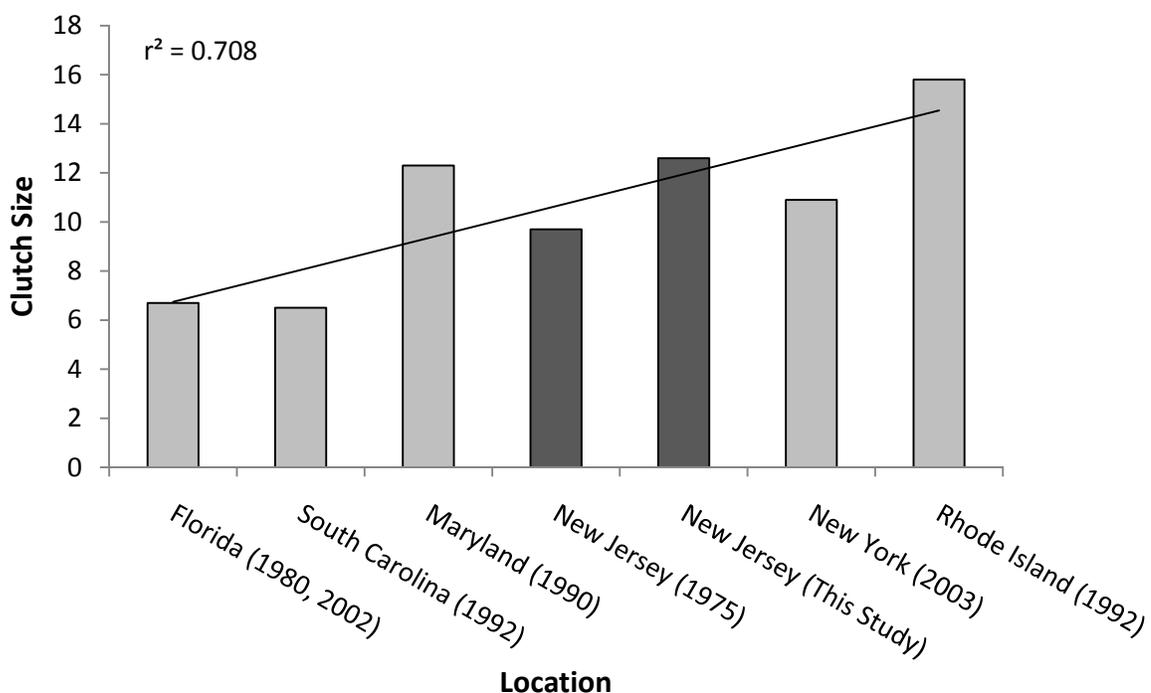
**Figure 25.** Frequency of age class captures at Spizzle Creek for all age-able terrapins (n = 481). White bars with dark outline represent juveniles (n = 70), dark bars represent males (n = 147) and gray bars represent females (n = 264). The oldest age-able captured female terrapin was 15 years and the oldest age-able captured male terrapin was 13 years. The youngest age-able captured female terrapins were four year old sub-adults (n = 5). The youngest age-able captured male terrapins were three year old adult males (n = 7).



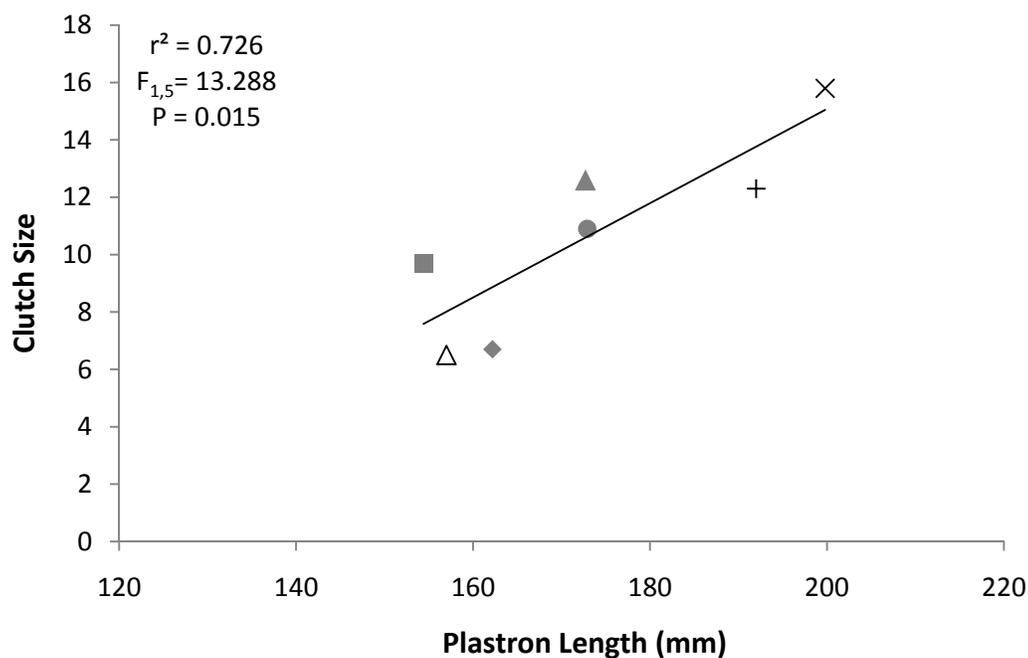
**Figure 26.** Distribution of all male and female terrapin plastron lengths (mm) at N. Sedge Island and Spizzle Creek throughout the study period. Plastron lengths are reported in 10 mm increments. Dark bars represent male terrapins (n = 235), gray bars represent female terrapins (n = 598).



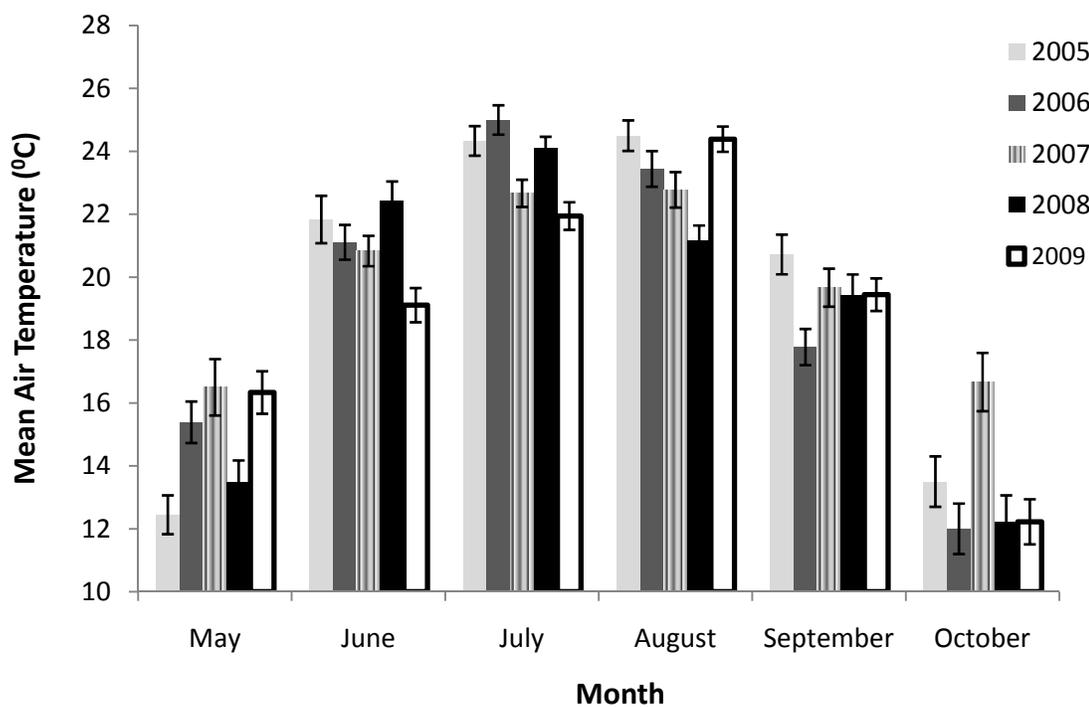
**Figure 27.** Regression analysis of the ln plastron length (mm) and ln of mass (g) of terrapins captured at Spizzle Creek. A) female terrapins (n = 440), B) male terrapins (n = 233), and C) juvenile terrapins (n = 70). There was a significant correlation between ln plastron length and ln mass for all terrapins captured ( $P < 0.0001$ ).



**Figure 28.** Mean clutch size variations among study sites ( $n = 7$ ) from Florida ( $28^{\circ} 35'$  N,  $80^{\circ} 40'$  W) to Rhode Island ( $41^{\circ} 46'$  N,  $70^{\circ} 18'$  W). There was a positive correlation between demographic location and clutch size from the south to the north. New Jersey (dark bars) showed a variation in mean clutch size between study sites ( $39^{\circ} 29'$  N,  $74^{\circ} 21'$  W;  $9.7 \pm 1.1$  SD) and ( $39^{\circ} 47'$  N,  $74^{\circ} 07'$  W;  $12.6 \pm 0.8$  SE). Maryland ( $38^{\circ} 30'$  N,  $76^{\circ} 41'$  W) had higher mean clutch sizes ( $12.3 \pm 0.1$  SE) than in New Jersey ( $9.7 \pm 2.6$  SD; 1975), New York ( $40^{\circ} 37'$  N,  $73^{\circ} 50'$  W;  $10.9 \pm 3.9$  SD) and Rhode Island ( $15.8 \pm 3.6$  SD).



**Figure 29.** Regression of mean plastron length (mm) with mean clutch size for mature female terrapins from Florida ( $28^{\circ} 35' N$ ,  $80^{\circ} 40' W$ ; filled square) to Rhode Island ( $41^{\circ} 46' N$ ,  $70^{\circ} 18' W$ ; "X"). There was a significant correlation between female plastron length and clutch size ( $F_{1,5} = 13.288$ ,  $P = 0.015$ ). Plastron lengths and clutch sizes also include South Carolina ( $32^{\circ} 35' N$ ,  $80^{\circ} 08' W$ ; filled diagonal), New York ( $40^{\circ} 37' N$ ,  $73^{\circ} 50' W$ ; filled circle), New Jersey ( $39^{\circ} 29' N$ ,  $74^{\circ} 21' W$ ; open triangle), this study ( $39^{\circ} 47' N$ ,  $74^{\circ} 07' W$ ; filled triangle), and Maryland ( $38^{\circ} 30' N$ ,  $76^{\circ} 41' W$ ; +).



**Figure 30.** Mean air temperatures ( $^{\circ}\text{C} \pm 1\text{SE}$ ) from May through October 2005 – 2009. Temperatures were recorded from a weather station at Seaside Park, NJ (12 km north of the study site).

**CHAPTER 5: CONSERVATION AND MANAGEMENT RECOMMENDATIONS  
FOR DIAMONDBACK TERRAPINS (*Malaclemys terrapin*) IN  
BARNEGAT BAY, NEW JERSEY**

Anthropogenic factors, including development and the effects of global climate change are responsible for loss of nesting habitats for turtles globally and diamondback terrapins in particular (Gibbons et al. 2001). Coastal areas are particularly impacted by sea level rise as a result of development (Titus et al. 2009). Nest placement is important for embryo survivorship in sea turtles that nest along coastal areas. If nests are not oviposited high enough above the waterline, a washover of tidal water can flood nests causing embryo mortality (in loggerhead turtles, Foley et al. 2006; in leatherback turtles, Caut et al. 2010). The diamondback terrapin, an estuarine emydid species, utilizes areas above the high tide line for nesting (Burger and Montevecchi 1975; Roosenburg 1991; Ernst et al. 1994; Roosenburg and Kelley 1996). Terrapins are one of 15 vertebrate species endemic to tidal salt marshes restricted only to the Gulf and Atlantic coasts (Greenberg et al. 2006). Terrapins have high nest site fidelity (Gibbons et al. 2001; Feinberg and Burke 2003) with some individual nesting females returning within meters of same landing sites to nest (Szerlag and McRobert 2007). Terrapin nests are susceptible to flooding as a result of high water (Roosenburg 1994) and significant rainfall events (Chapter 2). Besides the risk of flooding, nest site selection is an important factor for terrapins for gender determination since they exhibit temperature-dependent sex determination (TSD; Jeyasuria et al. 1994). Nests in open areas maintain warmer temperatures, thus more female hatchlings versus nests in shaded areas that maintain cooler nest temperatures and produce more male hatchlings (Burger 1977; Palmer and Cordes 1988; Roosenburg and Kelley 1996). Burger (1977) reported that

terrapin eggs oviposited closer to the surface on a sandy beach experienced temperatures greater than 32°C which caused a decline in survivorship of embryos. Nest site selection is critical for the reproductive ecology of terrapins and other species. Nest sites may be in decline as coastal habitats are being altered, eroded, and threatened by sea level rise. Enhancement and development of coastal nesting areas may be necessary for stable populations of terrapins and other coastal vertebrate species.

### **Loss of habitat**

Terrapin populations are being negatively impacted with the loss of coastal habitats (i.e., barrier island beach, marshes) as a result of human development (Gibbons et al. 2001), erosion (Jamaica Bay, Feinberg 2000) and sea level rise (Greenburg et al. 2006). There is little known about population sizes of terrapin across their range, and terrapin populations in the northern part of their range are listed as endangered in Massachusetts and threatened in Rhode Island (Watters 2004; Greenburg et al. 2006). In New Jersey, terrapin populations can be found in estuarine marsh habitats from Sandy Hook (Feinberg 2000) to Cape May, New Jersey (Wood and Herlands 1997). In New Jersey, diamondback terrapins are a species of special concern with little information about population structures (e.g., movement and size) throughout the state (D. Jenkins, NJDFW, personal communication). New Jersey lost over 60% of coastal habitat with higher development along barrier islands than other states along the Atlantic Coast including Delaware, Maryland, Virginia, North Carolina, South Carolina and Georgia (Titus et al. 2009).

In Barnegat Bay, approximately 30% of marsh and wetlands areas have been anthropogenically altered (BBEP 2001). In some parts of the Barnegat Bay watershed, there is 70% development (e.g., Silver Bay). As a result of development, approximately 38% of Barnegat Bay contains armored structures along shorelines, called bulkheading (BBEP 2001). Bulkheading was a shoreline stabilizing method used to prevent erosion; however, it alters wetland function (Titus et al. 2009). Although there are regulations limiting the addition of new bulkheading along the bay shoreline; there are still losses of shoreline as a result of erosion and sea level rise (Lathrop and Love 2007). Between 1888 and 1995, 4190 ha of marsh were lost throughout Barnegat Bay as a result of development and erosion (BBEP 2001). However, there was a minimal loss of marsh areas from 10,472 ha in 1972, to 9,941 ha in 1995 as a result of natural erosion processes and laws to protect coastal habitats (BBEP 2001).

Several species of shorebirds have declined as a result of loss of salt marsh and shoreline habitat including colonial nesting gulls and terns in Barnegat Bay (Jones and Strange 2008). Between 1989 and 1995, the gull population decreased by more than half from approximately 11,000 gulls, mostly laughing gulls (*Larus atricilla*), to approximately 5000 gulls, mostly herring gulls (*Larus argentatus*) and great black-backed gulls (*Larus marinus*). The same trend was observed in terns which declined from approximately 5,000 terns in 1989, to approximately 2600 terns in 1995, mostly common terns (*Sterna hirundo*; Jones and Strange 2008). A shorebird survey by U.S. Fish and Wildlife (1997) on Holgate Beach, Barnegat Bay, reported that Holgate Beach within Barnegat Bay had a decrease in nesting black skimmer (*Rynchops niger*) populations from 1500 in 1985 declining to 570 in 1995. Jones and Strange (2008)

conclude that loss of coastal habitat from sea level rise and anthropogenic factors (e.g. development) would cause a decline in the number of “least tern (*Sterna antillarum*), a state-listed endangered species, and piping plover (*Charadrius melodus*), a federally-listed species.”

Significant erosion rates are predicted along the mid-Atlantic coastline between New Jersey and Virginia (Gutierrez et al. 2009). As a result of coastal erosion, there will be a decrease in the size of barrier islands, segmentation of barrier islands and increased frequency of overwash of coastal areas (Gutierrez et al. 2009). The loss of shoreline habitat becomes confounded with stochastic events such as hurricanes and major storms. In New Jersey, 100 year storm (three meter storm surge) inundation would encompass 79% (1,200 km<sup>2</sup>) of natural land cover, primarily tidal salt marshes and freshwater wetlands (Lathrop and Love 2007).

In New Jersey, there are no regulations specifically addressing nesting terrapin habitat quality; however regulations regarding coastal zone management may overlap with some nesting areas (Table 19). The Coastal Area Facilities Review Act limits construction within coastal areas including shoreline projects. The Clean Water Act supports restoration projects if such projects enhance wildlife and do not alter coastal ecosystem function (Titus et al. 2009). The National Research Council identified ecosystem restoration as a key priority for federal agencies and scientists (reviewed in Costa-Pierce and Weinstein 2002).

### **Dredge-filled islands as nesting habitats**

Dredge-filled areas are not just repositories where bottom sediment is stored, they can serve as open space and habitat for plants and wildlife (Blanchard 1995). In Barnegat Bay, dredge spoil islands formed during the dredging of channels, serve as wildlife habitats including shorebird and terrapin nesting sites (Blanchard 1995). Common terns and Foster's terns (*Sterna forsteri*) build their nests on the ground, therefore building nests on dredge islands provides a nesting area with minimal mammalian predation (Burger 1977). Sand that accumulates along the shoreline of dredge-filled islands, including "dredge-spoil island" is used by black skimmers and least terns to nest (Blanchard 1995). Dredge Spoil Island, adjacent to the Barnegat Inlet, is used as a containment area for sediment dredged from the channels to Barnegat Inlet and along the intra-coastal waterway (Blanchard 1995). As recent as 2008, dredge sediment was pumped onto dredge spoil island to maintain the Oyster Creek Channel (pers. obs.). Dredging was performed from July through September and overlapped with terrapin nesting season.

There are examples of marsh-filled areas used as terrapin nesting habitats in New York, Maryland, and New Jersey (Feinberg 2000; Roosenburg et al. 2003; Roosenburg et al. 2009; this study). Jamaica Bay in New York was extensively dredged over the past 130 years to create shipping channels and the construction of John F. Kennedy Airport (Black 1981). Alterations reduced marsh by 50% of the original designation (Feinberg 2000). Individual marshes were connected using dredge material starting in the early 1900s (Black 1981). Over time, terrapins began nesting on these dredge-filled marshes (Feinberg 2000). At Poplar Island, Chesapeake Bay, Maryland, over 100 years ago, there

was over 400 hectares of marshlands that eroded to four smaller islands less than a total of four hectares by 1996 (Roosenburg et al. 2009). The United States Army Corps of Engineers (USACE) and Maryland Port Authority are restoring Poplar Island using clean dredge material from the Chesapeake Bay Approach Channels to the Port of Baltimore (Roosenburg et al. 2009).

Costa-Pierce and Weinstein (2002) detail a plan to utilize dredge sediment for wetlands and habitat restoration. Uncontaminated dredge sediment should be utilized for restoration projects and the projects should be maintained at a central data base maintained by the National Oceanic and Atmospheric Association or the U.S. Army Corps of Engineers (Costa-Pierce and Weinstein 2002). The USACE has 24 projects on the beneficial use of dredge material throughout the United States with 22 of the projects consisting of at least sand substrate, and a majority consisting of a combination of sand and silt substrates (reviewed in Costa-Pierce and Weinstein 2002). Sand mixed with silt were the predominant substrate types found throughout Barnegat Bay during previous dredging operations to recover dredge sediment to use as fill (Brown 2001). Shoreline enhancement projects could utilize substrate from Barnegat Bay to fill existing areas and establish nesting areas for species including diamondback terrapins.

### **Human activity**

Human activity may result in changes in nesting behavior in some vertebrate species. Human disturbance affected the nesting behavior of the western snowy plover, a shorebird, in southern California by causing the plover to abandon nests (Lafferty 2001). Human disturbance (e.g., boating, passive recreation) was observed on beaches along the

Pascagoula River in southeastern Mississippi where yellow-blotched map turtles, *Graptemys flavimaculata*, attempted to nest (Moore and Seigel 2006). Moore and Seigel (2006) found that yellow-blotched map turtles frequently returned to water, abandoning their nests as a result of human disturbance. They reported that only 15 of 79 nesting attempts by yellow-blotched map turtles resulted in oviposition (Moore and Seigel 2006). Conversely, nesting activity of painted turtles (*Chrysemys picta*) at the Thomson Causeway Recreation Area (TCRA) in Illinois was not negatively affected by recreational vehicle activities at the TRCA (Bowen and Janzen 2008). Roosenburg et al. 2003 reported that the mean clutch size at Poplar Island was 11, which was lower than that of the Patuxent River population (13) possibly as a result of human disturbance during construction. Terrapins may have deposited incomplete clutches as a result of the activity (Roosenburg et al.2003).

Diamondback terrapins have nest site fidelity with most nesting routes less than 10 m from the water in Maryland (Roosenburg 1994). Burger and Montevecchi (1975) found terrapin nesting routes within 200 yard of the water. Szerlag and McRobert (2007) reported that approximately 40% of nesting females return to within 50 m of the same location where captured one year prior. Therefore, human disturbance may result in a change in nesting behavior as demonstrated on Poplar Island (Roosenburg et al. 2003). My research indicates that there was a decrease in terrapin landings at North Sedge Island from the initial three years of the study, 2002 to 2004, versus 2005 – 2009 (Table 9, Chapter 4). This may be the result of increased human activity at North Sedge Island as group programs have increased since 2002 (J. Merritt, personal communication). In

2009, there were programs scheduled on 48 of 61 days (between June 1 and August 1) at the Island during terrapin nesting season (K. Leskie, personal communication).

Vegetation is increasing throughout North Sedge Island. We have observed an increase in density of grasses that is filling in open areas between 2002 and 2009.

Vegetative cover, greater than 50% can result in reduced nesting (Palmer and Cordes 1988). Terrapins prefer to nest in areas vegetated between 25% and 50% (Burger and Montevecchi 1975). The increase in vegetation may also be contributing to the decline in female terrapin landings.

### **Other estuarine turtles**

The mangrove (river) terrapin, *Batagur baska*, and the painted terrapin, *Callagur borneonsis*, nest on upland shoreline areas in estuaries from Central and southeast Asia (Nagelkerken et al. 2008). In parts southwestern Thailand, female *C. borneonsis* migrate up rivers to nest on sand bars and beaches (Ernst et al. 1997). Both species are critically endangered with loss of mangrove habitats as a factor for decline (IUCN 2006). The river terrapin, *B. baska*, occur in the Irrawaddy Delta in Myanmar in southeast Asia where the species was thought to be extinct (Arceo and Cheung 2002). Research indicates that both species travel great distances to nest (Ernst et al. 1997). Populations of *B. baska* are in decline due to egg-collecting, overharvesting of adults, and destruction of nesting areas and mangrove swamp forests (Platt et al. 2008). As a result of habitat loss, these two species of turtles are in decline (Arceo and Cheung 2002, Place et al. 2008). There is little known about populations throughout their range, and conservation of these species become increasingly difficult as efforts must be multi-national in scope.

## **Management recommendations for the conservation of terrapins**

### **Effective use of dredge sediment**

Dredge sediment, if drained (dewatered) is an effective nesting substrate for terrapins and should be used for coastal wetlands enhancement. Our research supports the use of dredge sediment, especially after one year. There was no hatching in new dredge terrapin nests in 2006 and there was a 59.4% hatching success in terrapin nests in one year aged dredge in 2007 (Chapter 2). Washing of dredge sediment with rainwater flushes out ions and reduces soil conductivity which makes dredge sediment a viable nesting substrate within a few months (Fig. 6, Chapter 3). However, a better technique to wash dredge may result in better hatching success. Our study supports the recommendations of Costa-Pierce and Weinstein (2002) to fund research efforts to develop new technologies and coordinate efforts to standardize methods for the effective use of dredge in restoration activities.

Restoration of wetlands and coastal habitats through the use of dredge sediment is necessary for wildlife habitat. There is a greater need for coastal shoreline enhancement as a result of the loss of coastal habitat. New Jersey's coastal barrier beaches are moving landward and shoreline is retreating (Phillips 1986). With the acceleration of sea level rise, the increasing threat of flooding along shoreline will result in an increase in shoreline armoring (Najjar et al. 2000). Sea level rise is an ongoing problem, even with a reduction in carbon emissions, New Jersey coastal regions must address sea level rise (Nicholls and Lowe 2004). Approximately 38% of the shoreline of Barnegat Bay is armored (e.g., bulkheading; BBEP 2001). The U.S. Army Corps of Engineers (USACE) has the authority to permit the building of structures as long as the structure does not have

a cumulative environmental impact (reviewed in Titus et al. 2009). It was determined that shore protection will not have such a cumulative impact, therefore the USACE can grant permits under a nation-wide application process (U.S. Army Corps of Engineers 2007; Department of the Army 2007). Increased armoring in New Jersey will result in decreased nesting habitats for many avian species and diamondback terrapins. Therefore, the need to enhance or develop wildlife nesting areas is increasingly important.

Dredging activity should be temporally regulated. The USACE recommends that no dredging take place during tern nesting season at Dredge Spoil Island (Blanchard 1995). However, dredging was permitted on a second dredge spoil island 300 m to the west during tern nesting season. This island is used as a rookery for gulls and terns (T. Virzi, personal communication), and terrapin nesting (pers. obs.). The island was used to deposit dredged sediment from the Oyster Creek Channel in 1998. Since the operation took place during terrapin nesting season, the dredge sediment would not be a viable nesting substrate and terrapin nests would fail. Our recommendation is that dredging be conducted in the fall (mid-September through November) to limit negative ecological impact to nesting species. My results indicate that with a regular moisture regime, salt ions should be washed out of the dredge sediment and the dredge sediment could be used as a viable nesting substrate the following nesting season (Chapter 3).

### **Structures on nesting areas**

Although there is limited construction in New Jersey's coastal areas as a result of the Coastal Area Facilities Review Act, there needs to be better management of building structure (e.g., sheds, decks, fences) in areas where terrapins nest. The effects of

structures that produce shade in terrapins nesting areas can also affect the gender of the species, with the likelihood of more males being hatched in shaded locations (Roosenburg 1992). In New Jersey, there are coastal regulations to limit the construction of structures that produce shade. Submerged aquatic vegetation (SUV) beds are protected to limit the construction of structures that may cause too much shade and a reduction in sea grass (CAFRA 1999). SUV types (e.g., *Zostera marina* and *Ruppia maritima*) in New Jersey are not considered threatened or endangered. However, SUV beds are considered in decline, which is evident in Barnegat Bay (BBEP 2001). Diamondback terrapins are a species of special concern in New Jersey, and there needs to be more information about their nesting locations and protection of nesting habitats. Although we found no difference in hatching success in terrapin nests in 50% shaded versus non-shaded treatments, there was still a significantly longer incubation time in nests in shade versus non-shade. Also, our results indicate that nest temperatures at N. Sedge Island are at, or below the pivotal temperature, thus a male-gender bias (Chapter 2). Our results also indicate that depth of eggs in nests at N. Sedge Island results in different genders in nests. In loamy sand nests, eggs incubating at the top (8 cm depth) of the nest had mean temperatures at 29°C (pivotal temperature). However, eggs incubating at the 12 cm depth and deeper were below the pivotal temperature and any hatchlings that emerge from these depths would be males (Chapter 2).

### **Human Activity on North Sedge Island**

Human activities at North Sedge Island should be managed to reduce disturbances in nesting areas both spatially and temporally. Our recommendation is to work with New

Jersey Division of Fish and Wildlife staff about emphasizing the peak nesting timeframe for terrapins and making adjustments in programming to facilitate nesting and meet the goals of the Sedge Island Natural Resource Education program. Our data suggest that terrapins access nesting areas from the east and west locations on North Sedge Island. During the months of June and July, human activities should be limited in these locations as a result of terrapin nesting on the Island (Fig. 12, Chapter 4). One of the more popular nesting locations is immediately to the west of the Sedge Island Natural Resource Education Center, a 16 person residential facility. As part of our long-term study on nesting ecology of terrapins, we maintain a hatchery on the west side of the residential facility. Residents frequently hang wet clothes to dry on the west side of the house. The clothes-line should be moved to another location, especially during the months of June and July.

Programs on North Sedge Island should be conducted in the early morning hours, prior to 9:30 a.m. and after 4:00 p.m. in the afternoon. This may result in less human disturbance for nesting females to complete their nesting cycles which are mostly from the mid- morning hours through mid-afternoon (Fig. 13, Chapter 4). Groups often conduct activities off the Island including kayaking and marsh exploration, which can take up to several hours (pers. obs.). Groups departing the Island usually depart in the morning; therefore, we recommend that groups depart by 9:00 a.m. Groups arriving at the Island usually arrive in the early afternoon. The timeframe is more variable and more difficult to manage as participants usually arrive separately and assemble at Island Beach State Park prior to taking a boat shuttle to Sedge Island. Our recommendation is that the groups depart for the Island during mid-afternoon.

We recommend that 50% of the vegetation be removed from nesting areas throughout North Sedge Island. This would provide for 25% to 50% cover, which is the recommended coverage for terrapin nests (Burger and Montevecchi 1975; Palmer and Cordes 1988). The vegetated areas are mowed regularly which can also result in compaction of soils in nests and cause mortality to hatchlings. Our results show that nest temperatures in 100% open soil treatments do not reach lethal temperatures (above 32°C); therefore, reducing vegetation should have no negative affect on hatching success. Our results show that 50% cover does not negatively affect the hatching success of terrapin eggs. However, there may be an increased incubation time with 50% cover or greater than in open areas. Root growth in vegetation is a cause of egg failure (Auger and Giovannone 1979), and can affect shading of terrapin nests (Roosenburg 1992).

Island Beach State Park and Sedge Island are within a Marine Conservation Zone; therefore, there are no commercial-supported activities and only recreational activities are permitted within the zone. This is the only study conducted in a conservation area in New Jersey that does not allow commercial activity, and one of the few throughout the range of diamondback terrapins (Gateway National Recreation Area, Feinberg 2000). More collaborative studies must be conducted between N.J. Division and Fish and Wildlife, conservation programs, and researchers to study terrapin nesting areas and terrapin populations throughout the state of New Jersey.

**Table 19.** Federal regulations and New Jersey regulations that affect building in coastal areas as well as regulations that regulate dredging in coastal waters. Regulations are presented in chronological order of adoption.

Act	Federal or State Statute	Year Initiated	Action
Waterfront Development Law*	N.J.S.A. 12:5-3	1914	Limit problems that new development may cause for existing navigation. Permits are needed for any project in tidally flowed waterways
National Environmental Policy Act	42 U.S.C. 4321 et seq.	1970	Established national environmental policies and laws. It regulates environmental impacts from the past, in the present and for the foreseeable future.**
Wetlands Act of 1970*	N.J.S.A. 13:9A	1970	It requires the N.J. Department of Environmental Protection to regulate development in coastal wetlands. You must have a permit to dredge, fill and excavate within a coastal wetlands.
The Clean Water Act (Federal Water Pollution Control Act)	U.S. EPA 33 U.S.C. 1251 et seq.	1972	Regulates development in water bodies as long as the development does not have a significant environmental impact. However, shoreline projects are still approved as long as there is minimal impact to the environment.**
Coastal Area Facility Review Act (CAFRA)*	N.J.S.A. 13:19	Amended 1999	Regulates all construction within coastal areas of N.J. including site preparation, shoreline protection and all construction projects.

\* New Jersey Department of Environmental Protection Division of Land Use Regulation

\*\* Titus et al. 2009

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Wnek, J. and H.W. Avery. 2010. Anthropogenic impacts on the nesting ecology of Diamondback terrapins, *Malaclemys terrapin*: a comparison of soil texture types and shade. Abstract. New Jersey Academy of Science Annual Meeting, Kean University, New Jersey, April 2010.  
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