Sub-tropical cyclone Sandy and its impact on diamondback terrapin (*Malaclemys terrapin terrapin*) nesting at Barnegat Bay, New Jersey.

by:
Jessica Caban

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THESIS

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COMMITTEE MEMBERS:

John Wnek, Ph.D. (Advisor)

Louise S. Wootton, Ph.D.

Michael F. Gross, Ph.D.

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Abstract

Barrier islands and the back-bay areas serve as habitat for the diamondback terrapin *Malaclemys terrapin terrapin*, which is a species of turtle exclusively found in brackish water and solely within the temperate zone. Mortality of terrapins can occur as a result of weather events, predation by animals and as a result of human influence. Causes of terrapin egg and hatchling mortality include erosion or tidal inundation. Hurricanes are capable of changing ecosystems and therefore affecting biotic inhabitants. Storm surge and the intense sea spray associated with major storms could change the compositional makeup of the terrestrial ecosystem too. On the 29th of October 2012 post-tropical cyclone Sandy (Hurricane Sandy) made landfall around Atlantic City, NJ. The intent of this study was to see if a high intensity event affects the population dynamics of the Northern Diamondback terrapin by comparing pre-storm nesting numbers and any changes to female reproductive effort before and for the two nesting seasons after Hurricane Sandy. Reproductive effort of females was calculated by comparing egg morphometrics.

From the analysis of number of nests on North Sedge Island among the years (2010-2014) it was clear that the nesting season after Hurricane Sandy (e.g. 2013) showed a substantial decrease in number of nests (n=32) when compared to years prior (2011 & 2012). However, the number of female terrapins nesting in 2013 (n= 66) on N. Sedge Island was not significantly different from the year prior (2012: n=67). Mean egg mass (n = 177) on N. Sedge Island was significantly different among the years 2010-2014 (one-way ANOVA, F = 5.235, p = 0.001, Kruskal-Wallis Test: p = 0.002). However, the mean egg mass (8.44g; n=31) for the nesting season directly after Hurricane Sandy (2013) was not significantly different from the nesting season before Hurricane Sandy (Tukey post-hoc test: 2012; 8.38g, n=41, p = 0.999) or two nesting seasons after Hurricane Sandy (Tukey post-hoc test: 2014; 8.71g, n=49, p = 0.699). Mean hatch success on N. Sedge Island was significantly different among years 2010-2014, with success being highest (88%) in nesting season 2014 (Univariate ANOVA, F = 3.469, p = 0.009; Kruskal-Wallis Test: p = 0.011). Overall for the species, there wasn't a significant change in reproductive output for selected female terrapins in regards to: mean egg mass, mean egg length, clutch size and total clutch production over the study period.

While we saw no evidence of decreased reproductive success or other reproductive measures following Hurricane Sandy, even had such a change been observed, such disturbances may not have long-term population effects because terrapins live a long time and are reproductively active for many years. This may provide this species with some degree of resiliency in the face of the expected increases in intensity and frequency of large coastal storms impacting the north Atlantic region as a result of climate change.

Chapter 1 – Introduction

Diamondback Terrapins

Barrier islands and back-bay areas serve as habitat for the diamondback terrapin *Malaclemys terrapin terrapin*, which is a species of turtle exclusively found in brackish water (Cagle 1952) and solely within the temperate zone (Hart and Lee 2007). There are seven sub-species of terrapins found in 16 states along the Atlantic and Gulf Coasts of the United States (Coker 1931, Hart 2005). Of these seven sub-species the northern diamondback terrapin (*Malaclemys terrapin terrapin*) ranges from Cape Cod, Massachusetts to Cape Hatteras, North Carolina (Hart 2005, Butler et al. 2006). Other than the Texas diamondback (*Malaclemys terrapin littoralis*), *M. t. terrapin* is the only sub-species not to be found along the Florida coast (Cagle 1952, Hogan 2003, Butler et al. 2006). A terrapin's diet varies by location and available food sources (Butler et al. 2012). Terrapins can be seen feeding on snails (Allen and Littleford 1955), mussels, crabs and small clams (e.g. saltmarsh periwinkles; Roosenburg 1994, Butler et al. 2012).

Terrapins nest (egg-laying) on land but mate within the water. Mating begins in spring, and nesting occurs during late May through July for *Malaclemys t. terrapin* in New Jersey (Burger and Montevecci 1975, Szerlag and McRobert 2006). Females have been reported to inspect the beach for several hours before nesting (Roosenburg 1994) making it seem as if they are deliberate in deciding where to lay their eggs. Nesting behavior is not exactly the same across the seven subspecies. In a review by Butler et al. (2006) a number of differences were established for terrapins, including but not limited to: response to high tide – for example: In Florida, terrapins were seen to move onto land with rise of tide but this was not observed in Maryland. The distance female terrapins traveled, after nesting, differed amongst geographic ranges: Florida (6-10 km), Delaware (8km) and Maryland ("offshore"). A terrapin's nesting response differs at varied times of day, including different types of weather, as seen in Maryland and Florida. In general, though, terrapins prefer to nest in sandy soil (Roosenburg 1994, Feinberg and Burke 2003) which is thought to allow for the best gas exchange for the developing embryos (Wnek 2010). In New Jersey, terrapins prefer to nest in or on sand dunes (Burger and Montevecchi 1975), beaches, sandy edges of marshes and dike roads (Seigel 1980a;

Dunson 1985, Roosenburg in Butler et al. 2006). Clutch size varies between subspecies of terrapins generally increasing from the south to north latitudinally within the species range: Florida's mean clutch size is 6.7 (Seigel 1980b), South Carolina's mean clutch is 6.9 (Zimmerman 1992), Maryland's mean clutch is 12.9 (Roosenburg and Dunham 1997), New Jersey's mean clutch is 9.2 (Burger 1977), Sedge Island New Jersey (Study Site) mean clutch is 12.7 (Wnek et al. 2014) and New York's mean clutch size is 10.9 (Feinberg and Burke 2003). Clutch size was seen to correlate positively with clutch mass, it does not relate to any measurements of egg size (Butler et al. 2006) Montevecchi and Burger (1975) found that all egg measurements (size and mass) decreased as the season progressed. Burger (1975) also found that there is no relationship between plastron length of the female terrapin and egg mass, length and/or width.

Incubation time for terrapin eggs varies across their geographic ranges. The emergence period follows incubation; this is the time where the hatchlings leave the nest. Hatching occurs from mid-August through mid-October (Burger 1977). Within New Jersey, the mean incubation time is 76.2 days (Butler et al. 2006). Incubation temperature impacts development: eggs incubated at higher temperatures hatched earlier than eggs in nests at lower temperatures (Roosenburg and Kelly 1996). As with many other reptiles, the gender of terrapins is determined by the nest incubation temperature (temperature-dependent sex determination- TSD). Nest temperatures between 24-27°C produce predominantly males and 30-32°C produce predominantly females (Jeyasuria et al. 1994). Hatch success or nest success is measured by comparing the number of hatchlings emerged from the nest to that of the eggs deposited within the nest. Hatch success is dependent on nest conditions and can vary in different regions. New Jersey has a wide range (variability) in regards to hatch success. There is no evidence to support any latitudinal correlation with hatch success (sometimes referred to as nest success) from state to state with rates of 12.8% in Rhode Island (Goodwin 1994) to 25-90% in New Jersey (Burger 1977; Wnek et al. 2013) and 97-100% in Maryland (Roosenburg et al. 2004). Despite seeming like a trend, hatch success can vary based on seasonal weather patterns and nest site composition (Wnek 2010).

Mortality of terrapins can occur as a result of weather events, predation by animals or as a result of human influence. Causes of terrapin hatchling and egg mortality

include erosion or tidal inundation (habitat degradation; Mitro 2003), which can be a result of weather-related events. Organisms such as the red fox (*Vulpes fulva*), laughing gull (*Larus atricilla*), raccoons (*Procyon lotor*) and crows (*Corvus brachyrhynchos*) are known to prey specifically on terrapin eggs (Burger 1977, Roosenburg 1994). In addition, adult terrapin mortalities are associated with human activities such as drowning in crab pots, (Wood 1997, Roosenburg et al. 2004), being hit by vehicles on roads (Wood and Herlands 1997, Szerlag and McRobert 2006), and boat propeller strikes (21% of N. Sedge Island terrapins; J. Wnek, personal communication), which are common within coastal areas (Gibbons et al. 2001).

A Barrier Island and a Hurricane

A barrier island is a coastal landform lying parallel to the mainland coast. Barrier islands are categorized as being composed of sand or gravel, parallel and relatively close (often less than a mile) to a mainland, and separated by salt marsh or open brackish water (Gibbons and Coker 1978). These coastal structures are constantly subjected to wave action and absorb energy causing them to be dynamic in nature and constantly changing. The barrier island protects the wetlands along the coast, which is critical in keeping these unique habitats rich in sediment and low in energy for the flora and fauna that inhabits them (Stone and McBride 1998). The Outer Banks of North Carolina, for example, are composed of three large barrier islands: Bodie Island, Hatteras Island and Ocracoke Island. Over time, the number of islands within the Outer Banks has changed as have the number of inlets that are caused by wave breaches along the fragile coastal shoreline. In September of 2003, Hurricane Isabel cut Hatteras Island in half creating Isabel inlet. This was later repaired, but in 2011 when Hurricane Irene made landfall, the island was again split and a temporary bridge was constructed (National Park Service US Department of the Interior: NPS.gov Updated September 2015).

Coastal areas are prone to flooding caused by storm surges (Boose et al. 2001). Breaching of barrier islands can have any impacts on bays including: circulation changes, beach erosion, and habitat isolation (Valiela et al. 1998). The low profiles of the barrier islands on New Jersey's coastline and their proximity to both ocean and bay waters means that hurricanes can be particularly destructive in these areas (Tilmant et al. 1994).

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The barrier islands of New Jersey are also densely populated by humans who can also be impacted by severe weather events (Bocheneck et al. 2001) such as coastal storms like nor'easters and tropical systems.

The magnitude of a hurricane is closely interconnected to warm (temperatures reaching above 28 °C) open water systems (Boss and Neumann 1995). Coastal storms (hurricanes, nor'easters, post-tropical cyclones and/or "Superstorms") generally decrease in strength as they travel into cooler waters or travel over land. However, with the current global climate predictions, rising water temperatures will increase the potential that hurricanes will sustain their strength rather than dissipate as they move towards the poles (Goldenberg et al. 2001; Shepherd and Knutson 2007). With the earth's surface warming, ice caps melting and storms increasing in strength, over the years, it is expected that sea levels will rise and storm surges will become more frequent, with major influences on ecosystems. According to Rutgers University's New Jersey Flood Mapper (2013; Figure 1-1A; funded by NOAA Costal Services Center), a portion of Sedge Island's tidal marshes, located in Island Beach State Park, will be transformed by the change in sea level rise of 1 foot (0.3m; Figure 1-1B). By 3 feet (0.9m; Figure 1-1C), of sea level rise, this study site will be almost completely altered from a tidal marsh to mud/sand flats or open water (http://slrviewer.rutgers.edu/).
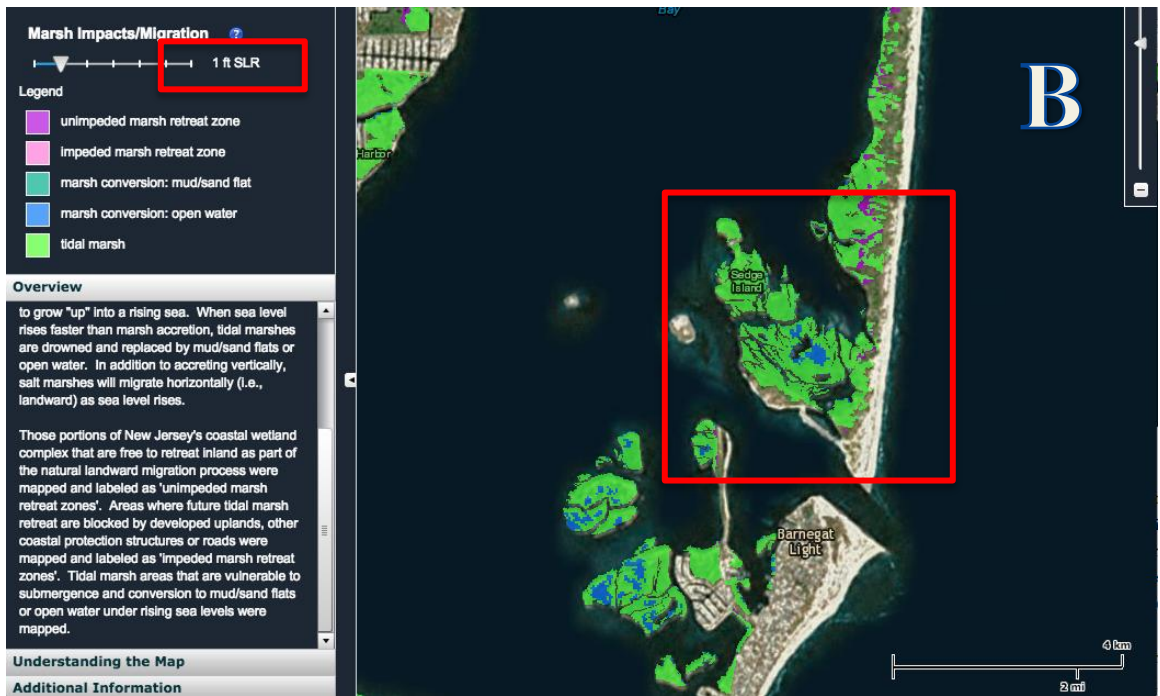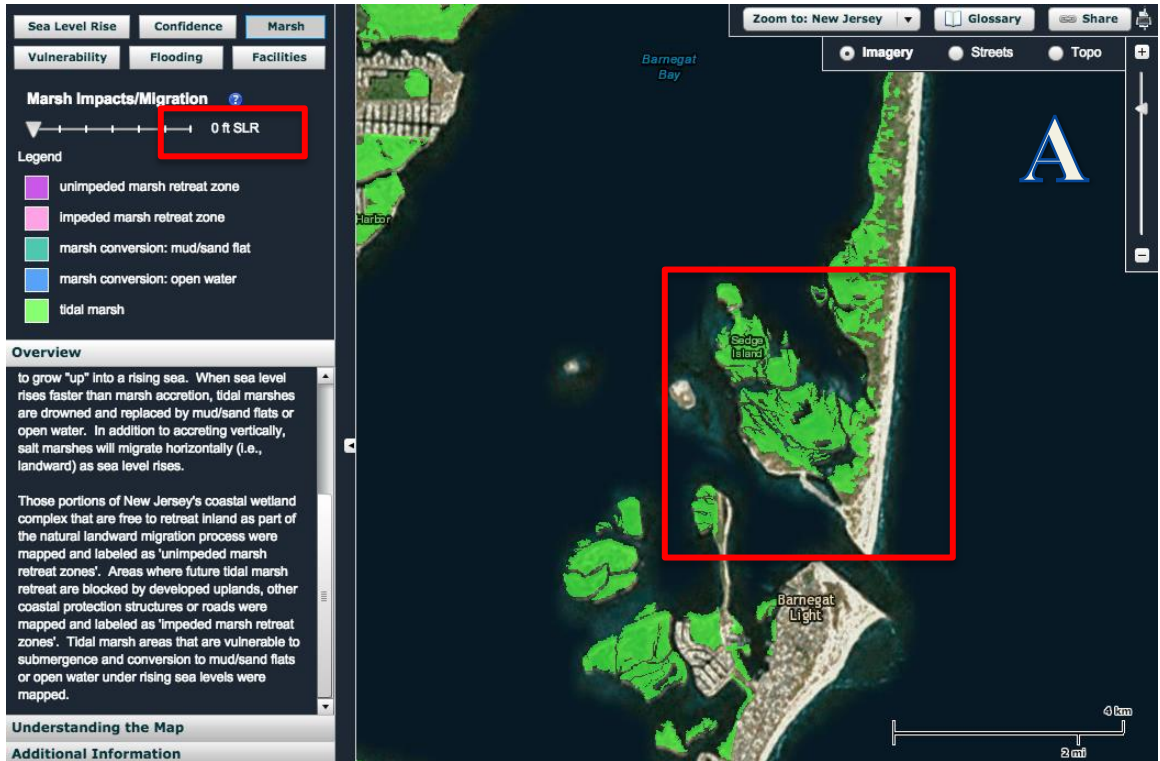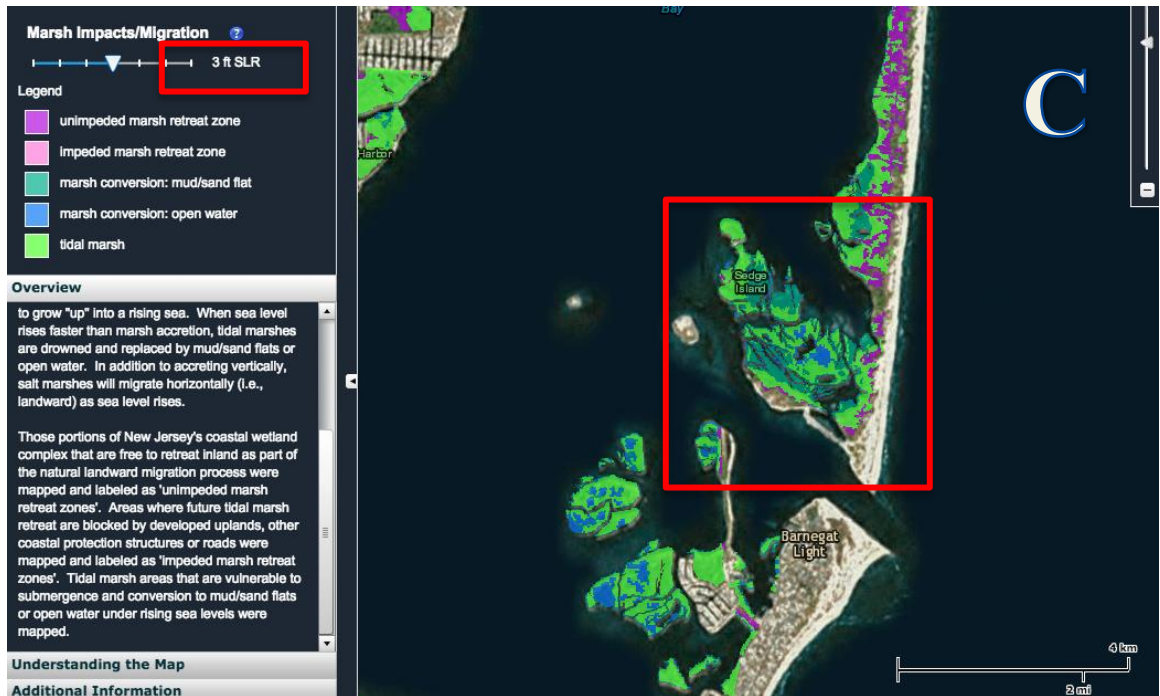
Figure 1-1. A. Shows the height of sea level (outlined in red: upper left) as it is to date and the habitat: salt marsh (light green) that is currently maintained in the Sedge Wildlife Refuge (outlined in red: lower right). B. Indicates a change in sea level by 1 foot, it also shows how this rise in sea level can change salt marsh habitat to areas of open water (blue) or unimpeded marsh retreat zones (purple). C. Indicates a change in sea level by 3 feet, showing larger areas of salt marsh habitat changing into open water, unimpeded marsh retreat zone, and mud/land flats (dark green) [http://njfloodmapper.org/ funding provided by NOAA's Cooperative Institute for Coastal and Estuarine Environmental Technologies (CICEET), and Sustainable New Jersey. Produced in collaboration with the NOAA Coastal Services Center (CSC) through a partnership with the Jacques Cousteau National Estuarine Research Reserve (JCNERR) and the Grant F. Walton Center for Remote Sensing and Spatial Analysis (CRSSA), Rutgers University.]

Another change that can have long-term effects on the salt marsh communities is a change in salinity, especially in Barnegat Bay because of its slow flushing rate (30 days in the winter to 74 days in the summer; Kennish 2001a). Terrapins reside in tidal and true salt marsh communities where water salinity can be in excess of 30 parts per thousand (ppt) (Martin 1959.) In a benthic monitoring report, conducted by Rutgers in Barnegat Bay between July 2012 and July 2013, the salinity of the marsh did not show any significant changes (Taghon and Belton 2015). However, this study did show a 0-3 ppt increase in bottom salinity (Taghon and Belton 2015) close to Sedge Island, this paper's study site.

Stochastic Events – Storms

New Jersey is impacted by storms within each season, some affecting its 130 miles of coastline (Beaver [mod 2006]). Nor'easters, Tropical (Hurricanes) and Post-Tropical cyclones can occur anywhere on Earth. In theory, changes in the world's climate over the last decade could be the cause for more intensified storms (Boss and Neumann 1995, Jones and Strange 2008). Extreme weather can impact habitats and the organisms that live within them. A rotating storm system with no frontal boundaries characterized by low barometric pressures, maximum sustained high winds (74 mph +) and extreme storm surges is denoted as a hurricane (Shepherd et al. 1991; NOAA Hurricane Facts). Rotating storms with lower wind speeds are categorized as tropical depressions (wind speeds less than 39 mph) and tropical storms (wind speeds 39-73 mph). Nor'easters are loosely defined by the National Oceanic and Atmospheric Administration (NOAA) as storms originating between Georgia and New Jersey, traveling in a northeasterly direction, within 100 miles of the Atlantic coast, with wind speeds 58 mph or greater (NOAA 2013).

Disturbances are characterized as infrequent events that unsettle an ecosystem, community or population structure by changing its resources, substrate accessibility, or physical environment (Dodd et al. 2006). If an ecosystem's structure is changed dramatically, its function for the organisms living in it could also be affected (Boose et al. 2001). Hurricanes are capable of changing ecosystems and therefore affecting their biotic inhabitants (Shepherd et al. 1991). Hurricane Hugo (Sept. 1989) made landfall near Pumpkinseed Island, SC (Shepherd et al. 1991). This island is nesting habitat for the largest wading-bird colony in the state. The bird colony includes, but is not limited to Great Egrets (*Casmerodius albus*), Snowy Egrets (*Egretta thula*), Tricolored Herons (*Egretta tricolor*), Glossy Ibises (*Plegadis falcinellus*) and White Ibises (*Eudocimus albusi*). Salt water entered up to 5 km into the coastal pine (*Pinus* spp.) forest causing extensive disturbance to vegetation (Shepherd et al. 1991). Bark erosion and cordgrass (*Spartina* spp.) detritus found on standing trees marked the height of the storm surge, which was calculated to have reached 2-3 m above mean high tide. The number of nests for Great Egrets, Tri-colored Herons, Glossy Ibises and White Ibises, which are predominantly tree nesters, all decreased on Pumpkinseed Island after Hurricane Hugo.

By contrast, Snowy Egrets, which typically nest in Marsh Elder (*Iva frutescens*), did not show a decline in the number of nesting pairs since they have the capability of nesting on the ground (Shepherd et al. 1991). Hurricane Rita struck the southwest coast of Louisiana in September 2005, generating enormous storm surges that resulted in the deaths of alligators that resided within Rockefeller Refuge in southwestern Louisiana (Lance et al. 2010). This hurricane resulted in highly saline conditions that persisted in the marsh for several months (Lance et al. 2010). This high salinity, a severe drought, and the pushing of the alligators further north by the storm all may have been factors in why no nests were found in the area in the summer of 2006 (Elsey et al. 2008). In the summer of 2007, two females returned to their nesting sites 20-170m from where they had laid before Hurricane Rita (Elsey et al. 2008).

Due to storm surges, saltmarsh wetlands could potentially be altered in ways that increase open water habitat, which may be a benefit to migrating waterfowl or loons but may limit their winter habitat. By contrast, fish (*Fundulus diaphanus*, *Fundulus heteroclintus*, *Menidia menidia*, etc.) may decrease in abundance or move elsewhere due to the loss of Submerged Aquatic Vegetation (SAV) or emergent marsh vegetation such as smooth cordgrass (*Spartina alterniflora;* Jones and Strange 2008). Smooth cordgrass shows significant sensitivity to precipitation, as indicated by decreased *S. alterniflora* biomass in high salinity areas, and less sensitivity in areas where freshwater creeks were adjacent to the plant biomass being measured (Gross et al. 1990). Coastal wetlands are among the most productive ecosystems on Earth (Kirwan and Megonigal 2013).

Storm surge and the intense sea spray associated with major storms could change the compositional makeup of the terrestrial ecosystem too. For example, these could cause changes in resource availability (soil composition, nesting habitat, brush cover) resulting in distribution changes as animal populations move to more favorable habitats (Dodd et al. 2006). Valiela et al. (1998) found that saltwater overwash (flooding for several days) from storm surges directly impacted the distribution of terrestrial animals due to extensive habitat damage. Invertebrates were severely impacted by Hurricane Bob (Category 3 - August 1991; Cape Cod, Mass.). For example, the Yellowjacket (*Vespula maculifrons)* and Bold-Faced Hornet (*Vespula maculate)* swarmed people during outside events after Bob; due to the loss of hollowed out trees and tree limbs, these structures

were no longer available for these organisms to create their nests (Valiela et al. 1998). There was no noticeable change in bird numbers (field-associated and water-associated) after Hurricane Bob according to the Massachusetts Audubon Society when they conducted surveys that December (Valiela et al. 1998). Minor effects on mammals were seen and there was no direct verification of mortality, suggesting vertebrates are more tolerant of large disturbances (Valiela et al. 1998). High degrees of disturbance can enhance the ability of invasive species to outcompete native plant species (Burkitt and Wootton 2011). Natural disasters allow fugitive plants (*Spartina patens, Juncus gerardi, Iva frutescens*) to persist within salt marsh communities (Bertness et al. 1992). After Hurricane Andrew (Category 5 – August 1992) made landfall on Florida and then moved on to the Gulf coast (weakening to a category 3) Conner et al. (2002) noticed an increase of the invasive species Chinese tallow (*Sapium sebiferum)* and its potential to dominate the habitat along the Gulf Coast in areas that were not severely altered hydrologically by the storm. Habitat changes, no matter how small, can have major impacts years later.

This study focuses on Hurricane Sandy's impact on nesting terrapins. However, Hurricane Irene (2011) also affected the area from which the data used for comparison prior to this storm were collected. These hurricanes impacted the coastline of New Jersey very differently. These storms also occurred during different times within a terrapin's reproductive cycle. Hurricane Irene in 2011 hit New Jersey as strong tropical storm along the Atlantic coast with winds at 69 mph (60 knots) and a central atmospheric pressure of 959 milibars (mb) on August 28th at 9:35 am (Avila and Congialosi 2011). The timing of this storm overlaps the incubation/emergence period of hatchlings (June-Sept; Burger 1977, Feinberg 2000). Irene caused catastrophic inland flooding due to 5.88 inches (15 cm) of rain (ICAO Site - Atlantic City) resulting in numerous record breaking crests on rivers. In addition, Sandy Hook Marine station observed storm surges between 4 and 6 feet (1.2 – 1.8 m) resulting in extensive beach erosion (Avila and Cangialosi 2011).

By contrast, post-tropical cyclone Sandy (Hurricane Sandy) made landfall around Atlantic City, NJ on the 29th of October 2012, which is after the major portion of terrapin eggs have hatched, and the hatchlings have emerged, or are capable of doing so if need be (Sharp 2012, Wehley 2012, Sullivan and Uccellini 2013). Sandy's pathway towards the shore was atypical in that it approached New Jersey from the east and not from the south

(Sullivan and Uccellini 2013). On the Saffir-Simpson scale Sandy was categorized as a Category 1 hurricane. However, the conditions of the atmospheric pressure (946 mb) and sustained maximum wind speeds, gusts of 90 mph (75 kts) peaking at 100 mph (Sullivan and Uccellini 2013), combined with a cold front from a nor'easter caused Sandy's impact to resemble a Category 3 hurricane (Metcalfe 2012). Sandy was 820 miles (1319 km) wide, which is more than double the size of Hurricanes Isaac [Louisiana: 2012] and Irene [East Coast, USA: 2011] combined (Wehley 2012). According to the National Hurricane Center Tropical Cyclone Report information gathered by Sullivan and Uccellini's team (2013) the post-tropical storm advanced into a tropical cyclone upon merging with an intense low-pressure system contributing to the size of Hurricane Sandy. The storm surge arrived on a spring tide, which is normally higher than the mean, resulting in severe damage of the coastal human infrastructure (Mallin and Corbett 2006) as well as natural ecosystems. The worst flooding occurred along the New Jersey shore specifically in Middlesex, Monmouth and Ocean Counties (Sullivan and Uccellini 2013). Sandy caused a storm surge of 13.31 feet (4m), (measured at Sandy Hook, NJ), which was 8.1 feet (2.4m) above the average high tide (Metcalfe 2012, Sullivan and Uccellini 2013). Despite the large storm surge there was no significant change in sea level within the back-bay 5 months following Hurricane Sandy (Aretxabaleta et al. 2014). Changes in mean water height (0.01-0.02m) within Barnegat Bay were attributed to typical winter weather patterns and not to barrier island breaching or geomorphic changes within the bay itself (Aretxabaleta et al. 2014).

Uniqueness of Research

There is little known about of how coastal nesting species of turtles are impacted by large storms. Studies have been conducted within Florida after Hurricane Andrew (August 1992) and within South Carolina after Hurricane Hugo (1989). These studies focused on sea turtles due to their endangered species status. Sea turtle beach nesting occurs concurrently with the onset and duration of hurricane season. This timing remains distressing to ecologists trying to assist with conservation efforts of endangered sea turtles. Milton et al. (1994) found that nests closer to the "eye" of a hurricane had the highest egg mortality rate as a result of inundation of sea water from storm surge.

Because sand topography changed, eggs that "survived" inundation often ended up suffocating due to the change in sand particle size, sand buildup and/or detritus deposition above the nests after storm surges subsided, but before beach "clean-up" of human infrastructures commenced (Milton et al. 1994). Although terrapins (estuarine habitat) and sea turtles (marine habitat) are different species, they are both coastal nesters. Also, nesting substrate is predominantly sand for terrapins (Burger and Montevecchi 1975) and sea turtles and both have cleidoic eggs. Thus being inundated with seawater would be expected to affect them in similar ways.

Because hurricane season (June-October) and the sea turtle nesting season (March-November) practically overlap is another reason these species and others like them need to be more closely studied to determine how their nesting is impacted by coastal storms. Pike and Stiner (2007) specifically looked at the impact of storms on three endangered sea turtle species. They noticed these storms occur most during the turtle's nesting periods. Pike and Stiner's (2007) study found loggerhead (*Caretta caretta)* and leatherback (*Dermochelys coriacea*) turtles nest early in the nesting season, generally before hurricane season is in full swing while green turtles (*Chelonia mydas*) nest the latest, almost always within hurricane season. An increase in storms may worsen the stability of the green sea turtle population impacting its status on the endangered species list (Van Houtan and Bass 2007). Since the sea turtle populations are already in decline, conservation efforts are much more urgent.

Most of the hurricane studies are focused primarily within the southern and Gulf Coasts. There are seldom hurricane events of severe impact within the mid-Atlantic and North-Eastern regions, so before this study there had been little information available from those regions. However, since terrapins are confined within estuaries and therefore could be more vulnerable to stochastic events such as hurricanes and nor'easters, such studies are much needed. Understanding the breeding success of terrapins within the Sedge Island, Barnegat Bay ecosystem after a stochastic event such as Hurricane Sandy is vital. Understanding how these events can affect breeding ecology here in Barnegat Bay, NJ could provide information for all subspecies of terrapins, which span the entire Atlantic coast and the Gulf Coast (Butler et al. 2006, Hart and Lee 2007). If Hurricane Sandy had occurred earlier in the hurricane season, the storm could have impacted the

success of incubating eggs due to storm surges and prolonged flooding. Such was the case on Sedge Island during Hurricane Irene, which made landfall on the New Jersey coast in late August 2011. Females captured that year (85) laid 49 nests. Twenty-three nests on Sedge Island had incubating eggs when Irene hit all of which were lost to the flooding and washover. As a consequence, only 155 hatchlings emerged during the 2011 nesting season (Wnek et al. 2014). If the same event were to have happened in 2014, all of the embryos in the nests would have been lost as emergence was delayed that year until early September.

Since turtles are long-lived and have traits that make studying their recovery rate after a population decline difficult (Dodd et al. 2006), assessing the reproductive output of turtles within a few years after a major stochastic event should provide interesting and useful results. Such a study would be a stepping-stone to provide the scientific community with more insight on how well certain organisms could adapt to a changed environment after a stochastic event (Dodd et al. 2006). Such a study would also provide managers and agencies with new information on how well a species may survive a catastrophic natural disaster, the use of an indicator species to indicate the health of a salt marsh, as well as provide baseline data for a possible future study of the long-term recovery of terrapin populations in the Barnegat Bay region. With the continued loss of shoreline habitat as a result of sea level rise, knowledge about how terrapin habitats and populations may be affected by severe storm events can result in or help inform actions to maintain populations and establish new nesting areas.

Research Objectives

The intent of this study is to see if a high intensity event, like a super storm, affects the population dynamics of the northern diamondback terrapin. Specifically, we compared pre- and post-storm nesting numbers to assess any changes to female reproductive effort during two nesting seasons after Hurricane Sandy. Reproductive effort of females was calculated by comparing egg morphometrics, as follows;

- Overall egg mass (g) and length (mm) on Sedge Island amongst years (2010-2014)
- Overall hatchling success (% of embryos that emerge from eggs versus the total number of eggs) on N. Sedge Island

- Comparison of specific female reproductive effort amongst years
  - Egg mass (g) and length (mm)
- Comparison of clutch size of specific females
- Comparison of specific female reproductive effort amongst years
  - Hatchling success (% of embryos that emerge from eggs versus the total number of eggs)

We compared the acquired data from nesting seasons 2013 and 2014 with data from a 10-year study conducted within this area prior to the storm (Wnek 2010, Wnek et al. 2014).

Chapter 2 – Reproductive Ecology and Nesting Habitat

Diamondback terrapins nest from early June through mid-July in New Jersey (Burger 1977, Feinberg 2000, Wnek et al. 2014). Terrapins nest on dunes, beaches and sandy edges of marshes (Burger and Montevecchi 1975, Roosenburg 1994). The sandy soil in which these turtles prefer to nest does not clog eggshell pores allowing for adequate gas exchange (Roosenburg 1994, Wnek 2010). Terrapins prefer to nest on sunny days than on days with rain. They also prefer to nest during high tide and in areas that are sparsely vegetated (20-50% cover) while areas with greater than 75% vegetation cover are less likely to be used (Burger and Montevecci 1975, Burger 1977, Palmer and Cordes 1988, Zimmerman 1992, Feinberg 2000). Nesting season is longer in warmer climates than in cooler climates, which is a result of latitudinal temperature variations (Zimmerman 1992, Roosenburg and Kelley 1996). However, environmental conditions such as increased rain or cooler temperatures within a nesting season can prolong incubation time (Roosenburg 1991).

Diamondback terrapin eggs are elongated and symmetrical with blunt ends, a shape attributed to the physical constraints of the oviduct of an individual female (Montevecchi and Burger 1975). This shape can also allow them to fit into a smaller nest cavity. Within the first 24 hours of oviposition, eggs tend to be more translucent and pink, but after 24 hours egg shells become more opaque and white (Butler et al. 2006). Nesting days are variable across the species' range, from 42-50 days in New Jersey (Burger 1977), 64-70 days in New York (per one study; Feinberg and Burke 2003) and 60 days in South Carolina (Zimmerman 1992). Montevecchi and Burger (1975) found that within their study, all egg measurements from females producing multiple clutches decreased as the season progressed. However, this is not an annual trend with terrapins. Some females may not nest multiple times a year, or even annually; this has been seen within our study area (J. Wnek, personal communication).

Study Site

The most anthropogenically altered areas of coastal wetlands are tidal marshes because they are found mostly in temperate areas where industrialization began (Kirwan and Megonigal 2013). From 1972 to 1995, the barrier islands surrounding Barnegat Bay underwent an increased amount of human development, resulting in a loss of 25% of salt marsh habitat (Lathrop and Bognar 2001).

The Sedge Island Wildlife Management Area, Barnegat Bay, NJ (Figure 2-1) is managed by the New Jersey Division of Fish and Wildlife within a Marine Conservation Zone designated in 2003. It is located approximately 50 miles (80 km) north of Atlantic City, 8 miles (13 km) south of Seaside Park and 2 miles (3 km) north of the Barnegat Inlet. N. Sedge Island is approximately 88,600 m^2 (21.9 acres)(Wnek 2010). It is a salt marsh habitat that was modified when dredge material from the bay floor was deposited on the island in the 1930s (Martin 1959, Wnek 2010). There are four types of true tidal-marsh communities that occur on the southern-most segment of Island Beach, by percent vegetation cover and ground water salinity (GWS): Typical Salt Marsh: 87% of vegetation cover was comprised of *Spartina patens* with GWS of 23-26.6 parts per thousand (ppt), *Salicornia virginica:* was found in areas between the typical salt marsh and the bay and covered roughly 74% of total vegetation with GWS of 30 – 36 ppt, Mosaic Salt Marsh: occupied by *Distichlis spicata, Spartina patens* and *S. alterniflora* from highest elevation to lowest, respectively with a GWS of 25-33 ppt and finally Low elevation: scattered plants of *S. alterniflora* with a GWS of 30-42 ppt (Martin 1959).

Sedge Island is covered predominantly with native salt marsh grass, *Spartina* sp., and non-native common reed *Phagmites australis*, near nesting habitats (Wnek et al. 2013). Between 2002 and 2013, 374 individual females were reported to nest on N. Sedge Island (Wnek 2010, Wnek et al. 2014). N. Sedge Island was impacted by Hurricane Sandy; which caused a storm surge that pushed over 60 cubic yards of sand, predominantly loamy-sand, out of the nesting area (Figure 2-2; J. Wnek, personal communication, Figure 2-3a –Nesting Enclosure before Hurricane Sandy and Figure 2-3b – Nesting area shortly after Hurricane Sandy). I hypothesized that the loss of nesting medium would decrease the number of nests on N. Sedge Island one nesting season after Hurricane Sandy. I also postulated that there would be no change in reproductive output

(egg mass/length, clutch size, hatch success and site fidelity) during the following nesting season after Hurricane Sandy.

Figure 2-1. Location of the study site, N. Sedge Island Wildlife Management within Barnegat Bay, indicated by the red box. [39°40'N and 39°56'N latitude and 74°02'W and 74°12'W longitude (from Kennish 2000)]

Figure 2-2. Approximate landfall map of Hurricane Sandy along the New Jersey coast (upper left). All other photos show the damage to nesting area from Hurricane Sandy (Fall 2012). Photos show a glimpse of the effects of loss of 60 cubic yards of sand lost within the Northwest area of Sedge Island. A total of 600 cubic yards of sand was lost from the entire island after Hurricane Sandy.

Figure 2-3. Sedge Island Terrapin Nursery, Barnegat Bay, New Jersey.
   A.   Before Hurricane Sandy (2002-2011). B. After Hurricane Sandy (Late Fall 2012).

Materials and Methods

Identifying Nesting Terrapins

Nesting females terrapins were hand-captured daily (600 – 1600hrs) and location of nests was documented using a Garmin Global Positioning System (GPS) 72 hand-held meter (Butler et al. 2004). Nests could not be physically marked because marking might provide potential predators with a visual cue (Roosenburg and Dunham 1997, Feinberg and Burke 2003, J. Wnek, personal communication). Date and time of oviposition was recorded and all captured terrapins were marked with a unique identification code consisting of a marginal notch designation (Cagle 1939, Plummer 1979; Figure 2-5). Each female terrapin was measured using a 40cm tree caliper (± 1 mm) for the following linear measurements: carapace length (mm), carapace width (mm), and carapace height (mm). All captured terrapins without identification markers on scutes were scanned for the presence of a passive integrated transponder (PIT) tag using a multiple portable reader (MPR). A Destron® 12mm x 2 mm PIT tag was implanted into each newly captured turtle. Tags were injected using a MK 6 implanter (134.2 kHz) with a sterile N 100 needle (Buhlmann and Tuberville 1998). Terrapins were aged using the number of pectoral plastral scute annuli present (Lovich and Gibbons 1990; Figure 2-5). The same measurements, described above, were taken for returning females, which had notches on marginal scutes and a PIT tag present. Each captured terrapin was released 10-15 minutes after being processed to the same location as capture.
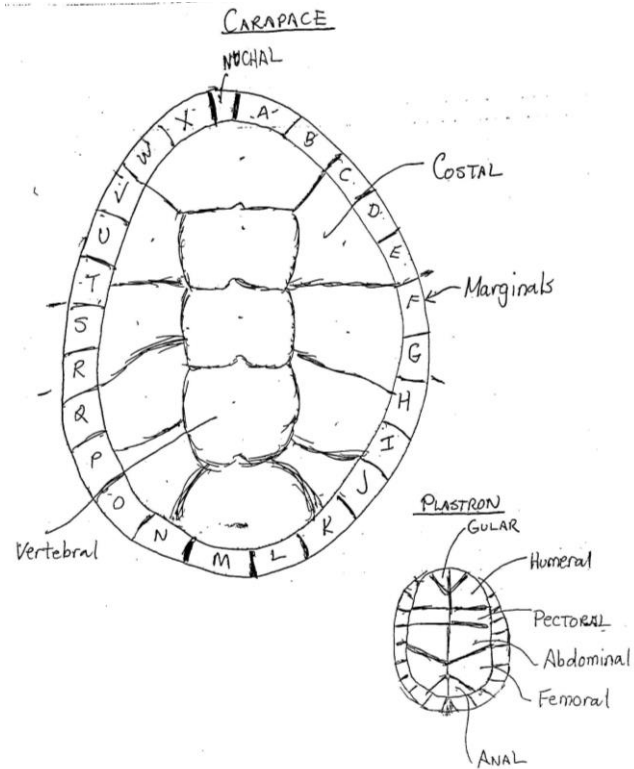
Figure 2-5. Nesting terrapin marked with unique nesting number for season. Morphometric measurements were taken and recorded with a 40cm tree caliper (± 1 mm) for the following linear measurements: carapace length (mm), carapace width (mm), carapace height (mm) and plastron length (mm). An approximate age of terrapins was made based on the number of plastral scute annuli present. An identifying "name" code was provided by the marginal scutes notched.

Reproductive Effort/ Nest Analysis

Females were captured at nesting sites after oviposition or prior if it was uncertain if the female terrapin was nesting. Nests were identified with a numeric value. A schedule for nesting coverage (observing nesting by females) was established with three other individuals who assisted me throughout the project to ensure that we encountered as many nesting terrapins at N. Sedge Island as possible. Numbers were assigned to each nesting female and painted on their carapaces to allow for terrapins to nest multiple times on the Island without needing to be recaptured. Gravid females that did not nest were also identified with a number on their carapace; these females were given priority observation when seen again during surveillance shifts. This ensured the maximum collection of eggs as well as decreased likelihood for eggs to be consumed by predators.

When a gravid female returned, the terrapin was allowed to nest and return to the water undisturbed. Nests were excavated and clutch sizes were determined. Nest depth was measured using a 30 cm ruler and rubber gloves were worn to prevent human scent from transferring to eggs, which may attract predators (Butler et al. 2004). Relatively frequently we had to fill holes dug by predators around the exterior of the hatchery, and place wooden blocks adjacent to most of the exterior walls to deter digging. Nests were strategically placed not near pen barriers for this reason. All eggs were weighed ($\pm$ 0.01 g) using an Ohaus® portable electronic scale. Egg length (mm) and width (mm) were measured using Mitutoyo 15 cm digital calipers (+/- 0.1 mm). Eggs were reburied in the same order, depth and orientation within the nest as that in which they were originally laid (Morjan and Janzen 2003). The eggs were moved into a predation free hatchery, on N. Sedge Island, each nest within the hatchery (a 24 square foot rectangular enclosure, placed approximately a foot deep within the ground with a foot of enclosure exposed. Enclosure "walls" are composed of metal mesh. The area was modified for nesting – void of vegetation) was identified with a serial number and covered by a predator excluder device made of 12.7 mm hardware cloth (Wnek 2010). A predator excluder device served an additional purpose, to keep emerging hatchlings contained for analysis before their release. Hand sanitizer was also used for additional protection against possible pathogens carried by the study species. After the eggs hatched, nests were assessed for hatching success (%), and egg mortality was also determined - sometimes the hatchlings are pipped (breaking open the egg) and die in the nest. Dead pipped terrapins were not recorded as hatchlings but "failed eggs".

Statistical Analysis

Hatching success was defined as the number of terrapins that emerged from the nest and/or were alive in the nest captivity during observations. A Univariate ANOVA with Tukey HSD post-hoc tests was used to compare arcsine-transformed percent hatched eggs between years (Roosenburg and Dunham 1997 and Wnek 2010). A Univariate ANOVA and Tukey HSD post-hoc tests were used to compare egg mass/length among years. A Kruskal-Wallis test was also used, for all ANOVA comparisons, to check for effects of unequal replication in terms of inflated type 1 error rate. A correlation analysis

was used to assess the relationship of mean egg mass to mean egg length on N. Sedge Island. Data are reported as means ± SE.

Results

It was predicted that a loss of nesting medium would cause a decrease in nests one nesting season after Hurricane Sandy. From the analysis of number of nests on North Sedge Island among the years (2010-2014) it was clear that the nesting season after Hurricane Sandy showed a substantial decrease in number of nests (n=32) when compared to years prior (2011 & 2012; Table 2-1). The similar nest number recorded in 2010 (n=38) was due to a lack of sampling effort because of another study being conducted on the Island (J. Wnek, personal communication). The number of female terrapins nesting in 2013 (n= 66) on N. Sedge Island was not considerably different from the year prior (2012: n=67). Individual eggs per nest have been averaged (n=177) to decrease replicate errors. There was a positive correlation shown between mean egg mass and mean egg length on N. Sedge Island (n = 177, $p < 0.001$). Mean egg mass (n = 177) on N. Sedge Island was significantly different among the years 2010-2014 (one-way ANOVA, $F = 5.235$, $p = 0.001$, Kruskal-Wallis Test: $p = 0.002$, Figure 2-6). Mean egg mass for 2010 (7.24g; n = 7) was significantly lower than all other years (Tukey post-hoc test: 2011-14; Mean mass, respectively: 8.15g, 8.38g, 8.44g, 8.71g, n = 170, $p < 0.02$). Mean egg mass for the 2013 nesting season (8.44g; n=31) was not significantly different from the nesting season before Hurricane Sandy (Tukey post-hoc test: 2012; 8.38g, n=41, $p = 0.999$) or the nesting season after Hurricane Sandy (Tukey post-hoc test: 2014; 8.71g, n=49, $p = 0.699$). Mean egg mass for the nesting season during Hurricane Irene (2011) was significantly lower (8.15g; n=49) than two nesting seasons after Hurricane Irene (Tukey post-hoc test: 2013; 8.44g, n=49, $p = 0.02$). Mean egg length (n = 177) on N. Sedge Island was significantly different among the years 2010-2014 (Kruskal-Wallis Test: $p = 0.009$, one-way ANOVA, $F = 1.668$, $p = 0.16$). Since the ANOVA did not determine a significant difference but the Kruskal-Wallis test did, there is no post-hoc test to determine which years were different from each other. Mean hatch success on N. Sedge Island was significantly different among years 2010-2014, with success being highest (88%) in nesting season 2014 (Univariate ANOVA, $F = 3.469$, $p = 0.009$;

Kruskal-Wallis Test: p = 0.011, Figure 2-8). The nesting season for 2013 was not significantly different for hatch success (71%) when compared to all nesting seasons prior to Hurricane Sandy (Tukey post-hoc test: 2010-12; respectively: 75%, 69%, 75%, p= 0.9) but was significantly lower than two nesting seasons after Hurricane Sandy (Tukey post-hoc test: 2014, 88%, p = 0.022).

Table 2-1. A comparison of diamondback terrapin nesting parameters over five years (2010-2014). Asterisks (*) indicates one female per year (AHPW and BIKO, respectively) produced three clutches within a single nesting season.

Nesting Year	Number of Nests	Number of New Captures	Number of Recaptured within the same season	Number Recaptured	Total Nesting
2010	38	8	2	69	77
2011	49	17	9*	72	89
2012	55	6	9	61	67
2013	32	9	5	57	66
2014	53	7	9*	65	72
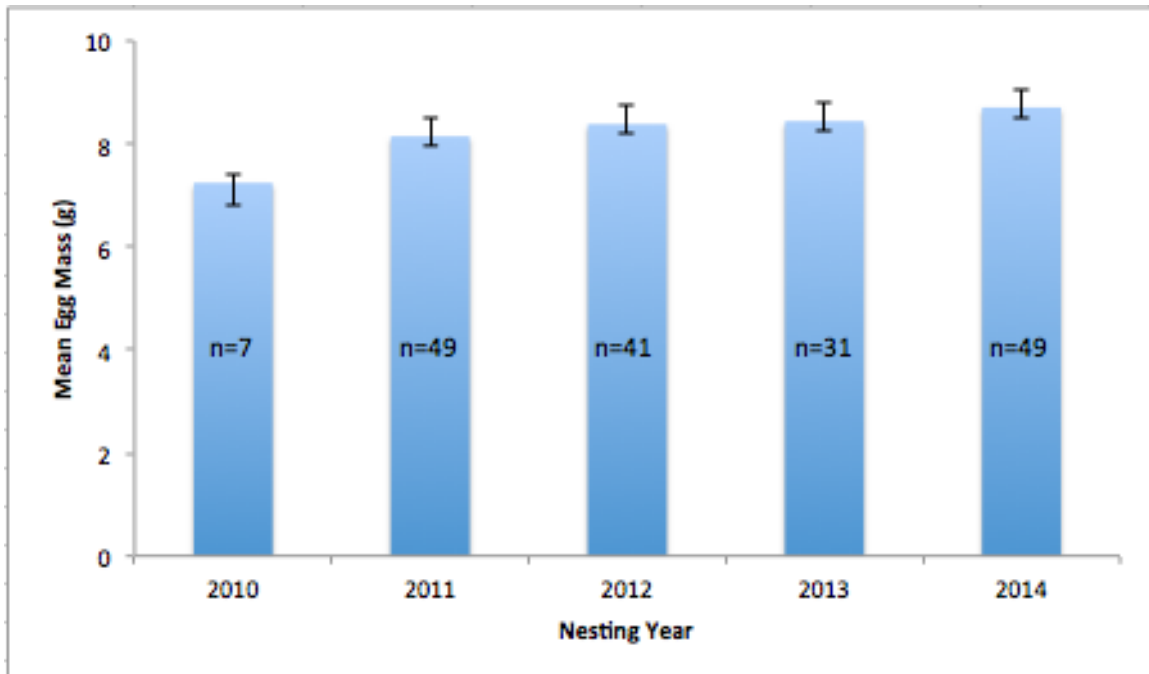
Figure 2-6. Mean mass (± SE) of all eggs deposited on North Sedge Island over five years (2010-2014).
The mean mass of eggs between the years showed a significant difference (ANOVA, F = 5.235, p = 0.001; Roosenburg 1992, Wnek 2010). Tukey post-hoc test indicates that the mean egg mass for the 2010 nesting season (7.24g, n=7) was significantly lower in comparison to all other years (2011-14).
Mean egg mass for the 2013 nesting season (8.44g) was not significantly different when compared to a year before Hurricane Sandy (Tukey post-hoc test: 2012, 8.38g, n=31, p = 0.999) nor two seasons after Hurricane Sandy (Tukey post-hoc test: 2014, 8.71g, n=49, p=0.699). Total number of eggs, per nest, were averaged in each year. Total number of averaged nests (n) are displayed.
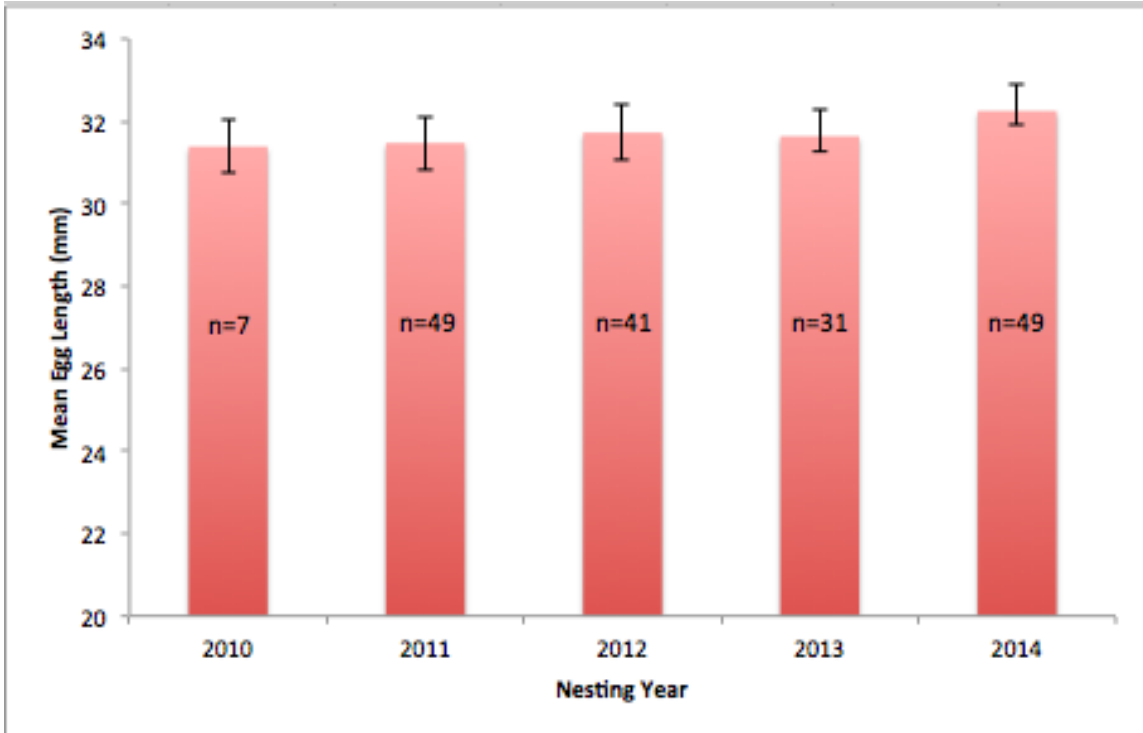
Figure 2-7. Mean egg length (± SE) of all eggs deposited on North Sedge Island over five years (2010-2014). Mean egg length showed a significant difference among the years 2010-2014 (Kruskal-Wallis Test: p = 0.009, one-way ANOVA, F = 1.668, p = 0.16; Roosenburg 1992, Wnek 2010). Total number of eggs, per nest, were averaged in each year. Total number of averaged nests (n) are displayed.
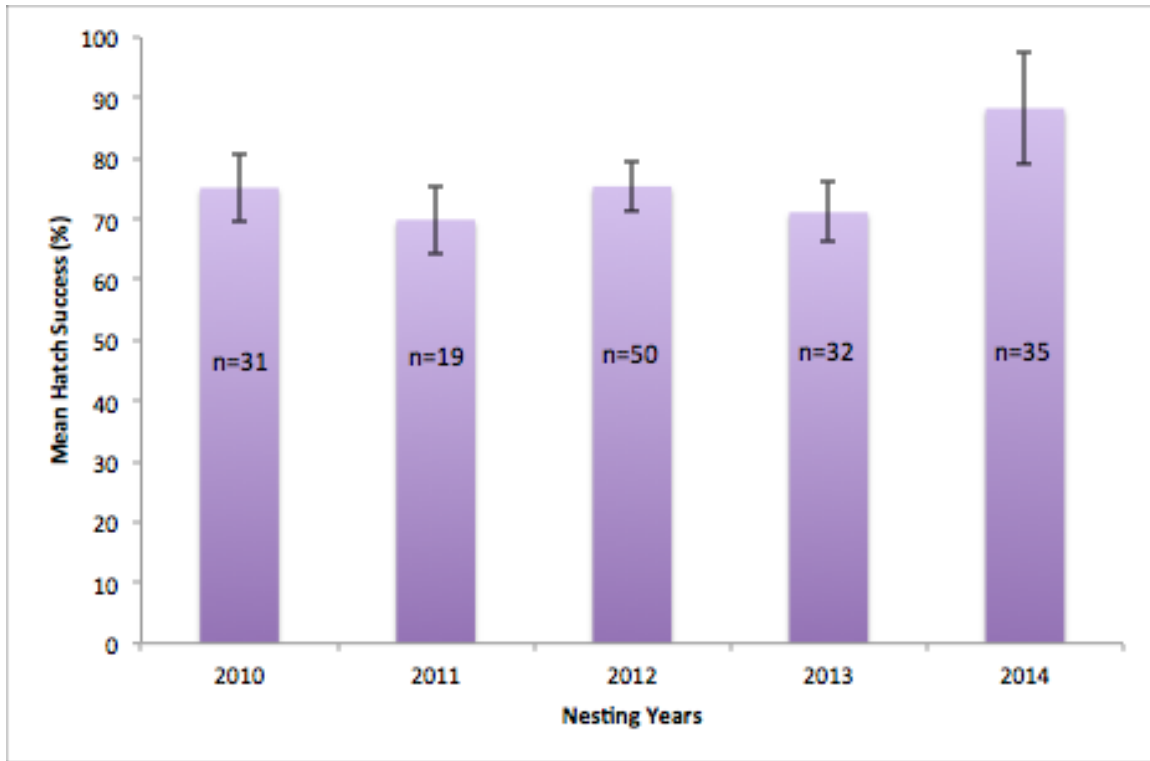
Figure 2-8. Mean percent hatch success (± SE) on North Sedge Island over five years (2010-2014). Mean hatch success showed a significant difference among years 2010-2014 (Univariate ANOVA, F = 3.469, p = 0.011). Hatch success for the 2013 nesting season (71%) was not significantly different when compared to all years prior to Hurricane Sandy (Tukey post-hoc test: 2010-12, n=100, p= 0.9). The 2013 nesting season's hatch success (71%) was significantly lower than the 2014 nesting season (88%) after Hurricane Sandy (Tukey post-hoc test: 2014, 88%, p = 0.022). Nests in which eggs were not recorded prior to emergences were omitted from count. The number of nests analyzed (n) is given. Hurricane Irene (Late August 2011), Hurricane Sandy (Late October 2012).

Discussion

Resource accessibility and species resistance/resilience after a disturbance are likely to be interconnected (Gleason et al. 2008). Species-specific resilience and resistance-tolerance was found within tree species in Queensland, Australia after Cyclone Larry. Site and habitat-specific resource limitations likely forced a tradeoff between a species' ability to exhibit resistance, resilience or tolerance after a large stochastic event. For example, the increase of reproductive output within a species would be considered "risky" after recovering from an injury (resilience) or if the organism maintains its reproductive output, despite the injury (tolerance). For the organism's overall survival these circumstances (resilience or tolerance) would cause a tradeoff within the organism

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itself or between the organisms' habitat and itself, but not both (Gleason et al. 2008). Within our study, we did not explicitly look for terrapins exhibiting resistance, resilience or tolerance after a stochastic event. However, based on the similarity of number in terrapins visiting the island to nest before and after both Hurricanes Sandy and Irene, this population must be exhibiting one or more of those characteristics. An estuary is comprised of an array of environmentally sensitive habitats: sand beaches, bay islands, SAV, fish nursery areas, shellfish beds and waterfowl nesting grounds (Kennish 2001b), all of which can be easily impacted by stochastic weather events. The idea defined by Clements, that each organism is interconnected directly or indirectly to the other (Gleason et al. 2008), effects that drastically impact one may undoubtedly impact them all, to some degree.

The low mean hatch success (69%; Figure 2-8) of terrapins in 2011, following inundation by Hurricane Irene (this study), is similar to the observed low success rate of sea turtles hatching in Florida after Hurricane Andrew (Saffir-Simpson Category 4) in 1992 (Milton et al. 1994). Massive storm surges closer to the "eye" of Hurricane Andrew caused great mortality of Loggerhead Sea Turtle eggs (24.5% loss) and Green Sea Turtles eggs (62.8% loss; Milton et al. 1994). However, such negative effects are not always seen. This study's 2012 season's final hatchlings emerged just weeks before Hurricane Sandy made landfall in New Jersey with a mean hatch success of 75%. This was probably why the mean hatch success in the 2012 nesting season was statistically similar to years where there were no major recorded storms (75% - 2010; 71% - 2013). Hurricane Bob (Saffir-Simpson Category 3) passed over Cape Cod, Massachusetts (1991) and only a modest effect was seen on water and field-associated birds, woodland nesters and tree-hole nesters, due to the timing of landfall and overall effect of tree damage (Valiela et al. 1998).

The inundation of soil with salt ions from storm surges, like Hurricane Irene and Sandy, can reduce the viability of terrapin eggs in nests. In one study, 66% percent of terrapin eggs in nests with soil containing a high conductivity (> 7000 uS/cm) became desiccated and thus failed to hatch (Wnek 2010). The same study showed that dredged soil (unsorted sediments from the bottom of the bay channels, salt content 32 ppt; Wnek 2010) improved as an incubation substrate, as a result of decreasing salt content from

percolation of rain and snow within one year (Wnek et al. 2013). This could be the reason why the 2014 hatch success (88%) was significantly different from nesting years 2011-13. The soil had time to decrease in salt content for a year before terrapins nested, post-Sandy.

Terrapin capture numbers (2012: n=65, 2013: +1 female; 2014: +9 females) suggest that the storm surge during Hurricane Sandy did not cause a significant displacement of mature female terrapins from their habitat. This could be a species-specific resilience or tolerance not seen before in the diamondback terrapin northern sub-species because of the infrequency of large storms. After Hurricane Sandy, a difference of 23 nests was seen between the 2012 (n= 55) and 2013 (n=32) nesting season, and a 21-nest difference between 2013 and two nesting seasons after Hurricane Sandy (2014; n=53). There was only a 6-nest difference after Hurricane Irene (2011; Table 2-1). The loss of 60 cubic yards of nesting medium could have reduced nesting events on the North Sedge Island during 2013. A reason why might be that females who accessed the Island did not find the habitat favorable for nesting or perhaps they were not producing eggs because of some other factor associated with the storm not studied here, such as changed food supply. There did not seem to be any increase in nesting medium the following nesting season (2014) giving no formal enticement to the females to come back, other than the species high site fidelity. Our study did not focus on loss of vegetation but noted loss of nesting medium. Sometimes after a disturbance, a healthy fully vegetated marsh will no longer be covered by vegetation (e.g. *Batis maritima, Salicornia* sp. *Monanthochloe littoralis*) resulting in perching birds becoming displaced but potentially increasing the area of suitable habitat for water-bird species (Darnell and Smith 2004). Much like how different types of avian groups (shorebirds, perching birds, wading birds, and gulls and terns) prefer to reside in the vegetation best suited for their needs this loss of nesting may have deterred this study's nesting females from selecting N. Sedge Island that year.

In general on N. Sedge island, egg mass tends to increase overall as females age, clutch production varied (Table 2-2) and the overall clutch size increased for three years, then decreased in 2013 and 2014 (J. Wnek Personal Communication). These findings support the experience and effort hypotheses. Age-specific reproductive success can be

explained by using three hypotheses: the experience hypothesis, effort hypothesis or the selection hypothesis. The first hypothesis states that, with experience, an organism's reproductive success would increase. The effort hypothesis states that the more effort an organism puts into reproducing the higher its reproductive output would be throughout its life. The final hypothesis selection, suggests that phenotypic variation will cause certain less-fit individuals to gradually disappear due to unfavorable traits and thus increase fecundity of the fitter phenotypic organisms. Mauck et al. (2004) found there to be a positive relationship between effort and experience, when experimenting with Leach's storm-petrel (*Oceanodroma leucorhoa*) seabirds. Within a 38-year study on painted turtles (*Chrysemys picta)* at the University of Michigan's E.S. George Reserve indeterminate growth was found to be an important factor for reproductive output of older turtles (Congdon et al. 2003). As these turtles grow larger they reproduce more (clutch production per season, egg size and hatchling size), but their frequency of nesting (season to season) and clutch size does not increase with age (Congdon et al. 2003).

To date there have been terrapin-related studies focusing on egg size theory (Roosenburg and Dunham 1997) but not on terrapin longevity or reproductive output, making study of this aspect of terrapin biology critical in the future. It has also been reported that terrapins along the southern Atlantic coast produce up to three nests within a single season (Seigel 1980a) probably due to a long nesting seasons in warmer climates (Zimmerman 1992). Triple clutching was observed within this study, but not as frequently as within the southern state studies. Seigel (1980a) reported that eggs from the Florida terrapin (*M. t. tequesta*) are significantly greater in both length and mass than those of its northern relatives (*M. t. terrapin* or *M. t. pileata*). This pattern may suggest that the subspecies follow different reproductive strategies; large clutches of small eggs laid in a defined area through the nesting season (temperate zones) or small clutches of large eggs laid continuously at random throughout the nesting season (tropical zones) (Moll 1979).

With the expected sea level rise as a result of climate change, there needs to be a greater emphasis on the study of the effects of storms on nesting habitats. We need to better understand site fidelity and the tolerance of terrapins to impacts on terrapin nesting

areas. We also need to better determine how this species adapts to changes in its nesting habitats, which will lead to better conservation practices.

Table 2-2. This data is part of a long-term study on N. Sedge Island in which this study gathered data towards. Selected females, indicated by notch code, among study years comparing egg masses (g) and clutch output per year. An asterisk (*) denotes eggs being laid but were not massed due to a soil sampling experiment being conducted that year.

ABHIW			BIKO			HJLWX		
Nesting Year	Clutch Number	Egg Mass(g)	Nesting Year	Clutch Number	Egg Mass(g)	Nesting Year	Clutch Number	Egg Mass (g)
2010	1	7.8	2010	N/A	N/A	2010	N/A	N/A
2011	2	7.4	2011	2	8.3	2011	1	8.4
2012	1	7.5	2012	N/A	N/A	2012	N/A	N/A
2013	N/A	N/A	2013	1	9.2	2013	1	8.5
2014	1	8.2	2014	3	8.4	2014	1	7.3
AHOW			CIPWX			NOVW		
Nesting Year	Clutch Number	Egg Mass(g)	Nesting Year	Clutch Number	Egg Mass(g)	Nesting Year	Clutch Number	Egg Mass (g)
2010	N/A	N/A	2010	1	5.22	2010	N/A	N/A
2011	N/A	N/A	2011	1	8.3	2011	1	8.1
2012	1	8.4	2012	1	8.5	2012	1	8.7
2013	1	8.4	2013	N/A	N/A	2013	N/A	N/A
2014	1	8.3	2014	1	N/A	2014	1	7.4
BCHW			CNPWX			NPQW		
Nesting Year	Clutch Number	Egg Mass(g)	Nesting Year	Clutch Number	Egg Mass(g)	Nesting Year	Clutch Number	Egg Mass (g)
2010	2	N/A *	2010	N/A	N/A	2010	1	7.1
2011	1	8.5	2011	N/A	N/A	2011	1	6.9
2012	2	8.0	2012	1	8.0	2012	1	6.7
2013	2	7.9	2013	1	8.4	2013	1	7.3
2014	2	8.6	2014	1	8.9	2014	N/A	N/A
BHIO			HIKNW			NPVW		
Nesting Year	Clutch Number	Egg Mass(g)	Nesting Year	Clutch Number	Egg Mass(g)	Nesting Year	Clutch Number	Egg Mass (g)
2010	N/A	N/A	2010	N/A	N/A	2010	N/A	N/A
2011	1	7.5	2011	2	9.2	2011	1	8.5
2012	2	8.2	2012	1	9.5	2012	N/A	N/A
2013	2	8.2	2013	N/A	N/A	2013	1	9.3
2014	1	8.9	2014	N/A	N/A	2014	1	8.6

Chapter 3 – Reproductive Ecology: Nesting Habitat, Site Fidelity and Hatch Success

Female terrapins are often seen walking through marsh grass (*Spartina* sp.) to the edge of sand dunes to lay eggs (Burger 1977). They often lay eggs away from vegetation and on high dune areas (Burger and Montevecchi 1975). Female terrapins can stop digging their nest if they become disturbed and subsequently leave if no eggs have been deposited (Burger 1977). Many studies focus on terrapin reproductive characteristics, such as clutch size, egg size, hatch success and nest site fidelity (Roosenburg 1991, Roosenburg 1996, Roosenburg and Kelley 1996, Gibbons et al. 2001 and Sheridan et al. 2010). Within the family Emydidae clutch size, egg mass and total clutch mass increase as female mass increases (Congdon and Gibbons 1985). Within terrapin populations in Chesapeake Bay, egg mass varied little within clutches (Roosenburg and Dunham 1997); mean egg mass was noticeably different between clutches and an increase in female plastron length correlated with an increase in clutch size (Roosenburg and Kelley 1996). A larger female terrapin (size of plastron length versus overall mass) is able to hold more eggs, which increases her clutch size. This could support the experience and effort hypotheses.

Nesting beaches may be a limiting factor (environmental control) to terrapin distribution (Mann 1995). Female terrapins have been observed returning to specific nesting sites within and among years (Roosenburg and Dunham 1997) despite being able to make long expeditions to other similar nesting sites within their marsh habitat (Roosenburg 1999, Gibbons et al. 2001). During a long-term study (1987-97) of diamondback terrapins near the Kiawah River, South Carolina, Gibbons et al. (2001) observed that site fidelity remained unchanged, even after Hurricane Hugo (Category 4) made landfall in the fall of 1989. Hurricane Hugo had sustained winds of 120 knots (140 mph) with an encompassing storm surge of 4 m (13 feet) above mean sea level when it made landfall near Sullivan's Island, SC (Armstrong 2014) approximately 10 km (6 miles) north of Gibbons et al. (2001)'s study site. Hart (2007) was testing mark and recapture methods for mangrove terrapins (2001- 07) within the everglades of Florida when Hurricane Wilma, a Category 3, (October 2005) passed directly over her study sites. Hart (2007) also found that there was no significant change in site fidelity after

Hurricane Wilma which had sustained winds of 100 knots (115 mph) but intensified to 110 knots (125 mph) as it made landfall (NOAA: National Climatic Data Center 2005).

The seasonal dispersal of female terrapins from foraging areas to nesting areas was observed within the "direct dispersal" section of the study by Sheridan et al. (2010). Sheridan and colleagues compared the dispersal of terrapins in a section of Barnegat Bay, New Jersey to Gibbons et al. (2001)'s long-term study in South Carolina. Sheridan et al. (2010) also found that females generally remain loyal to nesting areas 149 individuals (21.5%) were recaptured at least once compared to Gibbons et al. (2001) 25 (5.7%) of 442 terrapins recaptured at least once. Due to this site fidelity, a female terrapin would probably still nest in an area that becomes degraded by the storm. This pattern could lead to a reduction in hatching success and thus could lead to an overall reduction in the overall population.

Terrapin hatch success varies from year to year and location to location due to predation and environmental/habitat conditions (Burger 1977, Feinberg and Burke 2003, Butler et al. 2004). Emergence of hatchlings does not generally occur before August in New Jersey (Montevecchi and Burger 1975). Hatchlings generally emerge from the nest one to nine days after pipping (Burger 1976). Within New Jersey, hatch success ranges from 25% - 84% (Burger 1977, Wnek et al. 2013) excluding predation loss (generally recorded during egg assessment). Nest predation is the major cause of low hatch success (Burger 1977, Roosenburg 1992, Goodwin 1994, Butler et al. 2004). Female terrapins become sexually mature at between 8-13 years old, with an estimated maximum output of 39 eggs per year (Roosenburg 1991). However, Wnek (2010) found that there was a maximum of 54 eggs produced within a single nesting season by a terrapin. Nest predation reduces hatch success to 1-3%, which would mean that a female would need to produce her maximum egg output for three years to replace herself (Roosenburg 1991).

I hypothesized that there would be no change in reproductive output (egg mass/length, clutch size, hatch success and site fidelity) during the nesting season one year after Hurricane Sandy relative to the years immediately before or since. Individual females that demonstrated annual or bi-annual nesting patterns were selected for this analysis.

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Materials and Methods

Reproductive Effort/ Nest Analysis

Nesting female terrapins were identified and captured both prior to, and after nesting (Roosenburg and Dunham 1997). All captured females were marked with a marginal notch code (Cagle 1939) and injected with a PIT tag (Buhlmann and Tuberville 1998). Each terrapin had a unique identifying number sprayed on its rear vertebral carapace scutes so that the same terrapin would not be re-captured if it returned within the same nesting season. All female terrapins were then released on the Island the same day as they were captured. Nests were excavated and clutch sizes were determined. Nest depth was measured using a 30 cm ruler and rubber gloves were worn to prevent human scent from transferring to eggs, which may attract predators (Butler et al. 2004). All eggs were weighed ($\pm$ 0.01 g) using an Ohaus® portable electronic scale. Egg length (mm) and width (mm) was measured using a Mitutoyo 15 cm digital caliper ($\pm$ 0.1 mm). Eggs were reburied in the same order, orientation and depth (cm) in which they were originally laid (Morjan and Janzen, 2003). Depending on the area eggs were laid on the island, some or all of the eggs were moved into a hatchery (a 24 square foot rectangular enclosure, placed approximately a foot deep within the ground with a foot of enclosure exposed. Enclosure "walls" are composed of metal mesh. The area was modified for nesting – void of vegetation), on N. Sedge Island, to prevent egg predation. Each nest within the hatchery was identified with a unique number and covered by a predator excluder device made of 12.7 mm hardware cloth (Wnek 2010).

After the eggs hatched, nests were further assessed for hatchling success (%), and egg mortality was also determined – sometimes the hatchlings were pipped (breaking open the egg) and died in the nest. We determined hatch success by measuring the percentage of eggs that hatched out of the total number of eggs deposited within the clutch. We further determined hatching success as the number of hatchlings that emerged from the nest and/or were alive in the nest cavity during observation. Individual females were selected for further analysis based on frequency of nesting on Sedge Island within the selected study time frame: 2010-2014 (Table 3-1). Sometimes, terrapin hatchlings emerged immediately and made their way to the nearest marsh system. However, some hatchlings remained in the nest cavity. This may be the result of hatchlings overwintering

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in the nest cavity as there is no advantage to the hatchlings leaving the nest cavity in the late summer or early fall, so they may remain in the nest until the following spring (Baker et al. 2006; Russ Burke, personal communication). When I observed emerging hatchlings, I dug into the cavity to assess the remainder of the clutch.

Statistical Analysis

Female terrapins were compared as individuals per year. Female hatch success could not be statistically compared with themselves between years or themselves against other selected females due to the variability of clutch production per season and/or the variability of nesting per season (annually vs. biannually or "random" patterns).

A Bonferroni corrected critical p value ($\alpha = 0.025$) was used to account for multiple comparisons within the raw data. A Univariate ANOVA and a Tukey post-hoc test was used to compare mean egg mass/length among years of individual selected females. A Univariate ANOVA with a Tukey post-hoc test was used to compare clutch size and egg count among years for individual selected females. A correlation analysis was used to assess any trends among a variety of aspects including female mass/plastron length to mean egg mass/length and mean clutch size. Correlation analysis was run for the nesting season directly after Hurricane Sandy (2013), the nesting season before Hurricane Sandy (2012) and two nesting seasons after Hurricane Sandy (2014). Correlation analysis was used to compare aspects of reproductive output (mean egg mass/length and number of eggs produced) to selected female terrapin measurements (plastron length and female body size). Table 3-1 shows the selected females chosen to be compared within this portion of the study.

Results

Overall for the species, there wasn't a definitive change for any of the aspects of reproductive output that I analyzed: mean egg mass (one-way ANOVA by year: F = 3.180 p = 0.025; one-way ANOVA by TerrapinID, F = 2.780, p = 0.015), mean egg length (one-way ANOVA by year: F = 0.435 p = 0.782; one-way ANOVA by terrapinID, F = 1.109, p = 0.392), clutch size (one-way ANOVA by year: F = 0.084 p = 0.987; one-way ANOVA by terrapinID, F = 2.710, p = 0.019), total clutch production (one-way

ANOVA by year: F = 0.189, p = 0.943; one-way ANOVA by terrapinID, F = 2.381, p = 0.03) over the study period. However, mean egg mass (comparing both year and selected terrapin) values, clutch size by selected terrapins and clutch production by selected terrapins were significantly different amongst years analyzed (2010-2014).

Figure 3-1 shows the fecundity of the selected females over the study years (2010-14). Some of the individuals exhibit variable output. This was indicated by significant differences in a few of the selected female terrapins for mean egg mass when compared to other selected females (Appendix A), mean egg mass when compared by year (Appendix B), egg count between selected female terrapins and total clutch production between selected female terrapins. A significant difference was found between selected female terrapins and total clutch production over this study period (one-way ANOVA: F = 2.610, p = 0.019). Table 3-2 indicates selected females total clutch output per year and the corresponding hatch success for the nesting season. There was no significant difference between amounts of egg produced by selected female terrapins within the study period (one-way ANOVA: F = 2.381, p = 0.030, Bonferroni corrected critical p = 0.025).

Mean egg mass for individual reproductive output showed a definitive change between terrapin notch code NPQW and two other female terrapins, code NPVW (Tukey post-hoc test: p = 0.039) and code HIKNW (Tukey post-hoc test: p = 0.017, Appendix A). Similarly, mean egg mass for individual reproductive output showed a definitive change between nesting season 2010 relative to 2013 (Tukey post-hoc test: p = 0.013) and 2014 (Tukey post-hoc test: p = 0.024, Appendix B), in this study. Mean egg length showed no definitive change for individual reproductive output among years in this study (one-way ANOVA: p = 0.782) or amongst other females (one-way ANOVA: p = 0.392).

Table 3-1. Twelve females selected for analysis were compared using: body mass to egg mass, body size to clutch size between and hatch success amongst years (2010-14). These females were selected because they are consistent nesters on the island, as well as nested for a minimum of one nesting season when a hurricane (Irene or Sandy) made landfall at this study site. An asterisk (*) indicates a female which laid more than one clutch within one year. A carrot (^) indicates a female which has laid more than one clutch within two or more years. Females indicated by a # had clutches that were completely lost (washed out of the nest cavity and failed) after Hurricane Irene made landfall during August 2011.

Terrapin ID	Mean Plastron Length (mm)	Mean Mass (grams)	Clutch Count (2010-14)
ABHIW	182.5	1311.5	5*
AHOW	176.0	1221.3	3
BCHW#	181.0	1421.8	9^
BHIO	177.2	1337.4	6^
BIKO#	170.7	1227.2	6^
CIPWX	163.2	986.2	4
CNPWX	170.6	1180.2	3
HIKNW#	189.5	1465.6	3*
HJLWX#	168.6	1057.7	2
NOVW	177.5	1432.8	3
NPQW#	162.7	1001.6	4
NPVW#	171.3	1144.0	3

Table 3-2. Hatch Success (%) per female per year.

Years denoted (*) have more than one clutch laid, (**) indicates a triple nester.

Hatch Success calculated by (Eggs Emerged/Egg Laid)*100.

Terrapin ID	Year	Eggs Laid	Eggs Emerged	Hatch Success (%)
ABHIW	2010	11	10	91
	2011*	30	11	37
	2012	15	12	80
	2013	N/A		
	2014	14	14	100
AHOW				
	2010	N/A		
	2011	N/A		
	2012	13	9	69
	2013	14	12	86
	2014	15	15	100
BCHW				
	2010*	15	14	93
	2011	14	0	0
	2012*	27	23	85
	2013*	30	30	100
	2014*	30	14	47
BHIO				
	2010	N/A		
	2011	14	11	79
	2012*	26	25	96
	2013*	28	20	71
	2014	14	9	64
BIKO				
	2010	N/A		
	2011*	28	0	0
	2012	N/A		
	2013	13	10	77
	2014**	30	27	90
CIPWX				
	2010	20	20	100
	2011	12	9	75
	2012	13	13	100
	2013	N/A		
	2014	N/A		
CNPWX				
	2010	N/A		
	2011	N/A		
	2012	10	4	40
	2013	10	6	60
	2014	8	7	88

HIKNW				
	2010	N/A		
	2011*	26	0	0
	2012	11	7	64
	2013	N/A		
	2014	N/A		
HJLWX				
	2010	N/A		
	2011	11	0	0
	2012	N/A		
	2013	14	13	93
	2014	12	10	83
NOVW				
	2010	N/A		
	2011	15	9	60
	2012	13	9	69
	2013	N/A		
	2014	15	14	93
NPQW				
	2010	11	9	82
	2011	10	0	0
	2012	12	12	100
	2013	11	11	100
	2014	N/A		
NPVW				
	2010	13	9	69
	2011	10	0	0
	2012	N/A		
	2013	11	3	27
	2014	14	10	71

One challenge in analyzing terrapin recapture data is that returning individuals do not consistently follow a nesting pattern. As a result, there may not be a chance to encounter all marked females annually. When comparing selected females' body mass (g) to mean egg mass (g) no correlations were found within the nesting season before (2012; $p = 0.138$), the year following (2013; $p = 0.580$), or two years after (2014; $p = 0.876$) Hurricane Sandy. When comparing selected females' body mass (g) to mean egg length (mm) no correlations were found within the nesting season before (2012; $p = 0.980$), the year after (2013; $p = 0.742$), or two years after (2014; $p = 0.809$) Hurricane Sandy. When comparing selected females' plastron length (mm) to the number of eggs the female produced a positive correlation was found only for the nesting year after Hurricane Sandy

(2013; p = 0.012, Figure 3-2), but not the season before (2012; p =0.532) or two seasons after (2014; p = 0.646). When comparing selected females' body mass (g) to the number of eggs the female produced no correlation for the season before (2012; p = 0.589), nesting season following (2013; p = 0.032, Bonferroni corrected critical p = 0.025, Figure 3-3), or two seasons after (2014; p = 0.311) Hurricane Sandy.

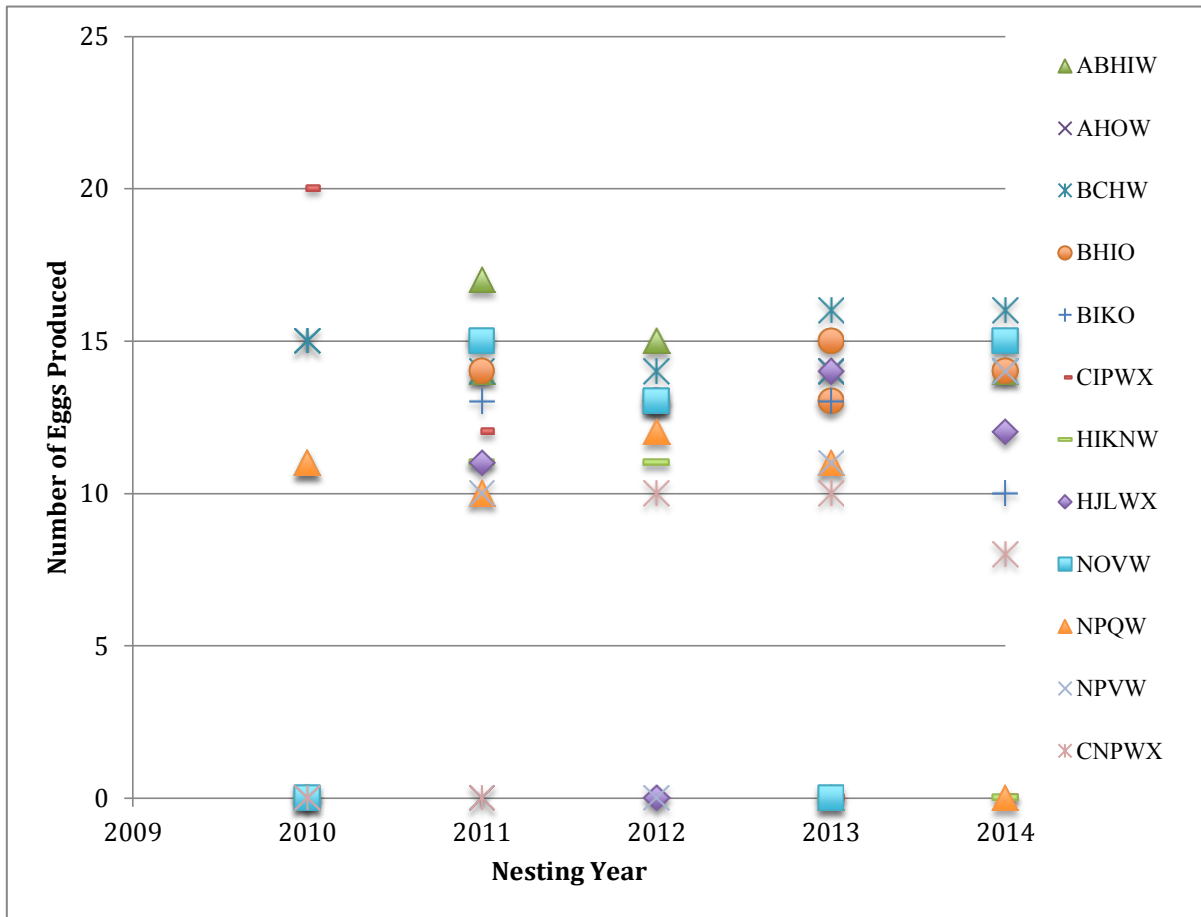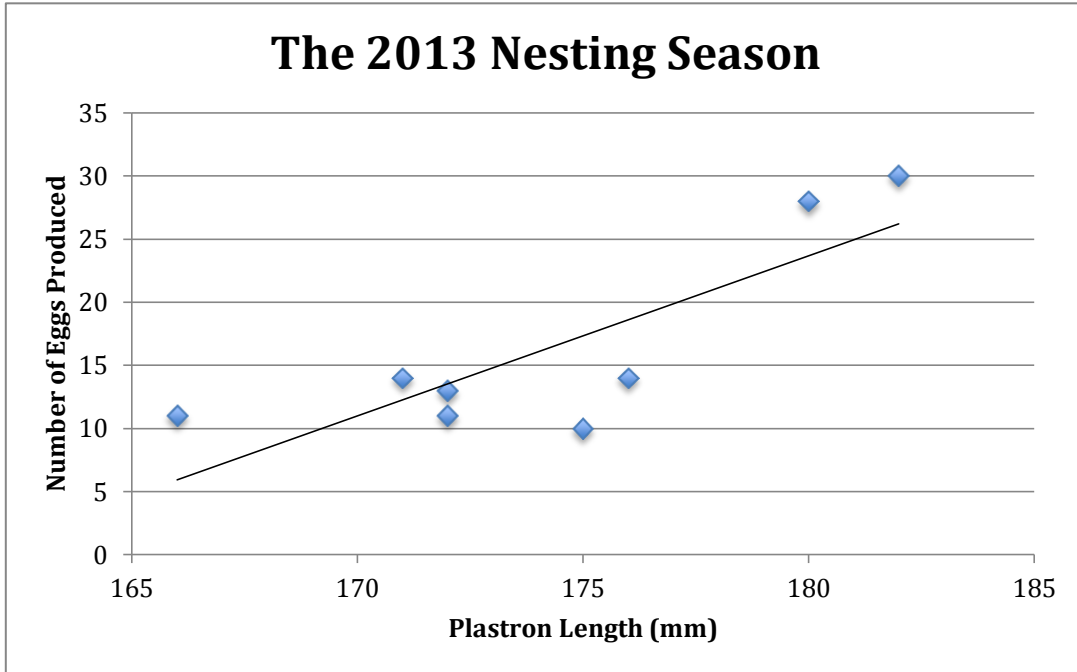Figure 3-1. Total fecundity (n=663) across successive nesting seasons for the 12 selected females from this study.

Figure 3-2. Correlation analysis comparing individual female plastron lengths (mm) to number of eggs produced in 2013 (p = 0.012, n = 8) at N. Sedge Island.
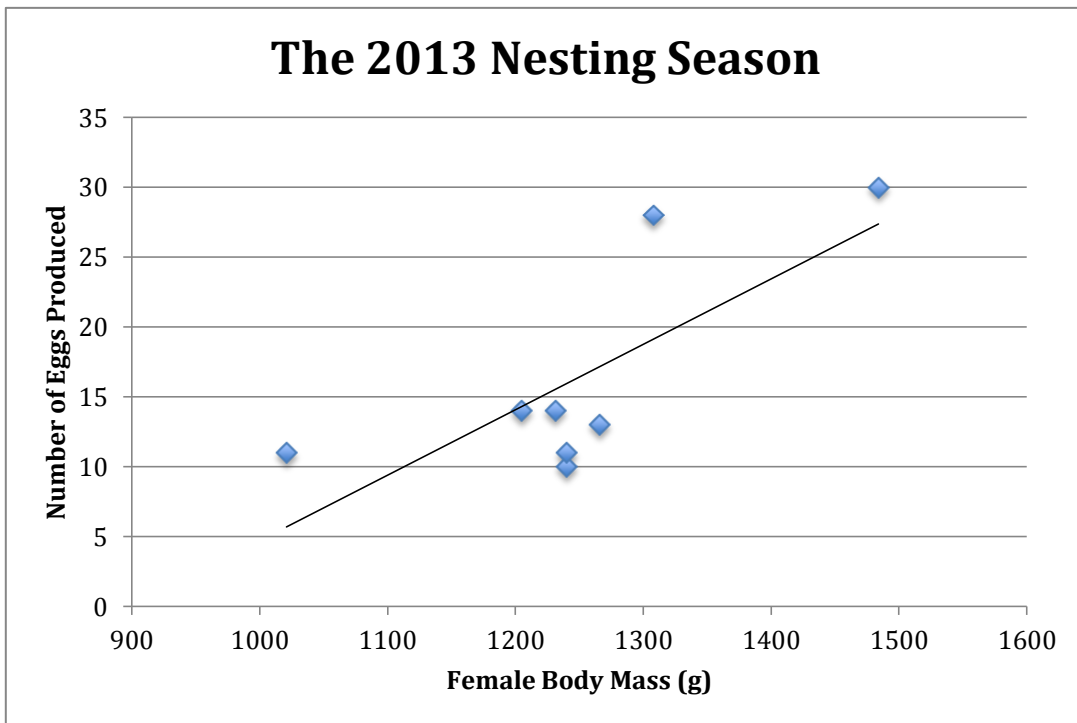

Figure 3-3. Correlation analysis comparing individual female body mass (g) to the number of eggs produced in 2013 (p = 0.032, n = 8) at N. Sedge Island.

Discussion

Site fidelity occurred in terrapins regardless of large environmental variations, year after year. This is evident in the selected female terrapins in this study (Table 3-1) which have returned to N. Sedge Island, NJ annually even after large stochastic events like Hurricane Irene and Hurricane Sandy. Gibbons et al. (2001) observed similar site fidelity over his 10-year study in South Carolina as did Hart (2007) within the Florida Everglades.

An environmental factor, like weather, can have varying effects on aspects on terrapins' reproduction. These aspects include: the length of incubation time (Roosenburg and Kelly 1996), gender determined by temperature during incubation (Jeyasuria et al. 1994), frequency of mating (multi-clutch; Seigel 1980a, Zimmerman 1992), and hatch success (Burger 1977). Out of the females selected for individual analysis, five females (42%) produced more than one clutch within their respective nesting years. This pattern of multiple clutches in a year is often seen within areas where there is a warmer, and subsequently longer nesting season (Zimmerman 1992). The data used for this study come from the nesting seasons 2010-2014. Over these years, mean hatch success ranged from 69 – 88% on N. Sedge Island. The lowest mean hatch success (69%) was seen after Hurricane Irene (Late August 2011). Mean hatch success from two nesting seasons after Hurricane Sandy (2014) increased by 17% from the nesting season following Sandy. Mean hatch success (2010; 75%) on N. Sedge Island during a year when an experimental soil conductivity tests was being conducted (Wnek 2010), did not differ from predicted ranges (25-84%) within this region (Burger 1977).

Table 3-3 shows the recorded temperatures and precipitation logged monthly at locations close to the research site (Beach Haven, Lanoka Harbor and Atlantic City, NJ). Coastal N.J. historic averages per month are values calculated from years 1971-2000 ("Old Normal"). Data values for study years were compared to "Old Normal" historic data. When data were retrieved for the months of June through October in this study's five years (June 2010 – October 2014), 21 of the 25 different temperature readings showed a warming of 0.2 - 2.9 degrees (°C) relative to the comparable historic "Old Normal" average monthly temperatures for coastal New Jersey (Table 3-3, Appendix C). Fourteen of the 25 different monthly precipitation averages were 0.6 - 21 cm wetter than

the historic "Old Normal" monthly average for precipitation along the coast for this study's years (Table 3-3, Appendix D). There was no significant difference in temperature (one-way ANOVA; F = 0.441, p = 0.91) or precipitation (one-way ANOVA F = 0.668, p = 0.62) during the years, comparing the same months across the years used within this study (2010-14).

Incubation times vary from state to state, with an average of 60-65 days in the southern states (Florida; Seigel 1980a, North Carolina; Butler et al. 2004 and Maryland; Roosenburg 1991) and 60-75 days in New Jersey (Burger 1977, Wnek 2010, Wnek et al. 2013, Wnek et al. 2014). An increase in temperature toward the end of the nesting season would allow the northern sub-species of terrapin more opportunities to oviposit multiple nests within a nesting season, like their southern counterparts. At lower temperatures (< 29°C) more male terrapin embryos are produced, but that also means a longer incubation time. If strong storms occur more frequently towards the end of the nesting seasons, these later nests, which can be assumed to be dominated by male embryos, will be at a greater risk for large storms to negatively impact them. Warmer average monthly temperatures during incubation would be expected to result in more terrapin embryos developing as female hatchlings (> 29.5°C) within each clutch. When comparing two sets of 30 years of historic coastal NJ average temperatures, 84% of our data (Table 3-3) for monthly temperature between June-October (2010-2014) is warmer by 0.2 - 2.9 °C. If warming trends continue within the next 30 years, one topic that should be at the forefront of ecological study is an emphasis on identifying gender ratios within known populations of terrapins, since this species exhibits temperature dependent sex determination.

Environmental factors such as, temperature and/or precipitation, in combination, may not have much net effect on hatch success. However, a longer season for nesting to occur would increase the chances of nest predation, though this might be offset by the increase in number of females producing more than two clutches per season. For August – October, 73% of the temperature values were higher than the mean historic value (Table 3-3, Appendix C). These temperature increases all occurred within the incubation/hatching portion of a terrapin's reproductive cycle. If higher temperatures become the "new normal" due to climate change, a pattern may be triggered for the nesting season to lengthen in the northern region. Firstly, this could cause more embryo

mortality as a result of predation within the nest. Secondly, hatchling size is negatively correlated with incubation temperatures such that warmer nests create smaller hatchlings (Cagle et al. 1993, Rhen and Lang 1999, Mullins and Janzen 2006). Longer incubation times, especially for nests laid later in nesting season, may allow nest predators more time to scavenge for them; this also allows for an increase in hatchling size, increasing the likelihood of high locomotor performance upon pipping (Doody 1999, Janzen et al. 2000, Freeberg et al. 2004, and Mullins and Janzen 2006). Lastly, if the nesting season for the northern sub-species of terrapin becomes extended and stochastic events become more frequent, within hurricane season, the two patterns will overlap. This overlap could cause much more mortality of eggs/hatchlings (later storms e.g. Irene), or an increased disturbance to nest substrate (e.g. Sandy). Terrapin eggs hatch from August through October. The latest eggs laid will hatch towards the end of the nesting season, when nighttime temperatures begin to drop, thus lowering nest temperatures. Overwintering of hatchlings in the nest can occur for two reasons. First, females historically deposit eggs into the nest in July. These hatchlings are then not fully developed until late September (Roosenburg et al. 2004). The safest place for them to stay at this time of the season is within the nest instead of trying to make their way towards the open water/reed grasses which would increase exposure to predation (Muldoon and Burke 2012). Secondly, the soil/sand composition can become more compact due to a precipitation change, making it more difficult for hatchlings to dig themselves out of the nest (Roosenburg et al. 2004). With the expected rise of temperature being greatest within the latter half of the nesting season, supported by preliminary data displaying June-Sept. 2015, (excluding Oct. difference from New Normal -0.28°C http://climate.rutgers.edu/stateclim_v1/data/coast_njhisttemp.html) as warmer than the historic "New Normal"; this could decrease the urgency for hatchlings to begin the overwinter process. Terrapin hatchlings can survive brief (12 hours) exposures of subfreezing temperatures (-1.2 °C), but are highly susceptible to inoculative freezing by contact with external ice within nesting soil (Baker et al. 2006). Even if the temperatures remain above normal during the day, at night temperatures can fall below freezing. During this time hatchling preparation for overwintering may not be complete (Baker et al 2006). Although there is little known about overwintering in this species, the change in temperatures could alter the "typical" lifecycle of a young terrapin.

Muldoon and Burke (2012) observed two types of overwintering: terrestrial outside the nest (TON) and terrestrial inside the nest (TIN). After Hurricane Irene (2011) passed over Rulers Bar Island in Jamaica Bay, NY six of 35 hatchlings that overwintered TIN were lost while other hatchlings that had already emerged and moved upland survived (Muldoon and Burke 2012). Since hurricanes are a regular occurrence along the Atlantic coast during incubation and emergence seasons these stochastic events may play an important selective role in hatchling success.

Table. 3-3. For the years 2010-2014, the temperature and precipitation records (Beach Haven, Lanoka Harbor and Atlantic City, NJ) near study location. (https://gis.ncdc.noaa.gov/maps/ncei/summaries/monthly). For the years 2010-2012 all temperature records were taken from the Beach Haven, NJ while 2013 and 2014 temperature records came from Atlantic City, NJ. All precipitation records were obtained from Lanoka Harbor, NJ. An asterisk (*) indicates values where temperature was above the historic coastal NJ average for that month. A carrot (^) indicates values that were above the historic coastal NJ average for that month for precipitation. Departure from the Normal represents the mean value per month difference from the given values within the row. 2010 values were compared to the "Old Normals" (Appendix C & D) and 2011-14 values were compared "New Normals" historical data sets (Appendix C & D). Historic values ("Normals") were calculated from an average monthly temperature from several stations throughout coastal N.J.
(Appendix C: http://climate.rutgers.edu/stateclim_v1/data/coast_njhisttemp.html).
Historic values ("Normals") were calculated from an average of precipitation totals recorded at several stations throughout coastal NJ and represent cm of liquid equivalent precipitation
(Appendix D: http://climate.rutgers.edu/stateclim_v1/data/coast_njhistprecip.html).

| | Average Temperature Recorded (°C) | | | | | |
Month	2010	2011	2012	2013	2014	Mean Departure From Normal
June	23.2*	23.0*	22.0*	21.3*	21.7*	+1.24
July	26.5*	26.0*	26.6*	24.6*	22.8	+1.80
August	24.7*	24.6*	25.5*	23.0	22.8	+1.16
September	21.9*	23.2*	21.4*	19.2	20.9*	+1.56
October	15.0*	15.6*	16.0*	16.1*	16.0*	+1.54

| | Average Precipitation Recorded (cm) | | | | | |
Month	2010	2011	2012	2013	2014	Mean Departure From Normal
June	4.3	7.4	17.4^	22.2^	5.5	+5.99
July	8.3	11.0^	14.1^	3.9	12.1^	+3.02
August	3.3	23.5^	10.9^	9.4	31.3^	+8.64
September	7.1	7.6	11.7^	4.1	9.6^	+2.23
October	21.7^	11.1^	17.4^	5.8	13.2^	+6.20

Terrapin IDs (notch code) NPQW, HIKNW and NPVW showed a difference for mean egg mass when compared to the other females. For all 12 selected female terrapins mean egg length and total egg production did not show a significant difference amongst the years studied (2010-2014) or between selected female terrapins. This may be not a result of the storm, or global climate change, but rather may just reflect the cyclic nature of terrapin reproductive output (J. Wnek, personal communication). Also, a sample size larger than 12 nesting female terrapins is probably necessary to determine if there was something substantially different about these years or if this cyclic reproductive output pattern within terrapins happened by chance.

Montevecchi and Burger (1975) found that all egg measurements (size and mass) decreased as the season progressed. This trend was not seen annually within the female terrapins analyzed or within our overall data. The correlation analysis did show a positive, significant relationship between plastron length and number of eggs produced within the 2013 season (directly after Hurricane Sandy). The general lack of significant correlations within my data may have been due to the small sample size analyzed. Of the females selected, only four laid eggs in the years before, of and after Hurricane Sandy (2012-14), which could have been the reason for the lack of significant results. This study supports Burger's 1975 finding that there was no relationship between female terrapin plastron length and egg measurements (mass, length and width). Differences between egg morphometrics (size and mass) seasonally may be a result of available resources in relationship to egg energetic reserves (Allman et al. 2012) and not the mother herself.

Mean hatch success ranged from 69-88% (average 77%) over the five years of this study, which is relatively high. Hatch success ranges from state to state, with a 12.8% in Rhode Island (Goodwin 1994), 25% in New Jersey (Burger 1977), 70% in a previous study, at this site (Wnek et al. 2013). The nesting season 2014 was by far the most successful in regards to mean hatch success (88%). When Hurricane Irene made landfall in New Jersey the recorded precipitation was 23.49cm in one event. However, that is less than the amount that fell during the emergence period of terrapin hatchlings three years later (August 2014; 31.34 cm). None the less, the arrival of that much rainwater over a short period of time can lead to flooding, whereas rain falling intermittently throughout a month might be expected to drain much more effectively; creating fewer opportunities for

waterlogging and associated oxygen stress for embryos. In 2006, Dr. Wnek and his volunteers observed high mortality of embryos in a nest that was inundated with water (15.24 cm) for just a few hours on N. Sedge Island (Wnek et al. 2013). Despite the high amounts of precipitation from Hurricane Irene, most of the rainfall in New Jersey occurred inland; coastal areas largely escaped heavy rainfall. Therefore, this inundation of terrapin nests in the area was more a result of seawater from storm surges along the coast. Flooding caused by rainfall was not an issue with Hurricane Sandy; however coastal flooding was severe.

As a result of climate change, there may be a lengthening of a terrapin's nesting season. However, this is highly speculative and not supported by this study. On the other hand, increased precipitation may result in a longer incubation time, which can lower hatch success.

This study shows a randomness of female terrapin reproductive output in terms of egg morphometrics each nesting season. As temperatures are expected to increase in the north as a result of Climate Change (IPCC Report 2014, pg 39), there may be an increase in the length of the nesting season, the emergence of hatchlings earlier in the summer as well as more females producing multiple clutches within a nest season. It has been reported that the southern sub-species experiences a longer nesting season. Along the coast of Texas, *M. t. littoralis* nests as early as the end of April (Hogan 2003). In Florida, Seigel (1980a) reported a nesting season 8-13 days longer (end of April – end of June) for the ornate terrapin (*M. t. tequesta*) when compared to Burger and Montevecci's (1975) 44 day nesting season (mid-May – mid July; *M.t. terrapin*) in New Jersey. The mid-latitudinal species (*M. t. centrata*), similarly has been recorded to begin the nesting season from late April – late July (78 days; Butler et al. 2004). A longer nesting season could allow females to forage longer between mating periods, which in turn, might result in a slight increase in egg mass output. An extension of time can make the embryos more vulnerable to a late summer/early fall weather event that could produce heavy rainfall or a storm surge. It was seen within Jamaica Bay Wildlife Refuge, New York that an increase in precipitation during the summer of 2004 decreased incubation time (Scholz 2006). A change in reproductive output for a species, however small, can eventually

cause a shift in the population structure if the factor causing the change in output continues. In this case, the factor is global climate change.

Chapter 4 - Conservation Management and Recommendations

Climate Change may cause a latitudinal shift in range of turtle species to more northern areas. Bombi et al. (2009) worked with Seychelle's freshwater turtles off the coast of Madagascar modeling habitat suitability and distribution shifts for *Pelusios castanoides* and *Pelusios subniger* under climate change scenarios. Bombi et al. (2009) found that the habitat stability of *P. castanoides* is expected to decrease greatly with a climate shift and this species will be forced to move further towards the coast. According to this model, *P. subniger* will also move south within its range in response to climate change, but will not have its habitat stability decrease due to this species ability to compete for space and food within sympatry (Bombi et al. 2009). Just because the terrapin's habitat is significantly further north does not mean that there is less cause for alarm for this aquatic species. Regions further from the equator will experience more of a global shift in temperature than regions near the equator.

Organizations all over New Jersey have been trying to increase the terrapin population since there have been high levels terrapin mortality within New Jersey. A diamondback terrapin's adult survival and fitness is particularly vital to maintaining the population because they are considered a harvested species in New Jersey, regardless of their population increase because of their protective game status (Wnek 2010). The Terrapin Conservation Project, supported by the Wetlands Institute, was launched in 1989 under the direction of Dr. Roger Wood, professor at Stockton University (formally Stockton College), due to a serious decline in the population within southern New Jersey. Mortality of females often occurs along roadways during the nesting season. The Conserve Wildlife Foundation of New Jersey began researching protective barriers to prevent terrapin road mortality in 2010. This organization had great success with halved corrugated tubing in 2012. Margate Terrapin Rescue Project focuses on decreasing road mortality by increasing public awareness. They too place a variety of fencing/barriers made of plastic Tenax half tubing along roadways in Little Egg Harbor, NJ. This tubing limits the female terrapin's ability to cross roadways. Road mortality isn't the only major

threat this species is facing. Human recreational activity and habitat loss can also harm terrapin populations. The Terrapin Nesting Project in Long Beach Island focuses on the protection of terrapin nests and their hatchlings. Landscaped yards, driveways, bulkheads and docks all decrease the sandy area terrapins require to nest. The main goal for this organization is to locate nests laid in unsuitable areas and relocate the eggs to a hatchery for incubation. Moving these eggs to areas that are habitable for this species has been one major component aiding in the increase of the population. Communities are coming together volunteering with these organizations. For example, the community of Sea Isle City has a young man transforming a garden, complete with two "Turtle islands" (an enhanced nesting area), in order to earn the prestigious Eagle Scout award.

At a broader level a number of legislative measures have been put in place to aid in protection of terrapins in New Jersey. In March 2015, the NJ Department of Environmental Protection recommended a temporary seasonal Executive Order to close the harvesting on terrapins (NJDEP 2015), which was set to expire March 31, 2016. In addition, Assembly Bill A2949 and Senate Bill S1625 would make terrapins a non-game species. Bill A2949 was unanimously passed by the Assembly on April 7, 2016, and Senate Bill 1625 is awaiting a vote. Executive Order 2016-02 stopped the harvest of terrapins for the remainder of the 2016 harvest season.

Terrapins have been studied in New Jersey since the 1970s, but it is still a challenge to estimate population size. The data from this study provided nesting population data for one area of Barnegat Bay. This study focused on effects of an alarming trend associated with climate change; increased intensity and frequency of large coastal storms impacting the north Atlantic region. There have not been many studies focusing on the impacts of storms on herpetofauna explicitly. Michener et al. (1997) exclusively focused on the impacts of Hurricane Hugo on waterbirds to identify how long-term studies focusing on biotic functions (community structure, natural selection, extinction rates and biodiversity) may benefit the scientific community. By contrast, Pike and Stiner (2007) focused on the level of vulnerability of three sea turtle species (leatherback, green and loggerhead) during and after a stochastic event. Pike and Stiner (2007) found that the severity of impact was determined by when the storm arrived and if it coincided with the peak nesting phase for that species of sea turtle; meaning for the

storm studies, leatherbacks were less affected than loggerheads, while most affected were green sea turtles, due to their late nesting season, which is predominantly (79%) in September. Terrapins may exhibit resilience when faced with a stochastic event. However, with a long-lived, slow maturing species coupled with low survivorship of eggs/hatchlings the effects of a large stochastic event may not be known for several more years in terms of the impact on the nesting population.

Estuaries provide habitat and breeding grounds for many species (Araujo 2002), including Black Skimmer (*Rynchops niger*), Piping Plover (*Charadrius melodus*), Roseate Tern (*Sterna dougalii*), Fiddler Crab (*Uca pugnax, U. minax*), Horseshoe Crab (*Limulus polyphemus*), Blue Crab (*Callinectes sapidus*) and the Northern Diamondback Terrapin (*Malaclemys terrapin terrapin*; Bochenek et al. 2001). Barrier islands are modified because of waves, tides and currents. Erosion along the coast influences the size of these barrier islands, especially in areas prone to flooding when major storms arise (Gutierrez et al. 2009). With an increased rise in sea level, storm tide levels become a greater threat to terrapin nesting areas. Our terrapin nesting site, N. Sedge Island, is within the 100 year flood zone (http://www.njfloodmapper.org/). According to the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model our study site would experience 3-6 feet (0.9–1.8m) of storm surge during a Saffir–Simpson Category 1 hurricane and 6-9 feet (1.8-2.7m) of storm surge in a Saffir–Simpson Category 2 hurricane (http://www.njfloodmapper.org/).

Studies previous to this have shown terrapin populations are negatively impacted by the loss of shoreline habitat (Feinberg 2000, Gibbons et al. 2001, Szerlag and McRobert 2006). With the increase of human recreation (kayaks, motor boats, fishing, etc.) and human development (bulkheading and dredging), change in the natural configuration of the coastline is likely to continue unimpeded, combining with more frequent flooding to decrease terrapin habitat (Winters 2013). Examining changes within a population during the nesting season, as was done in this study, will allow for the improvement of management practices and protection for terrapin habitats (Szerlag and McRobert 2007).

This study supports the fact that terrapins display nest site fidelity. Since site fidelity is constant for terrapin species an effort should be taken to create nesting areas in

eroded zones or to incorporate living shorelines (http://delawareestuary.org/living-shorelines) to aid in conservation efforts. Nest site enhancement projects are a method by which these eroded zones can be restored in ways that allow them to be utilized as nesting habitat by terrapins. The Massachusetts Audubon Society at Wellfleet is working on with Cape Abilities in Eastham creating steel wire cages to protect eggs from predators. Within New Jersey, the Marine Academy of Technology and Environmental Sciences (MATES) is working with Project Terrapin in partnership with the Conserve Wildlife Foundation in developing "Turtle Gardens" (Figure 4-1). A "Turtle Garden" is a patch of sandy soil above the high water line that provides nesting habitat for diamondback terrapins and other nesters. These "gardens" provide a safe place for terrapins to nest. They are composed of a mixture of sands and soils with different particle sizes. This mixture imitates the natural conditions of terrapin nesting habitat with plenty of space to dig down without being below the high water line. This group provides needed conservation efforts for terrapins but also, provides the opportunity to foster aspiring young minds at the grass roots of educational research. Aiding in conservation efforts is not only completed by sponsored organizations but by the communities as well.

Figure 4-1. Turtle Garden at Long Beach Island Foundation of the Arts and Sciences (LBIF), Loveladies, NJ, 2015.

Acknowledgements

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Appendix A. Mean egg mass (g) comparisons per selected females.

Multiple Comparisons

Dependent Variable: MeanEggMass

	(I) TerpID	(J) TerpID	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Tukey HSD	ABHIW (1)	2.00	-.66417	.51187	.972	-2.4899	1.1616
		3.00	-.55750	.47390	.987	-2.2478	1.1328
		4.00	-.50750	.47390	.994	-2.1978	1.1828
		5.00	-.90083	.51187	.825	-2.7266	.9249
		6.00	.38250	.51187	1.000	-1.4433	2.2083
		7.00	-.75750	.51187	.934	-2.5833	1.0683
		8.00	-1.60250	.58040	.251	-3.6727	.4677
		9.00	-.31750	.51187	1.000	-2.1433	1.5083
		10.00	-.33750	.51187	1.000	-2.1633	1.4883
		11.00	.74000	.47390	.908	-.9503	2.4303
		12.00	-1.14083	.51187	.545	-2.9666	.6849
	AHOW (2)	1.00	.66417	.51187	.972	-1.1616	2.4899
		3.00	.10667	.51187	1.000	-1.7191	1.9324
		4.00	.15667	.51187	1.000	-1.6691	1.9824
		5.00	-.23667	.54721	1.000	-2.1885	1.7152
		6.00	1.04667	.54721	.742	-.9052	2.9985
		7.00	-.09333	.54721	1.000	-2.0452	1.8585
		8.00	-.93833	.61180	.918	-3.1205	1.2439
		9.00	.34667	.54721	1.000	-1.6052	2.2985
		10.00	.32667	.54721	1.000	-1.6252	2.2785
		11.00	1.40417	.51187	.259	-.4216	3.2299
		12.00	-.47667	.54721	.999	-2.4285	1.4752
	BCHW (3)	1.00	.55750	.47390	.987	-1.1328	2.2478
		2.00	-.10667	.51187	1.000	-1.9324	1.7191
		4.00	.05000	.47390	1.000	-1.6403	1.7403
		5.00	-.34333	.51187	1.000	-2.1691	1.4824
		6.00	.94000	.51187	.785	-.8858	2.7658
		7.00	-.20000	.51187	1.000	-2.0258	1.6258
		8.00	-1.04500	.58040	.804	-3.1152	1.0252

		9.00	.24000	.51187	1.000	-1.5858	2.0658
		10.00	.22000	.51187	1.000	-1.6058	2.0458
		11.00	1.29750	.47390	.261	-.3928	2.9878
		12.00	-.58333	.51187	.990	-2.4091	1.2424
	BHIO (4)	1.00	.50750	.47390	.994	-1.1828	2.1978
		2.00	-.15667	.51187	1.000	-1.9824	1.6691
		3.00	-.05000	.47390	1.000	-1.7403	1.6403
		5.00	-.39333	.51187	1.000	-2.2191	1.4324
		6.00	.89000	.51187	.835	-.9358	2.7158
		7.00	-.25000	.51187	1.000	-2.0758	1.5758
		8.00	-1.09500	.58040	.757	-3.1652	.9752
		9.00	.19000	.51187	1.000	-1.6358	2.0158
		10.00	.17000	.51187	1.000	-1.6558	1.9958
		11.00	1.24750	.47390	.311	-.4428	2.9378
		12.00	-.63333	.51187	.980	-2.4591	1.1924
	BIKO (5)	1.00	.90083	.51187	.825	-.9249	2.7266
		2.00	.23667	.54721	1.000	-1.7152	2.1885
		3.00	.34333	.51187	1.000	-1.4824	2.1691
		4.00	.39333	.51187	1.000	-1.4324	2.2191
		6.00	1.28333	.54721	.472	-.6685	3.2352
		7.00	.14333	.54721	1.000	-1.8085	2.0952
		8.00	-.70167	.61180	.989	-2.8839	1.4805
		9.00	.58333	.54721	.994	-1.3685	2.5352
		10.00	.56333	.54721	.995	-1.3885	2.5152
		11.00	1.64083	.51187	.109	-.1849	3.4666
		12.00	-.24000	.54721	1.000	-2.1918	1.7118
	CIPWX (6)	1.00	-.38250	.51187	1.000	-2.2083	1.4433
		2.00	-1.04667	.54721	.742	-2.9985	.9052
		3.00	-.94000	.51187	.785	-2.7658	.8858
		4.00	-.89000	.51187	.835	-2.7158	.9358
		5.00	-1.28333	.54721	.472	-3.2352	.6685
		7.00	-1.14000	.54721	.638	-3.0918	.8118
		8.00	-1.98500	.61180	.100	-4.1672	.1972
		9.00	-.70000	.54721	.975	-2.6518	1.2518
		10.00	-.72000	.54721	.970	-2.6718	1.2318
		11.00	.35750	.51187	1.000	-1.4683	2.1833
		12.00	-1.52333	.54721	.241	-3.4752	.4285
	CNPWX	1.00	.75750	.51187	.934	-1.0683	2.5833

(7)		2.00	.09333	.54721	1.000	-1.8585	2.0452
		3.00	.20000	.51187	1.000	-1.6258	2.0258
		4.00	.25000	.51187	1.000	-1.5758	2.0758
		5.00	-.14333	.54721	1.000	-2.0952	1.8085
		6.00	1.14000	.54721	.638	-.8118	3.0918
		8.00	-.84500	.61180	.958	-3.0272	1.3372
		9.00	.44000	.54721	.999	-1.5118	2.3918
		10.00	.42000	.54721	1.000	-1.5318	2.3718
		11.00	1.49750	.51187	.187	-.3283	3.3233
		12.00	-.38333	.54721	1.000	-2.3352	1.5685
	HIKNW (8)	1.00	1.60250	.58040	.251	-.4677	3.6727
		2.00	.93833	.61180	.918	-1.2439	3.1205
		3.00	1.04500	.58040	.804	-1.0252	3.1152
		4.00	1.09500	.58040	.757	-.9752	3.1652
		5.00	.70167	.61180	.989	-1.4805	2.8839
		6.00	1.98500	.61180	.100	-.1972	4.1672
		7.00	.84500	.61180	.958	-1.3372	3.0272
		9.00	1.28500	.61180	.627	-.8972	3.4672
		10.00	1.26500	.61180	.647	-.9172	3.4472
		11.00	2.34250*	.58040	.017	.2723	4.4127
		12.00	.46167	.61180	1.000	-1.7205	2.6439
	HJLWX (9)	1.00	.31750	.51187	1.000	-1.5083	2.1433
		2.00	-.34667	.54721	1.000	-2.2985	1.6052
		3.00	-.24000	.51187	1.000	-2.0658	1.5858
		4.00	-.19000	.51187	1.000	-2.0158	1.6358
		5.00	-.58333	.54721	.994	-2.5352	1.3685
		6.00	.70000	.54721	.975	-1.2518	2.6518
		7.00	-.44000	.54721	.999	-2.3918	1.5118
		8.00	-1.28500	.61180	.627	-3.4672	.8972
		10.00	-.02000	.54721	1.000	-1.9718	1.9318
		11.00	1.05750	.51187	.648	-.7683	2.8833
		12.00	-.82333	.54721	.927	-2.7752	1.1285
	NOVW (10)	1.00	.33750	.51187	1.000	-1.4883	2.1633
		2.00	-.32667	.54721	1.000	-2.2785	1.6252
		3.00	-.22000	.51187	1.000	-2.0458	1.6058
		4.00	-.17000	.51187	1.000	-1.9958	1.6558
		5.00	-.56333	.54721	.995	-2.5152	1.3885
		6.00	.72000	.54721	.970	-1.2318	2.6718

		7.00	-.42000	.54721	1.000	-2.3718	1.5318
		8.00	-1.26500	.61180	.647	-3.4472	.9172
		9.00	.02000	.54721	1.000	-1.9318	1.9718
		11.00	1.07750	.51187	.624	-.7483	2.9033
		12.00	-.80333	.54721	.937	-2.7552	1.1485
	NPQW (11)	1.00	-.74000	.47390	.908	-2.4303	.9503
		2.00	-1.40417	.51187	.259	-3.2299	.4216
		3.00	-1.29750	.47390	.261	-2.9878	.3928
		4.00	-1.24750	.47390	.311	-2.9378	.4428
		5.00	-1.64083	.51187	.109	-3.4666	.1849
		6.00	-.35750	.51187	1.000	-2.1833	1.4683
		7.00	-1.49750	.51187	.187	-3.3233	.3283
		8.00	-2.34250*	.58040	.017	-4.4127	-.2723
		9.00	-1.05750	.51187	.648	-2.8833	.7683
		10.00	-1.07750	.51187	.624	-2.9033	.7483
		12.00	-1.88083*	.51187	.039	-3.7066	-.0551
	NPVW (12)	1.00	1.14083	.51187	.545	-.6849	2.9666
		2.00	.47667	.54721	.999	-1.4752	2.4285
		3.00	.58333	.51187	.990	-1.2424	2.4091
		4.00	.63333	.51187	.980	-1.1924	2.4591
		5.00	.24000	.54721	1.000	-1.7118	2.1918
		6.00	1.52333	.54721	.241	-.4285	3.4752
		7.00	.38333	.54721	1.000	-1.5685	2.3352
		8.00	-.46167	.61180	1.000	-2.6439	1.7205
		9.00	.82333	.54721	.927	-1.1285	2.7752
		10.00	.80333	.54721	.937	-1.1485	2.7552
		11.00	1.88083*	.51187	.039	.0551	3.7066

Appendix B. Mean egg mass (g) of selected females compared amongst years (2010-14).

						95% Confidence Interval	
	(I) Year	(J) Year	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Tukey HSD	2010.00	2011.00	-1.40000	.48979	.052	-2.8104	.0104
		2012.00	-1.46222*	.49603	.043	-2.8906	-.0339
		2013.00	-1.72125*	.50372	.013	-3.1717	-.2708
		2014.00	-1.58556*	.49603	.023	-3.0139	-.1572
	2011.00	2010.00	1.40000	.48979	.052	-.0104	2.8104
		2012.00	-.06222	.34186	1.000	-1.0466	.9222
		2013.00	-.32125	.35293	.891	-1.3375	.6950
		2014.00	-.18556	.34186	.982	-1.1700	.7989
	2012.00	2010.00	1.46222*	.49603	.043	.0339	2.8906
		2011.00	.06222	.34186	1.000	-.9222	1.0466
		2013.00	-.25903	.36154	.951	-1.3001	.7820
		2014.00	-.12333	.35075	.997	-1.1333	.8867
	2013.00	2010.00	1.72125*	.50372	.013	.2708	3.1717
		2011.00	.32125	.35293	.891	-.6950	1.3375
		2012.00	.25903	.36154	.951	-.7820	1.3001
		2014.00	.13569	.36154	.996	-.9054	1.1768
	2014.00	2010.00	1.58556*	.49603	.023	.1572	3.0139
		2011.00	.18556	.34186	.982	-.7989	1.1700
		2012.00	.12333	.35075	.997	-.8867	1.1333
		2013.00	-.13569	.36154	.996	-1.1768	.9054

Appendix C: Historic mean coastal temperature values are calculated from several stations throughout division 3: Atlantic, Cape May, Monmouth and Ocean counties within 10 miles of the coast.
(http://climate.rutgers.edu/stateclim_v1/data/coast_njhisttemp.html). Updated 5/10/16.

	Historical Climate Data: Coastal, NJ Average Temperature (°C)
Month/Year	"Old Normals" 1971-2000
June	20.6
July	23.7
August	23.2
September	19.8
October	13.8

Appendix D: Historic mean coastal precipitation values calculated from several stations throughout division 3: Atlantic, Cape May, Monmouth and Ocean counties within 10 miles of the coast. Values represent cm of liquid equivalent precipitation
(http://climate.rutgers.edu/stateclim_v1/data/coast_njhistprecip.html). Updated 5/10/16.

	Historical Climate Data: Coastal, NJ Average Precipitation (cm)
Month/Year	"Old Normals" 1971-2000
June	7.5
July	9.8
August	10.8
September	8.7
October	8.5