Assessing anthropogenic and natural impacts on ghost crab (Ocypode quadrata) populations at Cape Hatteras National Seashore, North Carolina

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ASSESSING ANTHROPOGENIC AND NATURAL IMPACTS ON GHOST CRAB (OCYPODE QUADRATA) POPULATIONS AT CAPE HATTERAS NATIONAL SEASHORE, NORTH CAROLINA

A Thesis
Presented to

The Faculty of the School of Marine Science
The College of William and Mary

In Partial Fulfillment
Of the Requirements for the Degree of
Master of Science

By
Cynthia B. Landry
2004
This thesis is submitted in partial fulfillment of

the requirements for the degree of

Master of Science

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgements</td>
<td>vi</td>
</tr>
<tr>
<td>List of Tables</td>
<td>vii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>viii</td>
</tr>
<tr>
<td>Abstract</td>
<td>x</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>2</td>
</tr>
<tr>
<td>2. Background</td>
<td>4</td>
</tr>
<tr>
<td>2.1 Barrier Island Ecology</td>
<td>4</td>
</tr>
<tr>
<td>2.2 Ghost Crabs (Ocypode quadrata)</td>
<td>6</td>
</tr>
<tr>
<td>2.2a Feeding Habits</td>
<td>7</td>
</tr>
<tr>
<td>2.2b Life History</td>
<td>8</td>
</tr>
<tr>
<td>2.2c Locomotion</td>
<td>10</td>
</tr>
<tr>
<td>2.2d Moisture Requirements</td>
<td>10</td>
</tr>
<tr>
<td>2.2e Gas Exchange</td>
<td>11</td>
</tr>
<tr>
<td>2.2f Communication</td>
<td>12</td>
</tr>
<tr>
<td>2.2g Burrows</td>
<td>12</td>
</tr>
<tr>
<td>2.2h Seasonal Variation</td>
<td>14</td>
</tr>
<tr>
<td>2.3 Off-Road Vehicles and Their Ecological Impact</td>
<td>14</td>
</tr>
<tr>
<td>2.4 Impacts of Off-road Vehicles on Ghost Crabs</td>
<td>18</td>
</tr>
<tr>
<td>3. Proposed Research</td>
<td>20</td>
</tr>
<tr>
<td>4. Purpose</td>
<td>21</td>
</tr>
<tr>
<td>5. Hypotheses</td>
<td>22</td>
</tr>
</tbody>
</table>
Appendix III. Descriptive Burrow Statistics.................................103
Literature Cited.................................................................106
Vita..................................................................................110
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List of Tables

Page

1. Portion of sediment samples analyzed..........................................................84
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Profile of a typical barrier island</td>
<td>54</td>
</tr>
<tr>
<td>2.</td>
<td>Coquina, North Carolina</td>
<td>56</td>
</tr>
<tr>
<td>3.</td>
<td>Avon, North Carolina</td>
<td>57</td>
</tr>
<tr>
<td>4.</td>
<td>Burrow density on the beach crest of Site 1</td>
<td>58</td>
</tr>
<tr>
<td>5.</td>
<td>Burrow density on the beach crest of Site 2</td>
<td>59</td>
</tr>
<tr>
<td>6.</td>
<td>Burrow density on the beach crest of Site 3</td>
<td>60</td>
</tr>
<tr>
<td>7.</td>
<td>Burrow density on the beach crest of Site 6</td>
<td>61</td>
</tr>
<tr>
<td>8.</td>
<td>Burrow density on the beach crest of Site 7</td>
<td>62</td>
</tr>
<tr>
<td>9.</td>
<td>Burrow density on the beach crest of Site 8</td>
<td>63</td>
</tr>
<tr>
<td>10.</td>
<td>Burrow densities across both field sites</td>
<td>64</td>
</tr>
<tr>
<td>11.</td>
<td>Burrow density through time</td>
<td>65</td>
</tr>
<tr>
<td>12.</td>
<td>Burrow densities pre- and post-storm</td>
<td>66</td>
</tr>
<tr>
<td>13.</td>
<td>Variations in burrow width among the sites</td>
<td>67</td>
</tr>
<tr>
<td>14.</td>
<td>Variations in burrow width pre- and post-storm</td>
<td>68</td>
</tr>
<tr>
<td>15.</td>
<td>Variations in burrow width through the field season</td>
<td>69</td>
</tr>
<tr>
<td>16.</td>
<td>Burrow size frequency distribution through the field season</td>
<td>70</td>
</tr>
<tr>
<td>17.</td>
<td>Variations in burrow depth through the field season</td>
<td>71</td>
</tr>
<tr>
<td>18a.</td>
<td>Variations in burrow depth in the dune through time</td>
<td>72</td>
</tr>
<tr>
<td>18b.</td>
<td>Variations in burrow depth in the mid-beach through time</td>
<td>72</td>
</tr>
<tr>
<td>18c.</td>
<td>Variations in burrow depth in the beach crest through time</td>
<td>72</td>
</tr>
</tbody>
</table>
19. Compaction between the sites.................................................................73
20. Compaction from the dune crest to the water line.................................74
21. Mean sediment grain size between the sites..........................................75
22a. Beach profiles at Site 1..........................................................................76
22b. Beach profiles at Site 2..........................................................................77
22c. Beach profiles at Site 3..........................................................................78
22d. Beach profiles at Site 4..........................................................................79
22e. Beach profiles at Site 5..........................................................................80
22f. Beach profiles at Site 6..........................................................................81
22g. Beach profiles at Site 7..........................................................................82
22h. Beach profiles at Site 8..........................................................................83
Abstract

Ghost crabs (*Ocypode quadrata*) are common on the open ocean sandy beaches in the eastern United States. Their burrows can be seen as far back as 400m from the waterline. The literature indicates that the use of off-road vehicles (ORVs) on the beaches may have a detrimental impact on ghost crab populations either directly through crushing or burying them or indirectly by interfering with their reproductive cycle or by altering their environment. The purpose of this study was to examine the impacts of ORVs on ghost crabs and the recovery rates of ghost crab populations in regions where ORVs were previously permitted at Cape Hatteras, North Carolina. Data on the density and sizes of the ghost crab burrows on the beaches and seaward side of the fore dune at Coquina Beach and Avon, North Carolina were collected along belt transects within closures of the beach crest to ORVs initiated for either 24 hours a day or from 8pm to 6am. Sediment grain size and compaction were measured in both traveled and untraveled zones. The occurrence of hurricanes Henri, Fabien, and Isabel permitted an analysis of the impacts of high-energy weather events on ghost crab populations, though it restricted the duration of the newly initiated vehicle closures to three weeks.

In the short-term, use of ORVs on the beaches of Cape Hatteras National Seashore caused a decrease in the density of ghost crabs. At Coquina, closing the beach crest to ORVs for 24 hours a day permitted an increase in burrow density (*p*=0.007) within that region before the occurrence of the storms. Closing the beach crest at Avon to ORVs for 24 hours a day (*p*=0.049) and from 8pm to 6am (*p*=0.015) both permitted an increase in burrow density within those regions before the storms. In the long-term, high-energy weather events caused a dramatic change in the population dynamics of the ghost crabs on the outer banks. After the passing of the storms, mean burrow densities in all study sites increased (*p*=0.008). Mean burrow width in all study sites decreased (*p*<0.001), indicating a removal of larger ghost crabs, and permitting the recruitment of smaller crabs and larvae into the region. After the storms, the ghost crabs were able to inhabit areas that they had previously been restricted from by the presence of ORVs.

Our results show that temporary closures of the beach crest may be used to reduce the short-term impacts of ORVs on ghost crab populations on the outer banks of North Carolina, though long-term impacts are ultimately controlled by the strength and frequency of high-energy weather events that can re-set the system. Further study is recommended to quantify recovery rates of ghost crab populations into those vehicle closures, as well as the long-term changes in the ghost crab populations after the occurrence of high-energy weather events.
ASSESSING ANTHROPOGENIC AND NATURAL IMPACTS ON GHOST CRAB (OCYPODE QUADRATA) POPULATIONS AT CAPE HATTERAS NATIONAL SEASHORE, NORTH CAROLINA
1. Introduction

The barrier island ecosystem is a dynamic environment, constantly changing in response to wind, waves, tides, sediment availability, sea level, and the interactions of plants, animals, and humans (Godfrey and Godfrey, 1976). Barrier islands dominate most of the East and Gulf coasts of the United States and many other areas of the world, particularly on passive continental margins (Komar, 1998).

Barrier island systems are important to the survival of many species. Sea turtles use the beaches of barrier islands to lay their eggs. Many species of birds, including the endangered piping plovers and the American oystercatcher, use this area for their nests and for foraging (Godfrey and Godfrey, 1976). Bacteria and algae thrive between sand grains and help decompose plant matter in the tidal flats (Godfrey and Godfrey, 1976). Mammals such as the red fox, deer, rabbits, raccoons, and skunks live in the secondary dune fields and maritime forests. Amphipods and invertebrates such as mole crabs, coquina clams, ghost crabs (Wolcott, 1978), fiddler crabs (Godfrey and Godfrey, 1976), and others play important roles in the ecology of the system through their roles as predators and prey in the food web.

The Outer Banks of North Carolina are a popular vacation destination. Many people build second homes close to the shoreline. Others live permanently on the barrier islands and make their living by fishing or through careers that serve the tourism industry on the Outer Banks. Others enjoy going to the barrier islands for recreation such as sunbathing, fishing, surfing, boating, bird watching, walking, or weekend trips. Off-road
vehicles (ORVs) are popular on the beaches, providing a means for transporting personal belongings onto the beach or just for joy riding.

Ghost crabs (*Ocypode quadrata*) are common along the sandy beaches on the outer banks of North Carolina and can be easily impacted by humans. Steiner and Leatherman (1981) found that ghost crabs can be positively impacted by pedestrian usage on the beaches but that off-road vehicles (ORVs) have a severe detrimental affect to the crab populations. In general, ghost crabs burrow on the upper beach, between the beach crest and the dune area, and emerge from their burrows at night to feed on the compacted foreshore where they are more susceptible to the impacts of ORVs. Changes in ghost crab populations, therefore, may serve as an indicator species for the health of the ecosystem as a result of their prominence and impacts from recreational use (Steiner and Leatherman, 1981).

This thesis investigated the impacts of off road vehicles on the density of ghost crab populations and recovery rates of those populations in relation to ORV use on the beaches and ORV usage regulations. Crab population dynamics were studied through the counting and measuring of individual burrows at two locations within Cape Hatteras National Seashore, Coquina Beach and Avon, North Carolina. These sites were chosen with the assistance of the Park Service personnel in order to minimize the impacts of different levels of recreational use and the impacts of a changing ecosystem. Additional information such as sediment compaction, mean sediment grain sizes, and beach profiles were collected to determine if other physical environmental factors contributed to the patterns in ghost crab distribution and abundance. The results of this work will be useful in the development of a comprehensive off-road vehicle use plan for the park.
2. Background

2.1 Barrier Island Ecology

Barrier islands are unique in their profile, which begins at the swash zone and foreshore or beach crest on the ocean side. Traveling landward from the swash zone, the next ecotone encountered is the backshore or mid-beach followed by the primary fore dune, secondary dune field, maritime forest, high salt marsh, low salt marsh, and finally the tidal flat and salt marsh areas (Figure 1). Each of these environments is characterized by elevation, vegetation, sediment, and water inundation. The entire barrier island system is extremely sensitive to changes in sea level, energy, sediment supply, and human interactions (Komar, 1998). As sea level rises, barrier islands “roll over” on themselves, with dunes moving landward and eventually covering the marsh sediments in the back barrier lagoon (Godfrey and Godfrey, 1976; Komar, 1998). This natural process helps the island preserve itself in the face of rising sea level, though human interactions such as housing developments and conservation efforts have begun to interrupt this process.

Beginning in the 1930s, the Civilian Conservation Corps (CCC) began a project to stabilize all of the primary fore dunes along the barrier islands of North Carolina by building sand fences and planting grasses and woody vegetation to trap the mobile sand (Godfrey and Godfrey, 1976). Due to the combination of the sediment stabilization, the resulting impairment of the barrier island’s ability to maintain itself by rolling over and
sea level rise, the beaches of the Outer Banks of North Carolina are becoming narrower and both human and animal habitat are being lost (Godfrey and Godfrey, 1976).

Natural forces such as sea level rise and storms also impact barrier islands. As relative sea level rises, man-made structures and stabilization activity prevent the natural migration of the barrier islands. Therefore, as sea level rises, the islands become narrower, and humans feel the need to increase their efforts to preserve them. Storms can accentuate this problem. Storms and changing sea level normally combine to determine the island’s primary characteristics (Godfrey and Godfrey, 1976). Storms are among the main agents of transport for sediment from one side of the barrier island to the other (Komar, 1998). Wash-over allows the dune system to move landward and maintain itself without net land loss (Godfrey and Godfrey, 1976). Wash-over can wipe out portions of roadways and other structures, causing humans to increase their efforts to reduce the natural changes in the barrier island environment. Storms also erode large portions of the beaches and dunes, destroying habitat for terrestrial plants and animals. This erosion of the beach may lead to the severe reduction of certain populations, such as that of ghost crabs (Ocypode quadrata).

Flora and fauna that reside on barrier islands have special adaptations in order to survive extreme conditions including salt spray, seawater flooding, water stress, moving sand, poor nutrient levels, and extreme temperatures (Godfrey and Godfrey, 1976). Plants have adaptations such as waxy cuticles on their leaves that prevent desiccation and protect them from salt and sand blast. Animals have adaptations such as specialized water uptake systems and burrowing that prevent them from becoming dehydrated.
Beach fauna can be classified according to the ecological zones of the beach. In general, the upper beach zones of the mid-beach are characterized by amphipods, isopods, and ghost crabs (*Ocypode quadrata*) (Nelson, 1993). Coquina clams (*Donax variabilis*), mole crabs (*Emerita talpoida*), and several polychaete species are found in the swash zone or beach crest (Nelson, 1993).

2.2 Ghost Crabs (*Ocypode quadrata*)

Ghost crabs are very common on open ocean sandy beaches in the eastern United States. *Ocypode quadrata* is the most common ghost crab of the Caribbean and temperate Atlantic North American beaches (Wolcott, 1976). The ghost crab is primarily nocturnal (Dahl 1953; Haley, 1969; Wolcott, 1978), but juveniles and the occasional adult may be seen on the surface during daylight hours near their burrows (Haley, 1969). In general, the crabs emerge from their burrows at dusk, moving and foraging actively on the foreshore until dawn (Wolcott, 1978). Wolcott (1978) suggested that the low level of activity during daylight hours was a result of high human activity during that time.

Ghost crabs (*Ocypode quadrata*) are differentiated from other species in the Family Ocypodidae by their stout eyestalks with conspicuous, enlarged, club-shaped cornea (Williams, 1984). The chelipeds of both sexes are also well developed and somewhat unequal (Williams, 1984). The adults tend to range in color from gray, pepper-and-salt, grayish white, pale yellow, straw color, or yellowish white imitating the color of the beach where they reside (Williams, 1984). Younger ghost crabs tend to be mottled gray and brown (Williams, 1984).

Due to their habitat, size, and abundance, ghost crabs have been used as an indicator species for the impacts of recreational beach use (Steiner and Leatherman,
1981). Barros (2001) determined that ghost crabs are a good indicator of the impact of human recreation on beaches and that counting burrows is a rapid and simple technique for estimating crab populations.

2.2a Feeding Habits

Ghost crabs feed on the lower fore shore of beaches at night (Dahl, 1953; Wolcott and Wolcott, 1984). Over 90 percent of their diet is as a result of predation, leaving 10 percent of their feeding efforts to facultative scavenging (Wolcott, 1978) or deposit feeding (Robertson and Pfeiffer, 1982). Ghost crabs prefer the high quality food afforded by predation, but will resort to scavenging if necessary (Wolcott, 1978). Mole crabs (Emerita talpoida) and coquina clams (Donax variabilis) make up most of their diet, with mole crabs contributing approximately 60 percent of the energy and coquina clams contributing approximately 25 percent (Wolcott, 1978; Fales, 1976). Other prey includes ghost crabs, lady crabs, amphipods, insects, lizards, land crabs, hermit crabs, fiddler crabs (Wolcott, 1978), and hatchling diamondback terrapins (Arndt, 1991).

Leber (1982) observed over 100 ghost crabs feeding on the foreshore. To locate their prey, the ghost crabs were observed digging in the wet sand, alternating strokes of the two chelae down and away from the body while opening and closing the dactyls. Crabs crack coquina clam shells open with their major chelae and feed on the viscera and mantle of the clam (Leber, 1982).

Wolcott (1978) observed ghost crabs scavenging for grasses, seeds, Sargassum, dead birds, shrimp, and barnacles. They will often burrow near a source of food, such as a dead bird or fish on the beach (Williams, 1984). Robertson and Pfeiffer (1982) observed ghost crabs deposit-feeding in areas of the beach that were covered with visibly
dense patches of benthic diatoms. Scavenging may be more important for individuals that reside in areas where mole crabs and coquina clams are not as prevalent as in other areas, such as the beaches of Bermuda and Texas (Wolcott, 1978), though this habit has not been well examined in those regions.

Ghost crabs have essentially no terrestrial competitors or predators other than themselves in the beach environment (Wolcott, 1978). According to Wolcott (1978), ghost crabs are the top carnivores in a simple, filter-feeding based food chain on the beach. They are thought to be preyed upon by foxes and some species of birds (Shields and Perry, pers. comm. 2004).

2.2b Life History

Mating and spawning seasons for ghost crabs are correlated with temperature and therefore, vary somewhat with latitude (Williams, 1984). Spawning in the Carolinas extends from April through July. Copulation is likely to occur throughout the year but in two peaks in the spring and summer (Williams, 1984). During mating of ghost crabs, the pair will have ventral sides juxtaposed for approximately 25 minutes, with the male in vertical position with the eyes pointed up and the passive female with eyes mostly retracted (Williams, 1984). In contrast, most other hard shell brachyuran crabs mate with the female uppermost (Williams, 1984).

The female ghost crab produces thousands of eggs. The larval stages hatch in seawater and are planktonic (Dahl, 1953). Development of zoeal stages to the megalopal stage takes approximately 60 days (Williams, 1984). The megalopa settle on the beaches seaward of the main distribution of the adults, indicating that the young post-larvae settle
at low tidal levels and move landward as they grow (Ansell et al., 1972). The average life span for a ghost crab is approximately three years (Haley, 1969).

Though little literature can be found regarding the settlement patterns of *Ocypode*, extensive research has taken place analyzing the settlement patterns and cues of *Uca* spp., a close relative of *Ocypode* within Ocypodidae, whose settlement patterns are likely similar. Mense, et. al. (1995), found that settlement of *Uca* spp. occurs with highest densities during waxing and full moon phases. Settlement episodes, which occurred in clusters of megalopae, of *Uca* spp. were found to occur daily beginning in mid summer and lasting through early Autumn (Boylan and Wenner, 1993; Jones and Epifanio, 1995).

The shape of the abdomen is the most common method of determining the sex of a ghost crab (Haley, 1969). In juveniles, the abdomens of both males and females are narrow, and virtually indistinguishable in the flexed position, though the abdomen of the adult female is generally broader than that of an adult male (Haley, 1969). Males typically enter into puberty when their carapace width reaches approximately 24 mm. Females are generally capable of copulation when their carapace width reaches approximately 26 mm (Haley, 1969). In addition, male ghost crabs grow at rates that are slightly higher than those for females and may mature earlier (Haley, 1969).

The major chelae of *Ocypode quadrata* is located on the right side of the body approximately 50 percent of the time, and is likely to be used as a courting device (Barrass, 1963; Haley, 1969), as in other Ocypodidae. Another proposed use for the major chelae is for defense purposes (Haley, 1969).
2.2c Locomotion

Locomotion of ghost crabs is accomplished through the use of all eight walking legs (Williams, 1984). In general, ghost crabs walk sideways or obliquely. When running at top speed, the body of the ghost crab is raised well off the ground and only two or three pairs of legs are used (Barnes, 1980). To distribute the work load between the flexors and the extensors on each side while running rapidly, ghost crabs will frequently stop and turn 180° so that the body is facing in the opposite direction before continuing running (Barnes, 1980).

Blickhan and Full (1987) found that ghost crabs and mammals use similar energy-conserving mechanisms with similar efficiency of locomotion. Intermittent locomotor performance limits of *Ocypode quadrata* are dependent upon movement velocity, movement duration, and pause duration (Weinstein, 1995). It is more energy-efficient for ghost crabs to move and pause regularly (Full and Weinstein, 1994). The movement periods for voluntarily active ghost crabs are brief with longer pause durations (Weinstein, 1995). Running at a steady pace will result in less ability to move, and less efficient oxygen consumption (Full and Weinstein, 1994). Weinstein (1995) found that ghost crabs do not move at a constant speed during each movement period but accelerate, decelerate, stop and start frequently.

2.2d Moisture Requirements

Sandy beaches are directly exposed to sunlight throughout the day, therefore increasing the risks of desiccation to the organisms that reside there. Ghost crabs have several adaptations and habits that help reduce the risks of dehydration. Weinstein, et. al. (1994) found that moderate dehydration in ghost crabs can substantially decrease their
capacity for sustained terrestrial locomotion. In general, crabs are most active when the ambient relative humidity is high (above 75 percent) (Weinstein, 1995). Ghost crabs also burrow into areas where water uptake rates are high. The depths of the burrows of crabs often extend below the water table, which increases the humidity and water availability for the crab (Weinstein, 1995). In intertidal zones, ghost crabs are directly exposed to shallow water and spray from incoming waves, particularly while feeding and foraging on the foreshore (Weinstein, 1995). When burrowing, ghost crabs tend to prefer areas with higher moisture regimes and can distinguish differences of as little as 1 percent moisture content (Warburg and Shuchman, 1979).

In terrestrial environments, ghost crabs must keep their gills moist for proper respiration function. They achieve this by directly exposing themselves to the ocean or by taking up water from the sediment. According to Wolcott (1984), ghost crabs can take up water in bulk when sufficiently dehydrated. Ghost crabs are able to extract water from soil that is less than 5 percent water through capillary action (Wolcott, 1976, 1984). Water is collected from soil spaces by the capillary tufts of setae, located between the second and third pair of walking legs and surrounding the posterior entrances to the branchial chambers, drawn into the gill chamber by suction, and at least some of it is passed into the mouth and swallowed (Wolcott, 1984).

2.2e Gas Exchange

Ghost crabs have a reduced number of gills, with additional accessory respiratory tissues in the gill cavity to aid in the retention of oxygen (Williams, 1984). In the genus *Ocypode*, air enters the branchial chambers through special posterior openings between the third and fourth or fourth and fifth legs and the usual anterior inhalant openings in
aquatic crabs are used for exhaling in these crabs (Barnes, 1980). These same openings may be used for replacing water lost from the gill chambers (Barnes, 1980).

2.2f Communication

Ghost crabs produce three different sounds for communication: bubbling, rapping, and rasping (Williams, 1984). When the crab is disturbed, rapping can be heard (Williams, 1984). Rasping occurs when one crab is forced into the burrow of another (Williams, 1984). Bubbling can be heard from lone animals in their burrows (Williams, 1984). Ghost crabs respond to both airborne and substrate-borne sound through a single receptor (Barth’s myochordotonal organ), but are most sensitive to substrate vibration (Williams, 1984).

2.2g Burrows

Burrowing occurs primarily during the daylight hours (Williams, 1984). Ghost crabs construct burrows 0.6 to 1.2 meters in depth from the high tide line to distances up to 400 meters from the water line (Williams, 1984). According to Wolcott and Wolcott (1984), burrow diameter is approximately equal to carapace width.

When constructing a burrow the crab emerges from its burrow carrying a mass of sand (Barrass, 1963). The sand is carried under the body, held by the smaller cheliped and the first two walking legs of the same side, with the other walking legs used for locomotion (Barrass, 1963). The sand is then either thrown or dropped before re-entering the burrow, and a mound of sand begins to form outside of the burrow (Barrass, 1963). The crab presses on the mound of sand with its legs and chelipeds as it returns to the burrow, therefore making the mound firm on the side that faces the burrow, and loose elsewhere (Barrass, 1963). When burrowing, the walking legs on the side of the smaller
cheliped are almost always used in digging (Barrass, 1963). As a result, the larger cheliped is uppermost, and emerges first when the crab comes out of its burrow (Barrass, 1963). Barrass (1963) also found that ghost crabs with the larger cheliped on the right side of their body will build a burrow that turns to the right and vice versa. The burrows tend to be more or less permanent due to maintenance by many different crabs (Dahl, 1953; Barrass, 1963).

After a night of foraging and feeding on the foreshore, older crabs move toward the backshore at dawn, looking for a suitable burrow to occupy and renovate (Williams, 1984). According to Wolcott (1978), ghost crabs can move up to 300 meters while foraging on the foreshore at night, and therefore do not return to their original burrows day after day. Hill and Hunter (1976) also found that ghost crabs will inhabit any large burrow found on the backshore, including those made by the south Texas pocket gopher. Young crabs tend to burrow closer to the water, occasionally beneath the high tide line subjecting themselves to periods of inundation (Williams, 1984). Toward noon, the openings of the burrows are plugged with sand in an attempt to conceal the burrow (Williams, 1984). To create a plug, crabs pull two masses of sand into the opening, and then climb over them into the burrow using the walking legs of one side to pull the sand over them and into the burrow (Barrass, 1963). The walking legs remain outside of the burrow, and are used to flatten the plug (Barrass, 1963). Ghost crabs can also use this method when the winds are strong to help protect their burrows from wind and sand (Barrass, 1963).

Ghost crab burrows can be classified into three general types: (1) short vertical burrows, generally constructed by younger crabs, (2) burrows sloping downward at
approximately 45° away from the shoreline, often having multiple branches, one of which may extend towards the surface, occasionally forming U-shaped burrows, or (3) burrows located higher on the beach or in the dunes, similar to type (2) but without the vertical side branches (Williams, 1984).

At Padre Island, Texas, Hill and Hunter (1976) found that variations in the density, size, morphology, and orientation of ghost crab burrows can be used to define the subenvironments of a beach. Along the beach, from the upper foreshore to the back edge of the beach, burrows of ghost crabs will increase in diameter, length, and complexity of shape, with a decrease in burrow density (Hill and Hunter, 1976). Hill and Hunter (1976) found that burrows on the backshore generally descend in a northwest direction. This direction is controlled by the direction of the onshore winds (Hill and Hunter, 1976).

### 2.2h Seasonal Variation

Ghost crabs remain underground in their burrows from October through April. These burrows are constructed approximately 1 meter deep along the seaward side and base of dunes (Leber, 1982). In April, crab activity is confined to the spray zone, but as summer approaches, the crabs become active over increasingly broader regions of the beach (Leber, 1982). Ghost crabs are rarely active at ambient temperatures below 15-20°C.

### 2.3 Off-Road Vehicles and Their Ecological Impact

Off-road vehicles (ORVs) are a popular method of transportation on and around the sandy beaches of the east coast of the United States. Their use has increased dramatically in the last few decades. Approximately one-half of the driving on sandy
beaches on the east coast of the United States is by fishers in search of schools of feeding fish (Godfrey and Godfrey, 1980). Other ORV use is due to tourism and official use, with some joy riders and racers (Godfrey and Godfrey, 1980). The effect that off-road vehicles have on the beaches has been well documented, including changes in the sediment and physical properties, populations of animals, and plant communities (Liddle and Moore, 1974; Godfrey and Godfrey, 1976; Godfrey and Godfrey, 1980; Burger, 1981; McAtee, 1981; Wolcott and Wolcott, 1984; Steiner and Leatherman, 1981; Burger, 1994; Kutiel et al., 1999; Barros, 2001; Perry, 2002). Resource managers are under pressure from many user groups, including land managers, conservationists, scientists, and ORV users, to determine the amount of ORV use that can be safely permitted on beaches.

All of the flora and fauna found on sandy beaches can be impacted by ORV use. For example, diatom populations can decrease by as much as 90 percent from ORV impacts on the foreshore of beach habitat (Godfrey and Godfrey, 1980). ORV use also breaks up detritus, and the bacterial populations that feed on detritus can be reduced by one-half (Godfrey and Godfrey, 1980). Plant seeds can be crushed, and young plants that are trying to establish themselves are often demolished by ORV use (Godfrey and Godfrey, 1980).

Vehicular and pedestrian traffic may greatly modify beach and dune sub-environments (McAtee, 1981). A primary effect of ORV usage on the beaches that has been observed is the reduced cover and species diversity of the vegetation (McAtee, 1981; McDonnel, 1981; Kutiel et al., 1999; Perry, 2002). Recreational activities may also destroy dune vegetation, therefore exposing the dune habitats to harsher conditions.
In addition, as the intensity of human activity increases, elevation of the sediment surface and average wind velocities near the ground surface decrease while wind-carried sand particles near the ground surface, soil salinity, soil pH, average soil temperature, range in temperature of the soil, soil bulk density, and soil water content increase (McAtee, 1981). Vegetation cover helps to reduce the daily and annual temperature range and the depth to which the variations in temperature penetrate in the soil (Liddle and Moore, 1974). The loss of vegetative cover may also impact habitat of animals that live in the sediments or shade of the vegetation.

Birds may also be impacted by off-road vehicles since they allow vehicles to come closer to their nests than humans or dogs (Godfrey and Godfrey, 1980). Slow-moving ORVs have less of an impact on the birds than do more active human activities (Burger, 1981). Several endangered species of birds, such as the piping plover, inhabit and nest in the beach environment. The presence of humans near piping plovers reduces their time spent foraging and increases their time away from the nest, therefore increasing the risks to their offspring (Burger, 1994), but impacts are often offset by beach closures during critical breeding periods.

The effects of off-road vehicles on the sediments of a sandy beach have been extensively studied and documented. ORV use on the fore dune area can effectively stop all seaward accretion of the dunes, thereby producing an acutely scarped dune rather than a gently sloping dune front (Godfrey and Godfrey, 1980). Dune growth may be stopped and erosion rates from the dune face may increase. With the low sediment supply to the back areas of the dunes, off-road vehicles may create dune hollows that threaten the
stability of the dune system from which recovery is very slow (Godfrey and Godfrey, 1980).

ORV use also impacts physical factors of the sediment on sandy beaches. Perry (2002) has shown that ORV use on the beach face can increase the compaction of the sand by as much as 50 percent. The mean sediment grain size on traveled versus non-traveled beaches was found to be greater (Perry, 2002) on traveled beaches. Beaches comprised of coarser sediments show greater elevation changes over the seasonal cycle and also show greater changes in response to individual storms (Komar, 1998).

McLachlan (1996) found that an increase in sand particle size may result in a change in the beach state and a decrease in the species richness and abundance. However, another possible reason for reduced numbers of organisms on some beaches is due to differences in the slope of the beach-face (McLachlan, 1983; Nelson, 1993). Coarser sand, which is consistent with beaches impacted by off-road vehicles (Perry, 2002) and steeper slopes may cause increased drainage rates and therefore may increase the risks of dehydration to beach organisms (Gauld and Buchanan, 1956).

The profile of a beach may be very important to the organisms that live there. “Fair-weather” beach profiles tend to contain wide, gently back-sloping beaches, with well-developed berms and bars (Godfrey and Godfrey, 1976; Komar, 1998). “Storm” profiles are greatly eroded, with narrow beaches, scarped dunes, and bars that have been transferred seaward, as a result of high wave energy acting on the beaches (Godfrey and Godfrey, 1976; Komar, 1998). Profiles of the beach also change daily with tides and winds as sediment is moved about (Komar, 1998). Annual changes in beach fauna are
related to changes in beach profile and changes in salinity as a result of rainfall (Ansell et al., 1972).

2.4 Impact of Off-Road Vehicles on Ghost Crabs

Wolcott and Wolcott (1984) found that ghost crabs are protected from the impact of off-road vehicles when they are in their burrows, even those as shallow as 5cm. The impact of ORVs on ghost crabs is primarily at night when the crabs are feeding on the foreshore. The crabs do not tend to run away from vehicles, and the density of crabs is so large as to make it difficult to avoid them (Wolcott and Wolcott, 1984). Burrows that are collapsed by vehicles may be easily dug out of (Wolcott and Wolcott, 1984).

Steiner and Leatherman (1981) found that the density of ghost crabs varies greatly with differing levels of recreation on the beach. The mean density of crabs per 1000 m² plots at Assateague Island, Maryland-Virginia, was 10 on an undisturbed beach, 19 on a pedestrian-impacted beach, 1 on a light off-road vehicle and pedestrian impacted beach, and 0.3 on a beach heavily impacted by off-road vehicles (Steiner and Leatherman, 1981). They hypothesized that off-road vehicles may damage the crabs by crushing or burying them, by interfering with their reproductive cycle, or by altering their environment so that they can no longer survive (Steiner and Leatherman, 1981). As a result, there is likely to be little to no reproduction and new inhabitants would need to migrate in from other areas (Steiner and Leatherman, 1981). Pedestrians appear to have little detrimental effect on ghost crabs, rather it is likely the crabs are positively impacted as they capitalize on the food scraps scattered across the beach by tourists (Steiner and Leatherman, 1981).
Off-road vehicle usage has been shown to increase the compaction of the sand on the beaches, almost doubling it in some areas (Perry, 2002). This increase in compaction may lead to shallower burrows if the crabs are not able to dig into the sand as easily as on non-compacted sand. In addition, Steiner and Leatherman (1981) found that compaction of the sand causes changes in the hydrology and temperature that may also affect the ability of the ghost crab to carry out its full life cycle in that area. Disturbances by off-road vehicle usage cause the upper layer of dry sand to be mixed with wetter sand below. This mixing leads to a decrease in the moisture levels in the sand that may kill the ghost crabs if their gills dry out due to lack of constant moisture. While the actual increase in shear stress and pressure due to the compaction of the sand does not kill the crabs, the moisture changes as a result of this pressure can (Steiner and Leatherman, 1981).
3. Proposed Research

While Wolcott and Wolcott (1984) found that there was very little impact on the ghost crabs at Cape Lookout National Seashore (North Carolina) these data were limited to areas with low levels of off-road vehicle (ORV) impacts. They recommended the closure of the foreshore from dusk to dawn in areas with high-level ORV usage. Godfrey and Godfrey (1980) also suggested closing the beaches to ORVs but retaining an “ORV corridor” where ORVs are permitted between the beach crests and the upper drift lines, except where birds are nesting.

Preliminary data showed a marked difference in the population levels of ghost crabs in relation to closure areas at Cape Hatteras National Seashore (North Carolina). In this study, we proposed to examine the effects of two ORV management schemes and their impact on the recovery rates of ghost crab populations in these managed areas.
4. Purpose

The primary objectives of this project were to test the hypothesis that off-road vehicles have a detrimental effect on the populations of ghost crabs at Cape Hatteras National Seashore and to determine possible alternatives to ORV usage that may minimize impacts to ghost crab populations. The implementation of new regulations that restrict off-road vehicle use on the beach and dune system may help to reduce this impact and allow the use of ghost crab populations as an indicator of the health of the beach ecosystem. Recovery rates of ghost crab populations are especially important in considering the regulations regarding ORVs on the beaches at Cape Hatteras National Seashore. Regulations that do not allow the recovery of the crabs may be detrimental to the ghost crab population status on Cape Hatteras.

From late August through mid-September, the outer banks of North Carolina were impacted by the presence of several high-energy weather events. This event allowed a study of the impact of storms on the dynamics of the ghost crab populations. An additional purpose was then added to this project in order to test the hypothesis that high-energy weather events have a detrimental impact on the populations of ghost crabs at Cape Hatteras National Seashore and also to look at the combined impact of ORVs and high-energy weather events on ghost crabs.
5. Hypotheses

Null Hypothesis 1: Off-road vehicle usage on the beaches has no impact on ghost crab populations.

Alternative Hypothesis 1: Off-road vehicle usage on the beaches has a detrimental impact on ghost crab populations.

Null Hypothesis 2: Designating vehicle-free areas of the beach will not result in recovery or colonization of ghost crab populations in that area.

Alternative Hypothesis 2A: Designating vehicle-free areas of the beach for 24 hours a day will result in the recovery of ghost crab populations in that area.

Alternative Hypothesis 2B: Designating vehicle-free areas of the beach from 8pm to 6am will result in the recovery of ghost crab populations similar to that in areas closed for 24 hours a day.

Null Hypothesis 3: High-energy weather events have no impact on ghost crab populations.

Alternative Hypothesis 3: High-energy weather events will reduce or increase the density of ghost crab populations.

Designating beaches vehicle-free from dusk to dawn will likely result in a very low impact on the crab population levels. During this study, we expected to find that the recovery of the crab populations was similar when the beaches are closed to off-road vehicle activity at night to when they are closed at all times. By allowing off-road
vehicle usage on the beach face during daylight hours, there would likely be a minimal impact on the ghost crabs and they will recover in those areas similarly to areas where off-road vehicle usage was restricted at all times. It is also possible that the impacts that off-road vehicles had on the beach environment during the day may impact the habitat and life cycles such that the ghost crabs would have increased difficulty in recolonizing and settling in these areas.

A management scheme which only restricts off-road vehicle access on the beaches from dusk to dawn likely would be more widely accepted by the public than a scheme which restricts off-road vehicle access at all times. In addition, closing the beaches to off-road vehicles during periods of high biological activity may limit the duration of closure periods. While the public might favor this idea to closing the beaches at all times, it might be difficult to determine the best time of year in which to close the beaches, for how long, and which species is most important to manage for.

High-energy weather events such as Hurricane Isabel can scour large portions of the beach and dunes and move the sediment off shore. As a result, ghost crabs may be also swept out to sea and likely perish. Once removed, new populations of ghost crabs may be able to inhabit the area. Recruitment may occur in the form of juvenile settlement to the area, or recovery may occur as crabs that had been moderately protected behind the dunes during the storm move to the beach face.
6. Methods

6.1 Site Description and Study Design

Eight sites were chosen in Cape Hatteras National Seashore for analysis and comparison. These sites include 4 sites at Coquina Beach, North Carolina (Figure 2) and 4 sites at Avon, North Carolina (Figure 3), which will be designated “Coquina” and “Avon,” respectively. These beaches were chosen with the advice of National Park Service staff in order to completely represent the beach habitats of Cape Hatteras National Seashore and to minimize the effects of different levels of recreational use that might also impact the ghost crab population densities.

Each set of 4 sites included: 1 control site which remained closed to all privately owned vehicles, 1 control site which remained open to all ORVs, 1 site newly closed to off-road vehicles from dusk to dawn (8pm to 6am), and 1 site newly closed to off-road vehicles at all times. Sites will be designated as “No ORV” or “ORV,” respectively. When presenting data concerning the new closures, those sites will be designated “PM closure” and “24hr,” respectively. Closures of the latter two began in early August. Data collection was performed along 3 randomly assigned transects in each site. Beach profiles were taken on a single permanent transect for each of the eight sites.

In order to satisfy both the Park Service and the general public while performing this study, only the front 20 meters of the beach landward from the water line was regulated. This created an ORV corridor in which drivers could drive between the signs
and the base of the dunes, park behind the signs, and walk through to the water line. This region will be designated the “beach crest.”

Coquina was assigned 4 sites (Sites 1 through 4) (Figure 2). Approximately 1100 meters separated Site 1 from Sites 2 through 4. Site 1 was designated vehicle-free at all times, and was located farther north than Sites 2 through 4 due to the changes in the Park Service’s ORV closure between summer and fall. During summer months, the vehicle-free regions that are designated by the Park Service stretch south to just north of Site 2. During the early fall, Park Service personnel moved the closure north to just south of Site 1 (Figure 2). Site 2 was located adjacent to the permanently closed area during summer months, and was 400 meters long in order to provide a 100-meter buffer zone to reduce edge effects in the study. The beach crest of Site 2 was closed 24 hours a day to privately owned ORVs. Site 3 was located adjacent to Site 2, on the southern end and was 300 meters long. The beach crest of Site 3 was closed to privately owned vehicles from 8pm to 6am. Site 4 was located adjacent to Site 3 on the southern end, and was 300 meters long. Site 4 remained open to all off-road vehicles.

Avon was assigned 4 sites (Sites 5 through 8) (Figure 3). Site 5 was the northern-most site, remained open to all vehicles at all times and was 300 meters long. Site 6, also 300 meters long, was adjacent to Site 5 on the southern end and the beach crest was closed to privately owned vehicles from 8pm to 6am. Site 7 was located adjacent to Site 6 on the southern end and the beach crest was closed 24 hours per day to privately owned vehicles. Site 7 was 400 meters long to allow for a 100-meter buffer zone to reduce edge effects. The permanent state closure at Avon was located adjacent to Site 7 on the
southern end. Site 8 stretches 400 meters south of the permanent closure and remained
closed to all privately owed vehicles.

Within each of the eight sites, burrow use, density, depth, and width were
recorded. The compaction of the sand and sediment grain size as well as the profile of
the beach was also recorded. Burrow and sediment data were collected in belt transects
perpendicular to the ocean across the beach from the crest of the fore dune to the water
line at 4 ½-meter intervals. Additional information was recorded regarding the time of
day, phase of the tidal cycle, and weather that may have influenced the results regarding
habitation of the ghost crabs.

Data were collected during 8 collection periods at two to three week intervals
beginning in early June 2003. Sampling dates are represented by a single date to simplify
the analysis. June 4-9 was designated June 4; June 25-28 was designated June 25; July 7-
10 was designated July 7; August 3-4 was designated August 3; August 21-23 was
designated August 23; September 12-13 was designated September 12; October 3-5 was
designated October 3; October 24-26 and November 3 was designated November 3.

With the help of the Park Service, the beach crest of the vehicle-free sites were
initiated on August 7, 2003. Measuring from the high water line on August 7, signs were
posted every 25 meters along the beach within each regulated site (Sites 2, 3, 6, and 7),
restricting the access of vehicles near the water line. The width of the beaches at both
Avon and Coquina allowed vehicles to park behind the closed areas and drivers and
passengers could then walk through to the water line. Data regarding the impact of the
management scheme were collected once, on August 23, before several high-energy
weather events impacted the study sites.
6.2 Burrow numbers and sizes

Within each site, three randomly assigned transects were designed for each data collection period. Each transect was perpendicular to the coastline and stretched from the crest of the dune to the water line. If the dune was too steep that climbing up it would create significant damage to the sediment formation and plants, the transect began at the highest point that could be safely reached. Each transect was 5 meters wide. The numbers of active burrows in each were counted and measured. Inactive or filled burrows were also counted.

Active burrows were differentiated from inactive burrows by their appearance. Active burrows had tracks around the opening as the crab traveled in and out of its burrow, or piles of sediment that had been removed from the inside of the burrow, indicating active use. Inactive burrows may quickly fill with sand, especially when the weather is windy or stormy. Inactive burrows often had a layer of sand just inside the burrow that had been blown there even by a light wind. For this reason, active burrows were often rounder than inactive burrows and were fairly simple to differentiate.

The width of a burrow is a good estimate of the size of the crab’s carapace (Wolcott and Wolcott, 1984). The widest diameter of each active burrow was measured to the nearest centimeter. To determine the depths of each burrow, a thin flexible tube with centimeter-markings was inserted into the burrow until the bottom was felt.

6.3 Sediment

Compaction of the sand on beaches with and without off-road vehicle usage was measured using The Investigator- Soil Compaction Meter (Spectrum Technologies, Inc.). This instrument is used by pushing the probe slowly and evenly into the sediment while it
measures the compaction levels at 0.05-meter (2 inch) intervals to a depth of 0.30 meters (12 inches). Compaction was measured at the landward edge of each quadrat over the entire length of each transect from the dune crest to the water line.

Surface grab samples were taken at 4.5 meter intervals along each transect, labeled, and brought back to the lab. Grain size analysis was performed with the Rapid Sediment Analyzer (RSA). The samples were washed through a 63-micron sieve to remove silts and clays and then dried in an oven. Approximately one gram of each dried sample was used to analyze the sediment sample. Each sample was allowed to fall through the water column of the RSA, and landed on the scale at the bottom. The rate of fall depended on the size and shape of the sediment particles in each sample. The computer then computed the mean (phi), median (phi), sorting, skewness, and kurtosis of the sediment grains within each sample. Only the mean and median are useful for this work. Mean grain size indicates the average grain size in the sample. Median grain size indicates the middle number in the range of grain sizes found in the sample. Due to the extremely high number of sediment samples that were collected over the summer (approximately 2000), limited time and resources for this project, the fact that the average sediment grain size is not likely to change dramatically among the sites in this short amount of time, and the fact that the sediment grain size data is used only as supplementary information for conclusions, only 32 samples were analyzed (Table 1).

Beach profiles were taken along permanent transects located within each site during each collection date. Emery’s Simple Method for measuring beach profiles was used (Emery, 1961) where three metal rods, two of which are 1½-meters in length and the third, a level, is 3-meters in length are employed. Two-centimeter markings were placed
along the length of each rod. The 1½-meter rods were placed vertically in a line across the beach. The 3-meter rod was held in between and was used as a level. The landward observer aligned the 3-meter rod across the top of the seaward rod and the horizon, and took a reading of the distance down from the top of his rod to the point that aligned with the horizon. If there was a back-slope on the beach, the reading was taken from the seaward rod. Rods were moved along the beach, and readings were taken every 3 meters. The differences in slope were summed and plotted against the horizontal distance to create a profile of the beach slope (Emery, 1961). Profiles were taken from the crest of the dune (when not too steep) to the water line.

6.4 Statistical Analysis

Variations in burrow density and size were compared with Analysis of Variance (ANOVA) and size-frequency distribution histograms to analyze changes throughout the summer, the impacts of off-road vehicles, and the changes that resulted from high-energy weather events. Levene’s test for continuous distributions was used to analyze any differences in variances. ANOVA was used to compare burrow sizes and burrow densities among sites. ANOVA was also used for comparing changes in crab burrow density through time. ANOVA was used to determine variations in burrow depth and diameter between the dune, mid-beach, and beach crest. ANOVA was used to analyze differences in compaction and mean sediment grain size on traveled and non-traveled beaches.

Graphs were constructed to analyze variations in burrow size frequency distributions, variations in burrow density among the sites through the field season, burrow density in the three regions of the beach for each site and date, and the
relationship between sediment compaction and burrow frequency. Additional graphs were constructed through the use of correspondence analysis to compare the levels of compaction in different sites on each date. Beach profiles were plotted in XY-scatter plot form. Profiles were plotted for each site, showing the changes in the profile between dates.

6.5 Analyzing the Impact of High-Energy Weather Events

Several high-energy weather events impacted the study sites during the study from late August through mid-September. These storms included Tropical Depression Henri, Hurricane Fabian, and Hurricane Isabel.

Hurricane Henri formed in the Gulf of Mexico on September 3, 2003 before it weakened to a depression and moved up the east coast of the United States towards the outer banks of North Carolina. Around September 7 and 8, Henri passed approximately 150 miles east of the study sites, initiating high wave energy along the beaches.

Hurricane Fabian developed on August 27, 2003, and hit Bermuda with category 3 strength before moving up the east coast of the United States. Around September 10 and 11, Fabian passed approximately 150 miles east of the study sites, causing high wind and waves to impact the beaches there. Data collection on September 12 was limited to the dune region due to high wave energy. During this data collection period, waves were passing over the closure signs, and often crashed on the base of the dunes.

Hurricane Isabel developed on September 6 and made landfall just south of the Avon study site on September 18 as a category 2 hurricane. Isabel created storm surges of 2-2.5 meters above the normal tidal level in this area. Many of the dunes were completely eroded by the storm, and all those remaining were scarped and cut through.
Beaches were closed to off-road vehicles for several weeks due to both the closure of the roads, and remaining high water levels. Data collection continued in October and November in order to gather data regarding the impacts of high-energy weather events on ghost crab populations.
7. Results

7.1 Beach Closure and the August 23 Data Collection Period

Closures of the beach crest in Site 2 (24hr), 3 (PM closure), 6 (PM closure), and 7 (24hr) were initiated on August 7, 2003. Mean burrow densities in the beach crest, mid-beach, and dune regions of the beach were compared between the pre-closure dates (June 4, June 25, July 7, and August 3) and the post-closure collection date (August 23) to determine impacts of the new closures on ghost crab population density.

At Coquina, closing the beach crest to ORV use for 24 hours per day resulted in a significant increase in mean burrow density while closing the beach crest to ORV use from 8pm to 6am did not show an increase in mean burrow density. Site 1 (No ORV) showed a significant, but highly variable change in mean burrow density from less than 1 to approximately 7 burrows per 22.5 m² on the beach crest from June 4 through August 23 (ANOVA, p=0.002, df=4, 10, F=9.51) (Figure 4). Site 2 (24hr) showed a significant increase in mean burrow density of approximately 1 burrow per 22.5 m² on the beach crest after the initiation of the closure as compared to the previous survey dates (ANOVA, p=0.007, df=4, 78, F=3.81) (Figure 5). Mean burrow density on the mid-beach in Site 2 (24hr) decreased significantly by approximately 1 burrow per 22.5 m² from June 4 through August 23 (ANOVA, p<0.001, df=4, 94, F=7.45). Mean burrow density in the dunes in Site 2 (24hr) showed no significant variation from June 4 through August 23 (ANOVA, p=0.869, df=4, 62, F=0.31). Site 3 (PM closure) showed no significant change in mean burrow density on the beach crest after the initiation of the
closure as compared to the previous survey dates (ANOVA, \( p=0.113, \ df=4, \ 56, \ F=1.96 \)) (Figure 6). Mean burrow density on the mid-beach of Site 3 (PM closure) decreased significantly by approximately 0.25 burrows per 22.5 m\(^2\) from June 4 through August 23 (ANOVA, \( p=0.020, \ df=4, \ 99, \ F=3.05 \)). Mean burrow density in the dune region of Site 3 (PM closure) did not change significantly from June 4 through August 23, though August 23 appeared to have the highest mean burrow densities (ANOVA, \( p=0.075, \ df=4, \ 59, \ F=2.25 \)).

At Avon, closing the beach crest to ORV use for 24 hours a day, and from 8pm to 6am resulted in a significant increase in mean burrow density in that region. Site 6 (PM closure) showed a significant increase in mean burrow density by approximately 0.5 burrows per 22.5 m\(^2\) on the beach crest after the initiation of the closure as compared to the previous survey dates (ANOVA, \( p=0.015, \ df=3, \ 81 \)) (Figure 7). Mean burrow density in Site 6 (PM closure) on the mid-beach and dune regions remained at zero burrows from June 4 through August 23. Site 7 (24hr) showed a significant increase in mean burrow density on the beach crest of approximately 0.2 burrows per 22.5 m\(^2\) after the initiation of the vehicle closure as compared to the previous survey dates (ANOVA, \( p=0.049, \ df=3, \ 72, \ F=2.75 \)) (Figure 8). Mean burrow density for Site 7 (24hr) in the mid-beach and dune regions remained at zero burrows from June 4 through August 23. Mean burrow density on the beach crest of Site 8 (No ORV) showed no significant change from June 4 through August 23 (ANOVA, \( p=0.059, \ df=4, \ 10, \ F=3.26 \)) (Figure 9).

7.2 Burrow Density

Mean burrow densities varied significantly among the Sites during the field season and varied from approximately 0.5 burrows to 3 burrows per 22.5 m\(^2\) (Figure 10). Mean
burrow densities for the field season were 3.13, 1.03, 0.32, 0.46, 0.25, 0.45, 0.79, and 1.91 for Sites 1 through 8, respectively. At Coquina, Site 1 (No ORV) was shown to have significantly more burrows than Sites 2 through 4 (all ORV) by an average of 2 burrows per 22.5 m² over the entire field season (ANOVA, p=0.008, df=3, 23, F=5.03) (Figure 10). Mean burrow density did not differ significantly among Sites 2 (ORV), 3 (ORV), and 4 (ORV) (ANOVA, p=0.373, df=2, 16, F=1.05), where the average burrow density was approximately 0.6 burrows per 22.5 m². At Avon, Site 8 (No ORV) was shown to have significantly more burrows than Sites 5 through 7 (all ORV) (ANOVA, p=0.007, df=3, 23, F=5.18) (Figure 10). Approximately 2 burrows per 22.5 m² were found in Site 8 (No ORV), whereas approximately 0.5 burrows were found in Sites 5 through 7 (all ORV). Mean burrow density did not differ significantly between Sites 5 (ORV), 6 (ORV), and 7 (ORV) (ANOVA, p=0.553, df=2, 16, F=0.61).

Mean burrow density was not significantly different between Site 1 (No ORV) and Site 8 (No ORV) (ANOVA, p=0.198, df=1, 14, F=1.82). Mean burrow density between the driven sites (ORV) at Coquina (Sites 2 through 4) and the driven sites (ORV) at Avon (Sites 5 through 7) was not significantly different (ANOVA, p=0.651, df=1, 36, F=1.21) (Figure 10). Levene's Test for continuous distributions showed no difference in the variances of burrow density among all of the sites (Test statistic=1.446, p=0.210).

Mean burrow density from the crest of the fore dune to the beach crest did not vary significantly through the field season (ANOVA, p=0.125, df=7, 46, F=1.73) (Figure 11), where the mean burrow density was found to be approximately 1.2 burrows per 22.5 m². Levene's test for continuous distributions showed no difference among the variances of burrow density through the field season (Test statistic=0.776, p=0.610).
Mean burrow density for all of the dates and sites did not vary significantly between the dune, mid-beach, and beach crest (ANOVA, p=0.090, df=2, F=2.45). However, mean burrow density did appear to be greatest in the dune region, and lowest in the beach crest region (mean=1.64, 0.96, 0.66 for the dune, mid-beach and beach crest, respectively). Mean burrow density in the beach crest did not vary significantly through the field season (ANOVA, p=0.505, df=7, 50, F=0.91); however, there was a significant variation in burrow density among the sites with respect to beach region (ANOVA, p<0.001, df=7, 50, F=5.01) where Site 1 (No ORV) and Site 8 (No ORV) were found to have more burrows located on the beach crest than Sites 2 through 7 (all ORV), as we had expected to find. Mean burrow density in the mid-beach did not vary significantly through the field season (ANOVA, p=0.287, df=7, 46, F=1.27); however, there was significant variation in burrow density among sites within the mid-beach (ANOVA, p=0.038, df=7, 46, F=2.36). Site 1 (No ORV) had significantly more burrows in the mid-beach region than Sites 2 through 7 (all ORV) and 8 (No ORV). Mean burrow density in the dune region varied significantly through the field season (ANOVA, p=0.004, df=7, 46, F=3.55). Mean burrow density in the dune region was found to be greater in the November 3 data collection period, than in any other collection period. Mean burrow density in the dune region did not differ significantly among the sites (ANOVA, p=0.057, df=7, 46, F=2.15). However, mean burrow density in the dune region did appear to be greater in Site 1 (No ORV) and 8 (No ORV) than in Sites 2 through 7 (all ORV) (mean=2.89, 0.51, 0.33, 0.13, 0.04, 0.03, 0.04, 1.35 for Sites 1 through 8, respectively).

Differences in mean burrow density for each site before and after the passing of hurricanes Henri, Fabian, and Isabel can be seen in Figure 12. Mean burrow densities
were averaged over June 4 through August 23 for pre-storm data points, and September 12 through November 3 for post-storm data points. No change in mean burrow density occurred at Site 8 (No ORV). A significant change in burrow density occurred after the passing of the storms (ANOVA, p=0.008, df=1, 52, F=7.68). For Sites 1 through 7, mean burrow density increased after the storms passed through the area, and the vast majority of these burrows were very small (see below), indicating colonization of the newly scoured beach.

7.3 Burrow Sizes

Mean burrow width showed significant variation among the sites (ANOVA, p<0.001, df=7, 2295, F=9.87) (Figure 13). Smaller burrow widths were found in Sites 4 through 6 (all ORV) than any other sites throughout the field season. Figure 14 shows variations in burrow width for each site before and after the storm impacts. Mean burrow size had a more significant change in Sites 2 (ORV), 3 (ORV), 4 (ORV), and 6 (ORV) than in Sites 1 (No ORV), 5 (ORV), 7 (ORV), and 8 (No ORV).

Mean burrow width changed significantly through the field season (ANOVA, p<0.001, df=7, 2295, F=71.93) (Figure 15). An increase in mean burrow width occurred from June 4 through August 3. A decrease in mean burrow width was noted for the September 12 data collection period, when Hurricanes Henri and Fabian were impacting the region. A decrease in mean burrow width also occurred prior to the October 3 data collection period, which was the first collection period after the passing of Hurricane Isabel. An additional increase in mean burrow width were seen between October 3 and November 3. The burrow size frequency distribution figures for burrow width also
indicated changes in burrow size groups through the field season (Figure 16), possibly due to maturation in the ghost crab population as well as impacts from the storms.

Mean burrow depth did not differ significantly between Site 1 (No ORV) and Site 8 (No ORV) (ANOVA, $p = 0.247$, df = 1, 1473, $F = 1.34$). Mean burrow depth for Site 1 and 8 was variable over time and changed significantly through the field season (ANOVA, $p<0.001$, df = 6, 1495, $F = 5.89$) (Figure 17). In general, shorter burrows occurred during periods following high-energy weather events (July 7 mean = 28.72 ± 16.10 and Oct 3 mean = 29.26 ± 18.20), and deeper burrows at other times. The deepest burrows occurred during both August periods (August 3 mean = 37.61 ± 11.56, August 23 mean = 37.72 ± 17.90) and the November 3 period (mean = 35.80 ± 28.12).

Mean burrow depth, pooled for both sites and for all of the dates, was significantly different between the dune, mid-beach, and beach crest regions of the beach (ANOVA, $p<0.001$, df=2, 1450, $F=10.70$) (Figures 18a, 18b, 18c). Mean burrow depth in the dune was significantly shorter than burrow depth in both the mid-beach and the beach crest. Mean burrow depth in the dune region of the beach varied significantly through the field season (ANOVA, $p=0.005$, df=7, 385, $F=3.13$) (Figure 18a). The data collection periods that took place soon after high-energy weather events generally resulted in deeper burrows in the dunes than those during fair weather, with burrow depths recorded on June 4 (mean=29.75±12.63), June 25 (mean=23.77±12.85), July 7 (mean=24.89±13.65), and August 23 (mean=29.28±12.54) being shallower than those burrow depths recorded August 3 (mean=33.86 ±8.34), October 3 (mean=36.00±29.39), and November 3 (mean=34.84±32.14). Mean burrow depth in the mid-beach varied significantly through the field season (ANOVA, $p=0.001$, df=7, 805, $F=3.78$) (Figure 18b). Mean burrow
depth on the beach crest varied significantly through the field season (ANOVA, p=0.009, df=7, 243, F=3.14) (Figure 18c), though no pattern was discernible.

7.4 Sediment Compaction

Mean compaction levels among the sites were found to be significantly different (ANOVA, p<0.001, df=7, 757, F=16.18) ranging from approximately 211 psi to 320 psi (Figure 19), with Coquina sites (1 through 4) significantly more compacted than Avon sites (5 through 8) (ANOVA, p<0.001, df=1, 763, F=78.15).

Mean compaction levels were significantly different within Coquina in Sites 1 (No ORV), 2 (ORV), 3 (ORV), and 4 (ORV) (ANOVA, p=0.001, df=3, 436, F=5.97). The highest mean compaction levels were found in Site 3 (ORV) (mean=320.28±90.68 psi), with compaction levels in Site 1 (No ORV) and 4 (ORV) being the lowest, and approximately equal (Site 1 mean=271.3±88.3 psi; Site 4 mean=283.7±88.7 psi). Mean compaction levels of Site 2 (ORV) fell in between (mean=294.03±94.38 psi). Mean compaction levels at Avon between Sites 5 (ORV), 6 (ORV), 7 (ORV), and 8 (No ORV) showed a significant difference (ANOVA, p=0.002, df=3, 321, F=4.92). Mean compaction in Site 8 (No ORV) (mean=211.67±72.29 psi) was significantly lower than compaction levels in Sites 5 through 7 (all ORV) (Site 5 mean=240.64±78.19 psi; Site 6 mean=248.58±81.69 psi; Site 7 mean=248.66±77.57 psi).

Mean compaction of the sediment changed significantly throughout the field season (ANOVA, p=0.006, df=7, 757, F=2.86), with September 12 showing the lowest mean compaction levels of approximately 220 psi. Compaction levels of the remaining data collection periods ranged were approximately 270 psi. Removing the September 12 survey trip, in which high waters only allowed analysis of the first 5-20 meters from the
dune crest and thereby possibly skewing the results, found no statistical difference in mean compaction through the field season (ANOVA, p=0.451, df=6, 700, F=0.96). Levene's test for a continuous distribution showed no difference in the variances of the compaction between dates, sites, or locations (Test statistic=0.896, p=0.648).

Mean compaction from the dune crest to the waterline, differed significantly for all sites (ANOVA, p<0.001, df=20, 744, F=7.41) (Figure 20). Compaction at the dune crest was shown to be lowest, with a gradual increase across the beach slope for all sites. Mean compaction levels were the greatest at the waterline.

7.5 Sediment Grain Size Analysis

Grain size characteristics were different between Avon and Coquina. Mean sediment grain size was significantly different between Coquina and Avon, with larger medium to coarse grain sand sizes at Avon and smaller fine to medium sand grain sizes at Coquina (ANOVA, p<0.001, df=5, 26, F=6.47) (Figure 21). Median grain size was significantly different between the sites, with a larger median grain size found at Avon and smaller median grain size found at Coquina (ANOVA, p=0.002, df=5, 26, F=5.04).

Mean sediment grain sizes were not significantly different between driven (ORV) and not driven (No ORV) sites at both Coquina and Avon (ANOVA, p=0.535, df=1, 30, F=0.39). Median sediment grain sizes were not significantly different between driven (ORV) and not driven (No ORV) sites (ANOVA, p=0.516, df=1, 30, F=0.43).

Mean sediment grain size did not change significantly through the field season (ANOVA, p=0.383, df=3, 28, F=1.06). Median grain size did not change through the field season (ANOVA, p=0.275, df=3, 28, F=1.36).
7.6 Beach Profiles

Beach profiles for each Site were highly variable between dates (Figure 22a-h). With a few exceptions, the beach profile was highest in elevation with the gentlest slope during the "fair weather" period before the storms on September 12. Data collection periods during and after September 12 generally showed a marked decrease in the elevation of the beach as well as sharply scarped dunes and shorter mid-beach regions. As was expected, the beach profiles that were taken at each site during each data collection period varied. Site 1 (No ORV) (Figure 22a) profiles were very flat and wide, and also variable through the field season. Profiles of the beach that took place after the passing of the storms were very steep, with a scarped dune face and steeper foreshore than profiles before the storms. Some recovery of the beach can be seen in the flattening and lengthening of the profile between October 3 and November 3. Similar cases can be seen in Sites 2 through 8, where the profiles are highly variable. In general, the steepest and shortest mid-beach region and scarped dune faces were seen during the September 12 through November 3 data collection periods. Analysis of the profiles taken in Site 8 (No ORV) show that in the beginning of the field season a second peak of the fore dune occurred below the beach crest. October 3 and November 3 profiles indicate that Hurricane Isabel was so strong that the second peak was completely removed from the dune face.
8. Discussion

8.1 Management Implications

This is the first report of the possible mitigation of ORV impacts on ghost crab populations. Closing portions of the beaches to ORV usage resulted in a small but significant increase in ghost crabs and their burrows at the beaches of Coquina. At Coquina, closing portions of the beach crest to ORV use for 24 hours a day resulted in a significant increase in mean burrow density by approximately 1 burrow per 22.5 m². While this increase was small, it was statistically significant and was approximately double the density of ghost crab burrows that had previously been found in that region. Burrow density within the 24-hour closure at Coquina increased significantly only on August 23, and was not as variable as the changes in burrow density found in Site 1 (No ORV). These increases in mean burrow density were therefore likely a result of beach closures to ORV use. On the basis of burrow width, immigrant crabs that inhabit this area were apparently those recruited from adjacent areas that had restrictions to ORV use. Burrows were typically large and not indicative of smaller crabs that would have been found there had settlement been occurring. The crabs may have migrated into the newly closed region at night while foraging on the foreshore, as Wolcott and Wolcott (1978) found that the crabs can move as much as 300 meters while feeding on the foreshore in one night. The crabs may also have migrated through the water while breeding or spawning (Williams, 1984). At Coquina, closing the beach crest to ORV use from 8pm to 6am did not result in a significant increase in the ghost crab population in that area.
The continued use of ORVs during the day likely reduced the ability of the ghost crabs to burrow and survive in that region. Simply closing the beaches at Coquina to ORV use during night hours when the ghost crabs were most likely to be out of their burrows and foraging on the fore shore as Wolcott and Wolcott suggested (1978) was not sufficient to allow them to re-inhabit that area.

At Avon, closures of portions of the beaches to ORV use also resulted in a significant increase in the densities of ghost crab populations. Closing the beach crest at Avon to ORV use for both 24 hours a day and from 8pm to 6am resulted in a small, but significant increase in mean burrow densities within these regions. While mean burrow density at Site 8 (No ORV) was somewhat variable, the variation in mean burrow density did not occur solely during the closure. As was found at Coquina, the ghost crabs that inhabited the newly closed portions of the beach were likely recruits from other regions that had restrictions to ORV use. At Avon, the closure of the beach crest to ORV use at night (Site 6) may have permitted the ghost crabs to re-inhabit the area. During the August 23 study period this site experienced little ORV traffic during the day. The reduced use of this region may have resulted in a modest immigration of the ghost crabs into the region than would have been seen if the region had been used by ORVs, as at Coquina.

8.2 Ghost Crabs

Ghost crab populations at Coquina and Avon had similar mean burrow densities. Burrow densities and sizes were similar for both the driven and not driven sites in both of the study areas. While no statistically significant differences were found between the burrow densities at Coquina and Avon, there were slightly lower mean burrow densities
at Site 8 (No ORV) relative to Site 1 (No ORV) (Figure 10). This could be related to the coarser sand, and steeper beaches that were found in Site 8 (No ORV). Gauld and Buchanan (1956) found that steeper beach slopes and coarser mean sediment grain sizes, as was found at Avon, may cause increased drainage rates and therefore may increase the risks of dehydration to the beach organisms, which can be detrimental to the survival of the ghost crabs (Wolcott, 1984; Weinstein et. al., 1994; Weinstein, 1998). McLachlan (1996) also found that increased sediment grain sizes might result in a decrease in species richness and abundance. Sediment characteristics have been shown to be important to the habitat use and population size of Uca species and other closely related ocypodid crabs (Gibbs, 1978; Icely, 1978; Montague, 1980; Thurman, 1984).

Off-road vehicles were shown to have a detrimental impact on the density of ghost crab \textit{(Ocypode quadrata)} populations at Cape Hatteras National Seashore. The study sites in which vehicles were permitted to drive on the beaches had significantly lower densities of ghost crab burrows than those sites remaining closed to privately owed vehicles. Steiner and Leatherman (1981) showed that ghost crabs could be killed or mortally injured by ORVs driving over them or through the alteration of their environment by ORVs. While Wolcott and Wolcott (1984) found no real impact of ORV use on ghost crab populations, the impact shown in this study may be due to higher ORV use on Cape Hatteras than on Cape Lookout, an area that Wolcott and Wolcott had defined as “low-usage.”

Steiner and Leatherman (1981) found that in a region which is heavily impacted by ORVs, there will be approximately 0.3 ghost crabs per 1000 m$^2$, and in a region impacted by pedestrians, there will be approximately 19 ghost crabs per 1000 m$^2$. In this
study, we found that there were approximately 0.5 ghost crab burrows per 22.5 m² within
the regions impacted by ORVs, which equates to approximately 22 crabs per 1000 m²
which is significantly higher than the densities found by Steiner and Leatherman (1981).
We also found that there were approximately 2 burrows per 22.5 m² within the regions
impacted by pedestrians, but not ORVs, which equates to approximately 88 crabs per
1000 m² which is again significantly higher than the densities found by Steiner and
Leatherman (1981). The study performed by Steiner and Leatherman (1981), as well as
the results from this study, found that the use of ORVs on the beaches caused a
detrimental impact on the density of ghost crab populations on the beach. The
discrepancies in scale may be due to differences in the sampling methods because Steiner
and Leatherman (1981) counted the number of crabs within a circle of light at night. We
used burrow counts as an approximate census of the burrow density. Leber (1982) found
that burrow counts in 1976 were nearly an order of magnitude greater along the upper
beach than crab counts along wash zone transects. Wolcott and Wolcott (1984) describe
burrow counting as a method that, while requiring subjective distinction between active
and inactive burrows, has the ability to describe population size and age structures.
Burrow counting also approximates the total population, rather than the proportion active
at a given time and thus available for visual censusing (Wolcott and Wolcott, 1984).
Quantitative nocturnal counts of surface-active crabs are extremely difficult due to the
rapid movements of the crabs, and may give much lower population estimates (Wolcott,
1978; Steiner and Leatherman, 1981; Wolcott and Wolcott, 1984; Leber, 1982).

While there was no significant variation in mean burrow densities found
throughout the field season, mean burrow density at Site 1 (No ORV) increased
dramatically by the November 3 sampling period as compared to the other study sites. Mean burrow width at Avon (Site 8 (No ORV)) was found to be significantly greater than mean burrow width at Coquina (Site 1 (No ORV)) for the November 3 data collection period. The increased presence of larger ghost crabs at Avon after the passing of three hurricanes suggests several possibilities. The higher density of larger surviving crabs at Avon may have resulted in greater predation on the smaller ghost crabs there in that region (Wolcott, 1978), whereas higher settlement at Coquina may have been due to the reduced numbers of larger crabs, and therefore reduced levels of competition and predation or differences in the physical habitats such as sediment grain size and compaction between Coquina and Avon.

The impact of high-energy weather events on ghost crab populations has not been well documented. Mean burrow densities at Coquina and at Avon changed dramatically after the passing of hurricanes Henri, Fabian, and Isabel (Figure 12). Burrow densities in the driven sites (ORV) increased after the passing of the storms due to the restricted ability of ORVs to access the beaches during and immediately following the high-energy weather events. Mean burrow densities also increased in Site 1 (No ORV) that was closed to all privately owned vehicles, but not at Site 8 (No ORV). After the passing of the three hurricanes, burrow densities in each site became highly variable. Even after the occurrence of the high-energy weather events, mean burrow densities in regions open to ORVs was less than that found in regions closed to all privately owned vehicles. It is possible that in the sites that were closed to ORV use throughout the season, some larger ghost crabs were able to survive the storms, whereas in regions that were open to ORV use, there was little to no competition for the settlement of juvenile ghost crabs.
Settlement of juvenile ghost crabs at Coquina and Avon occurred after the hurricanes and was particularly evident by the October and November sampling periods. Settlement of Uca species, a closely related Ocypodidae, occurs in clusters or waves (Jone and Epifanio, 1995), with larvae developing in the open ocean for approximately 60 days (Williams, 1981) prior to being driven ashore by various transport mechanisms such as tides, winds, and currents (Jones and Epifanio, 1995; Brubaker and Hooff, 2000; Garland, et. al., 2002; Forward, et. al., 2004). Such waves of settlement resulting from wind-driven transport explain the large increases in small crabs after the hurricanes.

The effect of hurricanes on mean burrow width of the ghost crabs was first noted in the September 12 data collection period, when the size classes had shifted down to the more frequent 1cm burrows. The high wind and wave energy of Henri and Fabian apparently removed or displaced the larger crabs when the waves passed over the beach crest and mid-beach regions scouring the beach and removing small organisms, or burying and suffocating them. The larger crabs may also have migrated to the dune field behind the fore dune to wait out the storm (Leber, 1982). If migration into the dune field occurred, only a few crabs then re-emerged back onto the beach face after the passing of the storm. Hurricane Isabel also dramatically changed the beach environment on September 18. By October 3, most of the burrows greater than 1cm diameter were gone. Many of the larger crabs that were able to survive Henri and Fabian were removed from the system after the passing of Isabel. By November there was a small, but apparent increase in 2, 3, and 4 cm burrows which suggested a migration of the larger ghost crabs back into the study sites, presumably from the protection provided from the high wind and waves by the dunes.
Mean burrow width in Coquina was highly variable with regards to the distribution of larger ghost crabs among the sites. Mean burrow width varied significantly among the sites at Coquina, with no apparent pattern. At Avon, the largest burrows were found in Site 8 (No ORV), which was closed to privately owed vehicles at all times and the smallest burrows were found in Site 5 (ORV) which had the greatest traffic, being located closest site to the ORV ramp onto the beach (Figure 3). ORV use on the beaches may therefore limit the size of ghost crabs in certain sites, possibly affecting the survival of larger crabs and reducing the crabs’ life expectancies in those sites, and therefore resulting in smaller mean burrow widths (Steiner and Leatherman, 1981).

Mean burrow width varied significantly within each site before and after the occurrence of hurricanes Henri, Fabian, and Isabel. All Sites except Site 8 (No ORV) showed significant declines in mean burrow width after the passing of the storms. Site 8 (No ORV) had a minimal change in mean burrow width, with only a slight decrease compared to the change in mean burrow width seen at the other Sites. At Coquina, mean burrow width decreased dramatically with the passing of the storms. After the passing of hurricanes Henri, Fabian, and Isabel, the system was apparently “re-set” at Coquina with regards to ghost crab population dynamics, with the sizes in each site being more uniform than before the storms, and most likely due to the “waves” of settling juveniles (Jones and Epifanio, 1995). Change in burrow width at Avon before and after the storms was much more variable. The largest change in mean burrow width occurred at Site 6 (ORV), while there was very little change at Site 8 (No ORV).
Mean burrow depth changed significantly through the field season (Figure 17). In general, shallow burrows were found immediately following high-energy weather events, with deeper burrows found at other times. High-energy weather events cause a significant amount of sediment movement, both through the wind and the water moving across the beach face (Swart, 1983), likely filling in established burrows (Hill and Hunter, 1976). It is possible that during periods of fair weather, as the beach face elevation increased, the burrow depth also increased, indicating a change in surface height rather than in burrow depth. This possibility was not addressed through the work of this study. Burrow depths recorded in the dune region during or after high-energy weather events resulted in deeper burrows than in other regions of the beach. This is likely due to the crabs moving to the dunes and inhabiting those burrows for shelter from the storms. These burrows may also have been kept open due to the increased usage than the burrows found in other regions of the beach. Ghost crabs may migrate back towards the dune and burrow there during periods of foul weather (Leber, 1982).

8.3 Physical Environment

Mean compaction levels among the sites were highly variable, with Coquina sites being significantly more compacted than Avon sites. At Coquina, the beach tended to be flatter and wider than Avon, which might have accommodated and attracted more ORV drivers. At Avon the sediment in general was very loose, increasing the risk of having an ORV become stuck in the sand, which may have deterred some ORV drivers. Differences in sediment characteristics may also have impacted the compaction levels at Coquina and Avon (Komar, 1998).
At Coquina, Site 3 (ORV) was significantly more compacted than Sites 1 through 4, with Site 1 (No ORV) and 4 (ORV) having approximately equal compaction levels. These results demonstrate that compaction at Coquina is highly variable, and is not strictly related to the presence of ORVs. Other factors that might impact the compaction of the sediment include the sediment grain size and the slope of the beach (Komar, 1998).

At Avon, Site 8 (No ORV) was significantly less compacted than Sites 5 through 7 (all ORV), which coincides with what was found by Perry (2002). This variation could be attributed to the impact of ORVs on the sediment characteristics of the beach. At Avon, it appears that the beach in Sites 5 through 7 (all ORV) is shorter in length from the dune crest to the waterline than in Site 8 (No ORV). The combined impact of ORV action and a greater mean sediment grain size (Komar, 1998) may increase the slope of the beach, which would likely shorten the distance from the dune crest to the water line.

Mean compaction showed no significant change through the field season. During a storm, high wave-energy causes much of the sediment on the beach face to suspend and re-settle. While it may have been expected that lower compaction levels would have been found following the storm events due to the resuspension of the sediment, this was not the case. It appears that the beach at Avon was less affected by the hurricanes than was at Coquina, and this may also explain the lower variability in burrow densities and widths at Avon after the hurricanes.

A significant change in mean compaction was found on the beaches from the dune crest to the water line. The compaction was the least in the dune region and greatest near the water line. In the dune region, pedestrians and vehicles are both restricted from entering the area, thus reducing compaction of the sediment from that source. Sediment
forms dunes through Aeolian transport, and any compacting action on the sediment in the
dune is due to the compaction of the sediment on itself (Swart, 1983). In addition, water
does not impact or compact the sediment in this region. Higher levels of compaction
were found on the mid-beach where vehicles and pedestrians do impact the sediment.
The compaction levels on the beach crest were highly variable as a result of the wave
action, with occasional vehicles driving on the area at low tide.

In contrast to what was found by Perry (2002), mean sediment grain size was not
significantly impacted by the presence of ORVs. Mean sediment grain size also did not
change through the field season. The mean grain size was significantly different between
Coquina and Avon with sediment grain sizes significantly smaller at Coquina beach.
The smaller grain sizes contributed to the increased compaction levels found in Coquina.
Smaller grain sizes are more easily compacted, with less air space present, than larger
grain sizes (Komar, 1998).

Compaction and mean sediment grain size do not appear to impact the presence or
absence or ghost crabs. The most likely predictor of the presence or absence of ghost
crabs in our study sites was the level of ORV usage on the beaches.
9. Further Areas of Study

9.1 Management Implications

Further study is recommended to determine the recovery rates of ghost crabs into regions of the beach that have been newly closed to off-road vehicles. Mark-recapture studies would facilitate the measurement of immigration and emigration rates from pristine areas into or out of impacted regions.

9.2 High-energy Weather Events

Further study of the impact of high-energy weather events on ghost crab populations would be beneficial. Is the population of 1cm crabs that inhabited the area after the passing of hurricanes Henri, Fabian, and Isabel, the population of larger crabs that is found on the beach the following summer? Is the change in burrow size frequency a result of the larger crabs already inhabiting their burrows for the winter?
10. Conclusions

Both off-road vehicles and high-energy weather events impact ghost crab populations at Cape Hatteras National Seashore. Off-road vehicles tended to reduce the ability of ghost crabs to inhabit an area. On the other hand, the occurrence of high-energy weather events in conjunction with the prime settlement period for these crabs changed the dynamics of the populations and permitted settlement of ghost crab larvae.

Park Service personnel use ghost crabs as a simple measure of the health of the ecosystem (Steiner and Leatherman, 1981; Jim Ebert pers. comm., 2003). As one of the top predators of the beach ecosystem, ghost crabs provide a simple marker for the health of the ecosystem, and counting burrows is a simple method for gathering data regarding the ghost crab populations. Off-road vehicles have a detrimental impact on ghost crab populations at Cape Hatteras National Seashore in North Carolina. By closing the beach crest to ORVs at both Coquina and Avon for 24 hours a day, the ghost crabs were able to migrate into and inhabit these areas. While closing the beach crest to ORVs from 8pm to 6am at Coquina was not sufficient to permit the inhabitation of ghost crab populations into this region, this nightly closure to ORVs did permit ghost crabs to burrow in the beach crest at Avon. Often, signs may act as a deterrent to ORV drivers who may not stop to read the signs but avoid that region. This behavior may have reduced the usage of the beach crest in the 8pm to 6am closure by ORV drivers.

High-energy weather events have a significant impact on the beach ecosystem, and particularly on the dynamics of ghost crab populations. Storms scour the beaches
and apparently remove larger ghost crabs. Ghost crab populations are essentially re-set by the passage of storms, which reduce the presence of larger ghost crabs and allow the settlement of smaller ghost crab larvae.

Compaction and grain size did not change significantly through the field season, and are not significantly impacted by the presence of off-road vehicles on the beach, nor by the passage of high-energy weather events. Compaction and grain size do not appear to have a significant impact on the presence or absence of ghost crab populations at Cape Hatteras National Seashore.

Long-term and short-term impacts affect the presence of ghost crabs on the beaches of Cape Hatteras National Seashore differently. Short-term impacts such as the usage of ORVs on the beach face cause a temporary marked decrease in the density of ghost crab populations. Through the results of this project it appears that long-term impacts on ghost crab populations such as the occurrence of a high-energy weather event has the ability to "re-set" the system, allowing the settlement of ghost crabs into regions which were previously barren of ghost crab burrows. It appears that while having ORVs drive on the beaches during the summer may decrease the density of ghost crab burrows in those regions, the occurrence of high-energy weather events permits the settlement of ghost crabs into those regions. When managing for long-term impacts on ghost crab populations, allowing ORVs to drive on the beaches, anticipating the on-set of a high-energy weather event to re-set the system, may be an option. Managers also must keep in mind that if all beaches are open to ORVs, reproducing ghost crab populations may be reduced, reducing the selection of larvae that inhabit the regions after a high-energy weather event.
In 1980, Godfrey and Godfrey recommended that if vehicles are to be permitted on the beaches, that they should be restricted to an “ORV corridor” between the beach crest and the upper drift lines, except where birds are nesting. The results of this project lead to a similar conclusion when managing for ghost crab populations. Within the realms of this project, closing the beach crest to ORVs for 24 hours a day was a sufficient management scheme to permit the habitation of ghost crabs in that region, even when permitting ORVs to drive behind the closed regions at both Coquina and Avon. Wolcott and Wolcott (1984) suggested that restricting the use of ORVs on the beach crest between dusk and dawn might allow ghost crabs to inhabit an area. The results of this project suggest that while closing the beach crest to ORVs from 8pm to 6am at Avon may be a sufficient management scheme, it is not sufficient at Coquina. Further study is required to analyze the applicability of this method of preserving ghost crab populations on the outer banks of North Carolina.
Figure 1. Profile of a typical barrier island. The typical barrier island profile begins at the swash zone and foreshore on the ocean side of the island. Traveling landward from the foreshore, the next ecotone encountered is the backshore, followed by the primary dune, secondary dune field, maritime forest, high salt marsh, low salt marsh, and finally the tidal flat and salt marsh areas. This project concentrates on the swash zone and foreshore through the backshore to the crest of the primary dune.
Figure 2. Coquina Beach, North Carolina. Site 1 was a control site which remained closed to ORVs, Site 2 (the front 20 meters) was closed for 24 hours a day to ORVs, Site 3 (the front 20 meters) was closed from 8pm to 6am to ORVs, and Site 4 was a control site which remained open to ORV use. Closures of the beach crest in each site were initiated on August 7, 2003 and lasted through August 21, 2003.
Figure 3. Avon, North Carolina. Site 5 was a control site that remained open to ORVs, Site 6 (the front 20 meters) was closed from 8pm to 6am, Site 7 (the front 20 meters) was closed for 24 hours a day, and Site 8 was a control site that remained closed to ORVs. Closures of the beach crest in each site were initiated on August 7, 2003 and lasted through August 21, 2003.
Figure 4. Variations in burrow density of Site 1 on the beach crest (first 20 meters of beach from the waterline). Site 1 remained closed to privately owned vehicles throughout the field season. Burrow densities on the beach crest of site 1 varied significantly.
Figure 5. Variations in burrow density of Site 2 on the beach crest (first 20 meters of beach from the waterline). Closures of the beach crest were initiated on August 7. The beach crest in site 2 was closed to privately owned vehicles for 24 hours a day. Burrow density after the closure was initiated was significantly higher than burrow densities on previous dates.
Figure 6. Variations in burrow density of Site 3 on the beach crest (first 20 meters of beach from the waterline). Closures of the beach were initiated on August 7. The beach crest in site 3 was closed to privately owned vehicles from 8pm to 6am. Burrow density after the initiation of the closures was not significantly higher than the burrow densities of previous data collection periods.
Figure 7. Variations in burrow density of Site 6 on the beach crest (first 20 meters of beach from the waterline) of site 6. Closures of the beach crest were initiated on August 7, from 8pm to 6am. Burrow density 3 weeks after the initiation of the closure was significantly higher on the beach crest than before the closures.
**Figure 8.** Variations in burrow density of Site 7 on the beach crest (front 20 meters of the beach from the waterline). Closures of the beach were initiated on August 7, for 24 hours a day. Burrow densities 3 weeks after the initiation of the closure were significantly higher than burrow densities earlier in the season.
Figure 9. Variations in burrow density of Site 8 on the beach crest (first 20 meters of beach from the waterline). Site 8 remained closed to privately owned vehicles throughout the field season. Burrow density on the beach crest in site 8 varied significantly through this period.
Figure 10. Burrow densities across both field sites, averaged throughout the field season shown with standard error of the mean. Sites 1 and 8 are closed to vehicles while sites 2 through 7 have vehicles driving on them. Mean burrow density was significantly different at Coquina between sites 1 through 4. Mean burrow density was significantly different at Avon between sites 5 through 8. Mean burrow density was not significantly different between sites 1 and 8 (not driven), or between sites 2 through 7 (driven).
Figure 11. Variations in burrow density for each site through time. September 12 represents data collection in the dune region of the beach only due to high wave energy. Burrow density did not change significantly through the field season.
Figure 12. Burrow densities pre- and post-storm, shown with standard error of the mean. Burrow densities were averaged over June 4 through August 23 for pre-storm, and September 12 through November 3 for post-storm. No change in burrow density occurred at Site 8 (No ORVs).
Figure 13. Differences in burrow width among the sites, shown with standard error of the mean. Burrow width was significantly different among the 8 sites. Mean burrow width was averaged for each data collection period for this figure.
Figure 14. Variations in burrow width before and after Hurricanes Henri, Fabian, and Isabel. Burrow widths were averaged for each site for data collection periods before and after the September 12 data collection period.
Figure 15. Variations in average burrow width throughout the field season, shown with 95% confidence intervals. Burrow widths were averaged among the sites. Burrow width changed significantly through the field season.
Figure 16. Burrow Width Frequency Distributions. Burrow width frequency distributions changed significantly through the field season.
Figure 17. Changes in average burrow depth through time, shown with standard error of the mean. Burrow depths for each data collection period were averaged over the site. Mean burrow depth changed significantly through the field season.
Figure 18. Variations in burrow depth on the (A) Dune, (B) Mid-Beach, and (C), Beach Crest, shown with standard deviations. Burrow depths are averaged among the sites.
Figure 19. Comparing compaction levels between Coquina and Avon, as well as among the sites, shown with standard error of the mean. Compaction at Coquina is significantly higher than compaction at Avon. At Coquina, compaction in Sites 1 through 4 varies significantly, with compaction levels at site 3 being the greatest. At Avon, compaction in sites 5 through 8 varies significantly, with site 8, where no vehicles are permitted, being significantly lower than compaction in the driven sites (5 through 7).
Figure 20. Compaction changes from the dune crest to the waterline, shown with standard deviations. Measurements are averaged for depth, and among the sites and dates. Compaction varied significantly from the dune crest to the waterline.
Figure 21. Mean sediment grain size differences between Coquina and Avon as well as among the sites analyzed. Coquina sediments were significantly finer than Avon sediments. No sediments were analyzed from site 3 or site 6. No ORVs were permitted in sites 1 and 8; ORVs were permitted in sites 2 through 7.
Figure 22a. Beach profiles taken at Site 1, beginning at dune crest, or highest point which could be safely reached.
Figure 22b. Beach profiles taken at Site 2, beginning at dune crest, or highest point which could be safely reached.
Figure 22c. Beach profiles taken at Site 3, beginning at dune crest, or highest point which could be safely reached.
Figure 22d. Beach profiles taken at Site 4, beginning at dune crest, or highest point which could be safely reached.
Figure 22e. Beach profiles taken at Site 5, beginning at dune crest, or highest point which could be safely reached.
Figure 22f. Beach profiles taken at Site 6, beginning at dune crest, or highest point which could be safely reached.
Figure 22g. Beach profiles taken at Site 7, beginning at dune crest, or highest point which could be safely reached.
Figure 22h. Beach profiles taken at Site 8, beginning at dune crest, or highest point which could be safely reached.
### Sediment Samples for Analysis

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**Table 1.** Portion of sediment samples analyzed. Plot sample numbers were chosen close to the waterline. Samples were taken from both driven and not driven sites for each date analyzed.
Appendix I

Monthly variation in burrow density at each site
Burrow Density at Site 1
Shown with Standard Error of the Mean Bars
Coquina Beach
No ORVs

Data Collection Period

Frequency of Burrows

Burrow Density at Site 3
Shown with Standard Error of the Mean Bars
Coquina Beach, ORVs
Burrow Density at Site 4
Shown with Standard Error of the Mean Bars
Coquina Beach, ORVs

Data Collection Period

Frequency of Burrows
Burrow Density at Site 7
Shown with Standard Error of the Mean Bars
Avon, ORVs

Data Collection Period

Frequency of Burrows

0 0.5 1 1.5 2 2.5 3 3.5 4

Burrow Density at Site 8
Shown with Standard Error of the Mean Bars
Avon, No ORVs

Data Collection Period

Frequency of Burrows
Appendix II.

Variation in burrow density among the sites for each data collection period.
Mean Burrow Frequency
June 4
Shown with Standard Error of the Mean Bars
Mean Burrow Frequency
June 25
Shown with Standard Error of the Mean Bars
Mean Burrow Frequency
July 7
Shown with Standard Error of the Mean Bars
Mean Burrow Frequency
August 23
Shown with Standard Error of the Mean Bars
Appendix III.

Descriptive Statistics of the Burrow Densities in Each Data Collection Period for Each Site.
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Fales, R.R... Apparent Predation on the Mole Crab *Emerita talpoida* (Say) by the Ghost Crab *Ocypode quadrata* (Fabricus). *Chesapeake Sci.* 17: 65; 1976.


Vita

Cynthia B. Landry