EVIDENCE-BASED RECOMMENTATIONS FOR ATLANTIC COAST PIPING PLOVER (*CHARADRIUS MELODUS*) CONSERVATION AND HABITAT RESTORATION

By

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A Dissertation submitted to the

Graduate School – New Brunswick

Rutgers, The State University of New Jersey

in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

Graduate Program in Ecology and Evolution

written under the direction of

Steven N. Handel

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New Brunswick, New Jersey

January, 2010

ABSTRACT OF THE DISSERTATION

Evidence-based recommendations for Atlantic Coast piping plover (*Charadrius melodus*) conservation and habitat restoration

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Conservation action and habitat restoration for threatened and endangered species are often guided by anecdotal evidence. Limited time and resources are wasted on ineffective strategies, or in some cases, on management that is detrimental to the target species. Therefore, rigorous scientific study must be easily translatable into pragmatic conservation directives. For the Atlantic Coast piping plover (*Charadrius melodus*), a threatened beach-nesting shorebird, two major threats exist for the recovery of the species – habitat degradation by beach stabilization practices and human disturbance, and intense predation pressure by the introduced red fox (*Vulpes vulpes*). This dissertation employs robust statistical methods to: 1) analyze piping plover nesting and foraging behavior, and 2) evaluate the effectiveness of predator exclosures to present evidence-based recommendations for the restoration of breeding habitat and the optimization of reproductive success.

Piping plover nests primarily occur in four distinct habitat conditions defined by percent shell and pebble cover, and distance to nearest dunes and high tide line. Characteristics also vary depending on where the nest is initiated (backshore, overwash fan, primary dune). I translate these results into practical restoration target parameters

and identify threshold values to assist managers in maintaining suitable nesting habitat. Restoration projects must also include accessible high quality foraging habitat to bolster reproductive success. Plover chicks foraged at higher rates and spent less time being vigilant or fleeing from threats at restored tidal ponds than at other potential foraging habitats. This result suggests that the study ponds offered adequate prey biomass, were visited less frequently by humans, and provided proximate refuge from approaching predators. The foraging models I created were validated externally and are applicable for evaluating future restoration projects.

Finally, long-term nest monitoring data indicate that predator exclosures do increase nest hatching success. Electrified exclosures are effective under certain conditions, but at sites with high fox density and human disturbance, nest abandonment becomes sizeable. While the direct cause of abandonments remains unclear, these results will assist managers in making informed decisions on using this technique. These science-based directives can help to create effective habitat designs and conservation strategies for this species.

ACKNOWLEDGEMENTS

My thanks undoubtedly go to my advisor, Steven N. Handel, who shares with me a love of the shore, of Broadway musicals, and most especially, an uncompromising devotion to the New York Yankees. His expertise, insight, and advice during this journey were most influential. An equal amount of gratitude is owed to Julie L. Lockwood, an advisor, mentor, and friend who has guided my career both by her example and by her interminable willingness to listen to my thoughts and encourage my ideas. Academically, Joanna Burger has provided expertise on shorebird ecology and animal behavior; but, on a personal level, she has always supported and endorsed my development into a young female scientist. I will never forget the day she asked me for one good reason why I shouldn't pursue a doctorate. I didn't have an answer; and as it turns out, I never found one. I thank Karl F. Nordstrom for educating me on the natural dynamics of beach ecosystems. I have grown up along the shore, but I will never look at it the same way again.

Special thanks go to Todd Pover of the Conserve Wildlife Foundation of New Jersey. Without his trust in my ability to conduct quality research on an endangered species, this dissertation would not have materialized. In the past five years, Todd and I have had many conversations on many topics, and I am thankful for his friendship on both a professional and personal level.

During my time at Rutgers, I have been positively affected by so many faculty, staff, and students, and I could not possibly list them all. There are a few that have made strong impacts. First, Marsha Morin, the department "mom," as I call her, always has a solution for every real or perceived crisis that occurs. I think I speak for every past, present, and future Ecology & Evolution graduate student when I say that no one can replace her. Jim Trimble was especially helpful in providing technical advice for the spatial analysis portion of my research. Peter Morin's door was always open for questions on statistics, insects, or just about any ecological question I had. Finally, I thank the graduate students in my department for the sense of camaraderie – it always feels good to be part of a family.

I will attempt to express my extreme thankfulness for my mother, Dolores. She has instilled in me a love of science, an affection for nature, and a drive to accomplish my goals. Her support of my endeavors and her gentle way of guiding me along the path is truly priceless. I cannot thank her enough for her willingness to help with my field work, for being enthusiastic about my research, and for being so proud of her daughter. She is my best friend, and I will always admire her. Lastly, I thank Renee Falivene, who has encouraged me from the very start of this process. In so many subtle ways, she has made my passage a little easier and a whole lot better.

ACKNOWLEDGEMENT OF PUBLICATIONS

Chapters 1 and 2 of this dissertation have been submitted for publication to peer-reviewed journals in the field of ecology, and are cited as follows:

Maslo, B., Handel, S.N., Pover, T. 2010 (*in review*). Realizing the fundamental niche: practical guidelines for beach-nesting bird habitat restoration. Restoration Ecology.

Maslo, B., Lockwood, J.L. 2009. Evidence-based decisions on the use of predator exclosures in shorebird conservation. Biological Conservation 142(12):3213-3318.

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INTRODUCTION

Threats to Sandy Beach Ecosystems

The ecological health of sandy beach ecosystems is highly compromised as a consequence of anthropogenic stressors (Defeo et al. 2008). Pollution, mining, off-road vehicles, and coastal armoring directly affect beach morphology and injure resident wildlife (Lercari et al. 2002; Williams, et al. 2004; Cho 2006; Dugan and Hubbard 2006). In addition, the overwhelming concentration of human visitors to the coast promotes the colonization of the beach environment by introduced species (Defeo et al. 2008), the aggregation of litter which is harmful to coastal biota (Derraik 2002), and multiple levels of human of disturbance that are particularly inimical to beach-nesting birds and turtles (Burger 1991; Antworth et al. 2006).

Because of the persistent expansion of the coastal population and the development needed to support it, coastal zone management and beach stabilization practices are routinely implemented to the further detriment of the beach ecosystem (Brown and McLachlan 2002). Beach nourishment, the artificial replenishment of sand lost by erosion, is currently the most common method of shoreline stabilization employed in the United States (Nordstrom 2005). Executed under the direction of the United States Army Corps of Engineers (Corps), the primary objectives of these beach restoration projects are to protect coastal property against wave and storm damage and to enhance the recreational value of the beach (USACE 2003). Nourished beaches are generally designed to have an elevated height, extended width, and a steep profile to dissipate the energy of storm waves and wind and protect landward infrastructure (Nordstrom 2008). Wildlife enhancement has been largely ignored, despite the tremendous rise in coastal ecotourism over the last decade (Agardy 1993; Hall 2001). This lack of attention to wildlife enhancement within the nourishment design plan often has deleterious effects on beach fauna (Greene 2002). Immediate ecological impacts include mortality by burial of terrestrial and intertidal invertebrates, loss of benthic habitat, and emigration of resident species due to disturbance (Bishop et al. 2006, Peterson et al. 2006).

While most studies of the ecological impacts of beach nourishment have been on benthic invertebrates, the effects on macrofauna such as beach-nesting birds and marine turtles is also apparent (Speybroeck et al. 2006). For example, the dredge spoils removed from navigation channels with which beaches are nourished commonly contain silts and clays, or the seeds and rhizomes of vegetation not indigenous to beach habitats (Nordstrom 2005). This substrate matrix results in suboptimal nesting substrate, which can cause reduced crypsis and enhanced predation in beach-nesting birds and can prevent female turtles from excavating nests (Crain et al. 1995; Maslo et al. 2009). In addition, reduced arthropod abundances at times when maximizing foraging efficiency is critical (i.e. chick development, migration) can reduce fitness and survival of shorebirds (Peterson et al. 2000). Further, the high elevation of a Corps-designed beach prevents seasonal overwash to the back-beach habitats, allowing vegetation to become established at densities that make unsuitable nesting habitat and refuge for mammalian predators. This type of berm also catalyzes the development of a vertical erosional scarp (Crain et al. 1995), considerably restricting the ability of chicks and turtle hatchlings to traverse the terrain, rendering them helpless against approaching predators.

Beach Habitat Restoration through Scientific Research

Beach nourishment projects do have the potential to positively affect coastal macrofauna due to the creation of large expanses of habitat (Nordstrom et al. 2000). Conservation agents are beginning to push for changes in beach stabilization protocols so that wildlife habitat will be either preserved or created. As an example, the United States Fish and Wildlife Service (USFWS) Atlantic Coast Piping Plover (*Charadrius melodus*) Recovery Team has recently placed an emphasis on restoring breeding habitat (USFWS 1996). This initiative has resulted in a partnership with the Corps to integrate habitat enhancement features into their beach nourishment guidelines. However, the design of ecologically functional beach habitats must be informed by well-articulated scientific research. Pragmatic studies can provide the framework for habitat design by identifying factors important in habitat selection, resource utilization, and animal performance (Morrison et al. 2006). Further, robust statistical analyses can establish performance measures to evaluate restoration success and create thresholds for effective adaptive management (Elphick 1996; Groffman et al. 2006). Unfortunately, much scientific research is not easily translated into applicable design criteria because of complicated statistical analyses and highly technical ecological jargon. Restoration projects are consequently implemented on a trial-and-error basis (B. Bandreth, pers. comm.).

The first chapter of this dissertation uses a robust and easily interpretable statistical analysis to present practical guidelines for the design of Atlantic Coast piping plover (*Charadrius melodus*) nesting habitat. The results also propose performance measures and thresholds for use in the development of adaptive management plans.

Case Study: The Cape May Meadows Piping Plover Habitat Restoration Project

In 2004, the Corps launched a piping plover breeding habitat restoration project in the lower Cape May Meadows, Cape May, New Jersey, USA. Features of this project included a lowered beach elevation, sandy, unvegetated nesting substrate, three foraging tidal ponds, and 'plover walkovers,' sections of the protective dune with a mild slope and no vegetation to allow the precocial chicks to access the foraging ponds. The plover population at this site rose from a pre-restoration average of 3.3 (max = 4) nesting pairs (1999-2004) to a post-restoration average of 8.0 (max = 11) nesting pairs (2005-2009) (New Jersey Division of Fish and Wildlife, unpublished data, 2009).

The restoration of Cape May Meadows appears to have been successful due to the increased population of adult piping plovers. However, as this project was completed on a trial-and-error basis, no foundation or evidence-based design directives exist. Further, since no habitat characteristics were quantified, thresholds for maintaining animal performance (in this case, reproductive success) cannot be identified. To advance the science of restoration ecology, informative metrics of habitat quality must be appropriated and standardized for broad conservation application.

Habitat quality, though, cannot be measured merely by an animal's presence within a habitat (Johnson 2007). More important than the presence of resources in a landscape is the target species' use of and access to them, which can be constrained by factors such as predator pressure or human disturbance. Therefore, an animal's behavior within that habitat is a more accurate predictor of quality and can be much more conclusive in assessing restoration success than direct measurements of habitat parameters (Morrison et al. 2006).

The second chapter of this dissertation assesses the success of the Lower Cape May Meadows piping plover habitat restoration project through a behavioral study. Since the completion of the project in 2005, this site has experienced a rise in both breeding pair numbers and productivity – number of fledged chicks per nesting pair – from its historic average. Since the management of plover breeding sites throughout New Jersey is consistent, the increased reproductive success at the site is likely a result of its restoration. However, without careful study, no clear cause and effect relationship can be established, and further refinement of plover habitat design is stalled. An understanding of plover-habitat relationships can assist in finding a direct link between habitat characteristics and reproductive success.

Foraging plays a significant role in plover chick growth and development, as weaker individuals may not be strong enough to survive the dynamic beach environment. Further, acquisition of fat reserves is critical for fledglings and adults to prepare for the fall migration. Therefore, access to prime foraging habitats may increase fledging success (Loegering and Fraser 1995; Goldin and Regosin 1998; Elias et al. 2000), and studying foraging behavior may provide causation for the observed increased reproductive success at the Lower Cape May Meadows. In this study, I create foraging behavioral models to determine the factors that drive selection of particular foraging habitats, identify factors that constrain their use, and evaluate the benefit of constructed tidal ponds in relation to naturally-occurring foraging habitats.

Evidence-Based Decisions for Piping Plover Conservation

Although we are making progress towards the routine restoration of ecosystem function within sandy beach habitats, ground-nesting shorebirds still are under tremendous threat of predation, particularly by native and introduced mammals (Jackson et al. 2004; Pauliny et al. 2008). Of the suite of potential predators, the red fox (*Vulpes vulpes*) is a particularly injurious menace (Witmer et al. 1996; Erwin et al. 2001; Neuman et al. 2004; McGowan et al. 2005). Piping plovers and other ground-nesting shorebirds have no evolutionary defense against these highly adaptable predators and can suffer minimal reproductive success at the hands of even a single individual occupying a nesting habitat; therefore, conservation measures must be implemented to thwart intense predation.

The urgency required by threatened species and the often limited resources appropriated for their conservation compel both ecologists and managers to realize effective conservation solutions through documented study (Stewart et al. 2005). However, decision-making in conservation is predominantly experienced-based, with practitioners routinely draw upon tradition, anecdotes, and existing management plans when organizing their own conservation directives (Pullin et al. 2004). Although experienced-based decisions can be successful under particular conditions, evidence-based decisions are more likely to be effective across varying conditions and can contribute to the construction of a solid scientific foundation upon which to advance biological conservation (Pullin and Knight 2001). In the third chapter of this dissertation, I revisit the debate over predator exclosures as a sound strategy for ground-nesting shorebird conservation.

The predator exclosure, first designed by Rimmer and Deblinger (1990), generally consists of low-gage, galvanized wire positioned in a circle around each nest, extending approximately 20-25cm belowground and upwards to a height of approximately 75-80cm, topped with plastic netting. Results of several studies indicate that predator exclosures have a significant positive effect on hatching success (Rimmer and Deblinger, 1990; Melvin et al., 1992; Estelle et al., 1996; Larson et al., 2002); however, other studies have challenged the effectiveness of predator exclosures, citing several drawbacks. In a study of piping and snowy plovers and killdeer (*C. vociferus*) conducted in southeastern Colorado, Mabee and Estelle (2000) found that although exclosures were effective at preventing avian and larger mammalian predators from accessing the nests, there was no significant difference in the daily survival rate of nests due to the large size range of the predator community. Due to the conflicting outcomes presented above, a land manager may have great difficulty in determining whether or not to use predator exclosures and is more likely to retreat to 'common sense' strategies or anecdotal evidence (Sutherland et al. 2004).

In some locations where mammalian predator pressure is extremely high, exclosures are surrounded by (but not touching) an electrified wire placed approximately 8cm off the ground and connected to a 6V battery, referred to here as an 'electrified exclosure.' The contention of this technique is to shock a mammalian predator that is attempting to excavate a tunnel under the exclosure to gain access to the nest. However, the effects of this arguably extreme strategy have not been formerly assessed and may have negative consequences for nesting plovers. For example, erection of the additional stakes, batter, and wire for an electrified exclosure cause a longer period of stress on the adults. Second, the electrified wire poses a direct threat to nesting adults if they come into contact with it. Finally, if a predator is shocked, the ensuing commotion may cause the adults to abandon the nesting attempt altogether.

At some sites in New Jersey, electrified exclosures are anecdotally successful; at others, a large proportion of nests within electrified exclosures are being abandoned. The third chapter of this dissertation uses a 10 years of piping plover nest monitoring data from the state of New Jersey, USA to provide a long-term perspective on the effectiveness of predator exclosures (non-electrifies) in shorebird conservation. The study also explores the factors associated with abandonments of electrified nests in order to assist managers in making informed decisions on whether or not employ this conservation technique.

CHAPTER 1

REALIZING THE FUNDAMENTAL NICHE: PRACTICAL GUIDELINES FOR BEACH-NESTING BIRD HABITAT RESTORATION

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Abstract

To effectively restore wildlife habitat, ecological research must be easily translated into practical design criteria. Further, managers must overcome financial and legal obstacles when attempting to enhance wildlife habitat. Clear directives from scientific research can support arguments that promote the need for changes in current habitat restoration strategies. For the federally-threatened piping plover (*Charadrius melodus*), beach stabilization practices often accelerate the degradation of suitable breeding habitat and could be revised to provide more advantageous habitat conditions. Studies of piping plover habitat selection have been conducted for over twenty years, yet useful and detailed design directives remain undeveloped. In this study, we use classification and regression tree (CART) analysis to: 1) determine the primary drivers and interactions of variables leading to nest establishment, and 2) develop target and threshold values for use in effective design and adaptive management of restored piping plover habitat. We found that nests primarily occur in four distinct habitat conditions defined by percent shell and pebble cover, and distance to nearest dunes and the high tide line. In addition, nest site characteristics vary depending on where in the landscape a nest is initiated (backshore, overwash fan, or primary dune). We translate these results into pragmatic target design parameters and identify trigger points for management action to maintain habitat that is attractive to plovers. This technique can be applied to many other wildlife habitat restorations. Future studies on niche parameters driving chick survival are necessary to realize the full potential of habitat restoration in increasing overall reproductive success.

Key words: piping plover, *Charadrius melodus*, CART, nest-site selection, wildlife-habitat relationships, habitat restoration, beach stabilization

Introduction

Well-articulated scientific research can provide the framework for habitat design by identifying factors important in driving habitat selection, resource utilization, and animal performance (Morrison et al. 2006). Robust statistical analyses can identify appropriate performance measures to evaluate restoration success and create thresholds for effective adaptive management (Elphick 1996; Groffman et al. 2006). However, pragmatic conservation approaches are not always apparent after ecological research, or the management actions recommended are not feasible due to legal obstructions associated with large-scale land use change (Pickett et al. 1997; Ostergren 2006; Rohlf 2006). Resulting small-scale, trial-and-error strategies threaten to waste limited time and resources on potentially ineffective strategies (Pullin and Knight 2001).

This study addresses a current and prime example of these issues, focused on efforts to conserve the federally threatened Atlantic Coast piping plover (*Charadrius melodus*), a rare beach-nesting shorebird. Since the listing of this species as endangered by the United States Fish and Wildlife Service (USFWS) in 1986, a large amount of research has been conducted on its life history, population viability, habitat requirements, and behavior (USFWS 1996). In addition, several conservation management strategies have been implemented to boost the plovers' protection and reproductive success. These methods include installation of signage and symbolic fencing to minimize human disturbance of nests (USFWS 1996), erection of predator exclosures around individual nests (Rimmer and Deblinger 1990), and construction of anti-predator electric fencing around entire nesting beaches (Mayer and Ryan 1991). While these actions do serve to reduce predation and human disturbance, reproductive success continues to be threatened by the degradation of prime breeding habitat by both natural and anthropogenic alterations (USFWS 1996).

The USFWS Atlantic Coast Piping Plover Population Recovery Team has recently placed an emphasis on the restoration of breeding habitat (USFWS 1996). This initiative has resulted in a partnership with the United States Army Corps of Engineers (hereafter, the Corps) to integrate habitat enhancement criteria into some of its beach stabilization protocols. For example, in 2004 the Corps launched a beach nourishment and ecosystem restoration project, creating features that facilitated nesting and mobility to enhance habitat viability (Smith et al. 2005). These features included a lowered beach elevation, sandy, unvegetated nesting substrate, three foraging tidal ponds, and ‘plover walkovers,’ sections of the protective dune with a mild slope and no vegetation to allow the precocial chicks to freely access the constructed ponds. The plover population at this site rose from a pre-restoration average of 3.3 (max = 4) nesting pairs (1999-2004) to a post-restoration average of 8.0 (max = 11) nesting pairs (2005-2009) (NJDFW, unpublished data, 2009).

Unfortunately, a large-scale beach habitat restoration such as the one described is the exception. Most beach stabilization practices, designed to temper the natural dynamics of wind and wave action, are generally performed without consideration of wildlife and can result in no advantage, or even adverse impacts, to beach-nesting birds (Greene 2002). Even when managers would like to restore beach-nesting bird habitat on a large scale, they cannot for two reasons: 1) coastal zone management laws prevent or limit the implementation of most habitat enhancement actions (i.e. lowered backshore elevation, vegetation removal) along developed shorelines because of the resultant potential reduction in storm protection (Nordstrom 2000), and 2) where there is no need for storm protection (undeveloped shorelines with immense habitat potential), there is rarely funding for beach nourishment projects. In the end, conservation managers are forced to make the most of small-scale restoration projects.

A technical literature exists to assist practitioners in creating suitable piping plover nesting habitat. Researchers have collected data on several characteristics important in selecting nest sites (Burger 1987; Prindiville-Gaines and Ryan 1988; MacIvor 1990; Patterson et al. 1991; Powell and Cuthbert 1991; Flemming et al. 1992; Espie et al. 1996; Cohen et al. 2008). The data, however, present several ambiguities and fall short of successful translation into practical restoration design. First, the habitat characteristics that have been reported typically show means with large standard deviations, indicating high variability. In addition, the results vary significantly between study sites, across years, and across studies. Burger (1987) reports significant differences between sites for percent shell cover, distance to dunes, water, and vegetation. In other instances habitat characteristics have been quantified using different metrics. For example, amount of vegetation has been reported as percent cover within 1 meter of nest, percent cover of surrounding habitat, or # of shoots. Excessive variability or lack of consistency may obscure the forces that ultimately drive a desired response (in this case, nest establishment). These studies have led to the use of vague qualifiers such as ‘sparse’ and ‘wide’ when describing the vegetative cover or beach width, respectively, of breeding beaches (Haig 2004). This issue leads to difficulty when translating research into applicable design criteria (Lindenmayer and Hobbs 2007).

Restoration designers need to know useful ranges of factors, such as dune slopes and heights, and vegetative cover, to create a mosaic habitat that will support the birds' persistence (Morrison 2001). Second, habitat variables are often presented individually (i.e. shell cover only), but combinations of nest characteristics (i.e. shell cover + distance to the nearest dune) may provide more successful recommendations. For example, nests located on dunes are likely to have more vegetative cover than nests on the backshore. Also, plovers may choose to nest in more vegetation when shell cover drops below a certain threshold. Flemming et al. (1992) alluded to the existence of multiple suitable nest sites that are contingent upon geographic and geomorphologic variation in beaches; but the authors presented no quantified parameters to guide restoration designers. Finally, no link exists between the results of these studies and management or restoration implications. With the exception of Cohen et al. (2008), who suggest the replacement of coarse grains on nesting sites, the majority of these studies are solely descriptive.

Given these abstractions, meeting the challenge of designing a nesting habitat that ensures multiple acceptable microhabitats proves to be an arduous task. More robust statistical analyses may help to refine rudimentary data collection, better explain variation as it pertains to habitat selection, and improve the interpretation of results for cogent application to restoration practice. In this paper, we use classification and regression trees (CART) to perform a statistically robust and easily interpretable analysis on multiple habitat characteristics associated with piping plover nest site selection. CART is a powerful statistical tool that can advance ecological studies by handling large data sets with several explanatory variables (De'Ath and Fabricius 2000; Kintsch and Urban 2002; Bourg et al. 2005). Based on the CART results, we determine both the primary drivers as well as the interactions of variable values leading to nest establishment. In addition, we develop performance measures and thresholds for use in effective adaptive management of restored piping plover habitat.

Methods

Study Area

We collected data on piping plover nests at 19 breeding beaches in New Jersey, USA from 2006-2008. Sites consisted of three main geomorphic types – mainland, barrier, and inlet beaches – and displayed wide ranges in beach width, dune characteristics, and degree of human development (Table 1).

Data Collection

During each breeding season, we surveyed former and potential piping plover breeding beaches for nests. Upon nest discovery, we recorded the geomorphology of the site and photographed the microhabitat within an approximately 2x2m square, with the nest in the center. Four photographs were taken at each nest, with one quadrat representing each of the four $1m^2$ quadrants around the nest. We collected approximately 60g of the surficial substrate within the area. We then measured the distance from the nest to the nearest dune and to the high tide line using a laser rangefinder (±0.9m accuracy) and recorded the presence or absence of a non-ocean foraging habitat (e.g. bay, tidal pond). Finally, we measured the height and slope of the nearest dune using the Emery Rod Method (1961). Nesting plovers were minimally disturbed for <10 minutes during data collection; in all cases, the attending adult returned to the nest within 5 minutes. In addition to nests, we collected data of habitat characteristics of randomly-selected locations, chosen from a sampling area bounded by the high tide line and the seaward limit of the secondary dune (or anthropogenic feature, if encountered first) and extending 100 meters north of the northernmost nest and 100 meters south of the southernmost nest within each nesting cluster.

Data Preparation

Using Adobe Photoshop CS2 (Adobe® 2005), we prepared the photographs for analysis by merging the four quadrats for each nest and random location and then overlaying onto this new image a 100-square digital grid. From the edited images, we measured the percent cover of vegetation, shells, and pebbles (4mm – 65mm), and recorded the presence/absence of driftwood. We ran the substrate samples through a 2mm sieve to determine the percent composition of sand (≤2mm) and gravel (>2mm). ANOVAs were used to determine significant habitat differences.

CART Analysis

We used CART ProV6.0 software (Salford Systems©) to create a decision tree that models nest-site selection for piping plovers in New Jersey. Ecological applications of CART primarily include predictions of species occurrence within a landscape. In this study, we are use CART as a design tool to create habitat that is attractive to nesting piping plovers. Using a series of dichotomous classifiers, CART attempts to split a response class (e.g. nest presence or absence) into homogenous groups using combinations of the fewest explanatory variables (Brieman et al. 1984). We first created an exploratory tree using all explanatory variables including year to determine if characteristics associated with selection of nest sites varied across years. Since the resultant tree did not include year as an important classifier, we removed it from subsequent analyses. We then performed an additional CART analysis using the remaining 12 explanatory variables (Table 2). We grew a series of trees using the Gini Index impurity measure splitting criterion and constrained the output to include a minimum of 10 observations in each terminal node. We performed a 10-fold cross validation and used the minimum cross-validation error rule to accurately predict the error estimate of each tree, which is quantified in terms of its relative cost, or misclassification rate. We selected the tree with the lowest relative cost as the optimal tree (Breiman et al. 1984; Bourg et al. 2005). We then calculated the variable importance, which can be defined as the role each variable plays in serving as a surrogate to the primary splitter of the best tree (Brieman et al. 1984). The variable importance is calculated by summing the changes in impurity for each node within the optimal tree and normalizing the result into a score of 0-100.

Results

Distribution of Nests in New Jersey

Over the 3-year period, we recorded 201 nests, which were nearly evenly distributed between beach types, with slightly more nests occurring along inlets (Figure 1). In general, nests were initiated on the backshore of the beach within 25m of the primary dune, in areas with 10% or less vegetative cover, moderate shell cover, and no pebbles or driftwood. Heights and slopes of the nearest dunes typically remained under 2m and 20%, respectively. Distance to the high tide line was variable, and nests were split nearly evenly between sites with and without an alternative water feature. Substrate composition was primarily pure sand; however, 27% (*n* = 54) of nests were initiated in 1-51% gravel.

Surficial habitat characteristics, dune height, and dune slope varied depending on the habitat in which the nest was initiated ($F = 18.7$, $df = 6$, $p < 0.0001$). For example, 81% of all nests sampled occurred in shell cover of 0-20%. A closer look at the data reveals that mean shell cover is significantly greater on overwash fans (19.6 ± 2.1) and the beach backshore (9.8 ± 1.6) than on primary dunes (5.6 ± 1.9) ($F = 8.5$, $df = 3$, $p < 0.0001$). In addition, pebbles were only observed on the beach backshore and in areas with little or no shell cover. Where pebbles were present, they occurred at an average percent cover of 14 ± 12. Percent vegetative cover also differed between habitats ($F = 19.2$, $df = 3$, $p < 0.001$), with an average of 12.7 ± 1.2 on dunes and 2 ± 6 on the remaining terrain. Finally, the average height and slope of dunes on which nests were constructed were significantly lower than dunes within the surrounding landscape ($F = 4.5$, $df = 3$, $p < 0.0045$; $F = 19.2$, $df = 3$, $p < 0.001$, respectively). Dunes on which nests occurred averaged 1.1m ± 0.2m in height and 13% ± 1.6% in slope, while dunes surrounding all other nests averaged averaged 1.6m ± 1.2m and 18% ± 13%, respectively. No nests occurred on dunes greater than 3.1m in height or 50% slope.

CART Results

The cross-validated CART analysis combined the nest data with the 373 random locations sampled and specified a tree with 10 terminal nodes and a relative cost of 0.294 as the best (Figure 2). This tree correctly classified 86% and 85% of actual nests and random locations, respectively, and grouped 64% of all nests into one terminal node. CART identified four of the 12 potential explanatory variables as making significant contributions to predicting nest establishment for piping plovers. In order of importance these are – percent cover of vegetation, percent cover of shells, distance to the high tide line, and distance to the nearest dune (Table 3). These variables represented the primary splitters in classifying the data into homogenous groups (Figure 2). The percent cover of shells served as the first primary splitter of the tree and is ranked second among the explanatory variables in importance.

Nests primarily fell into four groups, each with varying combinations of habitat conditions (Table 4). One hundred twenty-nine of the 201 total nests sampled (64%) were found in areas with shells, ≤33.5% vegetative cover, relatively close to dunes (≤77.5m), and >9.5m from the high tide line. Random locations separated into six homogenous groups, with two terminal nodes accounting for 266 (71%) of the total random locations observed (Table 4). One hundred forty-three random locations (38%) occurred in areas with no shells, no pebbles, and no vegetation (pure sand), while 123 (33%) occurred in areas with no shells, no pebbles, and >15.2% vegetative cover. All terminal nodes classified as containing random locations reported misclassification rates of 16.7% or less; two of these six terminal nodes were 100% pure (no misclassified samples). These results indicate that the CART analysis succeeded in describing microhabitats that are mostly avoided by nesting plovers.

Discussion

Due to the severe anthropogenic stressors placed on the beach environment and their negative impacts to beach-nesting birds, restoration and maintenance of suitable breeding habitat is critical to conserve of these imperiled species. Limited financial resources and restrictions on physical manipulation of the beach compel restoration practitioners to design small-scale enhancement projects. Our analysis provides practical ecological guidelines for both habitat manipulations and adaptive management plans. Table 5 lists restoration target and threshold values for important breeding ground habitat features identified in this study. Mean values listed in former studies for percent vegetative, shell, and pebble cover fall within our target ranges, and the distance to the nearest dunes are predominantly congruous, differing in some cases by a only a few meters. The information in Table 5 can be broadly applied to piping plover habitat across its breeding range. The distance to the high tide line (or lakeshore) was variable across all studies and should be considered as site-specific.

Piping Plover Breeding Habitat Restoration Targets

The majority of nests found occurred on inlet beaches, which highlights their importance as preferred breeding habitat. Inlet beaches in New Jersey are commonly >150m wide and undeveloped, and they attract more breeding plovers than elsewhere (Kisiel 2008). High restoration priority should be given to inlet beaches to make the most out of limited funds.

Most nests were initiated on the backshore of the beach within 25m of the primary dune, and between 9.5m and 64.5m from the high tide line. The literature suggests that dune blowouts and overwash fans are the preferred habitats for nest establishment (USFWS 1996); our study supports this conception since plovers initiated nests in blowouts if this habitat was present. These formations occur as a result of both ocean and bay wave action overtopping dunes and creating an minimally vegetated sandy substrate landward of the foredune (Davis and Fitzgerald 2004). Plovers are attracted to these habitats because they offer flat, often mottled, topographies that are sheltered from spring and storm tides (Kumer 2004; Cohen et al. 2009). Highly stabilized beaches do not permit such dynamic habitat features to exist, except in rare cases of severe storms. Current Corps design regulations adjure the construction of an elevated backshore (landward portion of the beach from the high-water line to the base of the dunes) to prevent water from reaching the protective dune. The high elevation also prevents seasonal overwash to the backshore habitats, which allows vegetation to become established at densities that make the habitat unsuitable for beach nesting birds and create a refuge for mammalian predators. Restoring these landforms, either artificially or by reestablishing normal dynamics, should be a leading restoration initiative. However, since current coastal zone management laws prohibit the destruction of protective dunes (Nordstrom 2000), targeting the area within 25m of the primary dune can also create beneficial secondary nesting habitat. Nourishment designers can draft a lowered berm, preventing the development of a vertical erosional scarp between the intertidal zone and the backshore, and allowing chicks to access seaward foraging areas (Crain et al. 1995; Nordstrom 2008). Also, dredge spoils placed on the backshore should be carefully strained to prevent the deposition of silts and clays, or the seeds and rhizomes of vegetation not indigenous to beach habitats (Nordstrom 2005), which can cause reduced crypsis, enhanced predation, and increased resource competition for other, more suitable nesting areas.

A significant proportion of nests occurred on primary dunes, a phenomenon that has important restoration implications. Along narrow beaches or low-lying areas, nests are extremely susceptible to storm-amplified and spring tides. After a nest is flooded, adults often renest on higher ground or further from the high tide line. However, nesting on steeper dunes with thicker vegetation carries an increased predation risk of nests or adults since the birds may not be able to see and respond to an approaching threat in time (Burger 1987; Espie et al. 1996). In addition, nests located at a higher elevation may be more visible to predators (Burger 1987). Dune heights and slopes were not deemed relevant factors for nest initiation by our CART analysis, most likely because the number of dune nests was small in relation to the nests in other habitats. When plovers in this study did nest on dunes, though, they selected ones with low profiles, gentle slopes, and moderate vegetative cover. We suggest that restoration design should accommodate environmental stochasticity by creating suitable alternative nest sites and include target parameters that limit the size, slope, and vegetative cover of primary dunes. The results of this study advocate a target range of dune height and slope as 1 - 1.2m and 10 - 14%, respectively. Additional sampling is needed to add robustness to this recommendation. Until more research is conducted, designers should err on the side of caution and keep dune heights and slopes as minimal as possible.

As the reestablishment of natural beach dynamics become more common, and overwash fans and dune blowouts become more abundant, the risk of flooding will be reduced. As a result, plovers may be less likely to nest on dunes. In such cases, modifications to dune heights and slopes may not be necessary. However, large, steep, thickly vegetated dunes do impede the mobility of chicks. Access to prime foraging habitats (bayshores, ephemeral ponds, mudflats) can be crucial to increasing fledging success (Loegering and Fraser 1995; Elias et al. 2000). Restoration design must still include dune modifications if they are positioned between nesting and foraging areas.

The microhabitat characteristics of the area immediately surrounding the nest appear to be the most influential in determining nest initiation, with percent vegetative cover being ranked first in importance. Eighty-six percent of all nests sampled here occurred in less than 10% vegetative cover. Beach nourishment projects often call for dense American beach grass (*Ammophila breviligulata*) plantings of up to 25% initial cover to stabilize dunes (French 2001; NYDEC 2005), already exceeding the appropriate range. The prevention of tidal overwash promotes even more vegetative growth, and unsuitable breeding conditions very quickly. The disparity between beach stabilization protocols and beach-nesting bird niche factors clearly dictates a change in nourishment project design to find planting configurations that maximize dune stability while minimizing vegetation density.

Percent shell cover was the first classifier in our CART analysis and indicated no splitting value. In addition, the node containing most random locations were those with no shells, no pebbles, and no vegetation, corroborating other findings that plovers seek mottled surfaces to aid in camouflaging themselves and their eggs (Prindiville Gaines and Ryan 1992; Cohen et al. 2008). Although it appears that the presence of shells at any coverage is attractive to nesting plovers, most nests were found in 1 - 20% shell cover.

The majority of nests with pebble cover or gravel were located at a site nourished in 2005. Standard Corps practices here created an elevated berm which prevented normal tidal uprush from reaching the backshore and reworking the sediments (Nordstrom 2008). The resultant pebble cover and gravel composition at this site ranged from 0 - 21% and 12 - 15%, respectively. Also, the mean values for nests with only shell cover or pebble cover were similar, implying that either of these crypsis-enhancing features is acceptable to nesting plovers, if added at a similar coverage rate. Based on the data reported here, we can confidently assign a target value of 17 - 18% shell or pebble cover to restoration design.

Adaptive Management Implications for Piping Plovers

The findings of this study can assist with the formation of practical adaptive management plans by establishing threshold values that trigger further restoration action (Block et al. 2001). Although most nests are established in 10% or less vegetative cover, our CART analysis revealed that under certain conditions, nests would be established in vegetative cover of up to 33.5%. Despite the few instances where plover nests occurred in greater than 33.5% vegetative cover, a threshold value can be set here to effectively manage the habitat. A 1-20% cover of a crypsis-enhancing feature (shells or pebbles) was concluded as a viable restoration target for backshore nesting areas. In backshore areas where this feature is lacking or upon its eradication after winter storms, shells or pebbles should be added prior to the birds' arrival on the breeding grounds. These substrate features are available from many commercial stone suppliers.

Mean values of dune measurements verified the premise that small, gently-sloping dunes are preferable to plovers (MacIvor 1990; Patterson et al. 1991). All nests occurred on dunes of ≤2.6m in height and ≤27% in slope. Therefore, we suggest trigger points (values that signal a management action) of 2.5m for height and 25% for slope in order to maintain dunes that have protective value but are still suitable nesting habitat for plovers. Monitoring studies and performance assessments can further refine restoration targets and triggers (Thom 2000; Block et al. 2001). Manipulations of vegetative, shell, and pebble cover in various locations along the backshore may provide direct evidence of piping plover nest site preferences.

Recovery and persistence of this species will depend on breeding habitat restoration guidelines presented here. Selection of nest-sites, however, is only one component of the habitat. Restoration practitioners must also consider the niche factors that promote the survival of chicks to fledging age. Identification of the controls and resources in the habitat that lead to refuge from predators and increased plover foraging rates are critical to meeting this end (Morrison 2001; Morrison et al. 2006). Parallel to this effort in habitat design, social understanding and community rules must continue to be refined to minimize anthropogenic pressures. Additional well-designed research on all these factors can make significant additions to the design criteria of beach-nesting bird habitat identified here.

Acknowledgements

We would like to thank Julie Lockwood for her valuable input to this manuscript, and Joanna Burger and Karl Nordstrom for their advice on this research. Our gratitude goes to the Rutgers University Graduate Program in Ecology and Evolution for financial support. We acknowledge the New Jersey Division of Fish and Wildlife – Endangered and Nongame Species Program for understanding the value of scientific research for endangered species conservation and for their cooperation during data collection.

Implications for Practice

- Piping plovers generally nest within 1 of 4 groups of habitat conditions categorized by percent shell cover, percent vegetative cover, distance to nearest dunes, and distance to the high tide line. When designing a breeding habitat restoration project, practitioners should include all nesting habitat types to create a mosaic habitat that will accommodate changes in preferred nest sites due to environmental stochasticity.
- Management action should be taken when the variables that drive nest-site selection exceed the thresholds identified here.
- Classification and regression tree (CART) analysis is a statistically robust and easily interpretable method that is useful in identifying design targets for restoration and also performance measures for adaptive management. The results of such analyses can facilitate the translation of ecological research into practical restoration directives for many wildlife restoration programs.

Table 1-1. General characteristics of New Jersey piping plover breeding beaches[a]

Site	*Geomorphology*	*Beach Width*[b]	*Degree of Development*[c]
Sandy Hook	barrier spit	wide	low
Sea Bright	mainland	narrow	high
Monmouth Beach	mainland	narrow	high
7 Presidents Park	mainland	narrow	moderate
Wreck Pond	mainland	narrow	moderate
National Guard Training Center	mainland	narrow	low
Barnegat Light	barrier island/inlet	narrow to moderate	low
Holgate	barrier island/inlet	moderate to wide	none
Little Beach	barrier island/inlet	wide	none
North Brigantine Natural Area	barrier island/inlet	moderate to wide	none
Ocean City	barrier island	moderate	high
Corson's Inlet State Park	inlet	moderate	none
Strathmere	inlet	moderate	high
Avalon	barrier island	moderate	moderate
Stone Harbor Point	inlet	wide	none
North Wildwood	barrier island	moderate	high
Cape May Nat. Wildlife Refuge	barrier island	narrow	low
Poverty Beach	barrier spit	moderate	high
Cape May Point State Park	mainland	moderate	low

[a]Appendix A lists the GPS coordinates of nesting areas within these breeding beaches
[b]Beach width: narrow = <80m, moderate = 81m-150m, wide = >150m
[c]Degree of development describes the level of human infrastructure behind the beach

Table 1-2. Explanatory variables included in CART analysis

Variable	*Description*
Geography	mainland, barrier beach, inlet beach
Distance to Nearest Dune	distance (in meters) from nest to the nearest point on dune line
Dune Elevation	height (in meters) of the apex of the nearest dune
Dune Slope	ratio of the change in height to the change in horizontal distance from the apex of the dune to the seaward toe of the dune
Distance to High Tide Line	distance (in meters) from nest to the nearest point on the line indicating the wet/dry interface
Alternate Water Source	0 (absent), 1 (present)
Vegetation Percent Cover	percentage of the 1-meter radius surrounding the nest covered by vegetation
Shell Percent Cover	percentage of the 1-meter radius surrounding the nest covered by shells or shell fragments
Pebble Percent Cover	percentage of the 1-meter radius surrounding the nest covered by pebbles (4-65mm)
Driftwood	0 (absent), 1 (present)
Substrate Composition	percent by weight of gravel (>2mm) within the surficial substrate

Table 1-3. Importance ranking for measured habitat characteristics

<table>
<tr><th>Variable</th><th colspan="2">Score</th></tr>
<tr><td>Percent Vegetative Cover</td><td>100.00</td><td>||||||||||||||||||||||||||||||||||||||||||</td></tr>
<tr><td>Percent Shell Cover</td><td>94.65</td><td>||||||||||||||||||||||||||||||||||||||||</td></tr>
<tr><td>Distance to High Tide Line</td><td>24.54</td><td>||||||||||</td></tr>
<tr><td>Distance to Nearest Dune</td><td>20.72</td><td>||||||||</td></tr>
<tr><td>Percent Pebble Cover</td><td>18.50</td><td>|||||||</td></tr>
</table>

Note: Variables are ranked based on their role as a surrogate to a primary splitter in correctly classifying the target variable (nest presence or absence). Scores are calculated by summing the changes in “impurity” of each node within the tree (Brieman et al. 1984) and are normalized to fall within a range of 0-100.

Table 1-4. Habitat characteristics for suitable and unsuitable nest sites

Node	*N*	*% of total sampled*	*Characteristics*
			Suitable
7	129	64	shells, vegetative cover ≤33.5%, distance to nearest dune ≤77.5m, distance to high tide line >9.5m
2	30	15	no shells, no pebbles, 0.34% < vegetative cover ≤15.2%
4	15	7	no shells, pebbles, vegetative cover ≤ 3.5%
9	8	4	shells, vegetative cover ≤ 33.5%, distance to nearest dune > 77.5m, distance to high tide line > 64.5
			Unsuitable
1	143	38	no shells, no pebbles, no vegetation
3	123	33	no shells, no pebbles, vegetative cover > 15.2%
8	22	6	shells, vegetative cover ≤ 33.5%, distance to nearest dune > 77.5m, distance to high tide line ≤ 64.5m
10	14	4	shells, vegetative cover > 33.5%
5	10	3	no shells, pebbles, vegetative cover > 3.5%
6	10	3	shells, vegetative cover ≤ 33.5%, distance to nearest dune ≤ 77.5m, distance to high tide line ≤ 9.5m

Table 1-5. Target and trigger values for important habitat characteristics

Characteristic	*Target*	*Trigger*
habitat	overwash fans & dune blowouts	N/A
vegetative cover		
backshore	<10%	>33.5%
primary dune	13%	>33.5%
shell cover		
backshore	17-18%	pure sand
primary dune	N/A	N/A
pebble cover		
backshore	17-18%	pure sand
primary dune	N/A	N/A
distance to high tide line	site dependent	<9.5m from MHW to toe of dune
distance to nearest dune	≤25m	
dune height	1.1m	2.5m
dune slope	13%	31%

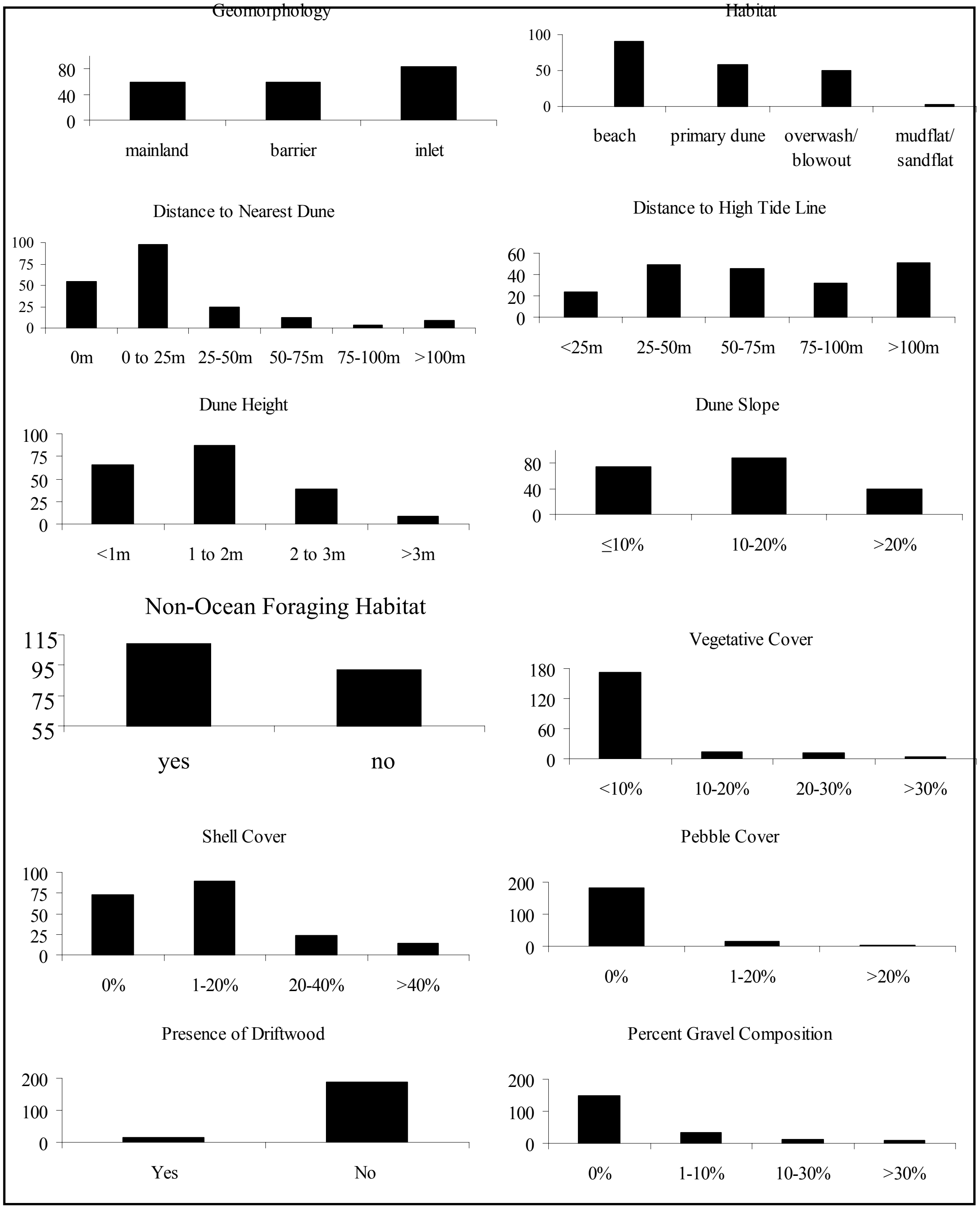

Figure 1-1. Number of nests found arranged by habitat characteristic.

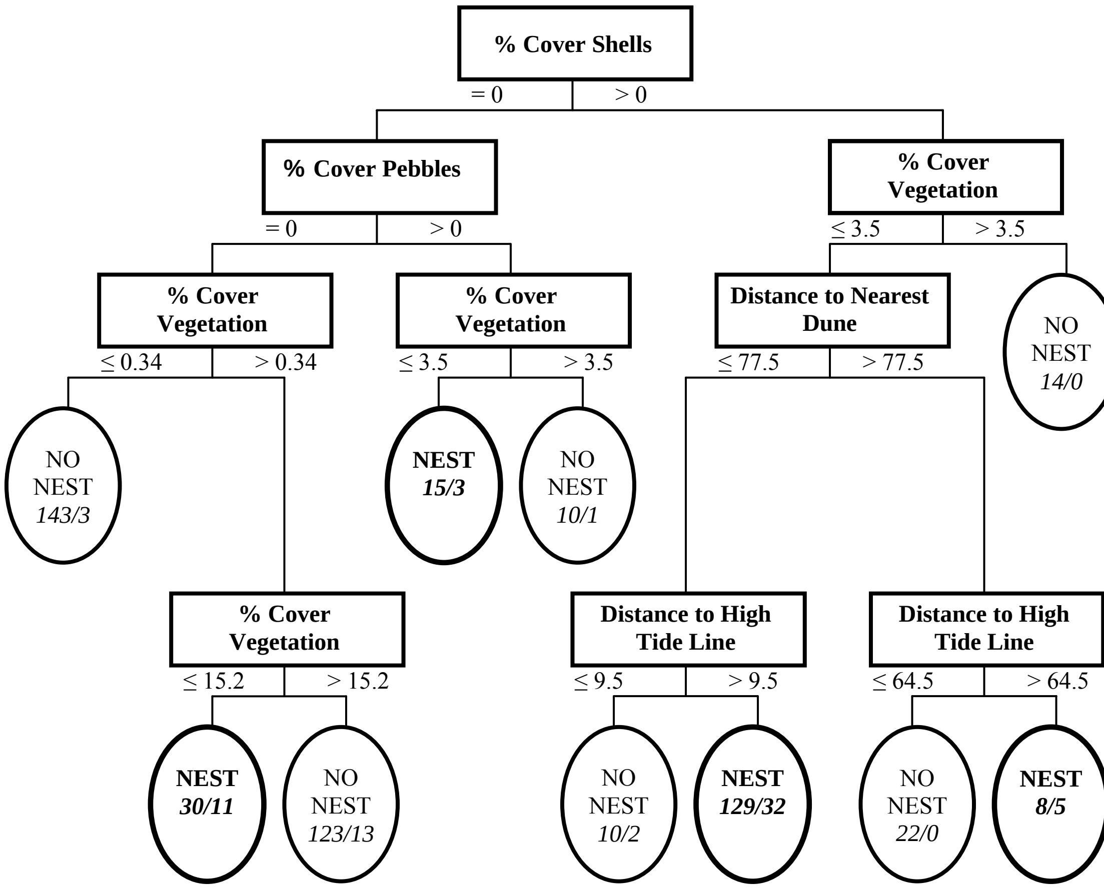

Figure 1-2**.** Cross-validated classification tree indicating the most important habitat characteristics associated with piping plover nest establishment. Rectangles illustrate the variable used to split data into more homogeneous groups. Numbers below the splitting boxes show the values of the habitat variables where the split occurred. Ovals depict terminal nodes, which are labeled with the dominant class (nest = bolded oval; no nest = unbolded oval). Numbers inside the ovals indicate the number of samples contained in that terminal node; the first number specifies correctly classified samples, the second number specifies misclassified samples.

CHAPTER 2

MODELING FORAGING PREFERENCES TO IMPROVE BEACH RESTORATION PRACTICE: A CASE STUDY WITH PIPING PLOVERS (*CHARADRIUS MELODUS*)

ABSTRACT

Understanding wildlife-habitat relationships is crucial to design successful habitat restoration projects. Quantifying animal behavior can identify the critical resources that lead to high quality habitat, which are ultimately linked to species' survival and reproduction. This study evaluates the success of a restored piping plover (*Charadrius melodus*) breeding habitat by: 1) identifying the major factors regulating foraging rates, 2) comparing foraging activity budgets at restored and natural habitats, and 3) using the evidence to examine the efficacy of artificial tidal ponds as a viable restoration alternative. Adults foraging rate was largely dependent on habitat, stage of the reproductive cycle, tidal stage, and number of people; chick foraging rates were most influenced by habitat, number of people, and number of avian predators. At constructed tidal ponds, piping plovers foraged at high rates and spent relatively little time in defensive behaviors (vigilance, crouching, fleeing) compared to other potential habitats. The findings of this behavioral study suggest that artificial tidal ponds are a viable, if not superior, foraging habitat; future beach restoration projects should include this feature to maximize habitat quality and restoration success.

Keywords: piping plover, *Charadrius melodus*, habitat restoration, beach nourishment, foraging behavior

1. Introduction

The ecological health of sandy beach ecosystems is highly compromised as a consequence of direct and indirect anthropogenic stressors (Defeo et al. 2008). The overwhelming appeal of the shore and the continued quest to stabilize its dynamics has led to the disruption of normal sediment transport, the introduction of harmful nonnative species, and the escalation of intrusive recreational activities (de Ruyck et al. 1997; Carlton and Hodder 2003; Nordstrom 2008).

The perpetual human encroachment on the beach ecosystem makes land preservation and habitat restoration critical strategies to ensure the persistence of beach-dependent species. As opportunities for land acquisition are limited in the coastal zone, restoration projects are under great pressure to be successful in attracting target species and increasing their survival or reproductive success. Restoration of high quality habitat is imperative to achieve this conservation objective.

However, the definition of habitat quality is not always conceptually clear (Hall et al. 1997; Knutson et al. 2006; Pidgeon et al. 2006), and the plethora of methods for measuring habitat are not all equally effective (Morrison 2001). The most popular approaches of assessing habitat quality are either directly measuring standard attributes of a landscape (e.g., vegetative composition) or determining the abundance or distribution of focal animals (Johnson 2007). Characterizing the physical environment surrounding an animal, however, does not always adequately predict its performance. Rather, an animal's behavior is more indicative of the quality of its habitat and ultimately linked to the animal's overall fitness (Olsson et al. 2002). An animal's use of critical resources within the habitat, its 'niche factors,' more accurately define its value. Ecological constraints, such as predator pressure or human disturbance, can also affect an animal's normal behavior and lower the habitat's quality (Morrison et al. 2006).

Behavioral observations can identify how sites differ in quality, which niche factors are valued by target species, and what resources may be lacking in a given restoration effort (Lindell 2008). Although conducting behavioral studies is more effort-intensive than directly measuring habitat-based parameters, the results are often much more conclusive and can lead to effective long-term management strategies (Morrison et al. 2006).

This study creates and tests behavior-based model to evaluate the quality of a restored piping plover (*Charadrius melodus*) habitat in New Jersey, USA. Atlantic Coast piping plovers are federally threatened in the United States and endangered in Canada, and the restoration of high quality breeding habitat is a leading directive of the United States Fish and Wildlife Service (USFWS) Atlantic Coast Recovery Team (1996). Equally as important as creating suitable nesting sites are creating accessible foraging areas for chicks. Piping plover foraging habitats include the intertidal zone and wrack line, but studies have shown that chicks prefer to feed in non-ocean habitats when available (Haig and Smith 2004). Access to prime foraging habitats (ephemeral pools, bay shores, mud flats) has been suggested to increase fledging success of young plovers (Loegering and Fraser 1995; Goldin and Regosin 1998; Elias et al. 2000). These studies imply that the construction of artificial tidal ponds can increase habitat quality at a restored site, but the forces driving higher productivity levels in these studies remain unclear. In addition, habitat constraints may negate the benefits of presumably prime foraging areas if the interaction between them and the birds is sizeable or continuous.

For example, human disturbance forces shorebirds to feed in less rewarding foraging habitats or at lower rates (Burger 1994; Thomas et al. 2003; Burger 2007). The real or perceived risk of predation from gulls, crows, foxes, or dogs also lowers normal foraging rates of shorebirds (Lafferty 2001; Burger et al. 2004; Peters and Otis 2005). Finally, foraging rates can also be impacted by weather variables, such as wind speed and air temperature. The design of an effective foraging habitat restoration project must integrate these potential constraints to identify those with the strongest effect on foraging rates.

This study aims to: 1) identify the major factors that regulate foraging rates of piping plover, 2) compare the foraging activity budgets of piping plovers at both restored and natural foraging habitats, and 3) use the evidence gathered in the field to examine the efficacy of artificial tidal ponds as a viable restoration alternative.

2. Methods

2.1. Study Area

The four major sites in this study were Barnegat Light, North Brigantine Natural Area (NBNA), Avalon, and Cape May Meadows (Cape May), New Jersey, USA (Figure 1). All sites consist of a sandy beach backed by dunes or tidal marsh and contain at least four foraging alternatives – intertidal/swash zone, wrack line, dunes, and a tidally-influenced non-ocean water source (tidal pond, ephemeral pool). NBNA also contains a low-energy bay shore, dunes, sand flats (dry sandy substrate), and mudflats (moist organic substrate). The tidal ponds at Cape May were constructed in 2005 during a United States Army Corps of Engineers (Corps) ecosystem restoration project, and are fed semi-diurnally by tidally-influenced groundwater. The tidal pond at Barnegat Light occurred naturally as the result of a breached jetty lining Barnegat Inlet and is fed semi-diurnally by high tide. Avalon is a wide, sandy beach, which contained an intertidal/swash zone, wrack line, and dunes in 2007. In 2008 and 2009, Avalon also naturally formed ephemeral pools on the upper shore (Figure 1).

2.2 Field Methods

I conducted behavioral observations from April – August of 2007-2009, during the hours of 0600-2100. I visited each site at least twice per week at varied times and walked a regular transect traversing all available foraging habitats. The transect at Barnegat Light spans approximately 2.5km of potential foraging habitat, including the tidal pool, intertidal/swash zone, and wrack line. The transect at NBNA covers approximately 4.5km of potential foraging habitat, including a back bay shore, intertidal/swash zone, wrack line, ephemeral pools, and sand flats. At Cape May, the transect traverses approximately 1.5km, surveying the intertidal/swash zone, wrack line, and 3 constructed tidal ponds. The transect at Avalon spans approximately 1.5km, covering the intertidal/swash zone, wrack line, and ephemeral pools (2008 and 2009).

When a feeding piping plover was encountered, I digitally videotaped the focal animal for 2 minutes from an unobtrusive distance (>75m). Burger (1991) asserts that a 2-minute sampling period is sufficient time for a piping plover to display the usual foraging behaviors. If the individual, during its usual foraging behavior, moved out of sight (e.g., behind vegetation or dune), I continued the observation if it moved into view within 1 minute. Otherwise, I aborted the sampling attempt. If the bird obviously altered its behavior due to my presence (e.g., gave a distress call, excessive vigilance), I discarded the sample. I recorded date, time of day, foraging location, reproductive stage (pre-nesting, nesting, brooding, fledging, non-breeding), and age (adult, chick, fledge) for each sample session. I logged wind speed and air temperature at each foraging habitat using a Kestrel® 2000 pocket wind meter, and I noted the tidal stage using a Garmin® GPSMAP® 76C global positioning system (GPS) unit. I also recorded the number of people, number of moving vehicles, and the number and type of potential predators (gulls, crows, dogs) within 50m of the focal bird for each sample. Each plover was sampled only once per site visit.

2.3 Video Analysis

Using Adobe Premiere Pro 2.0 software (Adobe® 2005), I downloaded the videos and played back each sample at a half-speed to analyze the activity of the bird in each sample. I prepared a foraging time budget for each sample, recording both the amount of time and the percentage of the 2-minute sequence an individual spent foraging, being vigilant, running or walking away (from a perceived threat), flying away (from a perceived threat), or crouching (a typical anti-predator response in plovers). Time spent engaged in any additional activities, such as preening or brooding chicks, were also recorded and categorized as "other." I then calculated the foraging rate of each bird as pecks/minute.

2.4 Statistical Analyses

I grouped the samples by age class (adults, chick, fledge) and performed one-way analyses of variance (ANOVAs) and Tukey's pairwise comparisons to look for significant differences in foraging behavior between years, sites, foraging habitats, age class, and reproductive stage.

I used multiple linear regression to model the foraging rates of adults and chicks using the behavioral data collected at the four study sites from 2007-2009. The sample size of fledglings was too small for reliable inference. Using an information-theoretic approach, I developed 10 *a priori* candidate models for both the adult and chick data set that potentially explained variation in their foraging behavior (Burnham and Anderson 2002). I used Akaike's Information Criterion corrected for small sample size (AIC_c) to rank the models according to their relative likelihood (Johnson and Omland 2004). I averaged all models exhibiting $\Delta AIC_c < 2$ and calculated parameter estimates based on the weighted averages of the parameters that occurred in the top models (Burnham and Anderson 2002; Johnson and Omland 2004). From these model-averaged parameter estimates, I calculated the relative importance of each variable by summing their Akaike weights of the top models in which it appeared (Burnham and Anderson 2002).

To validate the regression model, I used an external data set collected from foraging plovers at seven other sites in New Jersey in 2009. I collected all behavioral observation in the same way as above. I used the model-averaged parameters from above to predict the foraging rate for each case in the external data set. I then calculated the mean squared prediction error and compared it to the mean squared error of the regression model to determine if the model is robust enough to be applied on a broader scale (Neter et al. 1996; Peksen 2007).

3. Results

3.1 Foraging Rates and Time Budgets

From 2007-2009, I recorded 471 2-minute sequences from a group of 151 adult piping plovers. Adults primarily foraged along the intertidal zone (*N = 210*), at constructed tidal ponds (*N = 125*), and along the wrack line (*N = 41*). To a seemingly lesser extent, adults chose sand flats (*N = 36*), ephemeral pools (*N = 26*), and bay shores (*N = 18*), and they very rarely chose dunes (*N = 4*). Adult mean foraging rates did not differ significantly by year. They did vary significantly by site ($F = 3.539, df = 3, p = 0.0147$), with adults foraging at a lower rate at Barnegat Light (11.6 pecks/min) than at Cape May (15.9 pecks/min). Foraging rates also varied significantly by habitat ($F = 3.494, df = 7, p < 0.0012$), with higher foraging rates occurring at constructed tidal ponds (16.9 pecks/min) than on sand flats (11.1 pecks/min) and wrack (12.0 pecks/min) (Figure 2). Finally, adults foraged at different rates during each reproductive stage ($F = 2.244, df = 5, p = 0.0491$).

On average, adults spent 71% of their time foraging, 22% of their time being vigilant, 4% running or walking away from a perceived threat, and 1% of their time flying, crouching, or engaged in other activities. However, there were significant differences in the foraging time budget between habitats (Figure 3). At constructed tidal ponds, adults spent significantly more time foraging (73%) and less time being vigilant (20%) than along the wrack line (53% and 36% sec, respectively), and less time running or walking away from a perceived threat (2%) than in the intertidal zone (6%).

I recorded a total of 83 observations from a total of 108 chicks, predominantly at tidal ponds (*N = 64*), along the wrack line (*N = 31*), on sand flats (*N = 25*), and in dunes (*N = 25*). Chick foraging rates did vary significantly by year (*F = 3.572, df = 2, p = 0.0304*), with mean foraging rates in 2009 (18.2 pecks/min) being >22% higher than the previous two years (14.9 and 14.6 pecks/sec in 2007 and 2008, respectively). Foraging rates also varied significantly by site (*F = 16.569, df = 3, p < 0.0001*), with a 54% and 49% higher mean foraging rate at Cape May (19.4 pecks/min) than at Barnegat Light and Brigantine (8.9 and 11.9 pecks/min, respectively). Chicks foraged differently between habitats as well (*F = 8.223, df = 6, p < 0.0001*), with significantly higher rates observed at constructed tidal ponds (20.7 pecks/min) than at the intertidal zone (13.8 pecks/min), wrack line (14.0 pecks/min), sand flats (12.1 pecks/min), or dunes (9.8 pecks/min) (Figure 2).

Chicks spent 82% of their time foraging, 11% of their time looking for predators or their parents, 4% of their time running or walking away from a perceived threat, 1% of their time crouching, and 2% of their time preening or being brooded. Similar to the adults, chicks experienced significant differences in their foraging time budget between habitats (Figure 4), spending much more time foraging at constructed tidal ponds (86%) than along the intertidal zone (59%) and wrack line (69%), and much less time being vigilant (11%) than along the wrack line (21%). Conversely, chicks spent a significantly larger amount of time walking and running away from perceived threats along the intertidal zone (15%) than in any other foraging habitat.

Fledglings were predominantly observed at constructed tidal ponds (*N = 23*) and along the intertidal zone (*N = 15*), and foraging rates were similar between years and sites. There were significant differences in foraging rates between habitats (*F = 3.375, df*

$= 6, p = 0.0077$), with 81% higher rates at constructed tidal ponds (19.6 pecks/min) than along the wrack line (10.8 pecks/min). Fledges spent 77% of their time foraging, 16% of their time being vigilant, 6% of their time running or walking away from perceived threats, and 1% of their time crouching, on average. The birds spent similar amounts of time doing each behavior, with the exception of running or walking away, where more time was spent on this behavior along the intertidal zone (19.1 sec) than at constructed tidal ponds (3.7 sec).

3.2 Foraging Behavior Models

The first-ranked model included foraging habitat, reproductive stage, tidal stage, and number of people present within 50m and explained the most variation in adult foraging rates (Table 1). A second model including these variable and wind speed reported a ΔAIC_c score less than 2; therefore, I model-averaged the parameter estimates included in these top two models and calculated their relative importance (Table 2). Of the five habitats in which I observed plovers feeding, constructed tidal ponds had the strongest positive effect on foraging rate, followed by the intertidal zone, then bay shore. Conversely, sand flats had a moderately negative effect on adult plovers. The results also indicated that the post-breeding stage had a strong positive effect on foraging rate. In addition, as both the number of people and vehicles increase, foraging rates decrease. Finally, high tide has a strong positive effect on foraging rates.

Factors explaining chick foraging rates varied somewhat from the adults. The top models for this age group did include foraging habitat and number of people; however, the presence of avian predators also clearly drives chick foraging rates (Table 3). The model-averaged parameter estimates for two top-ranked models indicate that bay shores and constructed tidal ponds have a strong positive effect on chick foraging rates, while dunes and sand flats have a strong negative effect (Table 4). In addition, foraging rates decrease as the number of people and gulls increase. Finally, crows reduce chick foraging rates by a factor of 10 times greater than the number people.

The calculated mean squared prediction error for the validation data was 67.2, on the same order of the mean squared error of the regression model (74.7). For the chick external data set, the mean squared prediction error was 54.9, similar to the mean squared error of 50.1 for the regression model. These results suggest that both models can be applied to a broader piping plover population.

4. Discussion

An understanding of wildlife-habitat relationships is critical to define clear directives for the restoration of high quality habitat to sandy beach ecosystems (Morrison et al. 2006). The evaluation of a given restoration project must not only determine whether or not the restored feature is successful, but it must also provide conspicuous causal evidence of the outcome. Foraging and anti-predator behaviors are often correlated with reproductive success (Lindell 2008), and quantifying these behaviors can effectively identify resources that are crucial to a species' survival, demonstrate how the resources are used, and provide evidence for changes in survival or reproductive success. Equally important is the identification of constraints on the use of these resources. My analysis was successful in identifying significant drivers of foraging rates and using them to evaluate the success of a piping plover foraging habitat restoration project.

The analysis quantified the negative effect of human disturbance on foraging piping plovers, as number of people appeared in the top models for both adults and chicks. As expected, chicks are impacted more severely than adults, due to their increased vulnerability as flightless animals. Vehicles have a larger negative impact on adult plovers than people on foot, presumably due to their large size and speed. Although vehicles were not included in the chick foraging models since most vehicles are banned from New Jersey beaches by the time the chicks hatch, their negative impact has been confirmed for quite some time (Flemming et al. 1988; Melvin et al. 1994).

In addition to human disturbance, environmental variables play a role in defining adult foraging rates as well. Wind speed has only a small positive effect, which is not supported by other foraging studies where environmental factors are largely influential (Pienkowski 1983; Beauchamp 2006). High tide was reported as having a strong positive effect on foraging rates, which appears to contradict the literature suggesting that shorebirds primarily forage at low tide when low-lying areas are exposed (Burger 1991; Fraser et al. 2005; Jing et al. 2007). However, a closer examination of the data reveals that during high tide, most adults chose to forage at either ephemeral pools or constructed tidal ponds, both of which have a significant positive effect on foraging rates in my models. Therefore, tidal stage may not be as important a driver of foraging rates as the model effect sizes indicate.

Reproductive stage also has a strong effect on adult foraging rates, with all stages except brooding and post-breeding having negative effects. The large standard errors around this effect, and thus confidence intervals that straddle zero, make inference based on these data unreliable (Burnham and Anderson 2002). The exception was the post-breeding stage, which demonstrated a strong positive effect. As expected, post-reproductive adults no longer must fight for a prime territory, guard a nest, or look after chicks (Haig and Smith 2004). The lack of constraints naturally results in higher foraging rates.

Although chick foraging behavior is affected by human disturbance, it is more so dependent on the presence of avian predators. Gulls lowered chick foraging rates only slightly, most likely because the majority of gulls in the vicinity of foraging chicks were either flying overhead in transit, foraging on invertebrates, or resting. These individuals had no apparent interest in the plovers, and the chicks did not seem overly affected by their presence in most cases. In contrast, crows had an inordinately large impact on chick foraging rates, greater than 10 times that of people and two orders of magnitude greater than gulls. Crows are large, intelligent and persistent predators that were often observed perched somewhere within the foraging habitat (Marzluff and Angell 2005). In addition, they seem to ignore adult piping plover attempts to mob or distract them. Even a crow flying overhead elicited a defense call from brooding adults and a prolonged flight response from the chicks. Although crows are a historic predator of piping plovers, their role as human commensals has led to rapidly expanding populations (Marzluff et al. 2001), and the ever-increasing strain on ground-nesting shorebirds is becoming more frequent.

The foraging habitat itself had a significant impact on the foraging behavior of both adults and chicks. For adults, the intertidal zone, bay shore, and the constructed tidal ponds all positively influenced foraging rates, but sand flats negatively influenced foraging rates. For chicks, bay shores and constructed tidal ponds both had large positive effects on foraging rate, but sand flats and dunes had strong negative effects. The intertidal zone offers an important food source for shorebirds due to the density of marine invertebrates; however, this habitat is also the site of the most active human recreation at the beach. Since adults are less vulnerable than chicks to human traffic because of their ability to fly away quickly, adults can forage in this zone at normal rates for a much longer period of time than can chicks. Unless the disturbance is constant, adult piping plovers can still take advantage of this rewarding foraging habitat. Sand flats negatively impact foraging rates for both adults and chicks, mostly likely due to a combination of factors. First, sand flats are dry substrates; they cannot support the diversity and abundance of marine or freshwater invertebrates that can moist substrates (Collazo et al. 2002; Fraser et al. 2005). Therefore, plovers, especially inexperienced chicks, spend more time searching for and capturing terrestrial prey. Also, this habitat is expansive with little refuge available, so adults are much more vigilant against predators. Dunes greatly reduce chick foraging rates because of a lack of available prey items. Dunes do offer refuge for chicks within the vegetation, and the choice to forage in this habitat reflects the tradeoff between safety and sustenance (Burger 1994). Finally, the wrack line and ephemeral pools both had smaller positive effects on foraging rates for both age groups, but the large standard error associated with the parameter estimates prevents reliable inference.

The analysis supports the concept that the constructed tidal ponds in Cape May offer high quality foraging habitat for piping plovers. Both adults and chicks exhibited higher mean foraging rates here than in any other habitat. In addition, they spent considerably low amounts of time being vigilant or running away from perceived threats.

The importance of this habitat is further supported by the behavior of brooding adults, choosing to bring their chicks to the tidal ponds almost exclusively. These results can be attributed to both the location of the ponds and to the immediate landscape around them. The ponds were constructed behind the protective dune, so they are somewhat isolated from the disruptive recreational activities occurring on the beachfront. More importantly, vegetation exists in close proximity to the pond edge. This configuration provides an almost immediate refuge for chicks, rather than having to traverse the entire beach in search of cover. In the presence of a predator, I repeatedly observed chicks quickly moving into the vegetation and reemerging as soon as the threat passed.

The attributes of the constructed tidal ponds in Cape May allowed adult piping plovers to forage nearly undisturbed in most circumstances. More importantly, chicks were buffered against normal habitat constraints of human disturbance and predator pressure, and they were able to forage at the rate necessary for proper growth and development. The results of this behavioral study suggest that artificial tidal ponds are an effective restoration initiative to improve habitat quality of sandy beach ecosystems and may be superior to naturally occurring foraging habitats such as the intertidal zone, wrack line, and ephemeral pools. During the design of restored beaches, these population ecology findings suggest a design plan which includes substantial and reliable tidal ponds to supplement the beach nesting microhabitat needs described elsewhere (Maslo et al. 2010). A full consideration of behavioral niche axes now known for various phases of the reproductive cycle (nest-site selection, foraging preferences) can maximize restoration success. The social and engineering values of beach replenishment activities can be married to wildlife ecological needs, advancing the value of the replenishment programs. Further behavioral research on artificial foraging habitats elsewhere may further refine the findings documented here.

Acknowledgements

Special thanks go to Steven N. Handel, Julie L. Lockwood, Joanna Burger, and Karl F. Nordstrom for their advice and influence on this research. Todd Pover was most helpful in providing logistical support and assistance. I would also like to acknowledge the Graduate Program in Ecology and Evolution at Rutgers, The State University of New Jersey for providing financial assistance during this study.

Table 2-1 - Model selection results for candidate model set of foraging adult piping plovers (*N=471*)*

Model	AIC_c[a]	ΔAIC_c[b]	ML[c]	K[d]	w[e]
habitat + reproductive stage + tidal stage + people + vehicles	**3328.45**	**0.00**	**1.00**	**6**	**0.42**
habitat + reproductive stage + tidal stage + wind speed + people + vehicles	**3330.30**	**1.85**	**0.40**	**7**	**0.17**
habitat + reproductive stage + tidal stage + wind speed + people	3330.67	2.22	0.33	6	0.14
habitat + reproductive stage + tidal stage + people	3330.75	2.30	0.32	5	0.13
habitat + reproductive stage + tidal stage + wind speed + air temperature + people + gulls + crows + vehicles	3332.44	3.98	0.14	10	0.06
habitat + reproductive stage + people + vehicles	3332.93	4.48	0.11	5	0.05
habitat + reproductive stage + wind speed + people + vehicles	3332.89	6.44	0.04	6	0.02
habitat + reproductive stage + people	3335.24	6.79	0.03	4	0.01
habitat + people	3358.99	30.5	0.00	3	0.00

Top 9 models are displayed.
* N = # of total observations from a pool of 151 adults
[a]Akaike's Information Criterion corrected for small sample size
[b]difference between the AIC_c value between each model and the top model
[c]model likelihood
[d]# of parameters within the model
[e]Akaike weight
Models with a $\Delta AIC_c < 2$ are in bold type

Table 2-2 - Model-averaged parameter estimates and relative importance values for top adult foraging models

Parameter	RI[b]	Estimate	SE[a]
intercept		11.78	1.71
habitat	1.00		
intertidal		3.97	1.52
wrack		1.37	1.83
ephemeral pool		2.65	7.27
tidal pond		5.52	1.68
bay shore		2.32	2.29
sand flat		-2.30	2.04
reproductive stage	1.00		
pre-nesting		-1.66	1.86
nesting		-0.65	0.87
brooding		0.57	0.98
fledging		-0.65	1.54
post-breeding		4.49	1.80
people	1.00	-0.80	0.26
vehicles	1.00	-1.87	1.39
tidal stage	1.00		
high		3.98	0.93
low		1.62	2.98
wind speed	1.00	0.01	0.03

[a]standard error
[b]Relative Importance Value = sum of the Akaike weights for models including that variable

Table 2-3 - Model selection results for candidate model set of foraging piping plover chicks (*N=83*)*

Model	AIC_c[a]	ΔAIC_c[b]	ML[c]	K[d]	w[e]
habitat + people + crows	**1214.16**	**0.00**	**1.00**	**4**	**0.49**
habitat + people + gulls + crows	**1214.24**	**0.08**	**0.96**	**5**	**0.47**
habitat + tidal stage + wind speed + air temperature + people + gulls + crows	1219.09	4.93	0.08	8	0.04
habitat + people	1224.40	10.24	0.01	3	0.00
habitat + people + gulls	1226.80	12.64	0.00	4	0.00

Top 5 models are displayed.
*N = # of total observations from a pool of 108 chicks
[a]Akaike's Information Criterion corrected for small sample size
[b]difference between the AIC_c value between each model and the top model
[c]model likelihood
[d]# of parameters within the model, including year as a random effect
[e]Akaike weight
Models with a $\Delta AIC_c < 2$ are in bold type

Table 2-4 - Model-averaged parameter estimates and relative importance values for top piping plover chick foraging models

Parameter	RI[b]	Estimate	SE[a]
intercept		17.26	1.76
habitat	1.00		
intertidal		-0.24	1.99
wrack		0.61	1.69
ephemeral pool		3.15	4.48
tidal pond		4.42	1.15
bay shore		6.16	2.03
sand flat		-4.17	1.51
dune		-7.47	1.63
people	1.00	-1.24	0.49
gulls	0.49	-0.10	0.04
crows	1.00	-11.72	4.21

[a]standard error
[b]Relative Importance Value = sum of the Akaike weights for models including that variable

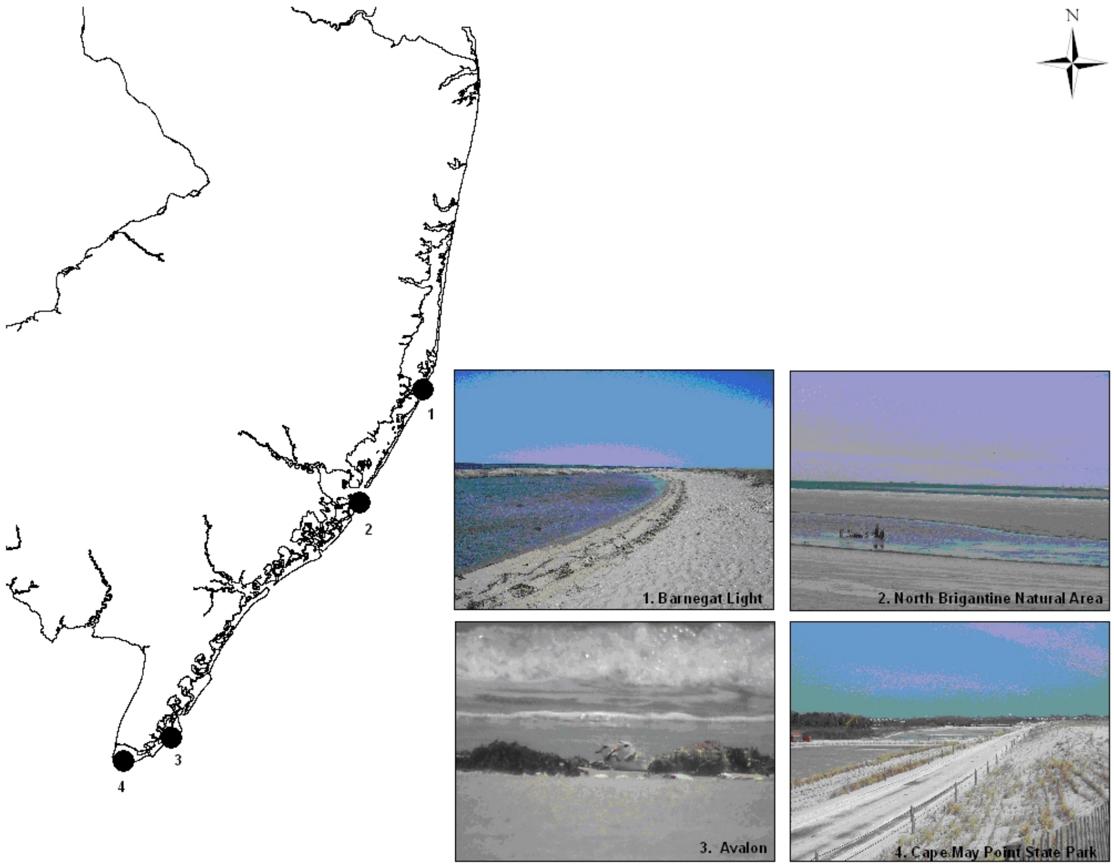

Figure 2-1 – Study sites along coastal New Jersey, USA, and a photographic representation of the naturally-occurring and artificial potential foraging habitats

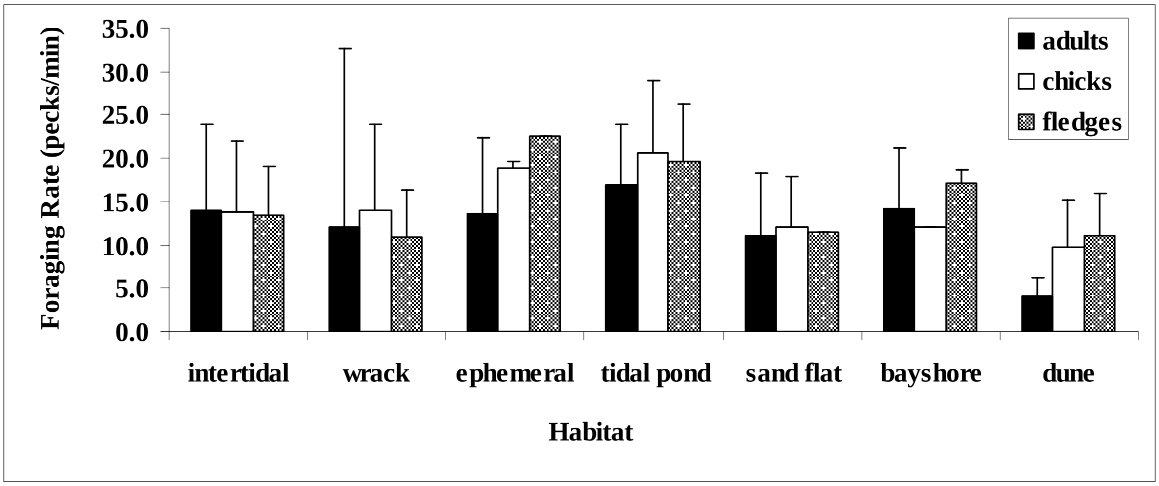

Fig. 2-2 – Mean foraging rates and standard deviations for adults, chicks, and fledges in each foraging habitat. Absence of error bars indicate that only 1 individual was observed in that habitat.

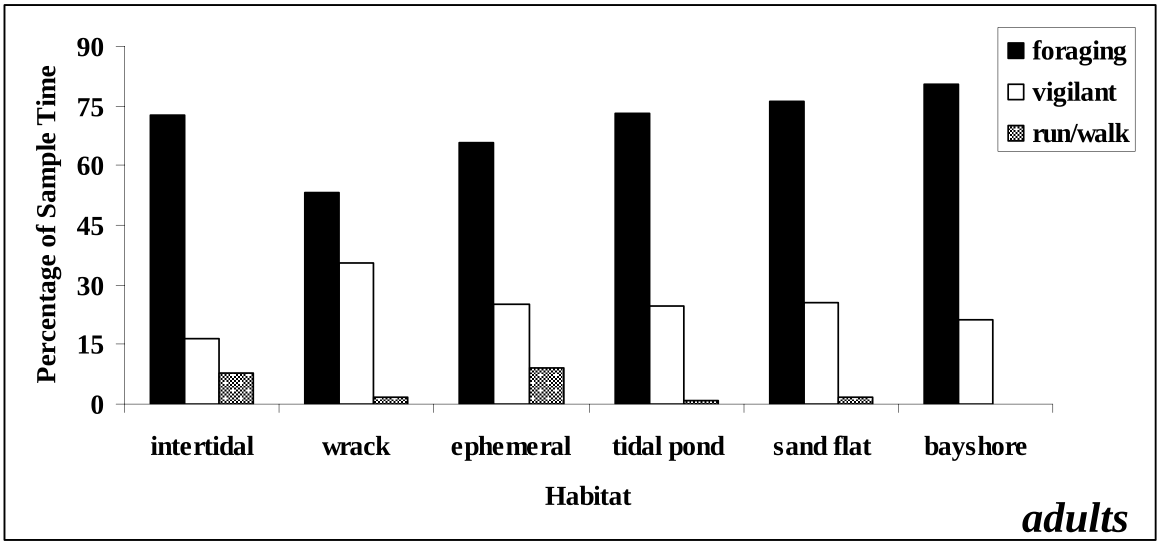

Fig. 2-3 – Significant differences in mean percentage of time adult plovers spent foraging ($F = 3.837$, $df = 7$, $p = 0.0005$), being vigilant ($F = 5.776$, $df = 7$, $p < 0.0001$), or running and walking away from a perceived threat ($F = 4.465$, $df = 7$, $p < 0.0001$) in different habitats.

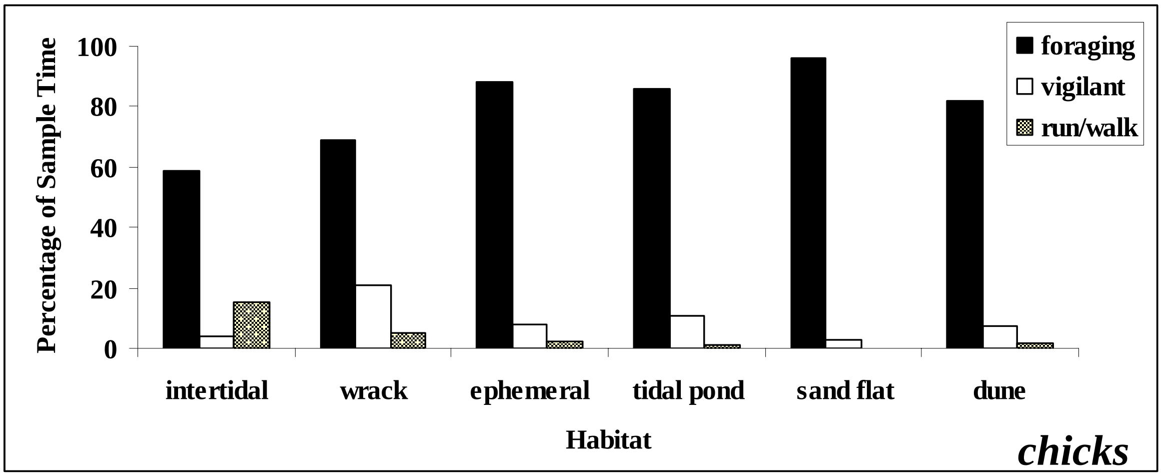

Fig. 2-4 – Significant differences in mean percentage of time plover chicks spent foraging ($F = 7.947$, $df = 6$, $p < 0.0001$), being vigilant ($F = 5.531$, $df = 6$, $p < 0.0001$), or running and walking away from a perceived threat ($F = 8.272$, $df = 6$, $p < 0.0001$) in different habitats.

CHAPTER 3

EVIDENCE-BASED DECISIONS ON THE USE OF PREDATOR EXCLOSURES IN SHOREBIRD CONSERVATION

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ABSTRACT

Conservation practitioners often rely on experience rather than scientific evidence when making management decisions. These experience-based measures can waste limited time and funding if the given conservation practice is ineffective. Unanalyzed conservation strategies may negatively impact the species that is being protected. The use of predator exclosures to increase hatching success in ground-nesting shorebirds has been studied for almost two decades, yet their effectiveness is still debated. In ecosystems where predation pressure is particularly strong, electrified exclosures have been adopted; however, there are no studies on their efficacy or potential negative impacts. We conducted a nest survival analysis for 10 years (1998-2007) of piping plover monitoring data to determine: 1) the effectiveness of predator exclosures and electrified predator exclosures, and 2) conditions associated with nest abandonments at electrified exclosures. We found that predator exclosures significantly increase nest hatching success. Electrified exclosures can also be very effective at increasing hatching success under certain conditions, but at sites with high human disturbance and red fox densities, the proportion of exclosed nests that are abandoned by parental adults becomes sizeable. The direct cause of nest abandonments remains unclear since fox behavior on beaches and the dynamics of foxes and plovers at exclosures have not been studied. Our results suggest

that such information is necessary if conservation practitioners can make more informed use of this direct management measure.

Keywords: piping plover, predation, exclosure, New Jersey, fencing, nest success

1. Introduction

Decision-making in conservation is predominantly experienced-based, with practitioners routinely drawing upon tradition, anecdotes, and existing management plans when organizing their own conservation directives (Pullin et al., 2004). Although experienced-based decisions can be successful under particular conditions, evidence-based decisions are more likely to be effective across varying conditions and can contribute to the construction of a solid scientific foundation upon which to advance biological conservation (Pullin and Knight, 2001). In many cases, management is implemented based on experience with the best of intentions but results in failure to meet management goals. In such instances it is nearly impossible to determine why the management failed. In the worst case scenario, the imposed management is a detriment to the target conservation organism(s). In this paper, we revisit the debate on the effectiveness of predator exclosures in increasing the hatching success of ground-nesting birds by examining a long-term monitoring data set for Atlantic Coast piping plovers (*Charadrius melodus*) in New Jersey, USA.

Ground-nesting birds, particularly shorebirds, have suffered drastic declines due to several anthropogenic factors, including habitat loss, habitat degradation, and human disturbance (e.g., Burger, 1981; Dolman and Sutherland, 1995; Dowding and Murphy, 2001). In addition to these threats, ground-nesters are susceptible to nest predation by both native and introduced species (e.g., Pauliny et al., 2008). Along the Atlantic coast, red foxes (*Vulpes vulpes*) and raccoons (*Procyon lotor*) are particularly injurious (Erwin et al., 2001, Neuman et al., 2004). In response to the severe decrease in reproductive success due to nest predation, several affected shorebird species have shifted their preference to other habitats where foxes were not present. Other beach-nesting species, such as piping and snowy plovers (*C. alexandrinus*), are incapable of successfully using alternative habitats due to their highly specialized cryptic plumage and the foraging requirements of their precocial chicks. Therefore, management strategies must be employed to counteract the negative impacts of mammalian predators on their reproductive success (Melvin et al., 1992; Neuman et al., 2004).

Electric fences that surround entire nesting areas have been used with varying success for piping plovers, least and Sandwich terns (Forster, 1975; Minsky, 1980; Mayer and Ryan, 1991; Murphy et al., 2003a; Ivan and Murphy, 2005), thus making this a potentially effective way of excluding ground predators. However, electric fences are an expensive alternative and require a great deal of maintenance along dynamic shorelines. Further, municipalities are reluctant to allow the electrification of large areas of public beaches due to the potential electrical shock risk to humans and their pets (T. Pover, Conserve Wildlife Foundation of NJ, pers. comm.). Also, this method does not prevent avian predation, which is often a significant source of reproductive failure in these species (O'Connell and Beck, 2002).

The most popular method of predator control around shorebird nests is Rimmer and Deblinger's (1990) predator exclosure. Although some variation exists between studies, these exclosures generally consist of a galvanized wire cage surrounding the nest and anchored to the substrate. Exclosures are also topped with wire or plastic netting to prevent avian predators from accessing nests. Results of several studies indicate that predator exclosures have a significant positive effect on nest hatching success (Rimmer and Deblinger, 1990; Melvin et al., 1992; Estelle et al., 1996); however, other studies have challenged the effectiveness of predator exclosures, citing several drawbacks (e.g., Mabee and Estelle, 2000, Murphy et al., 2003b; Isaakson et al., 2007; Niehaus et al., 2004; Vaske et al., 1994).

Due to these conflicting outcomes, conservation practitioners may have great difficulty in determining whether or not to use predator exclosures in any particular situation. Thus, they may be more likely to retreat to ‘common sense’ strategies or anecdotal evidence to guide their actions (Sutherland et al., 2004). However, these personal experience approaches may be biased by uncommon yearly phenomena. Repeated predation events by a single nuisance individual at a breeding site in a given year may negatively bias inferences. Even a statistical analysis on a limited number of nests may lack the statistical power to generate a universal conclusion. Therefore, long-term analyses across several sites are warranted to generate a universal evidence-based decision on the employment of predator exclosures to protect the eggs of ground-nesting birds. Our analysis of 10 years of piping plover nesting data from the US state of New Jersey provides this needed long-term perspective.

Predator exclosures are routinely used in New Jersey to reduce predation of piping plover nests by red foxes and other mammals living in coastal habitats. Because of the lack of recovery within New Jersey and observational evidence that most nests are lost due to fox predation, at some sites piping plover nests are protected with an additional barrier consisting of electrified wire surrounding the exclosure, referred to here as an ‘electrified exclosure’. This intensive management technique was first implemented to a limited extent in Maine in 1995, but no experimental tests or analyses were documented at that time (USFWS 1996). Conservation practitioners in New Jersey adopted the practice at a small number of breeding sites, and beginning in 2004, electrified exclosures have been used routinely in some locations.

The use of electrified exclosures carries obvious direct risks to the parental birds, and has the potential to negatively impact nest survival in more obscure ways. Erection of these exclosures induces a longer period of stress to nesting adults during their construction. The electrical wire surrounding the nest can cause injury or death to adults if they come in contact with it. The likelihood of contact with the electrical wire is increased when the adult is active, as may be the case when they are disturbed by human activity or predator. Any feature of the nest site that increases adult activity therefore may result in abandonment of active nests. Our aim is to identify whether predator exclosures increase hatching success among piping plovers nesting on New Jersey's beaches, and whether electrifying exclosures results in increases in nest success above the effect of the non-electrified structure. We also explore the driving factors behind nest abandonments among those with electrified exclosures in order to assist managers in more selectively implementing this arguably extreme conservation measure.

2. Methods

2.1. Data Collection

We obtained piping plover nest monitoring data from the New Jersey Division of Fish and Wildlife Endangered and Nongame Species Program (ENSP) for the years 1998-2007. Observers provided detailed accounts of each nest including: the day the nest was discovered, each day the nest was checked, the management technique(s) employed, and the fate of each nest. For failed nests, ENSP staff listed a presumed cause of failure (flooded, predated, abandoned). Additional information recorded by observers included a ranking of mammalian predator pressure based on the number of times evidence of a mammalian predator (i.e. tracks, scat) was observed within 10m of the nest (0 = never, 1 = 1-3 times, 2 = 4-6 times, 3 = 7+ times), and the amount and types of recreational activities (i.e. sunbathing, jogging) that occurred within 50m of the nest.

2.2 Study Areas

Our nest survival analyses span the New Jersey coastline from Sandy Hook to the southern tip of New Jersey and include all beaches where piping plovers are known to breed. Predator exclosures are commonly used throughout the state. Electrified exclosures are predominantly used at three beaches in New Jersey - Gateway National Recreation Area – Sandy Hook Unit (Sandy Hook), North Brigantine Natural Area (Brigantine), and Corson's Inlet State Park (Corson's Inlet) (Fig.1). Sandy Hook is a 10,500 hectare (ha) barrier spit that contains, in addition to beach, dune, and maritime forest habitats, a series of paved roads, parking lots, and public buildings. Brigantine is a 460ha portion of a barrier island that consists of beach, dunes, and tidal marsh. Corson's Inlet is a 40ha undeveloped portion of a barrier island that consists of beach and dunes.

2.3 Nest Exclosure Protocol

Managers of piping plover breeding sites within New Jersey follow a standardized exclosure protocol (USFWS 1996). Exclosures consist of low-gage, galvanized wire positioned in an approximately 1.8m diameter circle around each nest, extending approximately 20-25cm belowground and upwards to a height of approximately 75-

80cm, topped with plastic netting. To electrify an exclosure, a single metal wire is connected to metal stakes arranged in a circle around (but not in contact with) the exclosure. The wire is then connected to a 6V battery housed in a protective box and is grounded with an additional metal stake. All nests are exclosed and/or electrified within days of discovery, usually upon the completion of a full clutch. Once an exclosure is erected, the nest is closely monitored to ensure that parental adults accept it and resume incubation. If the adults do not accept the exclosure within approximately one hour, the structure is removed.

2.4 Nest Survival (Protected vs. Unprotected Nests)

We grouped all nests for which the fate was known by conservation treatment – unprotected, exclosed, and electrified – and calculated the percentage of abandoned nests for each study site and across all New Jersey breeding beaches. A nest was considered successful if at least one egg hatched. We then entered each group into Program MARK, which uses the Maximum Likelihood Estimator (MLE) of the daily survival rate (DSR) of each nest under a given conservation treatment (White, 2007). DSR is defined as the probability that a nest will survive one day. By raising the DSR estimate to the 35th power (equal to the average number of days in the laying and incubation period for piping plovers), we determined and compared piping plover nest survival from the completion of the clutch to hatching between conservation treatments. Note that sample size was too small at Corson's Inlet to provide reliable statistics for this analysis, and this site was thus not considered.

2.5 Nest Survival (Electrified Exclosures)

In a second MARK analysis, we built models that potentially explained variation in DSR of electrified nests when failure was due to abandonment only. Excluding all flooded and depredated nests, we focused solely on abandoned vs. hatched nests. We investigated the effects of two site characterization variables and four landscape variables on DSR of electrified nests (Table 1). Using an information-theoretic approach, we developed 13 *a priori* candidate models and one global model that contained all explanatory variables (Burnham and Anderson, 2002). These models represented several competing hypotheses in determining what site and landscape characteristics are associated with nest abandonment.

When analyzing large scale and long-term observational studies, one cannot adequately control for all inherent but unmeasured site differences that may be influencing the dependent variable (in our case DSR of electrified exclosures). To assess this issue, we calculated the DSR by site for hatched and abandoned nests that were exclosed only (i.e. not electrified). The DSR for nests (hatched or abandoned) at Sandy Hook and Brigantine was 0.9908880 and 0.9921868, respectively. With a total percent difference of 0.13% in DSR between sites, we are confident that our independent variables accounted for all relevant differences between sites.

Since the implementation of an electrified exclosure is projected to eliminate predation regardless of the time of the breeding season, we assumed a constant DSR for all models, with one exception where DSR varied throughout the nesting season. This null model accounted for changes in DSR due to time-varying factors, such as adult investment in older nests.

We tested the performance of each model using Akaike's Information Criterion (*AIC*), corrected for small sample size (AIC_c). *AIC* is a measure of the goodness of fit of a given statistical model. MARK ranked the models by calculating both the difference between each model and the model with the lowest AIC_c value (ΔAIC_c) and the Akaike weight (*w*), which is the relative likelihood of the model, given the data (Johnson and Omland, 2004). The model with the lowest ΔAIC_c is considered the best model, given the data. To reduce model selection bias and uncertainty, we averaged all models exhibiting $\Delta AIC_c < 2$ and calculated parameter estimates based on the weighted averages of the parameters in the top models. Finally, we calculated the relative importance (*RI*) of each variable in the top model set by summing the Akaike weights of each model in which it appeared (Burnham and Anderson, 2002).

3. Results

3.1 Nest Survival (Protected vs. Unprotected Nests)

The DSR for unprotected nests was substantially lower than for exclosed and electrified nests (Fig. 2). This difference in DSR translated into a three-fold increase in the probability that a piping plover nest will hatch at least one young when exclosed (Table 2). However, hatching success does not increase proportionately with intensity of management technique (Fig. 2 and Table 2). Instead, with the use of electricity hatching success appears to decline below the rate associated with exclosed-only nests. Conversely, nest abandonments increase with conservation treatment intensity, with electrified nests being nearly twice as likely to be abandoned if electric fencing is erected. Nest abandonments across all New Jersey breeding beaches increase from 7% for unprotected nests to 19% and 30% for exclosed and electrified nests, respectively (Table 3). Sandy Hook and Brigantine mirror this trend. Corson's Inlet displays the opposite trend, showing 20% abandonment for unprotected nests. However, the small sample size at this site artificially inflates the importance of the one recorded abandonment. A closer examination of the DSR of electrified exclosures indicates that at Sandy Hook the hatching success rate drops to 34%, while at Brigantine hatching success remains high at 78% (Table 2). Further, 55% of the failed nests at Sandy Hook were attributed to abandonment.

3.2 Nest Survival (Electrified Nests)

Of the 13 candidate models proposed as explanations for variation in DSR within hatched and abandoned electrified nests, the additive model including mammalian predation pressure and the distance from the nest to the nearest beach access point became the top-ranked model (Table 4); however, four additional models demonstrated $\Delta AICc$ values <2. For proper inference, we model-averaged parameter estimates across the top five models (Table 5). The top models included one or a combination of MAMMALIAN PREDATOR PRESSURE, HUMAN DISTURBANCE, and DISTANCE TO NEAREST BEACH ACCESS POINT, indicating their strong influence on the fate of electrified nests. The relative importance values of these variables identified mammalian predator pressure as the leading determinant in abandonment of electrified nests (Table 5). As mammalian predator pressure increases, DSR of electrified nests decreases considerably (Fig. 3). Similarly, the level of human disturbance has nearly the same model-averaged effect (negative) on DSR of electrified nests, as does mammalian predation pressure (Table 5; Fig. 3). As distance to the nearest beach access point increases, DSR of electrified nests increases; however this effect is slight (Table 5). As expected, the model describing time-varying DSR received little support.

4. Discussion

Extensive management actions must sometimes be employed for the recovery of threatened and endangered species. In the case of shorebirds, both the ever-increasing human demand for the coastal landscape as well as the myriad of opportunistic predators that humans attract surpasses the adaptation capabilities of some ground-nesting species (Nordstrom and Mauriello, 2001). Under these circumstances we should expect population numbers for these species will continue to decline, and there may be strong incentive to use active management options such as the erection of nest predation barriers. Alternatively, these techniques create their own disturbance and induce stress in breeding adults. Thus, managers must carefully consider options to ensure that a given conservation strategy does, in fact, significantly increase nest success. If not, limited time and conservation funds should be spent on widespread use of less intensive management techniques.

Our survival analysis support previous research that suggests predator exclosures (non-electrified) are an effective tool for increasing the hatching success of ground-nesting shorebirds. Two factors make our result especially notable. First, our analysis shows that predator exclosures exhibit a strong positive effect on hatching success despite using a data set in which we should expect inconsistencies in data recording. Seasonal personnel with varying levels of experience were employed for monitoring nests, and the crew composition often changed from year to year. Second, this strong positive effect occurs over a span of 10 years, allowing a reliable inference on the use of exclosures to be made while minimizing reservations due to seasonal variation. Therefore, properly designed and carefully monitored predator exclosures can be applied to increase hatching success of ground-nesting shorebirds.

Although electrified exclosures do increase hatching success over unprotected nests, the apparent increased risk of nest abandonment warrants careful planning and informed decisions on their use. Our analysis identified three critical factors in explaining nest survival of electrified nests, in order of relative importance – the level of mammalian predator pressure, the amount of human disturbance, and the distance from a nest to the nearest beach access point.

Even though red foxes seem to avoid humans (MacDonald and Newdick, 1982), beaches are generally unoccupied by people at night, when foxes normally forage. The vestiges of human activity may lure foxes out of the dunes to scavenge for trash, fish-heads, or other discarded items (Doncaster et al., 1990). In addition, where foxes are fed by fishermen, they may lose their fear of humans (Panek and Bresinski, 2002) and venture out in times of higher human activity. This increased traversing of the beach may raise the probability of a fox encountering a plover nest, and if this nest is electrified, the ensuing commotion may be enough to force the adult plovers to abandon their nesting attempt. Fox behavior in relation to exclosures is poorly understood, however, and such research is clearly needed to provide insight on a more profitable electrified exclosure design.

The influence of human disturbance is at least as high as that of mammalian predators in our analysis. Sandy Hook, where approximately 55% of the electrified nests in our dataset were abandoned, accommodates over two million (human) visitors per year, and the beaches and access paths are densely populated by recreation-seekers throughout the breeding season. At our other two study sties, electrified exclosures were not associated with nest abandonment. Although Brigantine allows off-road vehicle use during the early part of the breeding season, human disturbance on these beaches drastically declines by the time most plover nests have been laid. Further, most piping plover nests at these sites are at least 2km from the nearest beach access point, which naturally creates a buffer zone between humans and plovers.

Until a large enough body of knowledge exists to make broader inferences on conditions favorable for employing electrified exclosures, we suggest that at breeding sites with high fox density and high human disturbance, the use of electrified exclosures should be either eliminated or used solely in areas that accommodate fewer recreational activities.

Acknowledgements

Our thanks go to Todd Pover, Steven H. Handel, Joanna Burger, and Karl F. Nordstrom for their constructive comments about this research. We thank Dave Jenkins and Christina Kiesel for supplying us with this valuable long-term data set. We appreciate the use of the Rutgers Center for Remote Sensing and Spatial Analysis and the technical help provided by Jim Trimble. We thank Ben Baiser and Tom Virzi for input on MARK analyses, and other conceptual issues.

Table 3-1 - Explanatory variables included in electrified nest analysis

Variable	Description
	Site Characterization
Mammalian Predator Pressure	Ranked 0–3 based on the number of times evidence of a mammalian predator (i.e. tracks, scat) was observed within 10m of the nest
Human Disturbance	Passive (i.e. sunbathing) and active (i.e. jogging) recreational activities occurring within 50m of the nest were each ranked 0-4 based on use: 0 = none, 1 = light (very rarely exceeds 3 people at once, total >10<50/day), 2 = moderate (often >3, rarely >10 people at once, total >10<50.day), 3 = heavy (often >10 people at once, >50/day); scores for active use were doubled and a total index of 0-9 was recorded
	Landscape
Distance to Nearest Dune Line*	Distance (in meters) from nest to the nearest point on dune line
Distance to MHW line*	Distance (in meters) from nest to the nearest point on the line indicating the wet/dry interface
Distance to Nearest Beach Access Point*	Distance (in meters) from nest to the nearest public beach access point
Sinuosity*	The portion of the dune line occurring within a 200m radius of each nest was extracted; sinuosity = total length of the dune line/linear distance from the starting and ending point of the line

*measured by plotting nests on digital orthophoto quadrangles and using the ArcMap 9.2 analysis toolbox.

Table 3-2 – Effects of conservation treatments on hatching success (1998-2007)

Condition	N	DSR[a]	Hatching Success	SE[b]	95% Confidence Interval Lower	95% Confidence Interval Upper
Unprotected						
NJ	522	0.95	19%	0.002	0.949	0.958
Sandy Hook	77	0.92	6%	0.009	0.903	0.941
Brigantine	25	0.92	6%	0.017	0.881	0.950
Exclosed						
NJ	464	0.99	62%	0.001	0.984	0.988
Sandy Hook	122	0.99	59%	0.002	0.980	0.988
Brigantine	12	0.99	81%	0.004	0.976	0.998
Electrified						
NJ	157	0.97	43%	0.002	0.972	0.980
Sandy Hook	96	0.97	34%	0.003	0.962	0.976
Brigantine	55	0.99	78%	0.002	0.987	0.996

[a]daily survival rate
[b]standard error
Sample size for Corson's Inlet is too small to obtain reliable statistical results.
Sandy Hook and Brigantine nests are included in the NJ results.

Table 3-3 – Percentage of Abandoned Nests Under Varying Conservation Treatments

Site	Unprotected	% Abandoned Exclosed	Electrified
All NJ Breeding Beaches[b]	7 (359)[a]	19 (373)	30 (187)[d]
Sandy Hook	6 (78)	19 (123)	39 (123)
Brigantine	0 (25)	0 (12)	0 (55)
Corson's Inlet	20[c] (5)	0 (2)	0 (8)

[a]Total number of nests under each conservation treatment is indicated in parentheses.
[b]N = 29
[c]Only 1 nest was abandoned at this site. Percentage is artificially inflated due to small sample size.
[d]Total number of nests includes the 3 study sites and 1 application of electric in Ocean City, NJ.

Table 3-4 - MARK results for candidate model set of electrified nests (N=218)

Model	AIC_c[a]	ΔAIC_c[b]	ML[c]	K[d]	w[e]
mammalian predator pressure + distance to nearest beach access	**487.02**	**0.00**	**1.00**	**3**	**0.25**
mammalian predator pressure + human disturbance	**487.51**	**0.49**	**0.78**	**3**	**0.19**
mammalian predator pressure + human disturbance + distance to nearest beach access point	**487.93**	**0.91**	**0.63**	**4**	**0.16**
human disturbance + distance to nearest beach access point	**488.92**	**1.90**	**0.39**	**3**	**0.10**
human disturbance	**488.98**	**1.96**	**0.38**	**2**	**0.09**
mammalian predator pressure + distance to nearest dune line + human disturbance + distance to nearest beach access point	489.35	2.33	0.31	5	0.08
distance to nearest beach access point	489.39	2.37	0.31	2	0.08
mammalian predator pressure + human disturbance + distance to nearest dune line + distance to MHW + distance to nearest beach access point+ sinuosity	491.85	4.83	0.09	7	0.02
mammalian predator pressure + distance to nearest dune line	492.28	5.26	0.07	3	0.02
mammalian predator pressure	492.46	5.44	0.07	2	0.02
mammalian predator pressure + distance to nearest dune line + sinuosity	493.95	6.93	0.03	4	0.01
distance to nearest dune line + distance to MHW	498.65	11.63	0.00	3	0.00
distance to nearest dune line	499.02	12.01	0.00	2	0.00
time-varying model (no variables)	502.72	15.71	0.00	2	0.00

[a]Akaike's Information Criterion corrected for small sample size
[b]difference between the AIC_c value between each model and the top model
[c]model likelihood
[d]# of parameters within the model
[e]Akaike weight
Models with a $\Delta AIC_c < 2$ are in bold type

Table 3-5 - Model-averaged parameter estimates and relative importance values for the variables contained in the top model set

Parameter	Estimate	SE[a]	RI[b]
Intercept	5.308	0.0676	
Mammalian predator pressure	-0.1618	0.0676	0.595
Human disturbance	-0.130	0.0511	0.537
Distance to nearest beach access point	0.0002	0.00008	0.498

[a]standard error
[b]Relative Importance Value = sum of the Akaike weights for models including that variable

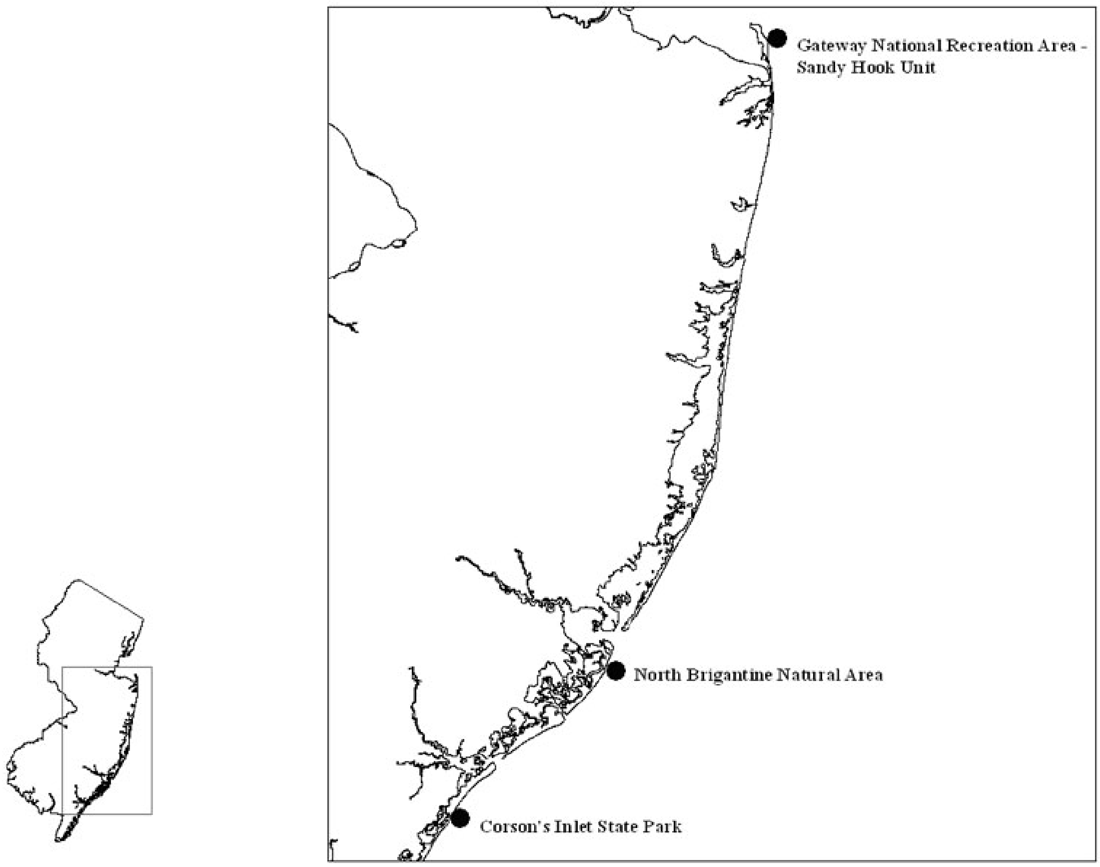

Figure 3-1 – Piping plover breeding sites in New Jersey where electrified exclosures are routinely implemented.

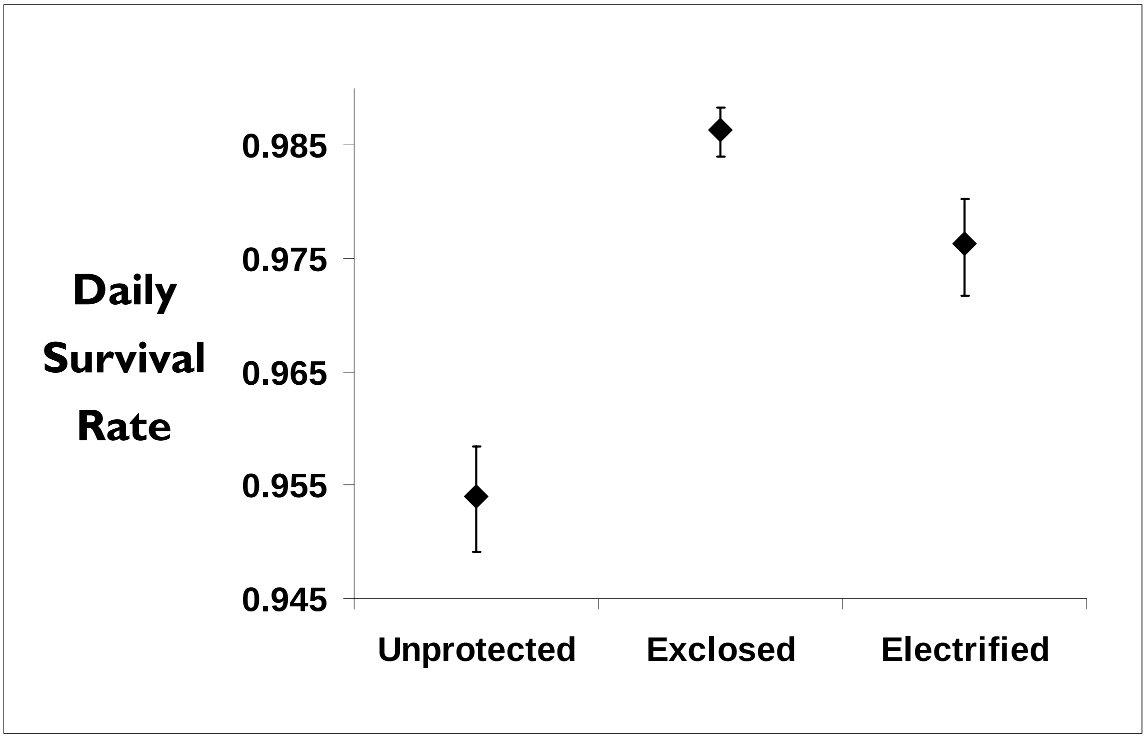

Figure 3-2 – Estimates of daily survival rate (DSR), with 95% confidence intervals for unprotected, exclosed, and electrified piping plover nests found in New Jersey from 1998-2007.

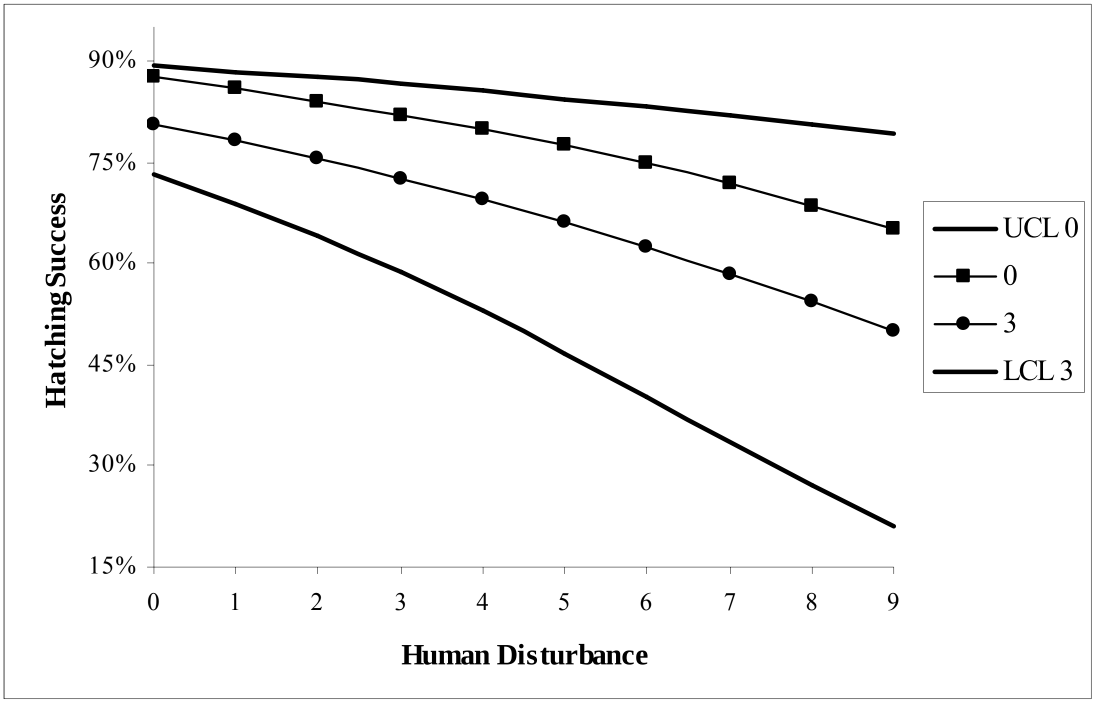

Figure 3-3 – Effect of human disturbance on hatching success of electrified exclosures at mammalian predator pressure levels of 0 and 3. Predator pressure levels of 1 and 2 show the same trend and have been excluded to increase clarity of the figure. UCL represents the upper 95% confidence interval for mammalian predator pressure level of 0. LCL represents the lower 95% confidence interval for mammalian predator pressure level of 3.

GENERAL DISCUSSION

Piping plovers and other beach-dependent species are in a state of constant threat due to the myriad of anthropogenic stressors placed on them and their environment. Although these species have evolved to be resilient again pulse disturbances and perpetually shifting microhabitats, the overwhelming levels of disturbance and degradation we have imposed on the beach ecosystem far surpass these species' ability to recover. Perhaps our biggest idealistic conservation goal should be the preservation of large expanses of dynamic shorelines which naturally regulate the balance of mosaic habitats and suppress populations of introduced predators. This vision, however, may never come to fruition because of the continued demand and appeal of people to the coast. In 2003, 53% of the United States population lived along the coast, which was an increase of 33 million people from 1980 (Crosett et al. 2004). Stabilization of the shoreline is necessary to support this multitude of people; however, shoreline protection need not come at the expense of the natural habitat.

Restoration of Piping Plover Breeding Habitat

This dissertation focuses on the restoration of habitat for the federally threatened Atlantic Coast piping plover (*Charadrius melodus*), but the approach defined here are applicable to the management of any beach dependent species with only minor modification. Using robust statistical techniques, I used a large data set with multiple observations of piping plover nests to define four habitat types that describe suitable nesting sites. These categories all contained a combination of varying ranges of four habitat characteristics, in order of relative importance – percent vegetative cover, percent shell cover, distance to the high tide line (m), distance to the nearest dune (m), and percent pebble cover. In addition, with the large number of observations in the data set, I was able to create frequency histograms of each measured habitat characteristic, which enable to prepare credible target values for the design of suitable nesting habitat. Two results were perhaps most striking: 1) the surficial characteristics within a 1-meter radius of the nest appeared to be the most influential factors driving nest-site selection, and 2) a significant proportion of the nests observed occurred on primary dunes. These phenomena have important restoration implications. The creation of suitable surficial characteristics is a relatively simple restoration directive that can be implemented on any stabilized beach to make the area more attractive to nesting plovers. Therefore, this recommendation can be easily included in current beach management plans. The occurrence of several nests on primary dunes supports that idea that a high quality habitat should include a mosaic of suitable microhabitats to accommodate shifts in behavior due to disturbances. When plovers did nest on primary dunes, they chose those with low profiles, gentle slopes, and moderate vegetative cover. To suit the full suite of niche requirements for nesting piping plovers, the design of constructed dunes should be modified to create smaller, gently-sloped dunes. Further, as vegetation is commonly planted to stabilize dunes, experiments on planting configurations should be performed to maximize dune stability while minimizing vegetation density.

The analysis also quantified habitat characteristics of unsuitable nesting habitats. Defining the threshold between suitable and unsuitable habitat is crucial to the development of effective adaptive management plans so that practitioners can maintain a habitat that is capable of supporting a maximum number of piping plovers. The values suggested act as general trigger points for management action and can be further refined one a site-by-site basis.

This dissertation also examined foraging behavior to evaluate the success of a piping plover habitat restoration project in the Lower Cape May Meadows, Cape May, New Jersey, USA. Since acquisition of ample food is directly linked to the growth and development of plover chicks, high foraging rates can be equated with productivity – number of chicks fledged per nesting pair. For this study, I quantified foraging rates of piping plover adults and chicks at the constructed tidal ponds of the restored site and compared them to the rates at other potential foraging habitats (intertidal zone, wrack line, ephemeral pools, etc.) at the restored site and three other sites in New Jersey. For each sample I measured both behavioral variables (e.g. # of people, # of predators) and environmental variables (e.g. wind speed, air temperature). I also prepared foraging activity budgets for each group to determine how much time was devoted to foraging, being vigilant, and fleeing from real or perceived threats.

The results indicated that the restored tidal ponds were superior foraging habitat for both adults and chicks. The birds in both age groups foraged at high rates in this habitat and spent relatively little time in defensive behaviors (vigilance, crouching, fleeing) compared to the intertidal zone, wrack line, and ephemeral pools. Based on the relative number of observations in the intertidal zone and the parameter estimates generated by the regression model, adults seem to prefer foraging along the intertidal zone, presumably due to the significant biomass of marine polychaetes and other invertebrates. However, in this study the chicks very rarely foraged in the habitat, their parents choosing to lead them instead to the non-ocean alternatives. In the Lower Cape May Meadows, chicks foraged at the restored tidal ponds almost exclusively, while at sites without this feature, they primarily foraged in the dunes or wrack line. This choice undoubtedly results from the high levels of human disturbance at recreational beaches. Chicks seek refuge among the vegetative cover of the dune at the expense of decreased foraging rates (Burger 1991). Foraging in dune in this study had a significant negative impact on chick foraging rates.

If more restored tidal ponds existed, studies directly comparing foraging rates at each site would help to clarify what features most influence the increased foraging rates. Two features of the tidal ponds in this study may have contributed significantly to the high foraging rates observed. First, the ponds were located behind the protective linear dune. Most active recreational activities (e.g. jogging, fishing) occur between the intertidal zone and wrack line, with more passive activities (e.g. sunbathing) occurring on the upper beach. Visitors behind the dune are generally just passing through or are interested in bird-watching and may naturally be more aware of the negative impact of disturbance on wildlife. Second, the ponds are surrounded by a zone of vegetation close to the shoreline. The close proximity of a refuge to a foraging habitat may be a critical component of ultimate fledging success. Especially on a recently nourished beach, traditional foraging areas along the intertidal zone or wrack line are some distance from any cover, leaving chicks extremely vulnerable to predators. At the constructed tidal ponds, when a predator arrives, the chicks immediately seek cover within the vegetation and then quickly emerge and resume foraging as soon as the threat is gone. On average, this behavior results in more time foraging, less time being vigilant, and notably less energy expended on running away.

A noteworthy result of this study was extremely large negative effect size generated for crows on chick foraging rates. Although crows have long been a predator of piping plover eggs and chicks, their role as human commensals has led to widely expanded populations throughout their range (Marzluff et al. 2001). Crows are large, intelligent and persistent predators that appear unaffected by parental plovers' attempts to mob or distract them. Their increasingly commonplace presence along beaches is call for concern, and conservation measure should be taken to temper this inevitable threat.

Finally, I validated the regression models with an external data set that I created by observing piping plovers at the remaining breeding sites in New Jersey. The results indicate that these models can be applied to other Atlantic Coast piping plover subpopulations. Therefore, this behavioral study can be used as part of a monitoring program to evaluate the success of other piping plover habitat restoration endeavors.

Implications for Piping Plover Conservation

Pressure of both native and introduced predators on ground-nesting shorebirds is well-documented (e.g. Pauliny et al. 2008). Several methods have been implemented to combat this pressure, from fencing entire nesting areas to shooting pyrotechnics to deter gulls (Mayer and Ryan 1991; Olyjink and Brown 1999). These methods, unfortunately, are usually implemented without rigorously analyzed scientific data (Pullin et al. 2004). In extreme cases, some conservation strategies may negatively affect the conservation target; or conservation managers waste limited time and resources on effective strategies.

The conflicting results of several studies on the effectiveness of predator exclosures warranted an analysis using a long-term data set that was robust to yearly variation and differences in observer skill level. To analyze the data, I used Program MARK, which is a Maximum Likelihood Estimator (MLE) of the daily survival rate (DSR) of nests under each conservation treatment (White 2007). The results indicate that predator exclosures do indeed increase the hatching success of piping plover nests over unprotected nests. However, success does not increase linearly with intensity of conservation treatment. Electrified nests, while still increasing hatching success over unprotected nests, are significantly lower than nests that are only exclosed.

A closer examination of the data revealed that electrified nests experience a high rate of abandonment. To determine the factors associated with abandoned nests, I ran a second MARK analysis on only the electrified nests. Results indicated that the use of electrified exclosures in areas with both high human disturbance and high mammalian predator pressure lead to increased levels of nest abandonments. The vestiges of diurnal human activity may lure nocturnal foxes out of the dunes at night, increasing the probability that they encounter a nest. If a nest is electrified and a predator is shocked, the ensuing commotion may be enough for the birds to abandon their nesting attempt. Fox interactions with exclosures and electrified exclosures are poorly understood, and more research is needed. Until enough knowledge exists to design a more profitable electrified exclosure, their use should be eliminated or used solely in areas that entertain fewer recreational activities.

Appendix A. GPS coordinates for piping plover breeding locations in New Jersey

Site	Latitude (N)	Longitude (W)
Sandy Hook	40 27.761	73 59.483
Sea Bright	40 22.860	73 58.326
Monmouth Beach	40 20.441	73 58.400
7 Presidents Park	40 18.996	73 58.590
Wreck Pond	40 08.278	74 01.585
National Guard Training Center	40 07.294	74 01.850
Barnegat Light	39 45.263	74 06.076
Holgate	39 30.129	74 17.864
Little Beach	39 28.475	74 18.980
North Brigantine Natural Area	39 25.827	74 20.254
Ocean City	39 15.802	74 35.501
Corson’s Inlet State Park	39 12.546	74 38.825
Strathmere	39 12.139	74 39.087
Avalon	39 04.839	74 43.867
Stone Harbor Point	39 01.793	74 46.613
North Wildwood	39 00.344	74 47.309
Cape May National Wildlife Refuge	38 56.966	74 51.400
Poverty Beach	38 56.280	74 53.495
Cape May Point State Park	38 55.886	74 56.903

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