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Restoring Beaches for Atlantic Coast Piping Plovers (*Charadrius melodus*): A Classification and Regression Tree Analysis of Nest-Site Selection

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Abstract

To effectively restore wildlife habitat, ecological research must be easily translated into practical design criteria. Clear directives from research can support arguments that promote more appropriate 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 conditions. Several studies of piping plover habitat selection have been conducted, yet useful and detailed design directives remain undeveloped. In this study, we use classification and regression tree analysis to (1) identify microhabitat characteristics and important variable interactions leading to nest establishment and (2) develop target, trigger, and threshold values for use in effective design and adaptive management of piping plover habitat. We found that nests primarily occur in three distinct habitat conditions defined by percent shell and pebble cover, vegetative cover, and distance to nearest dunes and the high tide line. 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 the following pragmatic target design parameters: (1) vegetative cover: less than 10% (backshore), 13% (primary dune); (2) shell/pebble cover: 17–18%; (3) dune height: ≤1.1 m; and (4) dune slope: ≤13%. We also recommend threshold values for adaptive management 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: beach nourishment, beach stabilization, CART, habitat restoration, piping plover, wildlife–habitat relationships.

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, and resulting trial-and-error strategies threaten to waste limited time and resources on potentially ineffective strategies (Pullin & Knight 2001).

This study addresses a current and prime example of this issue, focused on efforts to conserve the federally threatened Atlantic Coast piping plover (*Charadrius melodus*), a rare beach-nesting shorebird. Since the federal listing of this species by the United States Fish and Wildlife Service (USFWS) in 1986, much research has been conducted on its life history, population viability, habitat requirements, behavior, and protection (USFWS 1996, 2009). Despite this intensive effort, many factors continue to limit species recovery (USFWS 2009).

The USFWS Atlantic Coast Piping Plover Population Recovery Team has placed a long-standing emphasis on the restoration of breeding habitat (USFWS 1996, 2009). This initiative has resulted in a partnership with the United States Army Corps of Engineers (hereafter, the Corps) to integrate habitat enhancement features into beach stabilization protocols. These features include a lowered beach elevation, sandy, unvegetated nesting substrate, 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 non-ocean foraging habitats (Smith et al. 2005). Unfortunately, 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

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no advantage, or even adverse impacts, to beach-nesting birds (Greene 2002; Defeo et al. 2009).

A technical literature assists practitioners in creating suitable piping plover nesting habitat, indicating that the niche requirements of both inland and coastal piping plovers are similar and can be used to make general statements about nesting habitat (Burger 1987; Prindiville-Gaines & Ryan 1988; MacIvor 1990; Patterson et al. 1991; Powell & 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 (Lindenmayer & Hobbs 2007). First, the habitat characteristics that have been reported typically show means with large standard deviations, indicating high variability. Second, results often varied significantly between study sites, across years, and across studies. In some cases, habitat characteristics have been quantified using different metrics. For example, amount of vegetation has been reported as percent cover within 1 m of nest, percent cover of surrounding habitat, or # of shoots. Lack of uniformity in methodology 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 "low" when describing the vegetative cover or dune height, respectively, of breeding beaches (Haig & Elliott-Smith 2004). Third, habitat variables were presented individually (i.e. shell cover only), but identifying interactions between nest-site 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 (Patterson 1988; MacIvor 1990). Also, plovers may choose to nest in more vegetation when shell cover drops below a certain threshold.

Finally, beaches are continually impacted by anthropogenic factors, and as a result are becoming less diverse and poorer in habitat quality on a regional scale (Brown & McLachlan 2002; Defeo et al. 2009). Identification of both target restoration values and performance thresholds for maintaining suitable habitat on human-impacted beaches may be critical to the persistence of piping plovers and other beach-nesting species.

Meeting the challenge of designing a nesting habitat with a diversity of 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 datasets with several explanatory variables (De'Ath & Fabricius 2000; Kintsch & Urban 2002; Bourg et al. 2005). Benefits of CART include no prior variable selection requirement, a resiliency to missing data, and the flexibility in include combinations of both categorical and continuous data (Guisan & Zimmerman 2000, Feldesman 2002). Most importantly, CART exposes hierarchical relationships and interactions among predictor variables, which may be very useful when designing habitat restorations (Kelly et al. 2007). Based on the CART results, we determine both important microhabitat characteristics 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, United States, from 2006 to 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 2×2 m^2, plot with the nest in the center. Four photographs (1,260 × 980 resolution) were taken from the edge of the plot at a height of approximately 1.5 m, with one quadrat representing each of the four 1 m^2 quadrants around the nest. We collected approximately 60 g 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 (±0.9 m accuracy) and recorded the presence or absence of an accessible non-ocean foraging habitat. These alternative foraging locations included bay shores, tidal ponds, and other moist substrates within 1 km from the nest (Patterson 1988; Loegering 1992; Melvin et al. 1994). Finally, we measured the height and slope of the nearest dune using the Emery Rod Method (1961). Nesting plovers were minimally disturbed for less than 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 on 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 m north of the northernmost nest and 100 m south of the southernmost nest within each nesting cluster. Over the 3-year study period, we observed 171 first nests and 30 renests. To avoid potential pseudoreplication, we eliminated the renests from our analysis.

Data Preparation

Using Adobe Photoshop CS2 (Adobe® 2005, Adobe, San Jose, CA, U.S.A.), 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

Table 1. General characteristics of New Jersey piping plover breeding beaches.

Site	*Latitude (N)*	*Longitude (W)*	*Geomorphology*[a]	*Beach Width*[b]	*Degree of Development*[c]
Sandy Hook	40 27 45.66	73 59 28.98	Barrier spit	Wide	Low
Sea Bright	40 22 51.60	73 58 19.56	Mainland	Narrow	High
Monmouth Beach	40 20 26.46	73 58 24.00	Mainland	Narrow	High
7 Presidents Park	40 18 59.76	73 58.35.40	Mainland	Narrow	Moderate
Wreck Pond	40 08.16.68	74 01 35.10	Mainland	Narrow	Moderate
National Guard Training Center	40 07 17.64	74 01 51.00	Mainland	Narrow	Low
Barnegat Light	39 45 15.78	74 06 04.56	Barrier island/inlet[d]	Narrow to moderate	Low
Holgate	39 30 07.74	74 17.51.84	Barrier island/inlet	Moderate to wide	None
Little Beach	39 28 28.50	74 18 58.80	Barrier island/inlet	Wide	None
North Brigantine Natural Area	39 25 49.62	74 20 15.24	Barrier island/inlet	Moderate to wide	None
Ocean City	39 15 48.12	74 35 30.06	Barrier island	Moderate	High
Corson's Inlet State Park	39 12 32.76	74 38 49.50	Inlet	Moderate	None
Strathmere	39 12 08.34	74 39 05.22	Inlet	Moderate	High
Avalon	39 04 50.34	74 43 52.02	Barrier island	Moderate	Moderate
Stone Harbor Point	39 01 47.58	74 46 36.78	Inlet	Wide	None
North Wildwood	39 00 20.64	74 47 18.54	Barrier island	Moderate	High
Cape May National Wildlife Refuge	38 56 57.96	74 51 24.00	Barrier island	Narrow	Low
Poverty Beach	38 56 16.80	74 53 29.70	Barrier spit	Moderate	High
Cape May Point State Park	38 55 53.16	74 56 54.18	Mainland	Moderate	Low

[a] Davis and Fitzgerald (2004).
[b] Beach width: narrow = less than 80 m, moderate = 81–150 m, wide = greater than 150 m.
[c] Degree of development describes the level of human infrastructure behind the beach.
[d] Beach was classified as an inlet beach if nesting habitat was within 1.6 km of the inlet shoreline (Kisiel 2008).

grid. From the edited images, we visually estimated the percent cover of vegetation, shells, and pebbles (4–65 mm) on the grid, and recorded the presence/absence of driftwood. We ran the substrate samples through a 2-mm sieve to determine the percent composition of sand ($\leq$2 mm) and gravel (>2 mm).

We grouped nests and random points by habitat (beach, dune, etc.) and performed one-way analyses of variance (ANOVAs) and Tukey's pairwise comparisons to determine whether nest-site characteristics differed significantly among habitats.

CART Analysis

We used CART ProV6.0 software (Salford Systems©, San Diego, CA, U.S.A.) to create a decision tree that modeled 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 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 whether characteristics associated with selection of nest sites varied across years. As 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

Table 2. Habitat characteristics included in piping plover classification and regression tree analysis.

Variable	*Description*
Geography*	Mainland beach, barrier beach, inlet beach
Distance to nearest dune	Distance (in meters) from nest to the nearest point on dune line
Dune height	Height (in meters) of the apex of the nearest dune to its seaward toe
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
Non-ocean foraging habitat	0 (absent within 1 km of the nest), 1 (present within 1 km of the nest)
Vegetation percent cover	Percentage of the 1-m radius surrounding the nest covered by vegetation
Shell percent cover	Percentage of the 1-m radius surrounding the nest covered by shells or shell fragments
Pebble percent cover	Percentage of the 1-m radius surrounding the nest covered by pebbles (4–65 mm)
Driftwood (>15 cm in length)	0 (absent), 1 (present)
Substrate composition	Percent by weight of gravel (>2 mm) within the surficial substrate

* Davis and Fitzgerald (2004).

impurity measure splitting criterion and constrained the output to include a minimum of 10 nests/random points 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 misclassification rate. We selected the tree with the lowest misclassification rate as the optimal tree (Brieman 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

The nests were nearly evenly distributed between beach types, with slightly more nests occurring on inlet beaches (Fig. 1). In general, nests were initiated on the backshore of the beach within 25 m 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 2 m and 20%, respectively. Distance to the high tide line was variable, and nests were split nearly evenly between sites with and without a non-ocean foraging habitat. Substrate composition was primarily pure sand; however, 29% ($n = 50$) of nests were initiated in 1–51% gravel.

Surficial nest-site characteristics, dune height, and dune slope varied depending on the habitat in which the nest was initiated. For example, 81% of all nests sampled occurred in shell cover of 0–20%; however, mean shell cover is significantly greater on overwash fans (19.5 ± 2.1) than on the beach backshore (8.5 ± 1.6) or primary dunes (6.1 ± 1.9) ($F = 8.4$, $df = 3$, $p < 0.0001$). 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 15 ± 13. Percent vegetative cover also differed between habitats ($F = 15.2$, $df = 3$, $p < 0.001$), with an average percent cover of 12.9 ± 1.4 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 ($F = 7.0$, $df = 3$, $p = 0.0002$; $F = 3.2$, $df = 3$, $p = 0.0258$, respectively). Dunes on which nests occurred averaged 1.0 ± 0.1 m in height and 13.4 ± 1.7% in slope, whereas dunes surrounding all other nests averaged 1.6 ± 1.2 m and 18 ± 13%, respectively. No nests occurred on dunes greater than 3.1 m in height or 50% slope.

Classification and Regression Tree Results

The cross-validated CART analysis combined the nest data with the 373 random locations sampled and specified a tree with nine terminal nodes and a misclassification rate of 0.290 as the best (Fig. 2). This tree correctly classified 89 and 88% of actual nests and random locations, respectively, and grouped 68% of all nests into one terminal node. CART identified 5 of the 12 potential explanatory variables as making significant contributions to predicting nest establishment for piping plovers. In order of importance these are—percent shell cover, percent vegetative cover, distance to the nearest dune, percent pebble cover, and distance to the high tide line (Fig. 2). These variables represented the primary splitters in classifying the data into homogenous groups (Fig. 2).

Nests primarily fell into three groups, each with varying combinations of habitat conditions. One hundred seventeen of the 171 total nests sampled (68%) were found in areas with shells, $\leq$33.5% vegetative cover, relatively close to dunes ($\leq$77.5 m), and greater than 9.5 m 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 (Fig. 2). One hundred forty-three random locations (38%) occurred in areas with no shells, no pebbles, and no vegetation (pure sand), whereas 123 (33%) occurred in areas with no shells, no pebbles, and greater than 15.2% vegetative cover. All terminal nodes classified as containing random locations reported misclassification rates of 10.0% or less; one of these six terminal nodes was 100% pure (no misclassified samples). These results indicate that the CART analysis succeeded in describing microhabitats that are mostly avoided by nesting plovers.

Discussion

Because of 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 conservation of these imperiled species. Restoration designers must be informed of useful ranges of nest-site parameters, such as surficial characteristics, dune slopes and heights, and vegetative cover to create a mosaic habitat composed of diverse microsites that will support species' persistence. Our analysis provides practical ecological guidelines for both habitat manipulations and adaptive management plans applicable to human-impacted breeding habitat for Atlantic Coast piping plovers. Table 3 lists restoration target, trigger, and threshold values for important breeding ground habitat features identified by the analyses 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 only a few meters (Burger 1987; Prindiville-Gaines & Ryan 1988; MacIvor 1990; Patterson et al. 1991; Powell & Cuthbert 1991; Flemming et al. 1992; Espie et al. 1996). This result supports the finding that all piping plovers have analogous niche requirements (Haig & Elliott-Smith 2004); therefore, our recommendations can be used as a guideline when designing many piping plover breeding habitats, particularly in the mid-Atlantic states, where stabilized beaches are common. However, it is important to note that sandy beach

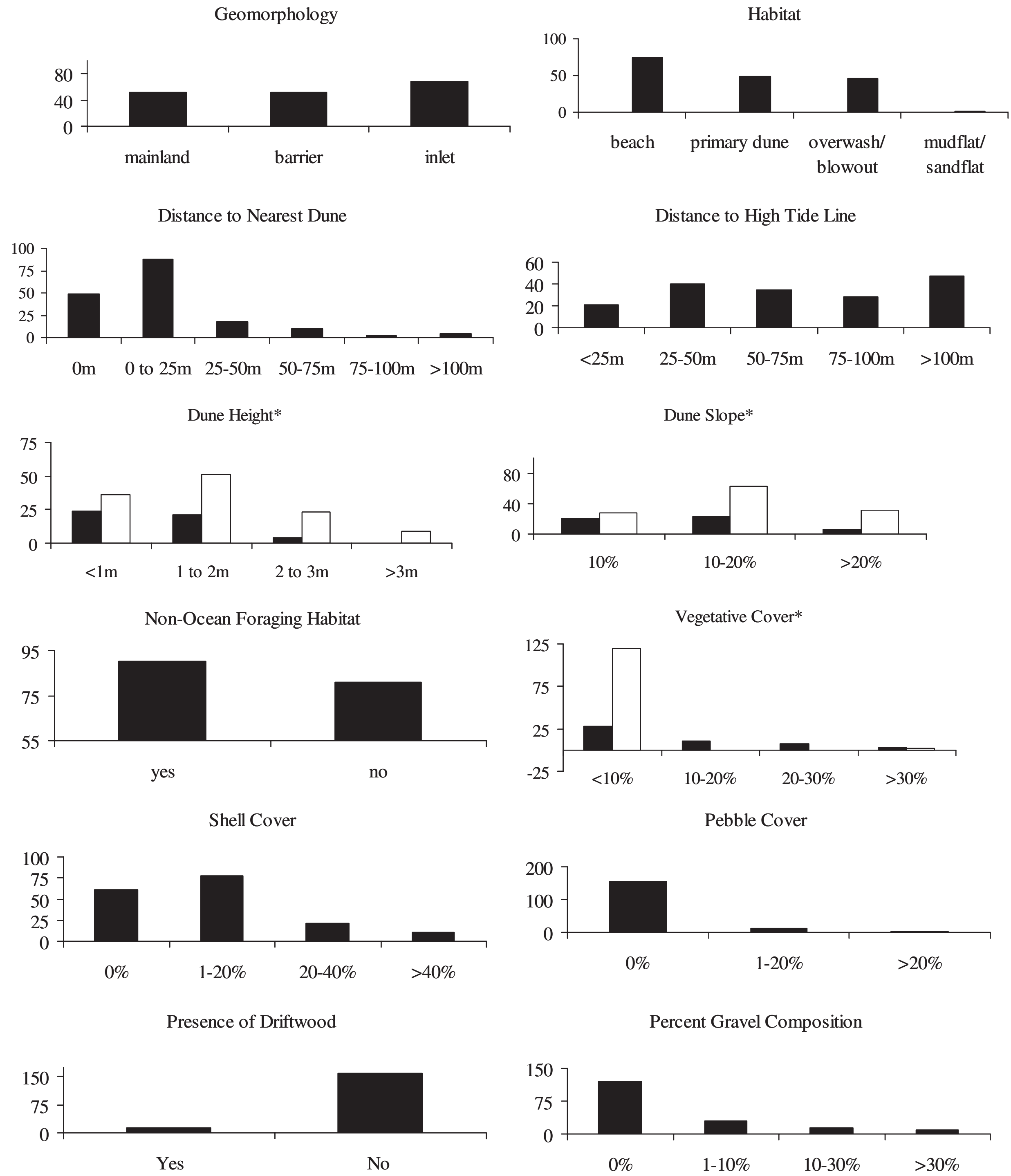
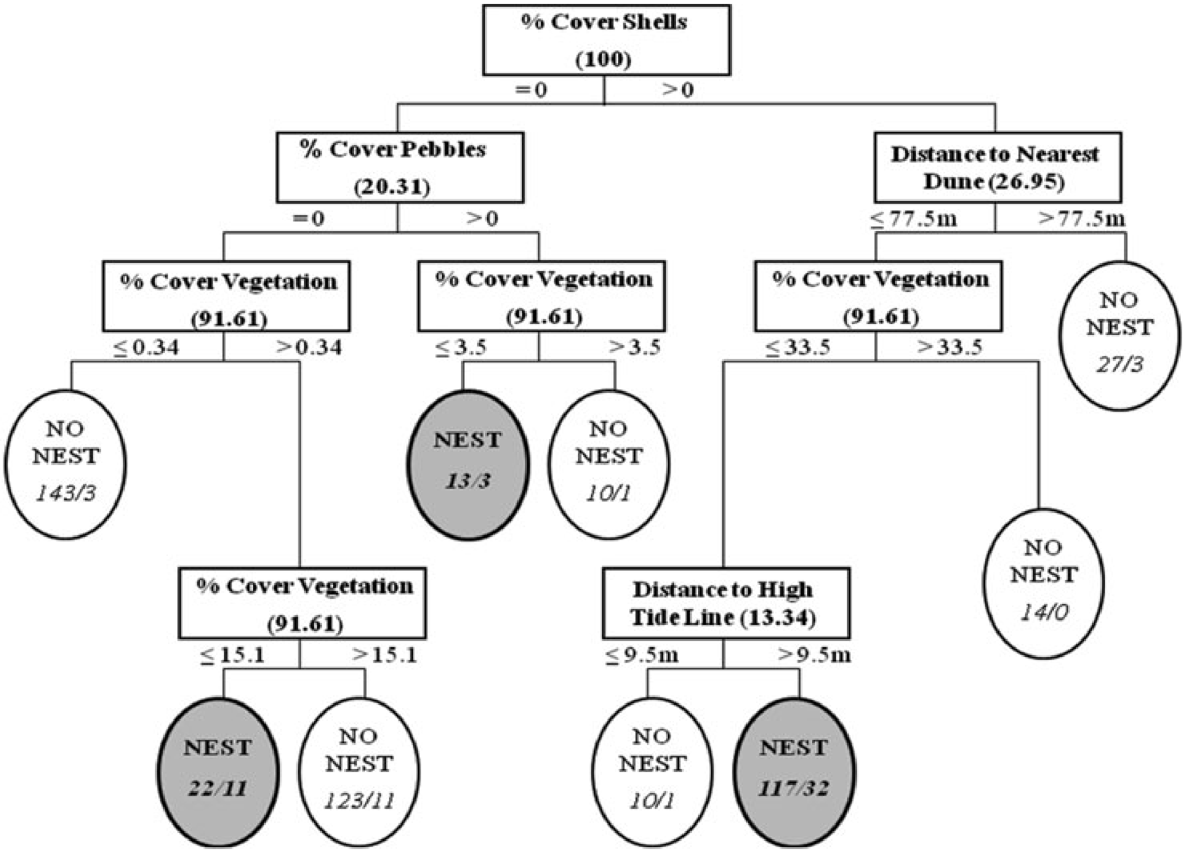


Figure 1. Number of nests found arranged by habitat characteristic. The total number of nests observed is $N = 171$. Open bars indicate nests located near dunes. *Closed bars indicate nests located on primary dunes.

habitats regulated by normal coastal dynamics do exist along the Atlantic coast. In these areas, the CART approach can still be applied using more site-specific dune measurements.

The majority of nests found occurred on inlet beaches, which highlight their importance as preferred breeding habitat. Inlet beaches in New Jersey are commonly greater than 150 m 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.



N	*% of total sampled*	*Characteristics*
117	68	shells, distance to nearest dune ≤77.5m, vegetative cover ≤33.5%, distance to high tide line >9.5m
22	13	no shells, no pebbles, 0.34%<vegetative cover ≤15.1%
13	8	no shells, pebbles, vegetative cover ≤3.5%

Figure 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. 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. 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 = shaded oval; no nest = unshaded oval). Numbers inside the ovals indicate the number of observations contained in that terminal node; the first number specifies correctly classified observations, the second number specifies misclassified observations. Below the tree is a summary of the three habitat conditions under which piping plovers established nests. $N = 171$ nests, 373 random locations collected from 2006 to 2009.

Most nests were initiated on the backshore of the beach within 25 m of the primary dune, and at least 9.5 m 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 concept because plovers initiated nests in blowouts if this habitat was present. These formations occur as a result of both water and wind action overtopping dunes and creating a minimally vegetated sandy substrate landward of the foredune (Davis & 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 promote the construction of an elevated backshore (landward portion of the beach from the

Table 3. Target, trigger, and threshold values for important habitat characteristics.*

Characteristic	*Target*	*Trigger*	*Threshold*
Habitat	Overwash fans and dune blowouts	N/A	N/A
Vegetative cover			
Backshore	Less than 10%	17%	Greater than 33.5%
Primary dune	13%	22%	Greater than 33.5%
Shell cover			
Backshore	17–18%	N/A	Pure sand
Primary dune	N/A	N/A	N/A
Pebble cover			
Backshore	17–18%	N/A	Pure sand
Primary dune	N/A	N/A	N/A
Distance to high tide line	Site dependent		Less than 9.5 m from the high tide line to toe of dune
Distance to nearest dune	≤25 m	N/A	N/A
Dune height	≤1.1 m	1.6 m	2.0 m
Dune slope	≤13%	17%	20%

* Target: goal set for restoration project.
Trigger: value signaling action is required to maintain suitable conditions (set at 50% of the threshold) value.
Threshold: value after which the habitat comes unsuitable.

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. 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 chosen to minimize the deposition of silts and clays, or the seeds and rhizomes of vegetation not indigenous to beach habitats (Nordstrom 2000, 2005). Fine sediments and alien plants will lower site accessibility, which may force birds to compete for better microsites elsewhere.

A significant proportion of nests in our study area 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 farther from the high tide line. However, nesting on steeper dunes with thicker vegetation carries an increased predation risk of nests or adults because the birds may not be able to see and respond to an approaching threat in time (Burger 1987; Espie et al. 1996). In addition, thicker vegetation can impede the mobility of chicks when accessing foraging habitats or running from a predator (Fraser et al. 2005; Cohen et al. 2009). Dune heights and slopes were not deemed relevant factors for nest initiation by our CART analysis, most likely because they were overshadowed by the strong effects of percent shell and vegetative cover. 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 all suitable microhabitat categories by creating alternative nest sites and minimizing inappropriate primary dune features. Although plovers prefer to nest on low, flat areas, the results of this study suggest that this species will place nests on dunes that are 1–1.2 m in height and 10–14% in slope. Therefore, we recommend keeping constructed dunes within these specifications.

If the reestablishment of natural beach dynamics becomes more common, and plovers nest on the more abundant overwash fans and dune blowouts, the risk of flooding will be reduced because nests will be located farther from the high tide line. 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 ability of chicks to access prime foraging areas. Non-ocean foraging habitats (bayshores, ephemeral ponds, mudflats) have been suggested as important macrohabitat selection criteria for piping plovers and can be crucial to increasing fledging success (Loegering & Fraser 1995; Elias et al. 2000). Therefore, 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 the selection of nest sites, with qualitative limitations placed on vegetative cover. Ninety-eight percent of all non-dune nests occurred in less than 10% vegetative cover; 80% of all nests on dunes occurred in less than 20% 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 disparity between beach stabilization protocols and beach-nesting bird niche factors clearly dictates a change in nourishment project design to research 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 & Ryan 1988; 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 (76%) 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 to 21% and 12–15%, respectively. In addition, 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 our data, we can confidently recommend a target value of 17–18% shell or pebble cover on the restored beach between the dunes and the high tide line.

The findings of this study can assist with the formation of practical adaptive management plans by establishing threshold values after which the habitat becomes unsuitable, and recommending trigger points that signal action required to maintain suitable habitat conditions (Table 3) (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 at this value and a trigger point recommended at 22% to effectively manage the habitat.

Although shells and gravel are common on less managed beaches due to Aeolian processes, beach-raking activities remove these surficial features. Therefore, beach-grooming activities should be eliminated, or in backshore areas where shells or gravel are lacking, they should be *added* prior to the birds' arrival on the breeding grounds. These substrate features are available from many commercial stone suppliers at low cost.

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 $\leq$2.6 m in height and $\leq$27% in slope. Therefore, we suggest threshold values of 2.0 m for height and 20% for slope and trigger points of 1.6 m and 17%, respectively, 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). Formally evaluated 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. The approach described here may be of value for other beach-nesting birds, whose species-specific nest-site requirements may be similar but not identical to piping plovers. Selection of nest-sites, however, is only one component of the habitat. Restoration practitioners must also consider the habitat characteristics that promote the survival of chicks to fledging age. New Jersey, in particular, has experienced lower reproductive success than other Atlantic Coast states, presumably due to high rates of predation and human disturbance (USFWS 2009). Therefore, making the habitat attractive to nesting plovers may not lead to increased reproductive output. Identification of the controls and resources in the habitat that leads to refuge from predators and increased plover foraging rates are critical to meeting this end (Morrison 2001; Morrison et al. 2006). For instance, predator removal efforts should be employed in beach habitats where unnaturally high densities or non-native predators exist. In addition, access to prime foraging habitat is critical to the fledging success of chicks (Loegering & Fraser 1995; Goldin & Regosin 1998; Elias et al. 2000; Maslo 2010).

Parallel to this effort in habitat design, social understanding and community rules must continue to be refined to minimize anthropogenic pressures. Human disturbance, off-road vehicles, and inappropriate beach management activities can also constrain habitat quality (Burger 1994; Melvin et al. 1994). With too many habitat constraints, any restoration effort will result in the creation of an ecological trap, attracting piping plovers to a habitat where they will experience little or no reproductive success. Additional well-designed research on all these factors can make significant additions to the design criteria of beach-nesting bird habitat identified here.

Implications for Practice

- Classification and regression tree (CART) analysis is a very useful statistical tool that can assist ecologists in effectively translating research outcomes into practical design criteria for restoration and adaptive management initiatives.
- Piping plovers generally nest within one of three groups of coastal habitat conditions categorized by percent shell or pebble cover ($>$0), percent vegetative cover (varies with microsite), distance to nearest dunes ($\leq$77.5 m), and distance to the high tide line ($>$9.5 m). When designing a breeding habitat, practitioners should include all possible nesting habitat types. This creates a mosaic habitat that can accommodate changes in nest-site selection if new environmental stresses occur.
- Adaptive management plans for piping plover breeding habitat should incorporate trigger points and thresholds that are generated from data collected on nest-site selection. Practitioners should create a mottled substrate, minimize vegetation, dune height, dune slope, and should allow for the creation of overwash or dune blowout habitats.

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