"Jolls, Claudia"
<JOLLSC@ecu.edu>
02/19/2009 12:58 PM

To "Britta_Muiznieks@nps.gov" <Britta_Muiznieks@nps.gov>
cc
bcc
Subject RE: Final Amaranth Report

History: This message has been forwarded.

Britta, it strikes me that what you have IS the final report, given the date of 9/25/04. It was a 143 pp. Word document with the file name "Jolls_et_al_Ampu_Final_Report_09_25_2004.doc", more than 3500 Kb. We typically include that header "***unpublished report in review: please do not duplicate or distribute*** " to protect the information given goal of publication in peer-reviewed journals. We discussed this with NPS staff before we used this header.

We also provided several digital copies as a CD of the interim and final reports, a final presentation form 8/13/2004 and GIS programming, jpegs, GPS data, shape files and PowerPoint presentations. Mike Rikard at Cape Lookout should have these, too.

I append one published manuscript from the work. A second manuscript from some of the transplant work was reviewed and is to be revised with a student who is in a doctoral program. A very little of the other work was related to yet a third M.S. in Biology thesis that will in all likelihood never be published, given a change in career path by that student.

I hope this helps,

best regards,

clj

-----Original Message-----
From: Britta_Muiznieks@nps.gov [mailto:Britta_Muiznieks@nps.gov]
Sent: Thursday, February 19, 2009 7:52 AM
To: Jolls, Claudia
Subject: Final Amaranth Report

Ms. Jolls-
I have been asked to locate the final report for the seabeach amaranth study that you conducted at Cape Hatteras National Seashore from 2001-2003. We received a draft final report dated 9/25/2004 which was an unpublished report in review (not for distribution). We have searched our files and as far as I can tell we have not received the final report for this study. There has been a large turnover in staff so you may have sent it to someone who is no longer employed by the Park. Can you please send me a copy of the final report for your study?

Thanks,

Britta Muiznieks
Wildlife Biologist
Cape Hatteras National Seashore

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Sellars&Jolls_JCR_23_5_2007.pdf

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Habitat Modeling for *Amaranthus pumilus*: An Application of Light Detection and Ranging (LIDAR) Data

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ABSTRACT

SELLARS, J.D. and JOLLS, C.L., 2007. Habitat Modeling for *Amaranthus pumilus*: An Application of Light Detection and Ranging (LIDAR) Data. *Journal of Coastal Research,* 23(5), 1193–1202. West Palm Beach (Florida), ISSN 0749-0208.

Anthropogenic management of dynamic ecosystems has led to decline of species dependent on processes that maintain suitable habitat, particularly on barrier islands. By evaluating environmental variables over large geographic areas, remote-sensing data and geographic information systems (GIS) hold increasing promise for management of these unique habitats and their species associates. We used light detection and ranging (LIDAR) data to extract habitat variables for *Amaranthus pumilus,* a federally threatened flowering annual of the Atlantic barrier islands. We asked: (1) can habitat variables for *A. pumilus* be extracted from remote-sensing data, and (2) can these variables be used to model suitable habitat?

We extracted topographic habitat variables for naturally occurring plants and evaluated habitat using multiple statistical techniques and other published model performance measures. We found that elevation was the most limiting topographic variable controlling the occurrence of *Amaranthus pumilus.* The most occurrences fell with in a 1.23 m range relative to local mean high water. Additionally, we used digital imagery collected concurrently with the LIDAR data to assess the role of vegetation cover in *A. pumilus* distribution. The occurrence of seabeach amaranth in previous years also was factored into the models. The models performed well, predicting 46%–100% of the plant occurrences using as little as 2% of the habitat.

Amaranthus pumilus can potentially serve as a conservation "umbrella" for coastal biodiversity. The methods presented here for identification of *A. pumilus* habitat, using GIS and model construction of potential habitat, can be applied to other species of concern, including nesting shorebirds and sea turtles.

ADDITIONAL INDEX WORDS: *Remote sensing, habitat assessment, habitat model, rare species, dune, beach, logistic regression, geographic information systems (GIS), global positioning system (GPS).*

INTRODUCTION

Species are being lost to extinction at a rate unprecedented in history, and much of this loss can be attributed to habitat destruction or alteration (Chapin *et al.,* 1997; Vitousek *et al.,* 1997). Anthropogenic influences such as beach stabilization, development, and dredging have greatly altered the barrier island system of the east coast resulting in imperilment of a number of species (USFWS, 1996). Understanding the habitat variables that control species occurrence is critical to developing conservation plans (Wiser *et al.,* 1998).

Plant distributions in the environment are not random (Greig-Smith, 1979); therefore, predicting plant occurrences is contingent on defining the set of ecological variables that restrict the distribution of the plants, a process which is methodologically similar to animal habitat modeling (Franklin, 1995). Wiser *et al.* (1998) advised that predictive models, when used for finding new populations or suitable habitat, are most useful when the variables of interest can be derived *a priori.* Statistical models enable investigators to examine the habitat variables at one site and make predictions about the occurrence of the target species at another site (Pearce and Ferrier, 2000). This process requires incorporating spatial data from many sources into one database, and analyzing, retrieving, and displaying the data. This can be accomplished using geographic information systems (GIS) and remote sensing. Remote sensing enables the collection of habitat information for single or multiple species over large areas, increasing the efficacy of delineating habitat and establishing conservation areas. GIS and remote sensing can aid conservation and management by integrating environmental features (topography, soil types, vegetation, species occurrences) and processes with physical structures and human activities (roads, political boundaries, public-use patterns). Knowledge gained by using GIS can then be passed on to policy makers (Savitsky, 1998).

Remote-sensing data combined with existing survey data in a GIS have been used to model species habitat, largely for animals but also for plants. These data have been used for

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habitat modeling in coastal habitats (Curnutt *et al.,* 2000; Shanmugam *et al.,* 2003) and rare species (Gerrard *et al.,* 2001; Gibson *et al.,* 2004a, 2004b; Luoto *et al.,* 2002b; Reunanen *et al.,* 2002; Scepan *et al.*, 1987; Thibault *et al.,* 1998), including rare plant species (Sperduto and Congalton, 1996; Wu and Smeins, 2000; Luoto *et al.,* 2002a). Variables of interest for rare plant distributions include elevation (Hill and Keddy, 1992; White and Miller, 1988), and slope and aspect (Sperduto and Congalton, 1996). These topographic characteristics can be extracted from digital elevation models (DEMs) (Sinton *et al.,* 2000; Thompson *et al.,* 2001).

The lack of high-resolution DEMs has been a limiting factor for some ecosystems, notably in dune studies (Brown and Arbogast, 1999). A recently developed technology, light detection and ranging (LIDAR), has provided a new source for generating these DEMs (Krabill *et al.,* 1995, 2000; White and Wang, 2003) with potential applications to ecological studies (Lefsky *et al.,* 2002). LIDAR is an active, airborne remote-sensing technology that uses laser ranges, airborne global positioning system (GPS), and orientation data provided by an inertial measurement unit (IMU) to generate elevation data with typical accuracies on the order of 0.15–0.20 m (Krabill *et al.,* 1995; Sallenger *et al.,* 2003).

Amaranthus pumilus (seabeach amaranth), an endemic annual plant of the east coast barrier island system, was listed as threatened by the United States Fish and Wildlife Service in 1993 (USFWS, 1993). *A. pumilus* typically occurs in sparsely vegetated areas (UFSWS, 1996) and requires extensive noneroding beach areas to maintain populations (Bücher and Weakley, 1990). *A. pumilus* occupies a narrow elevation range within a small geographic range (USFWS, 1996) in a highly dynamic habitat. Natural forces such as beach erosion, storm-related erosion, dune movement, and tidal inundation can threaten the success of individual plants and populations. However, these "threats" also are the dynamic processes required by this fugitive annual for maintenance of habitat and elimination of competition; the threat from this natural dynamism of the shore exists only in cases of unfavorable timing. Provided plants have matured and set seed, these same natural processes can disperse seeds, create a seed bank, and expose seeds for germination.

The protection and restoration of *Amaranthus pumilus* can be fostered by (1) determination of important habitat variables and (2) the identification of habitat containing those habitat variables (USFWS, 1996). Our objectives were to determine whether *Amaranthus pumilus* occurs in distinct areas based on topographic characteristics of the beach, evaluated from remotely sensed data, i.e., LIDAR, and whether we could predict suitable habitat from these data. The delineation of *A. pumilus* habitat, based on physical habitat variables, can aid conservation of suitable habitat areas and the identification of potential habitat for reintroduction.

METHODS

We asked (1) whether *Amaranthus pumilus* is distributed at random throughout the beach landscape, (2) whether a model used to predict habitat can be applied to this threatened plant species, and (3) whether we can forecast suitable habitat for this species. We approached the first question by evaluating plant occurrences in 2000 at two sites with logistic regression and analysis of variance. The second and third questions were addressed by using this habitat variable information and a technique developed by Dettmers and Bart (1999) to assess how well we could predict *A. pumilus* habitat for two other sites in 2000. In 2001, LIDAR were not available; however, we extended our inferences for seabeach amaranth occurrences in 2001 by using LIDAR data, passive reflectance data, and locations of plants the previous year to forecast potential habitat.

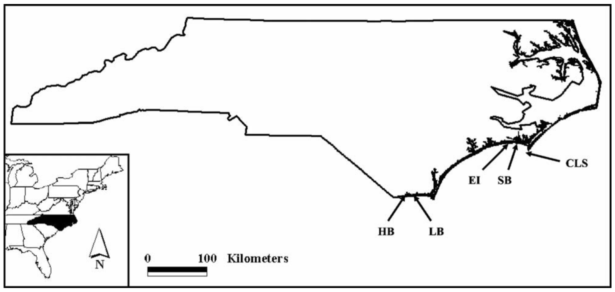

Figure 1. The Holden Beach (HB) and Long Beach (LB) study sites are located in Brunswick County, North Carolina. The Emerald Isle (EI) and Shackleford Banks (SB) are located in Carteret County, North Carolina.

Study Sites

We surveyed five barrier island sites along the North Carolina coastline (Holden Beach [HB], Long Beach [LB], Brunswick County; Emerald Isle [EI], Carteret County; and Shackleford Banks [SB] and Cape Lookout Spit [CLS], Cape Lookout National Seashore, Carteret County, Figure 1) for populations of *Amaranthus pumilus* in 2000 and 2001 (SB and CLS in 2001 only). Although we observed seabeach amaranth at other sites throughout the state, these areas were not covered by LIDAR or had been heavily modified by human activities, such a bulldozing, following Hurricane Floyd in 1999. The HB site contained 24 *A. pumilus* plants, and the LB site contained seven plants, for a total of 31 plants. Sites EI and SB contained 133 and 13 plants in the year 2000, respectively.

Selection of Habitat Variables and Construction of Models: 2000 Plant Occurrences

The HB and LB sites were selected to determine whether habitat variables could be extracted from remote-sensing data. The Emerald Isle (EI) and Shackleford Banks (SB) data were withheld from the habitat variable calculations here for later use in the model development and testing section. A total of 168 plants at SB and CLS in 2001 were used in our forecast of potential habitat.

Data Acquisition

The high-resolution elevation data used in this project were collected from an airborne sensor by the Airborne LIDAR Assessment of Coastal Erosion (ALACE) partnership (National Oceanic and Atmospheric Administration [NOAA], National Aeronautics and Space Administration [NASA], and U.S. Geological Survey [USGS]). LIDAR data have been collected for much of the U.S. coast. Data for the study were obtained through the NOAA Coastal Services Center's (NOAA-CSC) online LIDAR Data Retrieval Tool (LDART, 2006) In 2000–2003 (Two years [1997, 2000] of raw elevation data were downloaded in the Universal Transverse Mercator [UTM] projection with the horizontal datum set to the North American Datum of 1983 [NAD83]. Elevation data were retrieved in the North American Vertical Datum of 1988 [NAVD88]). Our objective in this study was to compare heights based on local sea level. NAVD88 orthometric heights are referenced to an equipotential surface (the geoid) and differ from local mean sea-level heights, which are a function of local physical effects and characteristics, such as water temperature and salinity, currents, wind, and local bathymetry (ZILKOSKI, 2001). Therefore, the NAVD88 orthometric heights were converted to the mean high water (MHW) local tidal datum. The conversions were performed using National Ocean Service (NOS) tidal benchmark data. The minimum and maximum elevation values for the HB and LB sites were converted to MHW values and yielded a range of 0.77–2.0 m above MHW. The MHW for sites EI and SB also was calculated using local tidal benchmarks.

Plant location data were collected using a differentially corrected global positioning system (DGPS) receiver (Garmin, Olathe, KS). Holden Beach was surveyed on September 7, 2000, and Long Beach was surveyed on July 20, 2000. The GPS receiver was held over each plant and allowed to average the position to further increase the accuracy. The DGPS system had an estimated 1.2 m horizontal accuracy, and the horizontal datum was set to NAD83. DGPS positions were not available for each individual plant ($n = 133$) at the EI site. Plants without a unique DGPS position were grouped into subpopulations, and a DGPS position was recorded near the center of the population. Typically, all plants of a subpopulation were within 1 m of the DGPS point. This method was used on 81 plants resulting in 42 DGPS positions. A 22 m × 40 m plot was created to record the location of the remaining 52 plants. These plants were grouped into subpopulations as well. The center of each subpopulation was measured from two corners of the plot. This allowed triangulation of the location within the plot. DGPS positions were recorded for the four plot corners. The triangulated locations were entered into ArcView as a text file and referenced to the DGPS corner locations using a conformal transformation (root mean squared error [RMSE] = 0.56). This method resulted in 32 referenced positions. The 42 DGPS and 32 referenced positions (74 occurrence points representing 133 plants at the EI site) were used in the subsequent model validation and are hereafter referred to as "occurrence points." All plants ($n = 13$) at the SB site were represented by unique DGPS points, for a combined site total of 87 occurrence points representing 146 plants.

Data Processing

The raw elevation text files were imported to ArcView 3.2 Spatial Analyst (ESRI, Redlands, CA) for processing. The 1997 and 2000 data covered slightly different areas. An analysis polygon was created that enclosed an area covered contiguously by the two files for the two sites. This polygon was used to "clip" the raw data points to ensure that areas not represented by data were excluded from the analyses. Five GRIDs (raster-based GIS layers composed of cells placed in rows and columns that represent values on a surface) representing different environmental variables were then created for analysis. The maximum extent of each GRID was 0.5 km × 3.4 km.

Elevation GRIDs for 1997 and 2000 data (variable "2000 elevation") were generated using inverse distance weighted (IDW) interpolation in ArcView Spatial Analyst. Interpolation is the process of generating surface GRIDs from elevation points. In the IDW routine, the interpolation is performed using a weighted average of the six nearest elevation points, where the weight of each point is inversely proportional to the distance from the analysis cell raised to a user-specified power. Increasing power values decreases the importance of points further away from the analysis cell. For this study, a power of one was selected. The GRID cells in these analyses were 3 m × 3 m, and visual inspection of the raw elevation data indicated the six nearest elevation points would generally occur within the analysis cell. All subsequent GRIDs were aligned with this GRID.

Erosion and deposition trends of the study sites were determined by subtracting the 1997 elevation GRID from the 2000 elevation GRID to create the variable "difference." Slope values (variable "2000 slope") in degrees and aspect GRIDs were calculated from the "2000 elevation" GRID. Two surface complexity GRIDs were created using standard deviation (STD) values from the 2000 raw elevation and the 2000 aspect GRID. These variables were "std elevation" (ROY and TOMAR, 2000) and "std aspect," respectively. The "std elevation" GRID was generated using a neighborhood statistics function in ArcView Spatial Analyst. The resultant cells represented the standard deviation of elevation points within a 30 m radius of the cell. The same function was performed on the 2000 aspect GRID with the search radius set to 15 m. The "std aspect" GRID was used for analyses instead of the aspect GRID to allow comparison between sites; specifically, using the standard deviation of the aspect compensated for potential differences between sites. For example, a southwest-facing beach would be expected to have a different average aspect than would a southeast-facing beach. The radius for these two functions was chosen based on familiarity with the sites and extensive surveys of habitat that contained *Amaranthus pumilus.*

One statistical approach to habitat evaluation to predict species occurrence is to ask whether animal or plant locations differ from those of random points on the landscape with respect to habitat variables (LIVINGSTON *et al.,* 1990; PEREIRA and ITAMI, 1991; SPERDUTO and CONGALTON, 1996). The Holden Beach (HB) and Long Beach (LB) sites were used to develop models with habitat variables derived from LIDAR to predict *A. pumilus* occurrence points. Random points were generated within the analysis polygon. Occurrence points from the 2000 survey data and the random points were overlain on the GRID layers (Figure 2). The values of the habitat

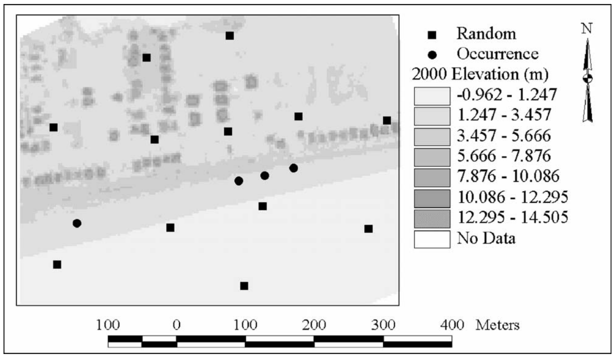

Figure 2. Random and occurrence points were overlain on the "2000 elevation" GRID. Elevation data were extracted for both groups and compared statistically. This graphic is a subset of the Holden Beach, Brunswick County, North Carolina, study site.

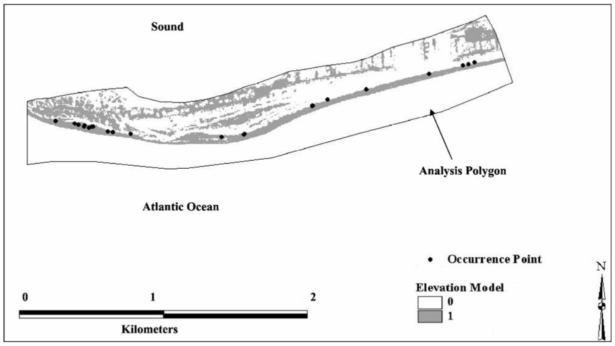

Figure 3. Year 2000 occurrence points of seabeach amaranth overlain on "2000 elevation" model at Holden Beach, North Carolina. Areas shaded in gray (value = 1) represent sections of habitat that were within the range of elevation values predicted for seabeach amaranth.

variables obtained from the random points provided an estimate of those variables in the surrounding habitat (MARCUM and LOFTSGAARDEN, 1980). Three times as many random points as occurrence points (SPERDUTO and CONGALTON, 1996) were used in order to capture the expected greater variation in the background environment (KVAMME, 1985). Random points were assigned in proportion to the number of occurrence points (KVAMME, 1985): 72 vs. 24 for Holden Beach and 21 vs. 7 for Long Beach, random to occurrence, respectively, for a total of 93 random points and 31 plant occurrence points.

Logistic regression was then used to determine the importance of the independent abiotic variables on *Amaranthus pumilus* occurrence points (STRAW *et al.,* 1986). The occurrence points were coded as 1, and random points were coded as 0. Kolmogorov-Smirnov Z-tests (GUISAN and ZIMMERMANN, 2000) were performed to determine whether the variables for occurrence points and random points had similarly shaped distributions and locations within their cumulative distribution functions (SPSS, 2000). The response variable (occurrence point or random point) was entered as the dependent variable, and the five values extracted from the GRIDs were entered as the independent covariates in the binary logistic regression and as test variables in the Kolmogorov-Smirnov Z-tests. The two means for occurrence points and random points for each of the habitat variables were compared using a one-way analysis of variation (ANOVA). The variable "2000 slope" was natural-log transformed to meet the assumption of equal variance; the variables "2000 elevation" and "std elevation" were reciprocal transformed (1/value). All analyses were performed in SPSS.

Two sites, Emerald Isle (EI) and Shackleford Banks (SB), Carteret County, North Carolina, then were used to validate the model. The range of values for each habitat variable, as determined in the previous section, was entered in the individual models. For example, the query string for the elevation model was: "2000 elevation ≥ minimum value and 2000 elevation ≤ maximum value." The binary result (0 = areas not in the query string, 1 = areas in the query string; Figure 3) was clipped to the analysis polygon (Figure 3) and converted to GRID format. The binary results were tallied and compared using the model performance measure developed by DETTMERS and BART (1999). This was done to determine the most important habitat parameter (i.e., the one that explained the largest number of occurrence points and excluded the greatest amount of surrounding habitat).

Two habitat variables known to influence the distribution of *Amaranthus pumilus,* elevation and elevation change through time (BÜCHER and WEAKLEY, 1990), were combined into a single model. The combined model was based on individual models using "2000 elevation" and "difference." This allowed us to determine whether a combined model performed better than the individual models.

Points not predicted by the model should occur closer to suitable habitat than random points in the environment (DETTMERS and BART, 1999). Distance to the center of a model cell was calculated for 50 occurrence points (representing 79 plants) that occurred outside the model and also for random points outside the model. This distance was reduced by 1.5 m, the minimum distance to the edge of the 3 m cell (Figure 4). The distances to suitable habitat for occurrence points ($n = 50$) and for random points ($n = 268$) were compared using a Mann-Whitney U-test.

Habitat Model Evaluation: 2000 Plant Occurrences

We next constructed models to predict *Amaranthus pumilus* habitat from those environmental variables used in our analysis of plant occurrences relative to randomly distributed points. The modeling methods were developed by DETTMERS and BART (1999) to predict songbird distributions from presence data. The authors developed a model-testing method that compares the proportion of observations predicted (P_O) to the amount of habitat defined as suitable (P_S). Models that predict a large proportion of occurrences (high P_O), with a minimal amount of suitable habitat (low P_S), are considered successful, i.e., a higher value for the term $P_O - P_S$ indicates better performance. Thus, using their methods, we would also predict that plant occurrences missed by the model should be

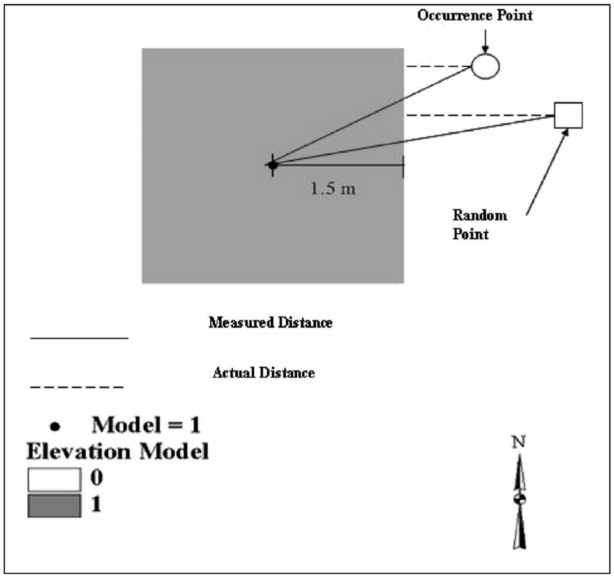

Figure 4. The model validation section required the calculation of the distance for an occurrence point or random point to the nearest predicted cell. This was done using an ArcView Avenue script that generated a point in the center of each model cell then executing a spatial join. The spatial join function calculates the distance between features in two ArcView Shape files. The distance to the nearest edge (1.5 m) was subtracted from the distance between features to obtain a more representative distance of the point to the cell.

closer to predicted habitat than randomly selected points through the beach landscape.

Habitat Models: 2001 Plant Occurrences

LIDAR data also generate grayscale images, based on passive reflectance, capable of differentiating open sand. As an annual, *Amaranthus pumilus* populations can disappear and then reappear in subsequent years, from *in situ* recruitment of seeds and/or their dispersal by wind and water. This imagery for 2000 became available in 2001, when natural occurrences of *A. pumilus* were more abundant. The elevation range determined from analysis of habitat variables in 2000 was used in conjunction with the imagery from 2000 at Shackleford Banks (SB) and Cape Lookout Spit (CLS), Cape Lookout National Seashore, to predict plant occurrences in 2001. We also used minimum distances to a previous year's plant location to ascertain whether proximity to a plant or consistency of habitat could further refine the models for predicting the occurrence of *A. pumilus* in 2001.

Imagery from 2000 was converted from 2 m resolution tagged image format (.tif) files to ArcView GRIDS (with values of 0–255) and resampled to 3 m using bilinear interpolation. The mean high water contour was used as the seaward extent of the area of interest (AOI). The landward extent of the AOI was the edge of the LIDAR coverage (Figure 5). The 2001 plant occurrence points (126 points representing 168 plants) were overlain on the passive GRIDs, and the values were extracted. This yielded a range of 84 (170–254). Distances between 2000 and 2001 plants also were calculated in ArcView. A distance GRID (distance from 2000 plant) was created to determine the possible influence of plant occurrences in the year 2000 on recruitment.

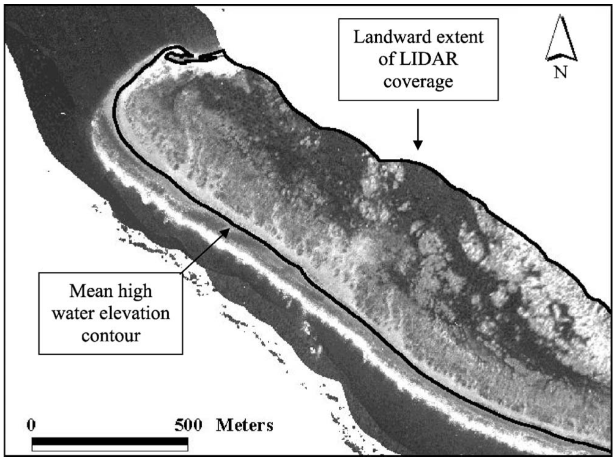

Figure 5. Passive LIDAR imagery for a subsection of the Shackleford Banks study site. The study area is the black polygon, the seaward extent of which was determined by the mean high water (MHW) line. The landward extent was limited by LIDAR coverage. Lighter areas represent higher reflectance values and less vegetation cover.

RESULTS

Habitat Variables

Amaranthus pumilus does not occur at random throughout the environment. The logistic regression model, used to determine the influence of abiotic factors, was significant (Table 1). All individual variables entered into the regression were significant with the exception of "difference" (Wald = 0.044, $P = 0.833$, df = 1, Table 1).

Mean elevation (variable 2000 elevation) for 31 *Amaranthus pumilus* occurrences did not differ significantly from 93 randomly selected points in the environment at Holden Beach and Long Beach ($F = 0.176$, $P = 0.676$, df = 1, 122, Table 2). The standard deviation and range were less for *A. pumilus* than for random points in the surrounding habitat (0.34 vs. 2.41, 1.23 vs. 12.10, respectively, Table 2). The dif-

Table 1. *Binary logistic regression indicated* Amaranthus pumilus *did not occur randomly with respect to topographic variables in 2000 at Holden Beach and Long Beach, Brunswick County, North Carolina.*

Variable	Wald	df	*P*
2000 elevation	14.012	1	<0.001
2000 slope	4.053	1	0.044
Difference	0.044	1	0.833
Std elevation	9.533	1	0.002
Std aspect	13.667	1	<0.001
Constant	5.842	1	0.016
Model chi-squared = 41.847		5	<0.001

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Table 2. *Descriptive statistics, ANOVA, and Kolmogorov-Smirnov Test values for 31* Amaranthus pumilus *occurrences (O = Occurrence) and 93 random points (R = random point) selected from the surrounding environment at Holden Beach and Long Beach, Brunswick County, North Carolina.* A. pumilus *did not occur at random with respect to topographic variables.*

Variable		Mean (±SE)	Range	ANOVA *F*	K-S *Z*
2000 elevation[1]	R	1.95 (0.25)	12.10	0.176	1.867**
	O	1.92 (0.06)	1.23		
2000 slope[2]	R	5.67 (1.08)	53.73	5.541*	1.037
	O	2.08 (0.36)	8.47		
Difference	R	0.24 (0.07)	4.42	3.911*	1.711**
	O	0.51 (0.09)	2.01		
Std elevation[1]	R	0.94 (0.11)	4.00	0.189	1.089
	O	0.54 (0.04)	0.90		
Std aspect	R	87.38 (3.45)	130.82	10.974***	2.437***
	O	65.89 (4.31)	96.45		

[1] Reciprocal transformation.
[2] Natural log transformation.
* Significant at the 0.05 level.
** Significant at the 0.01 level.
*** Significant at the 0.001 level.

ference in the dispersion measures was indicative of the significant difference in their cumulative distribution functions (K-S $Z = 1.867$, $P = 0.002$, $n = 124$, Table 2).

Amaranthus pumilus occurred on slopes that were less steep than randomly selected points (2.08 ± 0.36 vs. 5.67 ± 1.08, Table 2). The mean slope differed significantly between the two groups when natural-log transformed ($F = 5.541$, $P = 0.020$, df = 1, 122, Table 2). However, the test for differences in their cumulative distribution functions was not significant (K-S $Z = 1.037$, $P = 0.232$, $n = 124$, Table 2).

Amaranthus pumilus was absent from sections of eroding beach at Holden Beach and Long Beach. The mean for the variable "difference" was higher (more deposition) for *A. pumilus* occurrences than for random points in the surrounding habitat (0.51 ± 0.09 vs. 0.24 ± 0.07, respectively, Table 2). These means were marginally different ($F = 3.911$, $P = 0.050$, Table 2). The cumulative distribution functions for the two groups were significantly different (K-S $Z = 1.711$, $P = 0.006$, n = 124, Table 2). The minimum value (greatest amount of erosion) for *A. pumilus* was −0.02 m, while the minimum value for the random points was −2.37 m.

Amaranthus pumilus occurred in areas that were less topographically complex than random points in the environment, as calculated from the surface complexity variables "std elevation" and "std aspect." The mean "std elevation" was lower for *A. pumilus* than for random points (0.54 ± 0.04 vs. 0.94 ± 0.11, respectively, Table 2). This was not a significant difference for the transformed variable ($F = 0.189$, $P = 0.189$, df = 1, 122, Table 2). The mean "std aspect" was significantly lower for *A. pumilus* than for random points (65.89 ± 4.31 vs. 87.38 ± 3.45, respectively, $F = 10.974$, $P = 0.001$, df = 1, 122, Table 2). The standard deviation and range were less for *A. pumilus* than for random points (24.00 vs. 33.30, 96.45 vs. 130.82, respectively, K-S $Z = 2.437$, $P < 0.001$, $n = 124$, Table 2).

Table 3. *Five models evaluate each of the habitat variables as a predictive model for the occurrence of* Amaranthus pumilus *on Holden Beach and Long Beach, Brunswick County, North Carolina.*

Variables Used in Model	P_O	P_S	$P_O - P_S$
2000 elevation	1.0	0.25	0.75
2000 slope	1.0	0.87	0.13
Difference	1.0	0.75	0.24
Std elevation	1.0	0.68	0.32
Std aspect	1.0	0.82	0.18
Elevation and difference combined	1.0	0.21	0.79

The last model combines two variables, "2000 elevation" and "difference." The models were tested for their ability to predict the occurrence of *Amaranthus pumilus* and their ability to exclude surrounding habitat. P_O = the proportion of plants included in the model, P_S = the proportion of study site suitable for analysis, $P_O - P_S$ = indication of model performance, with larger values indicating better performance (after Dettmers and Bart, 1999).

Habitat Models: 2000 Plant Occurrences

All models explained 100% (31/31) of the plant occurrences at the model development sites (HB and LB). This would be expected as the models were developed on these sites. However, the models ranged widely in their ability to exclude background habitat (Table 3). Models based on "std elevation," "difference," "std aspect," and "2000 slope" showed decreasing performance values, ranging from 32% to 13%. The elevation model performed extremely well, excluding 75% of the landscape as unsuitable habitat. The combined model, using values from the variables "2000 elevation" and "difference," performed only slightly better and excluded 79% of the surrounding habitat (Table 3).

Plant occurrences at the EI and SB sites were used to validate the elevation model. Combined models were not used due to the relatively minor increase in performance as shown above. The elevation model predicted 46% (67/146) of the plants at the two model validation sites and excluded 72% of the surrounding habitat (Table 4). Occurrence points not predicted by the model were significantly closer to suitable habitat than would be expected by chance alone (1.72 ± 0.19 m for 50 occurrence points and 53.30 ± 2.78 m for 268 random points, Mann-Whitney $U = 523.00$, $P < 0.001$).

Table 4. *The elevation model was constructed using two sites (development), and tested using two different sites (validation), to test its ability to predict the occurrence of* Amaranthus pumilus *and to exclude surrounding habitat.*

	Elevation Model		
Site	P_O	P_S	$P_O - P_S$
Development (Holden Beach and Long Beach)	1.0	0.25	0.75
Validation (Emerald Isle and Shackleford Banks)	0.46	0.28	0.18

P_O = the proportion of plants included in the model, P_S = the proportion of study site as suitable habitat, $P_O - P_S$ = indication of model performance (after Dettmers and Bart, 1999). Higher values of $P_O - P_S$ indicate better performance.

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Table 5. *Occurrences of* Amaranthus pumilus *in 2001 on Shackleford Banks and Cape Lookout Spit were predicted based on LIDAR elevation and passive data from 2000 and distance from a plant in 2000.*

	Model Evaluation		
Model	P_O	P_S	$P_O - P_S$
2000 elevation	0.88	0.48	0.40
Above + passive	0.88	0.16	0.72
Above + distance	0.72	0.02	0.70

The proportion of plants predicted (P_O) by the term is compared to the proportion of habitat predicted to be suitable (P_S). Higher values of $P_O - P_S$ indicate better performance.

Habitat Models: 2001 Plant Occurrences

The model based on 2000 elevation predicted 88% (148/168) of the 2001 plant occurrences using 48% of the total study area ($P_O - P_S = 0.40$; Table 5). Adding the imagery predicted the same proportion of the plants but required only 16% of the habitat ($P_O - P_S = 0.72$; Table 5). The majority of plants (83%) in 2001 occurred within 300 m of a 2000 plant location (Figure 6). Adding this term to the model predicted 72% of the 2001 plants using 2% of the study area ($P_O - P_S = 0.70$; Table 5).

DISCUSSION

Habitat Variables

Elevation is the most important topographic variable of those measured controlling the distribution of *Amaranthus pumilus* on Holden Beach and Long Beach, North Carolina. *A. pumilus* occurred in a narrower elevation range (1.23 m) than did random points in the surrounding habitat. This result is similar to the 1.3 m range reported by Bücher and Weakley (1990).

The low slope values for *Amaranthus pumilus* support field observations that the plant seldom occurs in areas of steep slope (Bücher and Weakley, 1990). Moreover, *A. pumilus* favors nonerosional beaches, as suggested by the lack of plants with large negative values for the variable "difference" (minimum value −0.02 m). Elevation in the dune environment is predictive of the frequency that an area will be impacted by tidal and storm events (Gares, 1990). Sections of beach below the mean high water elevation will be inundated almost daily and would preclude any dune strand plants from becoming established. Conversely, with increasing elevation (Gares, 1990) and increasing distance from the shore (Maun *et al.,* 1990), the frequency of disturbance decreases. Herbs that rely on disturbance for the maintenance of suitable habitat (Hill and Keddy, 1992) would be excluded from these less dynamic sections of beach.

The preferred habitat of *Amaranthus pumilus* consists of overwash flats and beach strand forward of the primary dune area (Bücher and Weakley, 1990) that are topographically homogeneous. The values of *A. pumilus* for the surface complexity variables ("std elevation" and "std aspect") reflect this preference. Low values for the "std elevation" are indicative of areas with little elevation change, while low values for "std aspect" are found in flatter areas. These terms allow the identification of areas that are more homogeneous and therefore more suitable for *A. pumilus.* Other metrics, such as those developed by Hodgson and Gaile (1999), could potentially be used to measure surface complexity.

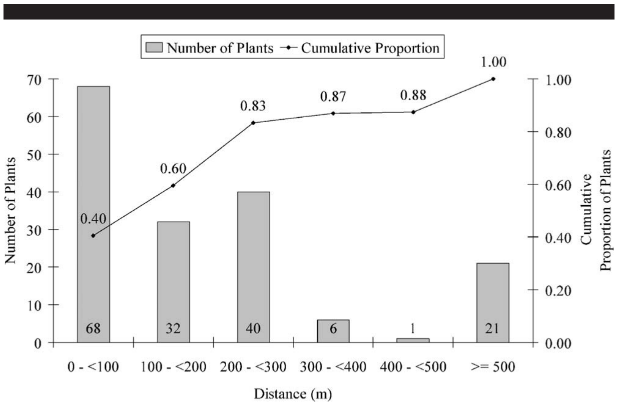

Figure 6. The distance from 2000 *Amaranthus pumilus* plant locations for plants in 2001 was calculated in ArcView for plants on Shackleford Banks and Cape Lookout Spit. The majority of 2001 plants (cumulative proportion of 83%) occurred within 300 m of a previous year's plant location.

Habitat Models: 2000 Occurrences

The predictive models, especially the elevation model, at first glance, did not appear to perform well, predicting only 46% (67/146) of plants at the Emerald Isle and Shackleford Banks sites. However, the plants not predicted by the elevation model narrowly missed being included in the model (1.72 ± 0.19 m horizontally). The estimated accuracy of the DGPS system was 1.2 m; the resolution of the LIDAR data was 3 m. Thus, all 79 plants missed by the model were less than 2 m away on average from predicted habitat; these same 79 plants could have been included in the model with greater accuracy of location and increased resolution of the LIDAR data. This further verified the efficacy of this approach.

The elevation model, however, was able to exclude the majority of the surrounding habitat (at least 72% of all sites), a factor that could increase the efficiency of field searches and site selection for conservation efforts. A further reduction of the study area to sections of the LIDAR scene above mean high water may also have increased the predictive ability of the slope and surface complexity variables. The ability of this model to exclude unsuitable habitat, based solely on elevation, can aid delineation of sections of beach that should be managed for the protection of *Amaranthus pumilus.*

Habitat Models: 2001 Occurrences

Elevation again was an effective delineator of *Amaranthus pumilus* habitat for plant occurrences at Cape Lookout National Seashore in 2001; however, the performance scores ($P_O - P_S$) were smaller than those for 2000. Although some of the same areas at Shackleford Banks were included in both years, the 2001 analyses using SB and CLS focused solely on Cape Lookout National Seashore. These beaches are protect-

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ed from human development. Areas used in the 2000 analysis included heavily developed sections of Emerald Isle. These areas have been built up to avoid storm overwash (i.e., elevations have been artificially increased). As a result, the elevation model in 2001 excluded a smaller proportion of the available landscape (P_S values were larger). Nonetheless, this model still predicted 88% of the natural plant occurrences at Cape Lookout in 2001.

Inclusion of the grayscale passive data greatly improved our ability to discern suitable habitat at the Shackleford Banks and Cape Lookout Spit sites; P_S values decreased from 48% to 16%. This is due to the dependence of *Amaranthus pumilus* on areas of open sand, created by disturbance, as are other dune annual herbs (HILL and KEDDY, 1992). Elevation is a surrogate measure of the frequency at which a site will be disturbed, and the passive data allow areas that have been disturbed in the past to be delineated. The combination of these terms is most useful in areas where large portions of the potential elevation range for *A. pumilus* are occupied by vegetation. While the passive data are not radiometrically calibrated (i.e., these data are sensitive to changes in illumination and atmospheric conditions), they do provide the ability to identify areas of open sand. While other studies have used high-resolution multispectral imagery with coastal species mapping (DEYSHER, 1993; GIBSON *et al.,* 2004a, 2004b), imagery can provide a low-cost alternative for some taxa.

The inclusion of the minimum distance to a previous year's plant did not improve model scores beyond that provided by elevation and the imagery. It did, however, exclude 98% of the landscape as unsuitable habitat. Exclusion of unsuitable habitat can allow managers to better define areas to protect for species of concern. Whether this association of plants among years is due to recruitment of seeds from a seed bank *in situ* or simply the persistence of suitable habitat between years is unknown. The seed bank can play a significant role in recruitment of temporally dynamic systems (KALISZ and MCPEEK, 1992), and some dune taxa recruit from fruits persisting on remnants of parent plants (BAPTISTA and SHUMWAY, 1998; ZHANG and MAUN, 1994). While further multivariate analyses would be useful, our results demonstrate that even using simple evaluations of habitat from LIDAR can be effective in biological applications.

CONCLUSIONS

Amaranthus pumilus is indigenous to the east coast of the United States and has historically occurred only on barrier islands between Cape Cod, Massachusetts, and northern South Carolina. *A. pumilus* is rare due in part to dependence on a habitat that is rare (RABINOWITZ, 1981). For the sites we studied, only 25%–48% of the total area contained elevations that were suitable, even within those limited spans of beach covered by LIDAR flights. The narrow elevation range of *A. pumilus* must also occur on sections of beach that do not experience a strong erosional trend and that have extensive areas of topographically homogeneous open sand. Our models suggest that, at a minimum, areas to be protected for *A. pumilus* should include elevation ranges between 0.77 and 2.0 m above mean high water, with limited vegetation cover, proximate to and including areas previously occupied by plants. Sound management practices, however, should include not only extant but potential sites, particularly given the dynamic nature of this taxon and its habitat. The evaluation of site characteristics over time could potentially identify areas that continually maintain appropriate habitat, but this approach has not yet been quantified. Current research in our laboratory is focusing on the availability of suitable *A. pumilus* habitat, as defined by LIDAR data, and the possibility that it has declined through time, perhaps related to human-induced changes in coastal systems.

Sympatric threatened and endangered associates of *Amaranthus pumilus* include colonial nesting shorebirds, such as the Least Tern and Piping Plover, as well as sea turtles. *A. pumilus* can potentially serve as a conservation "umbrella" for coastal biodiversity and aid efforts in ecosystem management (BROWN and MARSHALL, 1996; CHRISTENSEN *et al.,* 1996; CLARK, 1999; GRUMBINE, 1994, 1997). The methods presented here for identification of amaranth habitat, using GIS and construction of models representing potential habitat, can be applied to these other species of concern.

LIDAR provides the ability to resolve small-scale shoreline features useful for coastal species assessment (REVELL *et al.,* 2002; STOCKDON *et al.,* 2002). There are more extensive ways to construct models of species associations with environmental variables extracted from LIDAR, using multivariable nonparametric techniques. We present this work hoping it will serve as the foundation for applications of LIDAR in biological systems. Our work adds to other contributions confirming desktop access to remote sensing and GIS as increasingly important tools in habitat evaluation for the conservation and management of threatened and endangered species, particularly of coastal habitats (PHINN *et al.,* 1996). However, the methods described here are limited by the availability and timely delivery of LIDAR data. Therefore, habitat assessment and selection of suitable areas for reintroduction would have to be based on the most recent data. LIDAR data originally were collected for the North Carolina coast to determine the feasibility of using the technology to detect shoreline change (MEREDITH *et al.,* 1999) and not specifically for biological purposes. Habitat variables, however, can be obtained from topographic data (HOST *et al.,* 1996; MASON *et al.,* 2003; SPERDUTO and CONGALTON, 1996). Remote-sensing data allow rapid and cost-effective collection of environmental data, but must be coupled with field reconnaissance and extensive knowledge of species ecology.

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LITERATURE CITED

Baptista, T.L. and Shumway, S.W., 1998. A comparison of the seed banks of sand dunes with different disturbance histories on Cape Cod National Seashore. *Rhodora,* 100, 298–313.

Brown, D.G. and Arbogast, A.F., 1999. Digital photogrammetric change analysis as applied to active coastal dunes in Michigan. *Photogrammetric Engineering & Remote Sensing,* 65, 467–474.

Brown, R.S. and Marshall, K., 1996. Ecosystem management in state governments. *Ecological Applications,* 6, 721–723.

Bücher, M.A. and Weakley, A.S., 1990. Status survey of seabeach amaranth (*Amaranthus pumilus* Rafinesque) in North and South Carolina. Raleigh, North Carolina: Report to North Carolina Plant Conservation Program, North Carolina Department of Agriculture, and Asheville, North Carolina: Endangered Species Field Office, United States Fish and Wildlife Service, 140p.

Chapin, F S., III; Walker, B.H.; Hobbs, R.J.; Hooper, D.U.; Lawton, J.H.; Salsa, O.E., and Tilman, D., 1997. Biotic control over the functioning of ecosystems. *Science,* 277, 500–504.

Christensen, N.L.; Bartuska, A.M.; Brown, J.H.; Carpenter, S.; D'Antonio, C.; Francis, R.; Franklin, J.F.; MacMahon, J.A.; Noss, R.F.; Parsons, D.J.; Peterson, C.H.; Turner, M.G., and Woodmansee, R.G., 1996. The report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management. *Ecological Applications,* 6, 665–691.

Clark, J.R., 1999. The ecosystem approach from a practical point of view. *Conservation Biology,* 13, 679–681.

Curnutt, J.L.; Comiskey, J.; Nott, M.P., and Gross, L.J., 2000. Landscape-based spatially explicit species index models for Everglades restoration. *Ecological Applications,* 10, 1849–1860.

Dettmers, R. and Bart, J., 1999. A GIS modeling method applied to predicting forest songbird habitat. *Ecological Applications,* 9, 152–163.

Deysher, L.E., 1993. Evaluation of remote-sensing techniques for monitoring giant-kelp populations. *Hydrobiologia,* 261, 307–312.

Franklin, J., 1995. Predictive vegetation mapping, geographic modelling of biospatial patterns in relation to environmental gradients. *Progress in Physical Geography,* 19, 474–499.

Gares, P.A., 1990. Predicting flooding probability for beach dune systems. *Environmental Management,* 14, 115–123.

Gerrard, R.; Stine, P.; Church, R., and Gilpin, M., 2001. Habitat evaluation using a case study applied to the San Joaquin Kit Fox. *Landscape and Urban Planning,* 52, 239–255.

Gibson, L.A.; Wilson, B.A.; Cahill, D.M., and Hill, J. 2004a. Modelling habitat suitability of the swamp antechinus (*Antechinus minimus maritimus*) in the coastal heathlands of southern Victoria, Australia. *Biological Conservation,* 117, 143–150.

Gibson, L.A.; Wilson, B.A.; Cahill, D.M., and Hill, J. 2004b. Spatial predication of rufous bristlebird habitat in a coastal heathland: a GIS-based approach. *Journal of Applied Ecology,* 41, 213–223.

Greig-Smith, P., 1979. Pattern in vegetation. *Journal of Ecology,* 67, 755–779.

Grumbine, R.E., 1994. What is ecosystem management? *Conservation Biology,* 8, 27–38.

Grumbine, R.E., 1997. Reflections on "What is ecosystem management?" *Conservation Biology,* 11, 41–47.

Guisan, A. and Zimmermann, N.E., 2000. Predictive habitat models in ecology. *Ecological Modelling,* 135, 147–186.

Hill, N.M. and Keddy, P.A., 1992. Prediction of rarities from habitat variables, coastal plain plants on Nova Scotian lakeshores. *Ecology,* 73, 1852–1859.

Hodgson, M.E. and Gaile, G.L., 1999. A cartographic modeling approach for surface orientation-related applications. *Photogrammetric Engineering and Remote Sensing,* 65, 85–95.

Host, G.E.; Polzer, P.L.; Mladenoff, D.J.; White, M.A., and Crow, T.R., 1996. A quantitative approach to developing regional ecosystem classifications. *Ecological Applications,* 6, 608–618.

Kalisz, S. and McPeek, M.A., 1992. Demography of an age-structured annual, resampled projection matrices, elasticity analyses, and seed bank effects. *Ecology,* 73, 1082–1093.

Krabill, W.B.; Thomas, R.H.; Martin, C.B.; Swift, R.N., and Frederick, E.B., 1995. Accuracy of airborne laser altimetry over the Greenland ice sheet. *International Journal of Remote Sensing,* 16, 1211–1222.

Krabill, W.B.; Wright, C.W.; Swift, R.N.; Frederick, E.B.; Manizade, S.S.; Yungel, J.K.; Martin, C.F.; Sonntag, J.G.; Duffy, M.; Hulslander, W., and Brock, J.C., 2000. Airborne laser mapping of Assateaque National Seashore beach. *Photogrammetric Engineering and Remote Sensing,* 66, 65–71.

Kvamme, K.L., 1985. Determining empirical relationships between the natural environment and prehistoric site locations, a hunter-gatherer example. *In:* Carr, C., (ed.), *For Concordance in Archaeological Analysis, Bridging Data Structure, Quantitative Technique, and Theory.* Kansas City, Missouri: Westport Publishers, Inc. pp. 208–238.

LDART (LIDAR Data Retrieval Tool), 2006. NOAA Coastal Services Center's (NOAA-CSC) LIDAR Data Retrieval Tool. http://www.csc.noaa.gov/cgi-bin/crs/tcm/ldart_start.pl.

Lefsky, M.A.; Cohen, W.B.; Parker, G.G., and Harding, D.J., 2002. Lidar remote sensing for ecosystem studies. *BioScience,* 52, 19–30.

Livingston, S.A.; Todd, C.S.; Krohn, W.B., and Owen, R.B., 1990. Habitat models for nesting bald eagles in Maine. *Journal of Wildlife Management,* 54, 644–653.

Luoto, M.; Kuussaari, M., and Toivonen, T., 2002a. Modelling butterfly distribution based on remote sensing data. *Journal of Biogeography* 29, 1027–1037.

Luoto, M.; Toivonen, T., and Heikkinen, R.K., 2002b. Prediction of total and rare plant species richness in agricultural landscapes from satellite images and topographic data. *Landscape Ecology,* 17, 195–217.

Marcum, C.L. and Loftsgaarden, D.O., 1980. A nonmapping technique for studying habitat preferences. *Journal of Wildlife Management,* 44, 963–968.

Mason, D.C.; Anderson, G.Q.A.; Bradbury, R.B.; Cobby, D.M.; Davenport, I.J.; Vandepoll, M., and Wilson, J.D. 2003. Measurement of habitat predictor variables for organism-habitat models using remote sensing and image segmentation. *International Journal of Remote Sensing,* 24, 2515–2532.

Maun, M.A.; Boyd, R.S., and Olsen, L., 1990. The biological flora of coastal dunes and wetlands. 1. *Cakile edentula* (Bigel.) Hook. *Journal of Coastal Research,* 6, 137–156.

Meredith, A.W.; Eslinger, D., and Aurin, D., 1999. An evaluation of hurricane-induced erosion along the North Carolina coast using airborne LIDAR surveys. Charleston, South Carolina: Coastal Services Center Technical Report, NOAA/CSC/99031–PUB.

Pearce, J. and Ferrier, S., 2000. An evaluation of alternative algorithms for fitting species distribution models using logistic regression. *Ecological Modelling,* 128, 127–147.

Pereira, J.M.C. and Itami, R.M., 1991. GIS-based habitat modeling using logistic multiple regression, a study of the Mt. Graham Red Squirrel. *Photogrammetric Engineering & Remote Sensing,* 57, 1475–1486.

Phinn, S.R.; Stow, D.A., and Zedler, J.B., 1996. Monitoring wetland habitat restoration in southern California using airborne multispectral video data. *Restoration Ecology,* 4, 412–422.

Rabinowitz, D., 1981. Seven forms of rarity. *In*: Synge, H. (ed.), *The Biological Aspects of Rare Plant Conservation.* New York: John Wiley & Sons, Ltd., pp. 205–217.

Reunanen, P.; Nikula, A.; Monkkonen, M.; Hurme, E., and Nivala, V. 2002. Predicting occupancy for the Siberian flying squirrel in old-growth forest patches. *Ecological Applications,* 12, 1188–1198.

Revell, D.L.; Komar, P.D., and Sallenger A.H., Jr., 2002. An application of LIDAR to analyses of El Niño erosion in the Netarts Littoral Cell, Oregon. *Journal of Coastal Research,* 18, 792–801.

Roy, P.S. and Tomar, S., 2000. Biodiversity characterization at landscape level using geospatial modelling technique. *Biological Conservation,* 95, 95–109.

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Sallenger, A.H., Jr.; Krabill, W.B.; Swift, R.N.; Brock, J.; List, J.; Hansen, M.; Holman, R.A.; Manizade, S.; Sontag, J.; Meredith, A.; Morgan, K.; Yunkel, J.K.; Frederick, E.B., and Stockdon, H., 2003. Evaluation of topographic Lidar* for quantifying beach changes. *Journal of Coastal Research,* 19, 125–133.

Savitsky, B.G., 1998. GIS. *In:* Savitsky, B.G. and Lacher, T.E., Jr., (eds.). *GIS Methodologies for Developing Conservation Strategies, Tropical Forest Recovery and Wildlife Management in Costa Rica.* New York, New York: Columbia University Press, pp. 41–47.

Scepan, F.D.; Davis, F., and Blum, L.L., 1987. A geographic information system for managing California condor habitat. *In*: *Second Annual International Conference, Exhibits and Workshops on Geographic Information Systems* (Falls Church, Virginia, The American Society for Photogrammetry and Remote Sensing American Congress on Surveying and Mapping), pp. 276–286.

Shanmugan, S.; Lucas, N.; Phipps, P.; Richards, A., and Barnsley, M., 2003. Assessment of remote sensing techniques for habitat mapping in coastal dune ecosystem. *Journal of Coastal Research,* 19, 64–75.

Sinton, D.S.; Jones, J.A.; Ohmann, J.L.; and Swanson, F.J.; 2000. Windthrow disturbance, forest composition, and structure in the Bull Run basin, Oregon. *Ecology,* 81, 2539–2556.

Sperduto, M.B. and Congalton, R.G., 1996. Predicting rare orchid (small whorled pogonia) habitat using GIS. *Photogrammetric Engineering and Remote Sensing,* 62, 1269–1279.

SPSS, 2000. Version 10.0.07. Chicago, Illinois: SPSS, Inc.

Stockdon, H.F.; Sallenger, A.H., Jr.; List, J.H., and Holman, R.A., 2002. Estimation of shoreline position and change using airborne topographic lidar data. *Journal of Coastal Research,* 18, 502–513.

Straw, J.A., Jr.; Wakeley, J.S., and Hudgins, J.E., 1986. A model for management of diurnal habitat for American woodcock in Pennsylvania. *Journal of Wildlife Management,* 50, 378–383.

Thibault, D.; Chalifoux, S., and Laperle, M., 1998. Using satellite imagery as a planning tool for Harlequin duck inventory. *International Journal of Remote Sensing,* 19, 5–9.

Thompson, J.A.; Bell, J.C., and Butler, C.A., 2001. Digital elevation model resolution, effects on terrain attribute calculation and quantitative soil-landscape modeling. *Geoderma,* 100, 67–89.

USFWS (U.S. Fish and Wildlife Service), 1993. Endangered and threatened wildlife and plants; determination of seabeach amaranth (*Amaranthus pumilus*) to a threatened species. *Federal Register,* 58(65), 18035–18042.

USFWS, 1996. Recovery plan for seabeach amaranth (*Amaranthus pumilus*) Rafinesque. Atlanta, Georgia: Southeast Region, U.S. Fish and Wildlife Service, 59p.

Vitousek, P.M.; Mooney, H.A.; Lubchenco, J., and. Melillo, J.M., 1997. Human domination of Earth's ecosystems. *Science,* 277, 494–499.

White, P.S. and Miller, R.I., 1988. Topographic models of vascular plant richness in the southern Appalachian high peaks. *Journal of Ecology,* 76, 192–199.

White, S.A. and Wang, Y., 2003. Utilizing DEMs derived from LIDAR data to analyze morphologic change in the North Carolina coastline. *Remote Sensing of Environment,* 85, 39–47.

Wiser, S.K.; Peet, R.K., and White, P.S., 1998. Prediction of rare-plant occurrence, a southern Appalachian example. *Ecological Applications,* 8, 909–920.

Wu, B.X. and Smeins, F.E., 2000. Multiple-scale habitat modeling approach for rare plant conservation. *Landscape and Urban Planning,* 51, 11–28.

Zhang, J.H. and Maun, M.A., 1994. Potential for seed bank formation in seven Great Lakes sand dune species. *American Journal of Botany,* 81, 387–394.

Zilkoski, D., 2001. Vertical datums. *In:* Maune, D.F. (ed.), *Digital Elevation Model Technologies and Applications: The DEM Users Manual.* Bethesda, Maryland: The American Society for Photogrammetry and Remote Sensing, pp. 35–60.