Mapping and Assessing Critical Horseshoe Crab Spawning Habitats of Delaware Bay

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INTRODUCTION AND SUMMARY

The **Delaware Bayshore Horseshoe Crab Spawning Habitat Mapping Project** consisted of inventorying of the Delaware and New Jersey shorelines of the Delaware Bay to assess the availability and spatial distribution of spawning habitat for horseshoe crabs *Limulus polyphemus*. Using visual interpretation of high spatial resolution (1 meter or better) color/color infrared digital aerial photography acquired in 2002, we on-screen digitized and mapped several categories of information that are relevant to the Bayshore's value as horseshoe crab spawning habitat: 1) beach type and width; 2) near-shore development; and 3) shoreline stabilization structures. Based on these characteristics and information from the literature, we classified the Bayshore's beaches into five categories of spawning habitat suitability: optimal, suitable, less suitable, avoided and disturbed.

Examination of the results of the habitat suitability classification suggests that only 34.5% and 17.4% of Delaware's and New Jersey's Delaware Bay shoreline, respectively, was classified as optimal horseshoe crab spawning habitat. Overall, less than a quarter (23.9%) of Delaware Bay's shoreline was classified as serving as optimal habitat. Only an additional 6.6% of the bay's shoreline (11.6% and 3.4% in Delaware and New Jersey, respectively) was classified as suitable habitat. This classification scheme and map of beach habitat suitability should only be considered a "first cut." It should be noted that this mapping does not include site specific consideration of beach morphology or wave energy characteristics that may be also be important in determining the suitability of the beach as horseshoe crab spawning habitat. Thus this mapping most likely overestimates the availability of optimal habitat.

Incorporation of wave energy characteristics was undertaken to refine the habitat suitability model. The estimated monthly average wind fetch length was used as an index of shoreline exposure to wave energy. During the crucial May-June spawning period, the prevailing wind direction is from the SSW, leading to higher wave energies along the New Jersey side of Delaware Bay. Elevated wind conditions can result in wave energies sufficiently high to directly inhibit the spawning activities of horseshoe crabs on these New Jersey beaches. Conversely during this same May-June spawning period, the Delaware beaches are in the lee of the prevailing wind and generally receive lower wind conditions.

Comparison of the Habitat Suitability Mapping results with the U.S. Geological Survey Horseshoe Crab Beach Survey Index of Spawning Activity (ISA) for the years of 1999-2004 did not show a clearcut relationship between mapped habitat type and ISA values. These results suggest that horseshoe crabs were using all sand or predominantly sand beaches without regard to the subtle composition differences that were interpreted and mapped. However, it should be noted that the ISA data measures only female crab spawning activity and not the ultimate reproductive success of that spawning activity (i.e., egg numbers, hatching success, over-wintering larval trilobite numbers). Further incorporation of horseshoe crab reproductive success and shorebird usage data (i.e., as recorded in monitoring surveys) should be explored to refine the habitat suitability mapping and to further identify priority areas for conservation protection.

Delaware Bay's sand beaches are subject to high human use and are the site of near shore development and shoreline stabilization structures that may negatively impact their habitat value. Approximately 5% of the Delaware Bay fore-shore is subject to beach armoring while an additional 2.5% of shoreline has stabilization structures in the back-beach or is fronted by near-shore development (approximately 8% of the shoreline). Sea level rise is expected to continue and will exacerbate ongoing shoreline erosion. However, while the ISA survey data suggests that female horseshoe crabs will use some severely disturbed beaches for spawning (e.g., Sea Breeze, NJ), the number of eggs laid, larval survival and the ultimate reproductive success was not ascertained. Beach replenishment through off-shore pumping of sandy sediments provides an alternative means of beach stabilization. However, to the best of our knowledge, the value of beach replenishment as a beach habitat restoration strategy in Delaware Bay or possible negative impacts on horseshoe crab population dynamics has not been studied. Alternatively, protection of sand beaches that aren't encumbered with backbeach development should provide for natural shoreline retreat zones that will maintain beach habitats in the long term. Approximately 41% of the optimal habitat (i.e., sand beach without adjacent development) in Delaware and 37% in New Jersey (or 39.5% combined) are in some form of conservation protection (i.e., federal, state, public utility or non-governmental organization). While significant stretches of the beach habitat is protected in some form of conservation ownership, there are key sections of optimal beach habitat that remain unprotected.

BACKGROUND

Delaware Bay, a major estuary of the United States Middle Atlantic coastal region, is located at the mouth of the Delaware River in the states of Delaware and New Jersey. Delaware Bay serves as critical stopover habitat for migrating shorebirds, especially during the spring migration when it supports some of the highest numbers recorded in the lower 48 states (Clark et al., 1993). Many of these migrants rely heavily on the eggs of horseshoe crabs, *Limulus polyphemus*, which come to spawn in Delaware Bay in high numbers (Myers, 1986; Tsipoura and Burger, 1999). Because a significant proportion of the red knots (*Calidris canutus*) population moves through Delaware Bay during the spring migration, this area is of critical concern.

Delaware Bay is fringed by extensive coastal marshes and mudflats that are typically fronted by a sandy barrier beach. The sandy barrier beaches overlay marsh sediments (generally a fibrous peat formed by the root mat of the marsh plants) and vary in thickness from a thin veneer to about 2 m thick (Phillips, 1986a). The back beaches, above normal high tide, form a low dune and are often colonized by common reed, *Phragmites australis* (Phillips, 1987). The intertidal portions of these sandy barrier beaches are of special significance as these are the locus of the horseshoe crab spawning activity and the red knots' foraging activities. Beach areas that provide spawning habitat are considered essential habitats for adult horseshoe crabs. Horseshoe crabs appear to prefer beaches dominated by coarse sandy sediments and avoid beaches that have a high amount of peaty sediments or are adjacent to exposed peat banks (Botton et al., 1988). Based on some of these factors, Botton et al. (1988) developed a classification scheme that ranked beaches as either preferred or avoided habitat for horseshoe crab spawning. Botton, et al. (1988) conducted beach surveys on approximately 80 kilometers of beach along the New Jersey side of the Delaware Bay and categorized approximately 10.6 percent (8.5 kilometers) as providing optimal spawning habitat and 21.1 percent (17.0 kilometers) as suitable spawning habitat. The Atlantic States Marine Fisheries Commission (1998) concluded that optimal spawning beaches may be a limiting reproductive factor for the horseshoe crab population.

Horseshoe crabs deposit most of their eggs 10-20cm deep in the sandy beach sediments (Botton et al., 1992); eggs are then redistributed to shallower depths by subsequent spawning and wave action where they are then available for shorebird foraging. Starting in 1999, systematic surveys were conducted to count intertidal (i.e., spawning) horseshoe crabs and their deposited eggs throughout Delaware Bay and quantified as an Index of Spawning Activity or ISA (Smith et al., 2002a; 2002b). These surveys have been continued and the ISA data is available online (Nichols, 2005). These surveys documented that horseshoe crab egg density varies by several orders of magnitude with densities sometimes exceeding 10^6/m of shoreline (Smith et al., 2002b). Smith et al. (2002b) found that beach morphology and wave energy interacted with density of spawning females to explain variation in the density and distribution of eggs and larvae between the study beaches. Horseshoe crabs appeared to prefer narrow, low-energy (i.e., wave-protected) sandy beaches. While the surveys only sampled bay-front beaches,

beaches along tidal creeks were also noted as being potential hotspots for horseshoe crab spawning and shorebird foraging. At a broader bay-wide scale, the use of intertidal beaches as horseshoe crab spawning habitat is limited in the north (i.e., Sea Breeze in NJ and Woodland Beach in DE) by low salinity and by ocean generated energy in the south (i.e., North Cape May, NJ and Broadkill, DE).

Not surprisingly, migratory shorebird abundance is spatially variable within the Delaware Bay estuary as a consequence of these larger bay-wide patterns of horseshoe crab abundance and spawning activity. In their study of site selection of migratory shorebirds in Delaware Bay, Botton et al. (1994) found that migrant shorebirds, including red knots, showed a strong preference for beaches with higher numbers of crab eggs. Shorebirds were recorded to aggregate near shoreline discontinuities, such as salt marsh creek deltas and jetties, that acted as concentration mechanisms for passively drifting eggs. Foraging and roosting shorebirds also react to human disturbance and are often displaced from prime foraging areas (Burger, 1986 Erwin, 1996). Thus near-shore development or high human use may lower a beach's value as optimal shorebird foraging habitat. These various studies suggest that a complex array of factors determine the optimality of particular Delaware Bay beaches as horseshoe crab spawning and shorebird foraging habitat.

While the status of Delaware Bay's intertidal beaches are the focus of this report, it should be noted that Burger et al. (1997) have documented that migrating shorebirds, including the red knot, move actively between Delaware Bay's various habitats with changes in tidal cycle. The shorebirds use all these various habitats for foraging, resting and other behaviors depending on location, seasonal date, time of day, tide and species. Though the beaches are of critical importance; during high tide, the beaches are often too narrow for foraging, and the birds go elsewhere. Burger et al. (1997) suggest that in addition to the massive food resource provided by spawning horseshoe crabs, Delaware Bay's complex mosaic of coastal habitat types of mudflats, beaches, tidal creeks and salt marshes is essential to maintain the large migrant shorebird population.

A Fishery Management Plan (FMP) for Horseshoe Crab (*Limulus polyphemus*), was approved and adopted by the Atlantic States Marine Fisheries Commission on October 22, 1998. The goal of the FMP is to conserve and protect the horseshoe crab resource to maintain sustainable levels of spawning stock biomass to ensure its continued role in the ecology of coastal ecosystems, while providing for continued use over time. The FMP contains a monitoring program that includes continuing existing benthic sampling programs, establishing pilot programs to survey spawning horseshoe crabs and egg density, evaluating post-release mortality of horseshoe crabs used by the biomedical industry, and identifying potential horseshoe crab habitat in each state. Whereas there has been some progress on most of these goals, there has been no recent systematic survey identifying potential horseshoe crab spawning habitat along the entire length of Delaware Bay's shoreline. The objective of this project is to address this information gap.

STUDY AREA

The Study Area on the Delaware side included most of the Delaware Bay shoreline of Kent and Sussex counties (**Figure 1**). On the New Jersey side, the Study Area included most of the Delaware Bay shoreline of Cumberland and Cape May counties (**Figure 1**).

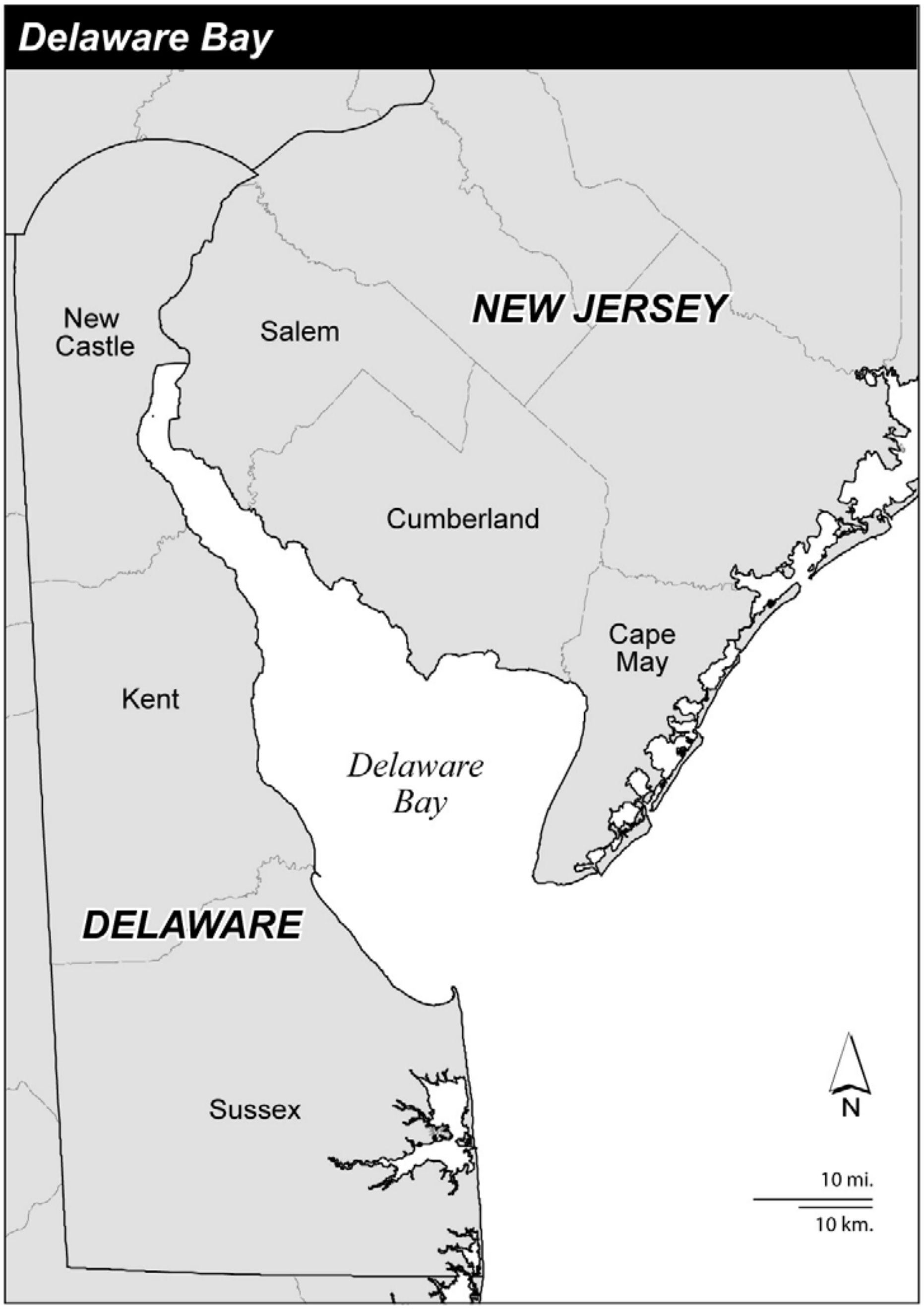

Figure 1. Study area for Delaware Bayshore Horseshoe Crab Spawning Habitat Mapping Project.

METHODS

Software and Imagery Used

A majority of the mapping was undertaken by one photointerpreter, Michael Allen. Other areas were mapped by three additional observers (Carl Figueiredo, Ishaani Sen, and Bernard Isaacson). These other areas were quality checked by the principal photointerpreter. The interpretation work was undertaken at the Rutgers University Center for Remote Sensing and Spatial Analysis.

All mapping was performed in ArcGIS 9.0 (ArcMap module) on a personal computer. Delaware imagery consisted of 2002 aerial color infrared ortho-photography in MrSid format with a ground cell resolution of 9 inches. New Jersey imagery was 2002 aerial ortho-photography in MrSid format, with a ground cell resolution of approximately 12 inches.

Visual Interpretation and On-screen Digitization

All mapping was done through on-screen editing of an ArcGIS shapefile overlaid on the imagery, at a scale of 1:1000. Between the shoreline and the dune-line, areas of like land covers were delineated into digital polygons. To classify land cover, a modified version of the NOAA C-CAP Land-Cover Classification System (Dobson et al.). The land cover types used are described in **Table 1**.

Table 1 – Descriptions of Land Cover Types Used

CODE	DESCRIPTION	CODE	DESCRIPTION
1.11	Commercial buildings, factories etc.	2.13.1	Bulkhead, with urban behind
1.12	Single residential	2.13.2	Bulkhead, with dune/sand behind
1.13	Road, Parking lot	2.21	Cobble, gravel
1.32	Managed grassland (lawn)	2.22	Sand
1.33	Dune-Mix of Sand/grass	2.24	Organic peat
1.33.1	Vegetated dyke or man-made burm	2.25	Rack
1.421	Evergreen Forest	2.31	Salt marsh
1.43	Mixed Forest (deciduous/coniferous)	3.11	Water
1.432	Mixed Scrub/Shrub	3.11.1	Open water
2.12	Rubble, riprap	3.11.2	Creek, Inlet
2.13	Bulkhead, pier or jetty		

While digitizing polygons, three main land cover categories were recorded into separate fields in the attribute table: 1) Shoreline land cover, 2) Interior-beach land cover, and 3) Adjacent area land cover. The compositions of these three categories dictated the placement of polygons during the digitizing process. In general, contiguous areas of like interior land cover, which shared common shoreline and adjacent area land covers, were delineated into single polygons.

In much of the study area, a fore-beach and a back-beach of different land covers were present (e.g. organic mud in front, and sand in back). In these instances the "Adjacent" field of the fore-beach polygon was recorded as the same as the "Interior" field of the back-beach polygon, and the "Shoreline" field of the back-beach polygon was left blank. When polygons were unusually large, divisions were sometimes made for the sake of convenience, and not because of any difference in land cover. When large rivers or inlets were encountered, digitizing proceeded approximately 200 meters upstream on either side.

Measuring Polygon Width

The minimum, maximum, and average widths of sand-containing polygons were measured and recorded into three attribute fields (MINIMUM_WI, MAXIMUM_WI, and AVERAGE_WI, respectively). A sand-containing polygon was defined as any area with an interior-beach containing sand; not necessarily located in the fore-beach. Sandy areas blocked by physical barriers such as bulkheads were excluded. Minimum and maximum widths were measured by visually scanning the polygons overlaying the imagery at a scale of 1:1000, and estimating where the minimum and maximum widths within each polygon were located. These were then measured using the "Measure" tool in the "Tools" module of ArcMap. Any width smaller than 0.5 meters, was recorded as "0.5 meters". An average width was determined by visual estimation based on measurements with the "Measure" tool.

Measuring Shoreline Length

The respective lengths of sand, organic peat, and beach armor (e.g. bulkheads), as well as the total shoreline length of both the New Jersey and Delaware shores were measured. This was accomplished through the creation of six new polyline shapefiles from the original polygon files. The lines in the shapefile were then measured in kilometers using the Xtools extension in ArcMap, providing length estimates of both shoreline and back-beach armor.

Beach Armor: To measure beach armor, polygons with impervious shorelines or interiors were first exported from the original shapefile into a new polygon shapefile. This was then converted to a polyline shapefile using the "Feature to line" tool in ArcToolbox. Back-beach and shoreline beach armor were delineated separately. Back-beach armor was defined as a hard, immovable structure located directly behind a beach, and shoreline armor as a similar structure located directly against the water. When a pier or jetty was encountered, the armor line was drawn across the base of the structure rather than around its perimeter to prevent exaggeration.

Sand: To measure the length of mapped shoreline covered by sand, a similar method was employed. A new polyline shapefile was created which traced the shoreline edge of only sand-containing polygons. In this instance, "sand-containing polygons" were defined as those areas containing sand which is washed by water at some point in the tidal cycle (as evidenced by the rack-line). Therefore, a sandy area with a rack-line, which is not directly on the water, but has an area of mud in-between, was still considered sandy shore and included in the polyline file and thus the length measurements. Smaller islands were not considered to be part of the shoreline length, and were deleted.

Organic/Total: After determining the lengths of sand and beach armor, the remainder of shoreline length was assumed to consist of organic material, defined as mud, peat, and/or salt marsh. To determine this length, the lengths of the total shorelines were first measured using a similar technique as above. The original polygon shapefile was dissolved and converted to a polyline shapefile. Smaller islands were not considered to be shoreline, and were deleted. To estimate the length of organic shoreline, the lengths of sand and shoreline armor were subtracted from the total shoreline length.

Mapping Accuracy Assessment

The field reference data (sometimes referred to as "ground truth") for the project consisted of two phases: field visits during the mapping process (two visits) and field visits made after the mapping was completed (four visits) for accuracy assessment purposes. During the two pre-completion visits, twenty sites in Delaware and fifteen sites in New Jersey were visited, with purpose of developing a search-image for the land cover types present. At each site, GPS coordinates were acquired, digital photos were taken, and a general site characterization was made. After the mapping was completed, four additional site visits were made with the intention of collecting field reference data to provide an unbiased assessment of the maps' accuracy. 150 randomly chosen locations within the study area were visited. The points were selected as follows:

1) The map was rasterized using a 2 meter cell size,
2) 200 Random points were generated within the beach polygons using the Accuracy Assessment module of ERDAS Imagine.
3) These points were overlaid on aerial imagery and digital maps, and the accessibility of each point was determined.
4) Inaccessible points were eliminated, leaving a total of 150 accessible points (82 on the Delaware side; 68 on the New Jersey side).

At each accuracy assessment point, data was collected in the form of a transect running through the point and perpendicular to the shoreline. The land covers at three locations along the transect were recorded: 1) Shoreline: the edge of the water, 2) Interior: the interior of each distinct land cover encountered through the upper-intertidal zone, and 3) Adjacent: the area adjacent to the beach on the landward side.

This data was then combined with data from the two initial visits (18 transects for Delaware, and 9 for New Jersey), making a total of 177 transects. The ground-data was then compared, at each location, with the land cover data in the digitized map, and a statistical accuracy assessment was performed (see **Results**).

Horseshoe Crab Spawning Habitat Suitability

Using the mapped shoreline GIS data, we classified the Delaware Bay shoreline into 5 categories of horseshoe crab spawning suitability based on criteria proposed by Botton et al. (1988). The 5 categories were:

1) Optimal: undisturbed sand beach;
2) Suitable: sand beach with only small areas of peat and/or backed by development
3) Less Suitable habitat with exposed peat in the lower and middle intertidal zone and sand present in the upper intertidal (Botton et al's Avoided AB category);
4) Avoided habitat with exposed peat or active salt marsh fringing the shoreline, no sand present (Botton et al's Avoided C category); and
5) Disturbed due to beach fill, riprap or bulkheading (Botton et al's Avoided D category) .

Wind/Wave Energy Assessment

While the beach sediment type is a major determinant of the suitability of the beach as horseshoe crab spawning habitat, other factors such as exposure to high wave energy may also be important. Smith et al. (2002b) did not record high levels of horseshoe crab spawning on otherwise suitable sand beaches, presumably due to the beaches' greater ocean and wind exposure leading to higher wave energies and less suitable beach morphology. To help account for the potential impact of higher wave energy in reducing the suitability of certain beach areas, we used a wind-wave fetch model to highlight sections of coast subject to high wind and wave exposure. We employed a wave energy model developed by David Finlayson, based on the U.S. Army Corps of Engineers Shore Protection Manual (3rd edition, 1984), to calculate monthly average wind fetch, which we used as an index of overall wave exposure.

Wind fetch was calculated using the average of 9 radials (3° separation) around the axis of wind origin. This method accounts for the shorter maximum fetch calculations relative to direct (single radial) models. Fetch calculations were based on average wind direction (by month) and speed recorded over a period between 1930 and 1996 at Dover Air Force Base, Delaware (National Climatic Data Center, 2005). In addition, fetch was calculated for a simulated Nor'easter storm, based on wind direction of 45° (NE). Wave height was not calculated, as it is contingent on wind speed and duration and thus more event focused. As the model was parameterized with boundaries that pertain to Delaware Bay, fetch values for grid points lying outside Delaware Bay (unbounded fetches) should be disregarded. The four wind fetch model results were gridded at a 5m cell resolution, overlaid, and the maximum fetch value recorded for each grid cell to serve as an index of wave energy regime. The composite model was coded into 3 categories based on an examination of the data distribution and Bayshore geography: 1) Low with <= 20km fetch; 2) Medium with 21-40km fetch; and 3) > 40km fetch. The composite wind fetch was then cross-tabulated with the crab habitat suitability model (polygonal) mapped results.

Comparison of Habitat Suitability and Wind Fetch Modeling with ISA data

UTM coordinates of transect endpoints of the U.S. Geological Survey Horseshoe Crab Beach Survey Index of Spawning Activity (ISA) data were acquired from the USGS (Pooler, personal communication) and used to create a GIS coverage. The ISA represents the average number of spawning females per $1m^2$ quadrat at the high tide line on the highest of the daily high tides at a given beach (Smith et al., 2002a). Approximately 100 quadrats per beach were sampled using systematic sampling with 2 random starts. The annual ISA average for the years 1999 to 2004 were extracted for each transect from the SPAWNAR database (Nichols, 2005). The transect GIS coverage was overlaid the Habitat Suitability and wind fetch GIS maps and the comparable data extracted for statistical comparison using regression analysis (alpha = 0.05). The Habitat Suitability mapped data (derived from 2002 DOQ imagery) were compared with only the 2002 ISA data, as these were closely comparable in time. The mean 1999-2004 ISA data were compared with both the annual maximum and the May/June seasonal average fetch values.

RESULTS AND DISCUSSION

Interpretation and Mapping

The area mapped on the Delaware side extends from Bombay Hook National Wildlife Refuge to the tip of Cape Henlopen (**Figure 2**). On the New Jersey side it extends from the Cohansey River, past Cape May Point, to Cape May Inlet. The total length mapped is approximately 249 kilometers (148km in New Jersey, 91km in Delaware). The results of the land cover mapping of the New Jersey and Delaware Bayshores can be found in the following ArcGIS shapefiles: **NJ_bayshore.shp** and **DE_bayshore.shp**. The Attribute fields for these shapefiles are explained in **Appendix A**.

Accuracy Assessment

There are two main sources of error or variability in the mapped shoreline polygons are 1) misclassification of beach substrate and adjacent land cover and 2) variations in shoreline position due to tidal fluctuations.

Although most land cover regions were clear and not difficult to delineate, some types (e.g. organic/peat/mud) exhibited significant variability in appearance in the imagery. In addition, transitional gradients from one land cover to another were present in many locations. Due to the limited number of site visits made, much of this variability was not able to be directly observed, and some locations may have been incorrectly classified. For example, areas of tidal mud flat present on the Delaware side were sometimes difficult to distinguish from adjacent water, and several mapped may have been partially or totally submerged. A related issue is that of tidal fluctuations, which can result in more or less shoreline being exposed. The aerial photography used as the basis of the maps was acquired at varying times during the non-growing season of 2002, and not all at the same tide level. Therefore, tidal areas are exposed in some images (and therefore mapped) and concealed in others. In neighboring images, which were likely taken at similar times, there is no detectable change in tide level. However, on a broader scale the level may fluctuate significantly.

The field reference data and the corresponding map data were compiled into three contingency tables each for Delaware and New Jersey: one for each of the Shoreline, Interior, and Adjacent land cover areas. These are displayed in **Tables 2-7** with field reference data in rows and map data in columns. For code explanations, see **Table 1**. In general, the tables suggest that land cover was mapped with a relatively high accuracy (most were greater than 90%). However, there are two significant areas where accuracies were lower than expected. These anomalies include a confusion between Marsh and Organic/Peat beach-interior on the New Jersey side (**Table 5**) and a discrepancy between adjacent Dune and adjacent Development in Delaware (**Table 6**).

Large contiguous areas of saltmarsh (2.31) were usually easily identified, but many smaller isolated patches were labeled as Organic/Peat (2.24). In New Jersey, only 2 of the 10 Interior polygons mapped as peat (2.24) were correctly identified on the map (**Table 5**). In most cases, these polygons were in fact salt marsh (2.31). The miscoding (2.24 instead of 2.31) was due largely to the fact that the base-map imagery used was "leaf-off" making it difficult to distinguish eroding peat benches from active salt marsh patches. On the Delaware side, however, there were far fewer such patches, and therefore fewer to be misidentified. This confusion in interpretation did not greatly affect the habitat suitability classification as both of these substrate types were classified as *Avoided*.

The discrepancy on the Delaware side was between adjacent Dune and adjacent Development. The Dune/Sand column in **Table 6** suggests that many adjacent areas called "Developed" on the map, were in fact "Dune". This stems from a difference in the definition of "Adjacent" used during field reference data collection vs. during the aerial photo interpretation and digitization on the Delaware side. During the digitizing process on the Delaware side, development up to approximately 40 meters from the back beach, with a dune in between, was still considered adjacent. However, on the New Jersey side (and during the ground-truthing), "adjacency" was limited to development approximately 0-15 meters from the back beach. This discrepancy in definitions between the two maps has the effect of making the New Jersey map appear more accurate with respect to adjacent land use (**Table 7**). Thus, if the New Jersey definition is adhered to, the Delaware map could be said to overestimate the amount of adjacent development present and thereby overestimate the amount of beach habitat classified as *Suitable*, rather than *Optimal*.

Table 2. Delaware: Shoreline Contingency Matrix

		Field Reference			
		2.22	2.24	2.12\2.13	Total
Map	2.22	75	5	0	80
	2.24	1	14	1	16
	2.12\2.13	1	0	3	4
	Total	77	19	4	100

Overall Accuracy: 92.0%

Table 3. New Jersey: Shoreline Contingency Matrix

		Field Reference			
		2.22	2.24	2.12 / 2.13	Total
Map	2.22	49	0	0	49
	2.24	0	12	0	12
	2.12 / 2.13	0	2	13	15
	Total	49	14	13	76

Overall Accuracy: 97.4%

Table 4. Delaware: Interior-Beach Contingency Matrix

		Field Reference						
		2.22	2.24	2.12\2.13	2.31	1.33	1.11/1.12/1.13	Total
Map	2.22	93	2	0	0	0	0	95
	2.24	0	13	1	1	0	0	15
	2.12\2.13	1	0	1	0	0	0	2
	2.31	0	0	0	0	0	0	0
	1.33	0	0	1	0	0	0	1
	1.11/1.12/1.13	0	0	0	0	0	1	1
	Total	94	15	3	1	0	1	114

Overall Accuracy: 94.7%

Table 5. New Jersey: Interior-Beach Contingency Matrix

		Field Reference						
		2.22	**2.24**	**2.12 / 2.13**	**2.31**	**1.33**	**1.11/1.12/1.13**	**Total**
Map	**2.22**	53	0	1	0	0	0	54
	2.24	1	2	0	7	0	0	10
	2.12 / 2.13	0	0	2	2	0	0	4
	2.31	0	0	0	2	0	0	2
	1.33	0	0	1	1	0	2	4
	1.11/1.12/1.13	0	0	0	0	0	7	7
	Total	54	2	4	12	0	9	81

Overall Accuracy: 81.5%

Table 6 - Delaware: Adjacent Land-Use Contingency Matrix

		Field Reference			
		1.33/2.22	**1.11/1.12/1.13**	**3.11**	**Total**
Map	**1.33/2.22**	58	1	0	59
	1.11/1.12/1.13	24	16	0	40
	3.11	0	1	0	1
	Total	82	18	0	100

Overall Accuracy: 74.0%

Table 7 – New Jersey: Adjacent Land-Use Contingency Matrix

		Field Reference					
		2.22	**1.11/1.12/1.13**	**2.12 / 2.13**	**2.31**	**3.11**	**Total**
Map	**2.22**	43	1	0	3	0	47
	1.11/1.12/1.13	2	16	0	0	0	18
	2.12 / 2.13	0	0	3	0	0	3
	2.31	0	0	0	3	0	3
	3.11	0	0	0	0	1	1
	Total	45	17	3	6	1	72

Overall Accuracy: 91.7%

Horseshoe Crab Spawning Habitat Characterization

Beach Composition

Sand beach dominates the fore-shore of the Delaware side of the bay, while organic beach composed of either eroding peat banks or salt marsh dominates the New Jersey side (**Table 8**). Overall, approximately 54% of Delaware Bay's shoreline represents the horseshoe crab's preferred spawning habitat of sand beach. These sand beaches are generally narrow in width, averaging only 10.9 m on the Delaware side and 5.9m on the New Jersey side of the bay. Some of the widest beaches (some up to nearly 100m in width) are found along the central and southern portions of Cape May in New Jersey and the central sections of the Delaware coast. Beach stabilization structures (e.g., armoring practices such as bulkheading or riprap) accounts for 4.0% of the Delaware shoreline and 5.6% of the New Jersey side (**Table 8**). An additional 2.9% and 3.4% of the Delaware and New Jersey shorelines, respectively, also had some form of armoring in the back-beach (Table 2), which may come into play as beaches erode and shorelines recede, exposing these structures in the future. Approximately, 8.0% of the bi-state Delaware Bayshore is subject to near-shore development. While some beaches in New Jersey have had development removed (i.e., Thompson's Beach), our "ground truthing" surveys in 2005 observed active construction of new development and redevelopment along some sections of the Delaware side of the bay.

The average width for all sandy beach polygons on the Delaware side was 10.9 m. (This figure is the mean of the "average widths" field described in the Methods section.) On the New Jersey side the average was 5.9 m. The reason for this discrepancy could be that the measurement is biased toward the larger number of small sand beaches found in marshier areas (which New Jersey has more of) as opposed to the lesser number (but greater overall length), of broad sandy beaches found in the lower portions of the bay. The range of sand beach widths on the Delaware side was 0.5 to 99.6 meters. On the New Jersey side it was 0.5 to 98.2 meters.

Table 8 – Shoreline Length Measurements
Note: that the back-beach armor and developed area measurement are separate from the total shoreline measurement.

Shoreline Type	Delaware as km & (%)	New Jersey as km & (%)
Sand	67.50 (74.3%)	61.86 (41.7%)
Armor (fore-shore)	3.66 (4.0%)	8.35 (5.6%)
Organic	19.68 (21.7%)	78.10 (52.7%)
Total Shoreline	90.84 (100%)	148.30 (100%)
Armor (back)*	2.67 (2.9%)	5.06 (3.4%)
Development	13.35 (14.7%)	5.72 (3.8%)

We judge these measurements to provide an accurate representation the shoreline compositions of the two bay-shores. However there are certain factors inherent in the measuring process which added uncertainty and error. The most important factor involves the fact that organic shoreline length was not directly measured, but estimated by subtracting sand and armor lengths from the total measured length. Since much of the shore was two-parted (e.g. mud in front and sand in back), the line measuring sand length does not always match up with the line measuring total shoreline length. The line measuring shoreline length was often less straight than the sand line, and this likely resulted in a slight underestimation of sand length, and an overestimation of organic length. Another factor that should be noted is that in areas where both organic and sand occupied the beach, the organic was ignored with respect to length measurements. So the "Organic" measurement in **Table 8** does not actually measure all shoreline length containing organic land cover, but only those organic areas where sand is not also present. This was done with the justification that sand is potentially more valuable to spawning horseshoe crabs, and therefore deserves more precise measuring.

Horseshoe Crab Spawning Habitat Suitability

Examination of the results of the habitat suitability classification suggests that only 34.5% and 17.4% of Delaware's and New Jersey's Delaware Bay shoreline, respectively, was classified as optimal horseshoe crab spawning habitat (**Table 9**). Overall, less than a quarter (23.9%) of Delaware Bay's shoreline was classified as serving as optimal habitat. Only an additional 6.6% of the bay's shoreline (11.6% and 3.4% in Delaware and New Jersey, respectively) was classified as suitable habitat. Examination of **Figure 2**, shows that most of the optimal and suitable spawning habitat is located on the lower (i.e., eastern) portions of Delaware Bay and becomes more fragmented further up the bay.

Table 9. Horseshoe crab spawning habitat suitability, measured as length of shoreline. The 5 categories are adapted from Botton et al., 1988. Note that due to differences in GIS processing, the total shoreline lengths are slightly different, as compared to Table 1.

Habitat Suitability	**Delaware as km & (%)**	**New Jersey as km & (%)**
Optimal	31.28 (34.5%)	25.69 (17.4%)
Suitable	10.56 (11.6%)	5.07 (3.4%)
Less Suitable	28.98 (32.0%)	48.88 (33.1%)
Avoided	16.78 (18.5%)	58.84 (39.8%)
Disturbed	3.08 (3.4%)	8.31 (5.6%)
Total Shoreline*	90.68	147.79

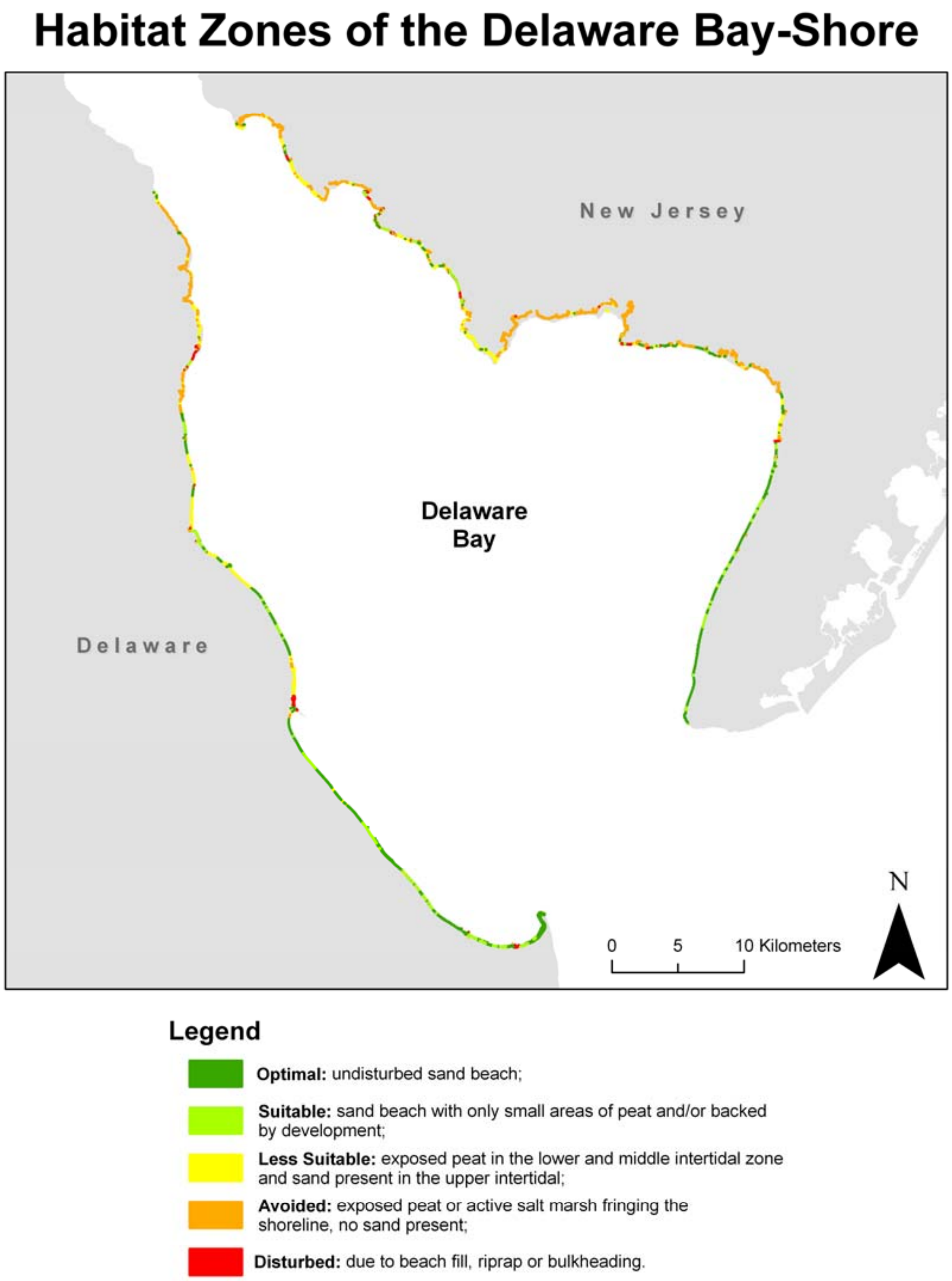

Figure 2. Map of horseshoe crab spawning-shorebird foraging habitat suitability based on beach sediment and development characteristics. Note that this mapping does not include consideration of beach morphology or wave energy characteristics that may be also be important in determining the suitability of the beach as horseshoe crab spawning habitat or other human disturbance or habitat factors that might influence bird usage.

Table 10 provides the percentage of each category of beach habitat that is in some form of conservation protection. Approximately 41% of the optimal habitat in Delaware and 37% in New Jersey (or 39.5% combined) are in some form of conservation protection (i.e., federal, state, public utility or non-governmental organization). While significant stretches of the optimal beach habitat is protected in some form of conservation ownership, there are key sections of optimal habitat that remain unprotected (**Figure 3**). For example, Slaughter Beach on the Delaware side, represents one of the longest stretches of optimal habitat that is largely unprotected. Cursory examination of **Figure 3** suggests that a long section of optimal or suitable beach habitat is protected by the Prime Hook National Wildlife Refuge. However, this is only partially true as some stretches of the barrier beach are in private ownership and developed (e.g., Broadkill Beach) and only the back-bay marshes and adjacent uplands are in refuge protection.

The high quality central portion of the Cape May peninsula on the New Jersey side has been the focus of land conservation acquisition as part of the Cape May National Wildlife Refuge, though the map shows that there are significant gaps in the existing refuge boundaries. Likewise, there are small pockets of optimal/suitable habitat along the northern Delaware Bayshore of the New Jersey side (e.g., Fortesque and Gandy's Beaches) that are largely unprotected. As stated above, the eastern most section of the Delaware shoreline (i.e., east of Broadkill Beach) and the southern third of Cape May peninsula (i.e., south of Villas), while mapped as optimal/suitable habitat and appearing as major gaps in conservation protection in **Figure 3**, may not be a priority for protection due to the higher wave energies on these beaches (see section below) which may lower usage by spawning crabs and foraging shorebirds.

Table 10. Length and % of each beach habitat suitability category that is in some form of conservation ownership (i.e., federal, state, public utility or non-governmental organization land that is primarily oriented to the conservation of wildlife or other natural resources). Note that % is based on category total (displayed in Table 2)

Habitat Suitability	**In Conservation Ownership Delaware as km & (%)**	**In Conservation Ownership New Jersey as km & (%)**
Optimal	12.87 (41.1%)	9.62 (37.4%)
Suitable	0.74 (7.0%)	0.13 (2.6%)
Less Suitable	18.57 (64.1%)	33.56 (68.6%)
Avoided	11.55 (68.8%)	48.87 (83.0%)
Disturbed	0.99 (32.1%)	0.53 (6.4%)

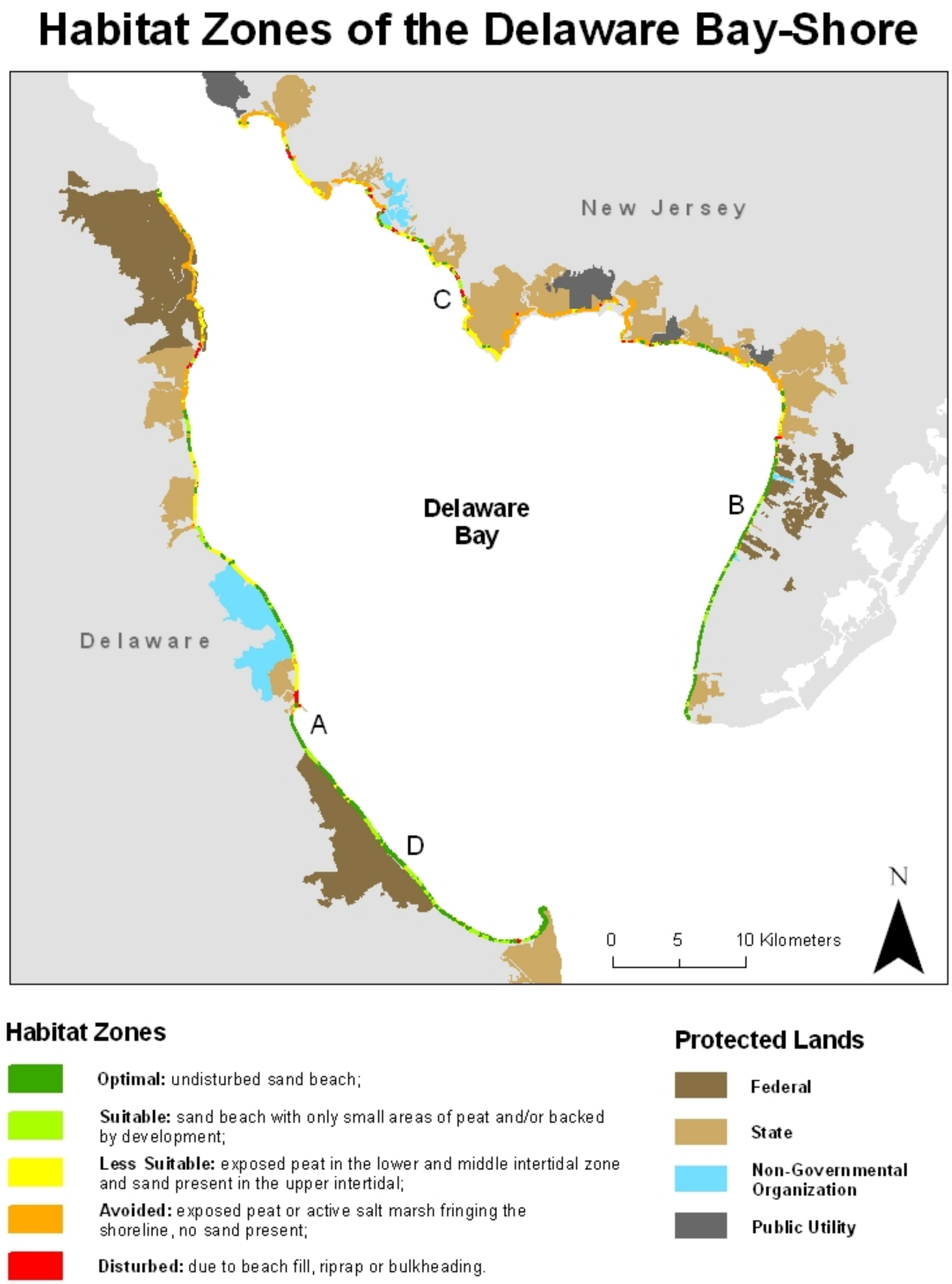

Figure 3. Map of horseshoe crab spawning-shorebird foraging habitat suitability with location of protected conservation lands. Several key locations have been annotated: A. Slaughter Beach; B. Cape May NWR; C. Fortesque; and, D. Broadkill Beach.

Wave Energy Assessment

This classification scheme and map of beach habitat suitability discussed above should only be considered a "first cut." It should be noted that this mapping does not include site specific consideration of beach morphology or wave energy characteristics that may be also be important in determining the suitability of the beach as horseshoe crab spawning habitat. Thus this mapping most likely overestimates the availability of optimal habitat. For example, the eastern most section (approximately 15 km in length) of the Delaware shoreline (i.e., south and east of Broadkill) and the southern third of the Cape May peninsula (approximately 8.5 km) on the New Jersey side were mapped as serving as Optimal or Suitable habitat; however, Smith et al. (2002b) did not record high levels of horseshoe crab spawning on these beaches, which they attributed to greater ocean exposure leading to higher wave energies and less suitable beach morphology. Incorporation of wave energy characteristics was undertaken to refine the habitat suitability model.

The estimated monthly average wind fetch length was used as an index of shoreline exposure to wave energy. While we did not explicitly model wave height or wave energy, the U.S. Army Corps Model Shoreline Protection Manual model calculates wave height on the basis of fetch length, along with wind speed and duration. Based on this model, we are equating that fetch length with wave energy; the longer the fetch length, the higher the wave energy. We have produced four different fetch models based on the prevailing average monthly wind direction. These are displayed as: **Figure 4a** NNW wind direction prevailing during the months of December, February and March; **Figure 4b** WNW wind direction prevailing during the months of January and April; **Figure 4c** SSW wind direction prevailing during the months of May through November; and **Figure 4d** a simulated nor'easter with NE wind direction. During the winter and early spring months the prevailing wind directions ranges from WNW to NNW, resulting in the highest wave exposures on the southern half of Cape May shoreline in New Jersey and the Sussex County shoreline of Delaware. During the remainder of the year (i.e., May through November), the prevailing wind direction is from the SSW, leading to higher wave energies along the northern half of Cape May and the eastern half of Cumberland County shorelines of New Jersey.

Botton et al. (1988) and Smith et al. (2002b) have noted that the eastern most section of the Delaware shoreline (i.e., south and east of Broadkill in Sussex County) and the southern third of the Cape May peninsula are not as heavily used by horseshoe crabs as spawning habitat even though the beaches are composed largely of sand. They attribute this lack of crab use to differences in beach morphology that are presumably due to differences in the wave energy regime. While our wind energy assessment is highly qualitative, it does lend support to these above observations in that the southern half of Cape May shoreline in New Jersey and the Sussex County shoreline of Delaware are subject to greater wind and wave exposure during the winter and early spring months and during nor'easter storms, when the average wind speed is also elevated (**Figure 4a, 4b, 4c**). The cross-tabulation of the composite wind fetch model and the habitat suitability

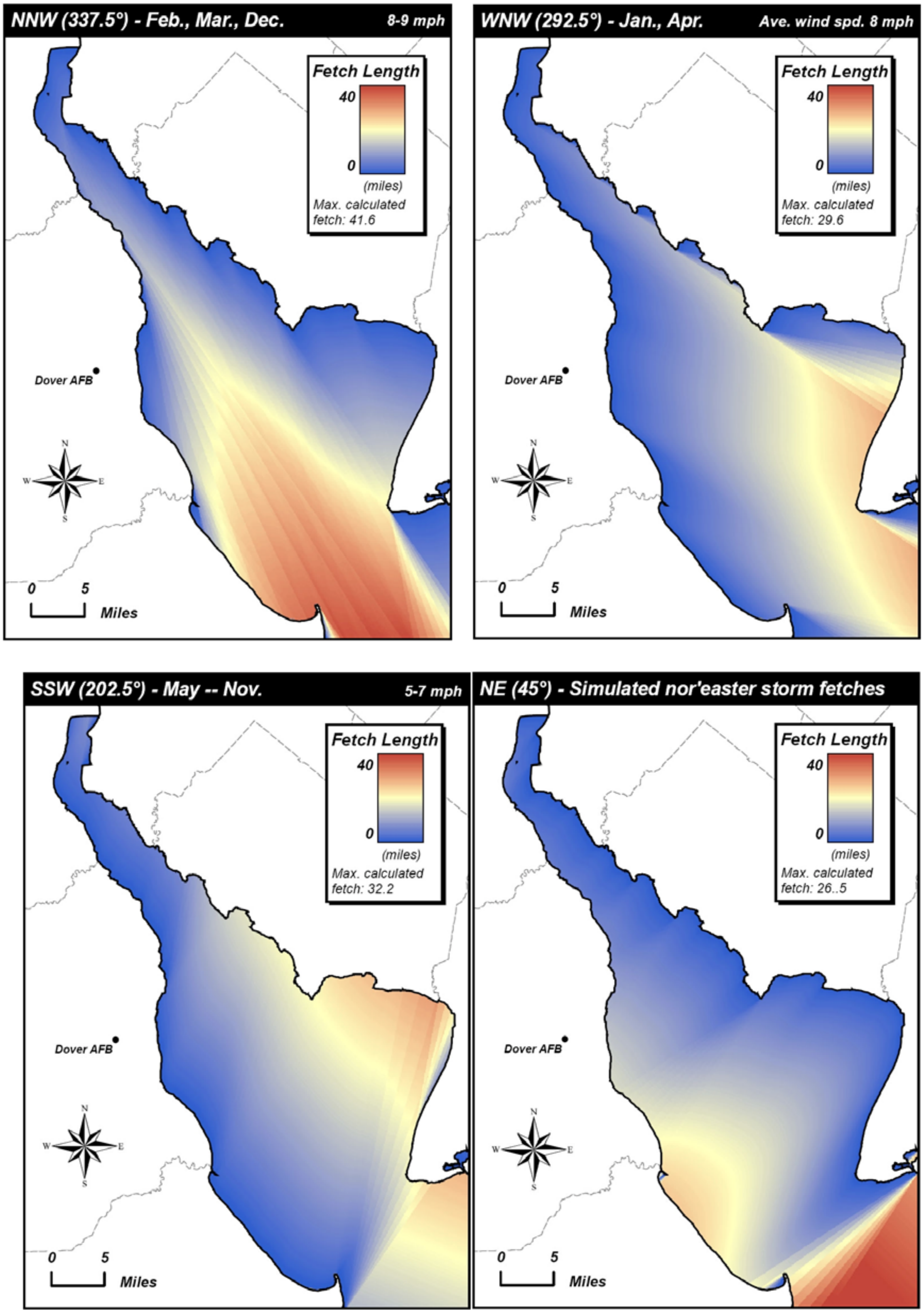

Figure 4. Estimated monthly average wind fetch length for A. December, February, March; B. January and April; C. May through November; and D. simulated nor'easter.

model reveals that approximately 62% and 47% of the Optimal Habitat in Delaware and New Jersey, respectively, was estimated to be subject to High wave energy. These prevailing wind and wave conditions during the winter to spring months may be controlling important aspects of the beach profile and overall beach morphology.

During the later spring and summer months, the prevailing wind direction switches to the SSW, leading to higher wave energies along the New Jersey side of Delaware Bay (**Figure 4c**). While the eastern shoreline of Cumberland County receives the brunt of this High wind/wave exposure, only small confined stretches of this shoreline is ranked as Optimal or Suitable spawning habitat. The southern and central portions of the Cape May shoreline, which are generally ranked as serving as Optimal or Suitable spawning habitat, are subject to elevated wind and wave energy during the late spring and summer months. Elevated wind conditions during the crucial spawning months of May and June can result in wave energies sufficiently high to directly inhibit the spawning activities of horseshoe crabs on these New Jersey beaches (A. Dey, personal communication). Conversely during this same May-June spawning period, the Delaware beaches are in the lee of the prevailing wind and generally receive lower wind conditions.

Table 11. Cross-tabulation of horseshoe crab spawning habitat suitability class and wave energy class, expressed on a percentage basis.

11a. Delaware

Wave Energy	Horseshoe Crab Spawning Habitat Suitability				
	Optimal	Suitable	Less Suitable	Avoided	Disturbed
Low	2.6%	2.2%	24.9%	83.0%	14.8%
Medium	34.9%	50.1%	66.0%	6.4%	55.6%
High	62.5%	47.6%	8.8%	0.7%	28.2%
Not modeled	0.0%	0.0%	0.2%	9.8%	1.3%

11b. New Jersey

Wave Energy	Horseshoe Crab Spawning Habitat Suitability				
	Optimal	Suitable	Less Suitable	Avoided	Disturbed
Low	3.4%	3.2%	23.6%	14.7%	16.4%
Medium	48.7%	65.5%	61.0%	17.3%	55.7%
High	47.3%	31.2%	11.6%	26.2%	25.3%
Not modeled	0.5%	0.0%	3.8%	41.8%	2.6%

Comparison of Habitat Suitability and Wind Fetch Modeling with ISA data

The ISA and mapped habitat data were extracted for 28 beach transects in total, 13 in Delaware and 15 in New Jersey (Table 12, Figure 5). Note that none of the transects were composed of beach classified as Avoided habitat (i.e., a shoreline composed of salt marsh or eroding peat). Comparison of the Habitat Suitability Mapping results with the mean 1999-2004 ISA and the 2002 data alone did not show a clearcut relationship between habitat type and ISA values (Figure 6). Note that 3 of the top5 NJ beach transects with the highest 2002 ISA values (i.e., above ISA = 1.0) were dominated or had significant proportions of Disturbed habitat (Figure 6). Also note that 3 out of the top 5 DE beach transects with the highest 2002 ISA values were dominated by Less Suitable Habitat (Figure 7). Comparing the proportion of the ISA beach survey transects that were mapped as optimal or suitable (combined) habitat with the 2002 ISA data (Figure 7) for Delaware beaches, shows no relationship between the proportion of these map categories and the 2002 ISA value (R^2 = 0.067, p-value = 0.3905). For New Jersey beaches, there appears to be a moderately strong but negative relationship between the proportion of a transect mapped as optimal or suitable habitat and the 2002 ISA value (R^2 = 0.763, p-value < 0.001) (Figure 7). This result would suggest that ISA increases with as the proportion of mapped optimal or suitable habitat decreases which is counter to prior expectation. Thus the mapped Habitat Suitability class does not appear to be a good predictor of horseshoe crab spawning activity as measured by the ISA. However, it should be noted that the ISA data measures only female crab spawning activity and not the ultimate reproductive success of that spawning activity (i.e., egg numbers, hatching success, over-wintering larval trilobite numbers).

These results suggest that horseshoe crabs were using all sand or predominantly sand beaches without regard to the subtle composition differences that were interpreted and mapped. It should be noted that the USGS beach transects included beaches accessible by road (Smith et al., 2002) and whether by design or happenstance did not include areas of shoreline dominated by salt marsh or eroding peat. Thus the ISA sampling can not be used to assess whether these shoreline habitat types serve as useful spawning habitat. Further, the Disturbed habitat category as presently mapped may not always constitute an impediment to horseshoe crab spawning activity. The Disturbed category includes shoreline that is both armored (bulkheaded or riprapped) or consists of coarse fill. Note that the New Jersey site with the highest ISA value recorded in 2002 in New Jersey, Sea Breeze, was mapped as 100% Disturbed (Figure 7). Further investigation of the 2002 DOQ imagery reveals that the Sea Breeze, NJ site was composed of a mix of sand and coarse beach fill backed by boulders and concrete rubble (Figure 8). Gandy's Beach, NJ had a component of rubble-armored beach and bulkheading with houses, while Reed's Beach had sections of bulkheaded shoreline with houses. It is interesting to note that these 3 beaches all showed much higher ISA values in 2002 than the mean for the 6 year 1999-2004 period.

Examination of the ISA data in relation to the wind fetch provides some interesting results. The mean fetch distance provides a measure of overall wind disturbance across the entire annual cycle. The mean ISA values (1999-2004) for the two states combined show a moderately strong negative relationship with lower ISA values with increased mean annual fetch distance (R^2 of 0.255, p-value = 0.0062) (Figure 9). Separating the 2 states shows that the DE beaches have a moderately strong negative relationship between fetch distance and ISA (R^2 = 0.499, p-value = 0.0070), while there is no statistically significant relationship for NJ beaches (R^2 = 0.0002, p-value = 0.9564).

Comparing solely the spawning season (May/June) fetch distance vs. ISA values shows a different picture (Figure 10). With the predominant wind direction coming out of the southwest during the May/June spawning season (Figure 4c), the Delaware beaches represent a lee shore with minimal wind impacting disturbance. Thus there is no statistically significant relationship between mean ISA (1999-2004) and May/June wind fetch (R^2 = 0.0094, p-value = 0.7531). Wind disturbance during the May/June spawning season does not appear to be a controlling factor along the Delaware shoreline but other factors must be determining the pattern of ISA data. Conversely, the NJ beaches show a moderately strong negative relationship between the May/June wind fetch and ISA values (R^2 = 0.2759, p-value = 0.0444) (Figure 9). Thus it appears that wind disturbance (as measured by maximum wind fetch) may be an contributing factor determining which beaches have high horseshoe crab spawning activity along the New Jersey shoreline, which is subject to high wind conditions. These results appear to confirm the personal observations of wildlife biologists that elevated wind conditions during the crucial spawning months of May and June can result in wave energies sufficiently high to directly inhibit the spawning activities of horseshoe crabs on New Jersey beaches (A. Dey, personal communication).

The relationship of the yearly average maximum and the May/June wind fetch vs. the ISA data shows conflicting results. DE beaches show a negative relationship between ISA values and yearly average but not May/June wind fetch. NJ beaches show the opposite. One possible explanation is that wind disturbance is not a major factor along the DE shoreline during the May/June spawning season and that other environmental or habitat factors are more important. However, wind disturbance during other seasons may play an important role in shaping the shoreline profile and affecting erosion and sedimentation conditions and thereby be an important factor in determining the habitat selection and spawning activity of the horseshoe crabs. Along the New Jersey shoreline, wind conditions during the May/June time period appear to be playing a role in determining horseshoe crab spawning activity but the yearly average wind conditions do not appear to have an influence. Combining the two wind fetch variables and the data for both Delaware and New Jersey into a single regression model provides a statistically significant model with (R^2 = 0.433, p-value < 0.001).

It must be noted that the wind fetch modeling as we have implemented it, represents a first cut approximation of characterizing wind and wave exposure. First, we did not incorporate wind speed into the analysis. Second, we used 60+ year average conditions and thereby did not fully capture the spatially and temporally dynamic nature of wind direction. Third, we did not incorporate information on the off-shore bathymetric profile or other physical environmental characteristics which may alter the incident wave energy on any particular beach.

Table 12. Data for USGS beach survey transects: ISA values for 2002 and mean values for 1999-2004 time period; and proportion of habitat mapped as optimal, suitable, less suitable or disturbed.

Beach Site	***State***	***ISA 2002***	***Mean ISA 1999-2004***	% optimal	% suitable	% less	% disturb
Lewes	DE	------	0.0838	31.3	68.7	0.0	0.0
Cape Henlopen	DE	0.0857	0.1309	77.3	0.0	22.7	0.0
Broadkill	DE	0.1347	0.1696	30.9	56.1	11.9	1.1
Bennetts Pier	DE	0.4713	0.4315	0.0	0.0	100.0	0.0
Primehook	DE	0.5908	0.5090	7.8	83.6	8.6	0.0
Fowlers	DE	0.2370	0.5459	47.7	0.0	52.3	0.0
Bigstone	DE	0.6265	0.7261	69.7	30.3	0.0	0.0
South Bowers	DE	1.1265	0.7675	10.2	3.2	86.6	0.0
North Bowers	DE	1.2142	0.9665	10.2	73.4	16.5	0.0
Slaughter	DE	0.7265	1.3236	98.0	2.0	0.0	0.0
Ted Harvey	DE	1.4446	1.6506	0.0	0.0	100.0	0.0
Kitts Hummock	DE	1.4667	1.8913	0.0	0.0	100.0	0.0
Pickering	DE	1.6950	1.9808	32.5	67.5	0.0	0.0
Raybins	NJ	------	0.0259	27.6	30.6	41.8	0.0
Higbee	NJ	------	0.0361	91.4	0.0	8.6	0.0
North Cape May	NJ	0.0845	0.0989	100.0	0.0	0.0	0.0
Sunset	NJ	------	0.1139	75.8	23.2	0.0	1.0
East Point	NJ	------	0.3458	0.0	0.0	0.0	100.0
Fortescue	NJ	------	0.4022	12.1	32.7	0.0	55.2
Town Bank	NJ	0.4589	0.4487	99.8	0.0	0.0	0.2
Sea Breeze	NJ	1.6283	0.4914	0.0	0.0	0.0	100.0
Kimbles	NJ	0.4976	0.5726	93.2	1.4	5.4	0.0
Norburys	NJ	0.6242	0.5728	77.4	6.9	7.9	7.8
Reeds	NJ	0.8768	0.5913	55.3	22.3	0.0	22.4
Gandys	NJ	1.4122	0.6707	0.0	61.3	0.0	38.7
Highs	NJ	0.4685	0.7060	84.1	15.9	0.0	0.0
Pierces Point	NJ	0.6730	0.7443	11.9	88.1	0.0	0.0
South Cape Shore Lab	NJ	0.6850	1.0119	81.4	18.6	0.0	0.0

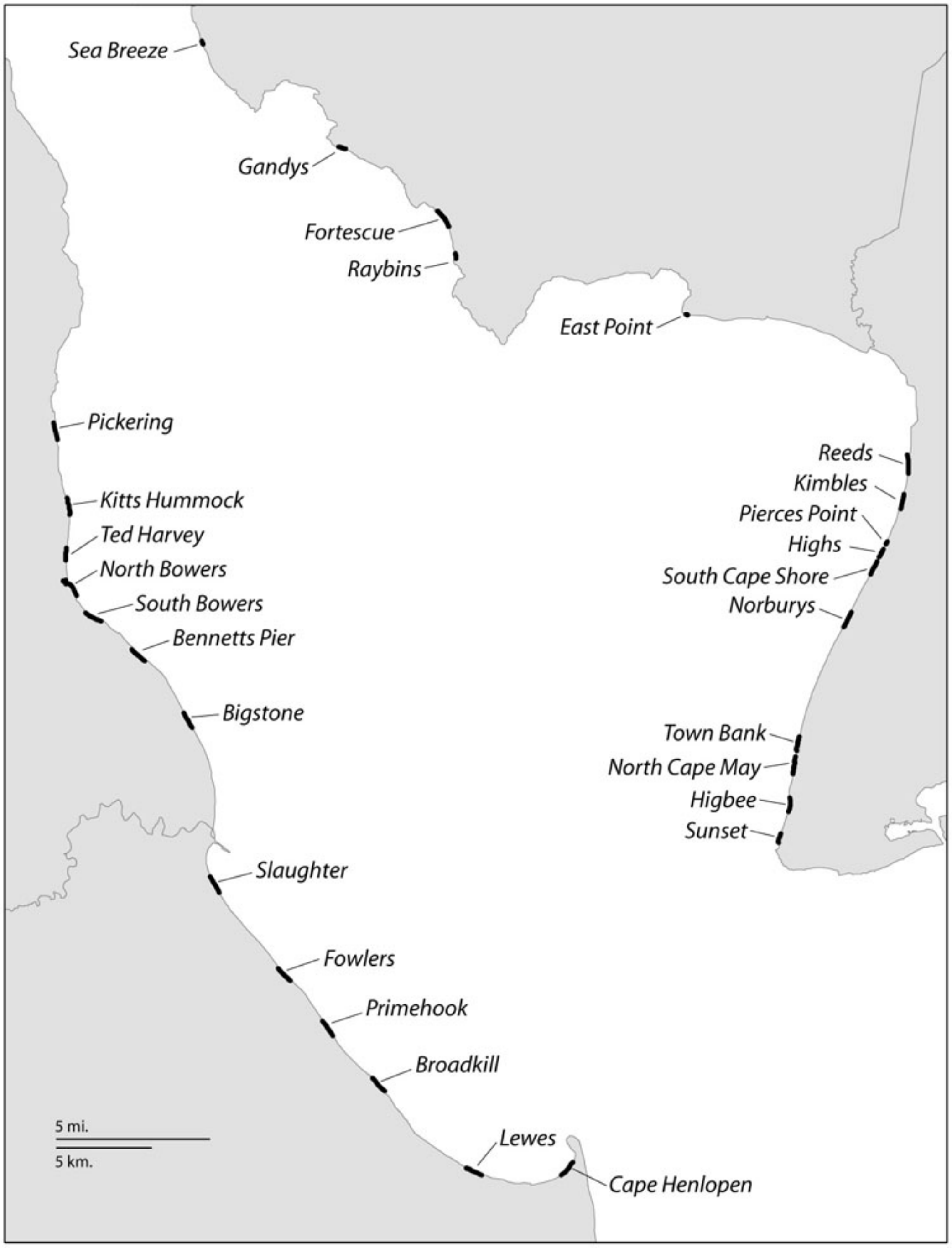

Figure 5. U.S. Geological Survey Index of Spawning Activity (ISA) beach transect sampling locations.

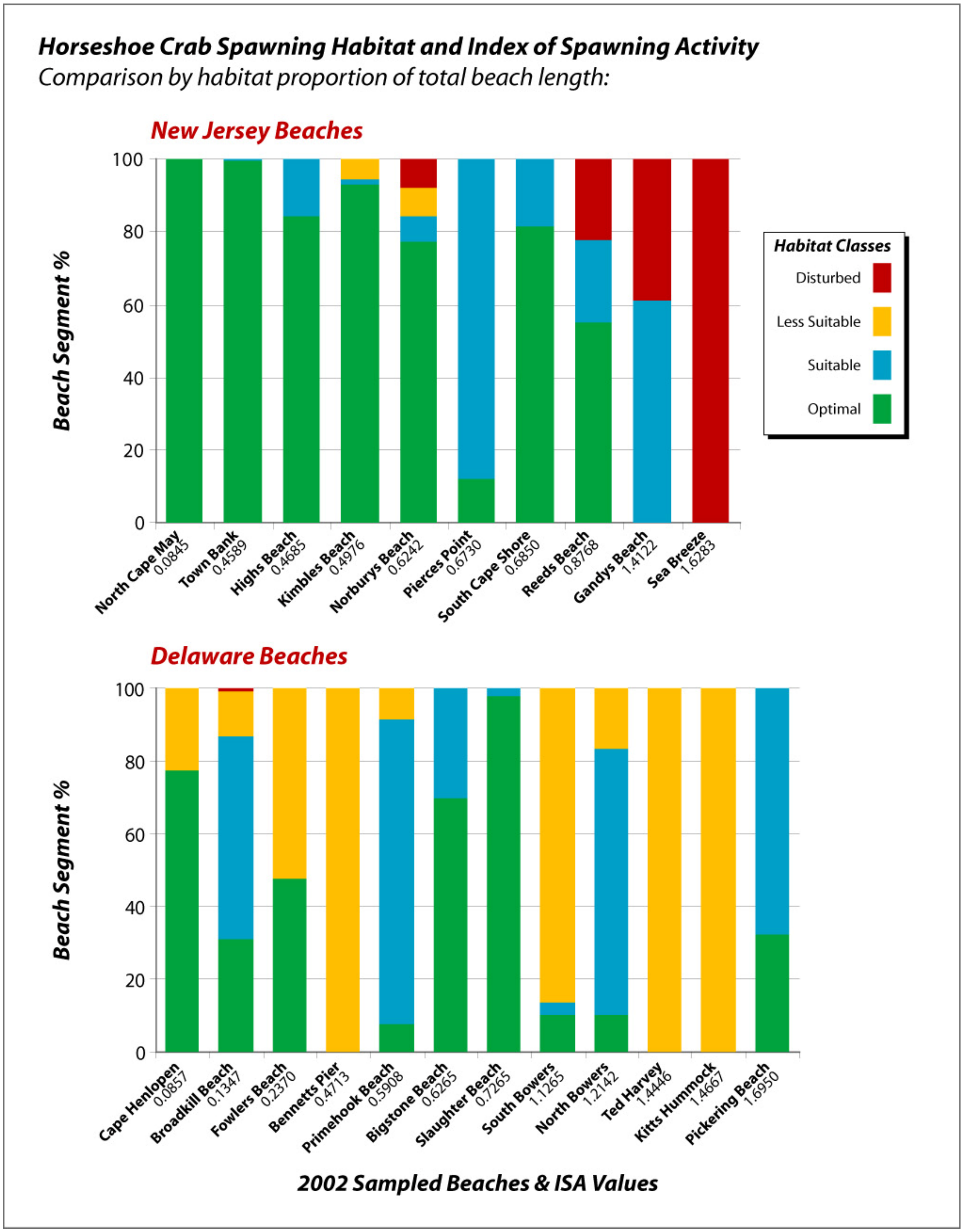

Figure 6. Comparison of horseshoe crab spawning habitat (expressed as proportion of total beach transect length) vs. 2002 Index of Spawning Activity (ranked low to high- left to right) for New Jersey and Delaware beaches.

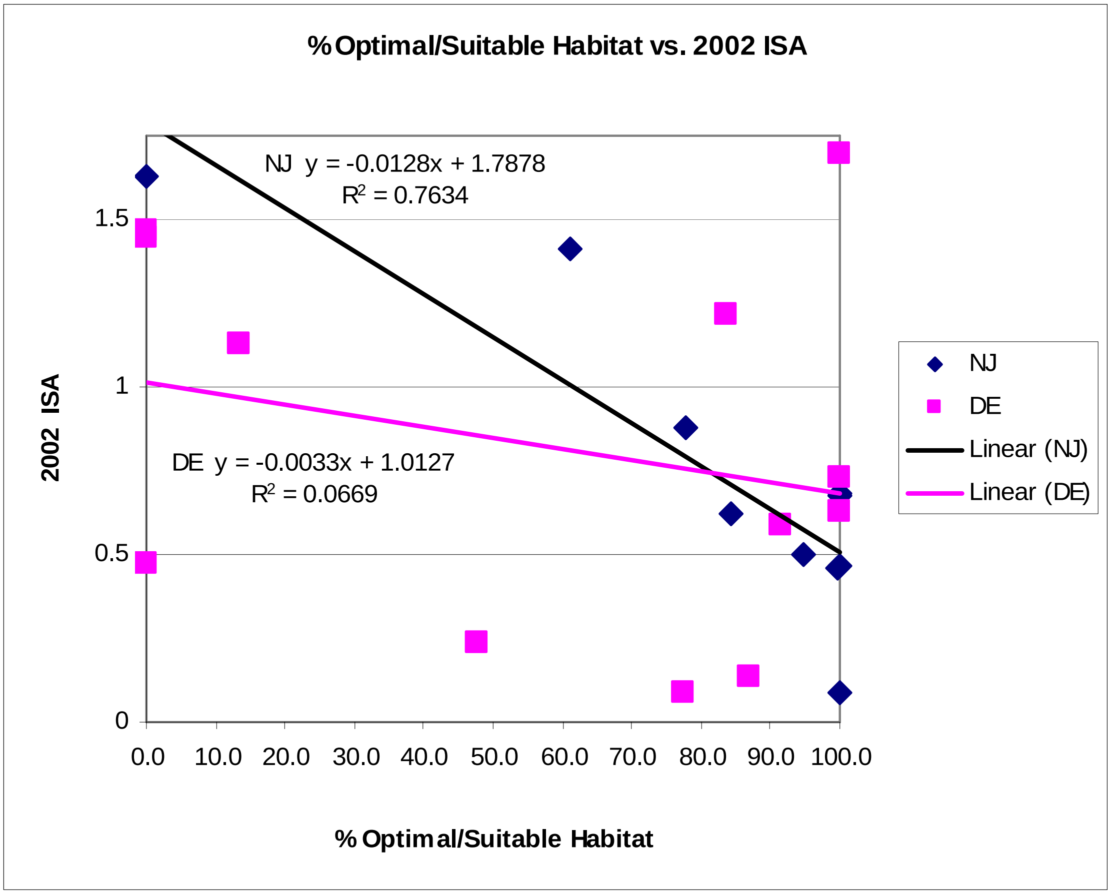

Figure 7. Plot of % Optimal and Suitable (combined) habitat vs. 2002 ISA values for USGS beach survey transects.

Figure 8. USGS Index of Spawning Activity beach transect (in red) overtop the 2002 CIR DOQ imagery (scale 1:1,000). Note the sand mixed with coarse beach fill and the boulders and concrete rubble on the backbeach.

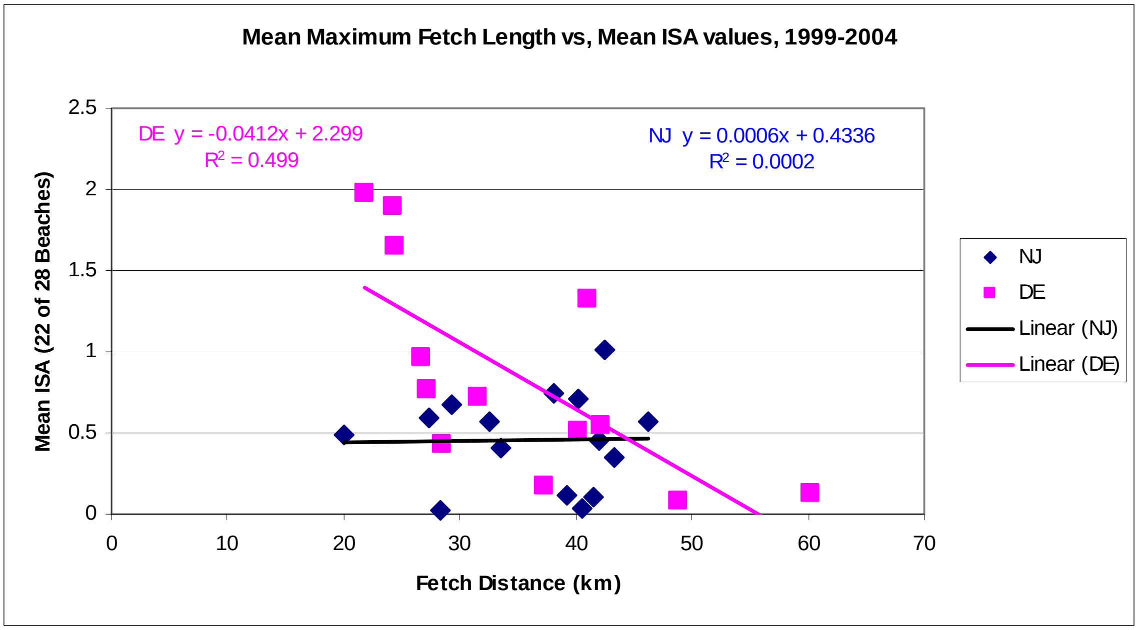

Figure 9. Scatter plot showing average USGS ISA values relative to mean maximum fetch distance of prevailing winds across all 4 seasonal time periods for sampled beaches in DE and NJ.

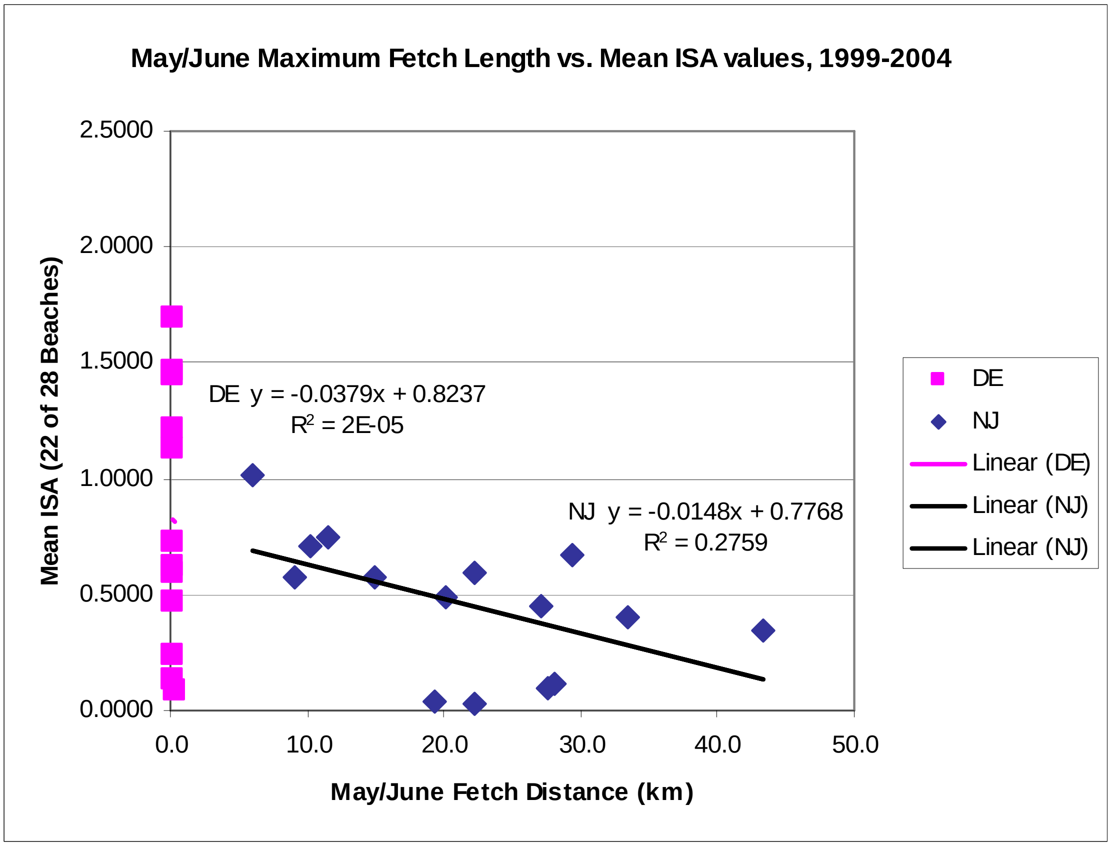

Figure 10. Scatter plot showing average ISA values relative to mean fetch distance of prevailing SSW winds during spawning season (May – June) for sampled beaches in DE and NJ.

Long Term Sustainability of Delaware Bay's Beach Habitats

The long term sustainability of Delaware Bay's beaches is of critical concern to the long term sustainability of the horseshoe crab populations and by connection, the migratory shorebirds. Delaware Bay's sandy barrier beaches are dynamic features that respond in a generally predictable manner, migrating landward by storm overwash as the bayward shoreline is also retreating landward in the face of continued sea level rise (Phillips, 1986a). While future rates are difficult to predict, the current level of sea level rise in Delaware Bay is generally thought to be about 3 mm/yr (Phillips, 1986a). This rise in sea level has resulted in erosion of the Bay's shorelines and a landward extension of inland edge of the marshes. During the period of 1940 to 1978, Phillips (1986a) documented a mean erosion rate of 3.2 m/yr for 52 km long section of New Jersey's Delaware Bay Cumberland County shoreline. He suggested that this was a high rate of erosion compared to other estuaries. The spatial pattern of the erosion was complex with differential erosion resistance related to local differences in shoreline morphology (Phillips, 1986b). Phillips shoreline erosion studies (1986a, 1986b) suggest that bay-edge erosion is occurring more rapidly than the landward/upward extension of the coastal wetlands and that this pattern is likely to persist.

Galbraith et al (2002) examined several different scenarios of future sea level rise as a consequence of global climate change and project major losses of intertidal habitat in Delaware Bay due to continued sea level rise. Under the 50% probability scenario (i.e., the most likely scenario), Delaware Bay is predicted to lose 60% or more of the shorebird intertidal feeding habitats by 2100. Under more extreme sea level rise, Delaware Bay may actually have a net gain of intertidal flats as the coastline migrates further inland converting dry land to intertidal habitat. However, this prediction assumes that the coastal protection structure do not constrain the ability of shorelines to migrate landward. Within the Delaware Bay system as elsewhere in the Mid-Atlantic region, coastal development and shoreline protection activities are expected to interfere with the longer term landward migration of shorelines (Najjar et al., 2000). Though Delaware Bay is less developed than many similar stretches of Mid-Atlantic coastline, some of the most optimal beach habitat is also the site of existing shoreline residential development. Significant sections of the Delaware Bay shoreline have already been impacted by shoreline stabilization projects. Coupled with continuing sea level rise and shoreline erosion, the demand for additional shoreline protection structures is expected to increase (Najjar et al., 2000). Shoreline stabilization projects employing bulkheading, riprap or other solid beach fill can either completely eliminate intertidal sand beach habitat or sufficiently alter sediment quality and beach morphology to negatively affect the suitability of the remaining habitat for horseshoe crab spawning (Myers, 1986; Botton et al., 1988). However, while the ISA survey data suggests that female horseshoe crabs will use some severely disturbed beaches for spawning (e.g., Sea Breeze, NJ), the number of eggs laid, larval survival and the ultimate reproductive success was not ascertained. Beach replenishment through off-shore pumping of sandy sediments provides an alternative means of beach stabilization. However, to the best of our knowledge, the value of beach replenishment as a beach habitat restoration strategy in Delaware Bay or possible negative impacts on horseshoe crab population dynamics has not been studied.

CONCLUSIONS

- Delaware Bay's sandy beaches serve as preferred habitat as horseshoe crab spawning. Sand beach represents only 54% of the Delaware Bay shoreline while the remaining 46% is composed of eroding peat banks, salt marsh or armored shoreline.

- Some stretches of Delaware Bay's sand beaches are subject to high levels of human use and are the site of near shore development and shoreline stabilization structures that negatively impact their habitat value. Approximately 5% of the Delaware Bay fore-shore is subject to beach armoring while an additional 2.5% of shoreline has stabilization structures in the back-beach. Approximately 8% is fronted by near-shore development.

- Slightly less than 25% of the Delaware Bay shoreline was classified as Optimal horseshoe crab spawning habitat (i.e., sand beach without significant amounts of eroding peat and undisturbed by development or shoreline stabilization structures).

- Significant amounts of otherwise high quality (i.e., Optimal or Suitable) beach habitat may be compromised by high wind/wave exposure that may modify the beach morphology or directly inhibit crab spawning activity. Our results suggest that wind exposure may be an important factor in determining which beaches receive high levels of horseshoe crab spawning activity (as measured by the Index of Spawning Activity (ISA) data collected by the U.S. Geological Survey). In particular, New Jersey beaches appear to be negatively impacted by high wind exposure while the Delaware beaches, generally on the lee shore, are less impacted during the critical May/June spawning season.

- Comparison of our habitat mapping with the ISA data did not show any discernable relationship between the mapped habitat suitability class and ISA values. These results suggest that horseshoe crabs were using all sand or largely sand beaches without regard to the subtler habitat or disturbance characteristics that we mapped. However, the ISA data does not provide sufficient insight as to the ultimate reproductive success of crabs using those beaches.

- Further incorporation of horseshoe crab reproductive success (i.e., egg numbers, hatching success, over-wintering trilobite numbers) and shorebird usage data (i.e., as recorded in monitoring surveys) as well as other statistical analysis and modeling techniques, should be explored to refine the habitat suitability mapping.

- Sea level rise and shoreline erosion is expected to continue into the future and will alter the present availability of high quality beach habitat wherever it occurs within Delaware Bay. Expanding shoreline stabilization/armoring programs and near-shore development will impinge on the natural landward migration of the barrier beach environment and most likely serve to exacerbate the loss and alteration of beach habitat.

- The removal of beach stabilization structures and near-shore development, along with beach replenishment, should be further examined as a possible strategy for beach habitat restoration in those areas that have been negatively impacted. Ideally, sand beaches should be permitted to go through a natural shoreline retreat process to maintain high quality beach habitats in the long term.

- While extensive stretches of the Delaware Bayshore are protected through some form of public conservation ownership, there are significant stretches of sand beach habitat that are unprotected. While horseshoe crabs did not appear to show a strong preference among the various classes of mapped sand beach habitat for their spawning activity, the beach habitat suitability class map still provides some value for conservation planning. Beaches classed as Optimal represent comparatively undisturbed sand beach habitat that should receive highest priority for conservation protection, as these beaches provide the greatest likelihood of being to adapt to sea level rise in the long term as natural shoreline retreat zones. Further, these beaches may also serve as high quality shorebird foraging and resting habitat during the critical spring migratory stopover.

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APPENDIX A – Explanations of Shapefile Attribute Fields

This Appendix provides further documentation of the GIS data produced as part of this project. The GIS data is available by request from the Walton Center for Remote Sensing & Spatial Analysis (contact Corresponding Author: Richard Lathrop; email: lathrop@crssa.rutgers.edu; www.crssa.rutgers.edu). The six length measurement shapefiles described in the Methods section are listed in **Table 1** below, with brief descriptions of their content. They consist of single lines, which trace the features described, and were used to determine the length measurements of shoreline land covers. **Tables 2** and **3** describe the attribute fields.

Table 1 – Descriptions of Length Measurement Shapefiles

File Name	Description of Contents
NJ_armorline.shp	All shoreline and back-beach armor on the New Jersey side
NJ_sandline.shp	All washed sandy beach on the New Jersey side
NJ_shoreline.shp	Entire shoreline of New Jersey side
DE_armorline.shp	All shoreline and back-beach armor on the Delaware side
DE_sandline.shp	All washed sandy beach on the Delaware side
DE_shoreline.shp	Entire shoreline of Delaware side

Table 2 – Attribute Fields of NJ_bayshore.shp and DE_bayshore.shp

Field Name	Field Description
OBJECTID	A unique identifier for each polygon in the shapefile.
SHORELINE	The land cover along the water's edge.
INTERIOR_B	The land cover of the interior of the polygon.
ADJACENT_L	The land cover of the area directly adjacent (landward) of the polygon.
MINIMUM_WI	The minimum width of the beach polygon.
MAXIMUM_WI	The maximum width of the beach polygon.
AVERAGE_WI	The approximate average width of the beach polygon.
NOTES	General notes regarding the polygon or surrounding area.

Table 3 – Attribute Fields of Length Measurement Shapefiles

Field Name	Field Description
UniqueID	A unique identifier for each polyline of the shapefile.
Length	A measure of each polyline's length in kilometers.
ARMOR	A field indicating whether beach armor is on the shore (= “front”) or
	at the back of the beach (= “back”).