3.20 Sea Level Rise Modeling Study

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Introduction

Over the past century, the rate of sea level rise has increased more than twice the average historical rate.[712] The U.S. EPA estimates that by 2100, sea level will increase nearly 2 feet in many coastal areas of the United States, with half of this increase directly attributable to global warming.[713,714] Rising sea level, often associated with land subsidence, coupled with human habitation of the shore zone and shoreline armoring with seawalls and similar structures, places shoreline property and coastal habitats and biota at risk.[715,716,717]

As the sea rises, beaches are eroded and tidal wetlands are gradually converted to open water. Seawalls and other armoring structures are often used to protect shoreline property. However, such structures also prevent the landward migration of wetlands that would otherwise follow sea level rise. In addition, waves scour away sand seaward of armoring structures, preventing natural replenishment of sand. The combination of increased sea level rise and shoreline armoring can result in the loss of wetlands, beaches, and other nearshore areas that are highly valued by humans and are necessary for the survival of fish, birds, and wildlife.

Unfortunately, potential impacts on shoreline property are often the sole focus of strategies for responding to anticipated sea level rise. However, planning must also consider responses that will protect natural ecological processes and coastal resources. Otherwise, there may be substantial and irreversible losses of coastal habitats and biota with unintended ecological and economic consequences.

We conducted a pilot study of coastal Ocean County, New Jersey, in which we developed and applied methods for evaluating risks to coastal ecosystems under alternative sea level rise and armoring scenarios. The study is one of the first attempts to quantify not just habitat changes but also changes in biota in response to sea level rise.[718]

The analysis focused on impacts to tidal marshes, SAV, sandy beaches, and open water. Maintaining tidal marshes in response to sea level rise depends on the availability of adjacent low gradient uplands to allow landward development of coastal marshes. As sea level rises, armoring structures will preclude the

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[712]Huybrechts et al., 2001 (see note 1).

[713]Barth, M.C. and J.G. Titus, 1984, *Greenhouse Effect and Sea Level Rise: A Challenge for This Generation*, Van Nostrand Reinhold, New York.

[714]Titus and Narayanan, 1995 (see note 3).

[715]Titus, J.G., R.A. Park, S.P. Leatherman, J.R. Weggel, M.S. Greene, P.W. Mausel, S. Brown, G. Gaunt, M. Trehan, and G. Yohe, 1991, "Greenhouse effect and sea level rise: The cost of holding back the sea," *Coastal Management* 19:171–204.

[716]Douglas, B., M. Kearney, and S. Leatherman (eds.), 2001, *Sea Level Rise: History and Consequences*, Academic Press, San Francisco, CA.

[717]Wu, S-Y., B. Yarnal, and A. Fisher, 2002, "Vulnerability of coastal communities to sea-level rise: A case study of Cape May County, New Jersey," *Climate Research* 22:255–270.

[718]The technical work that forms the basis for this report was funded by EPA's Office of Atmospheric Programs under Contract No. 68-W02-027. The report itself was prepared by Stratus Consulting with corporate development funds. James G. Titus, the EPA work assignment manager, developed the sea level rise and armoring scenarios that were evaluated as well as the habitat-elevation relationships used in the inundation model. Dr. Michael P. Weinstein of the New Jersey Marine Sciences Consortium, Sandy Hook Field Station provided valuable assistance with the analysis of effects on fish production of changes in marsh habitat. Dr. Michael Kearney of the University of Maryland developed accretion rates. ICF Consulting Inc. provided elevation data, and Industrial Economics developed the armoring scenarios in consultation with local planners. The conclusions presented in this report are those of the authors and do not represent the opinions of subcontractors or the official position of the EPA.

inland movement of most tidal wetlands, and will influence the exchange of nutrients, other allochthonous materials, and organisms from watersheds to estuaries.

Most critically, without the ability of intertidal habitats to migrate or accrete sediments seaward of a structure at an accelerated rate, they will ultimately "drown" and be eliminated as sea level rise inundates the shoreline seaward of the armored structures.

This study considered potential impacts of sea level rise and shoreline armoring on:

- finfish and shrimp with varying dependency on SAV and *Spartina* marshes; and
- birds that depend on coastal habitats for feeding, resting, or nesting.

The following key questions were addressed:

- What habitat changes are likely to occur?
- What species are associated with these vulnerable habitats?
- To what extent can habitat and species changes be quantified?

We first present an overview of the study area and the habitats and species evaluated. Next we describe the inundation model developed to evaluate habitat changes under various sea level rise and armoring scenarios and defines the scenarios that were evaluated. We present methods used to evaluate potential changes in biota in response to predicted habitat changes, and then discuss results of the analysis and directions for future research. The appendix presents GIS maps of modeled habitat changes.

Study Habitats and Biota

Study Area

The study area included all of coastal Ocean County, New Jersey, including Barnegat Bay, inland to the boundary of the zone defined by New Jersey's Coastal Areas Facilities Review Act (CAFRA) (Plate 1 in the appendix). The CAFRA zone includes the area considered by CAFRA to be vulnerable to sea level rise. The study area includes a system of barrier beaches, tidal wetlands, and productive, shallow, backwater lagoons that are important for estuarine fish and shellfish, migratory and wintering waterfowl, migratory shorebirds, colonial nesting waterbirds, migratory passerines and raptors, and resident terrapin sea turtles.[719] Important habitats include barrier beach and dune, open water, SAV, intertidal sand and mudflats, salt marsh islands, and fringing tidal salt marshes. While recognizing the importance of all of these habitats, this study examined potential changes only in the areal extent of tidal marshes, SAV, sandy beaches, and open water.

Habitat Classification Scheme

Based on review of a number of habitat classification schemes amenable to analysis using a geographic information system (GIS), we selected a classification scheme that was developed by the Grant F. Walton Center for Remote Sensing and Spatial Analysis (CRSSA) at Rutgers University. We selected this scheme because it links well with National Wetlands Inventory (NWI) data[720] and has many classes that coincide well with other classification schemes. It also incorporates some finer scale data that were developed for use in a study of habitat loss and alteration in the Barnegat Bay watershed (Figure 3.1).[721]

Submerged aquatic vegetation. The SAV of Barnegat Bay is dominated by eelgrass (*Zostera*

[719] USFWS, 1997 (see note 172).
[720] Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe, 1979, Classification of Wetlands and Deepwater Habitats of the United States, FWS/OBS-79/31. USFWS, Washington, DC.
[721] CRSSA, 2000, Rutgers University, 20000731, New Jersey 1995, Level III Land Cover Classification. Digital GIS data. Center for Remote Sensing and Spatial Analysis.

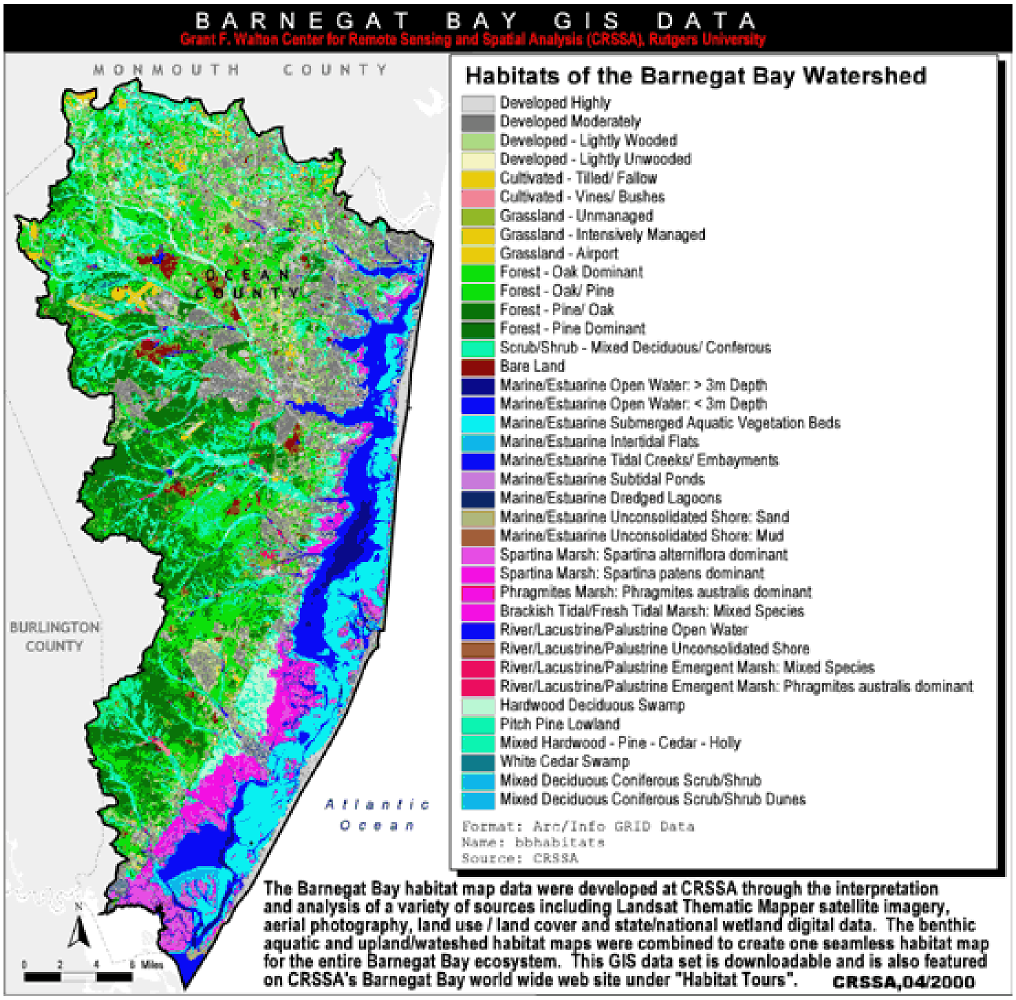

Figure 3.1. Habitats of the Barnegat Bay Watershed. Source: Grant F. Walton Center for Remote Sensing and Spatial Analysis, Rutgers University.

marina), occurring in dense beds at water depths of 1 meter or less.[722] SAV beds provide spawning and nursery areas for epibenthic fishes such as fourspine stickleback (*Apeltes quadracus*), naked goby (*Gobiosoma bosci*), northern pipefish (*Syngnathus fuscus*), and rainwater killifish (*Lucania parva*), and refuge for decapod crustaceans such as blue crab (*Callinectes sapidus*), grass shrimp (*Hippolyte pleuracanthus*), and sand shrimp (*Crangon septemspinosa*).[723]

SAV beds are also important feeding grounds for waterfowl. Midwinter aerial waterfowl counts in Barnegat Bay average 50,000 birds, mostly brant (*Branta bernicla*), American black duck (*Anas rubripes*), scaup (*Aythya* spp.), mallard (*Anas platyrhynchos*), bufflehead (*Bucephala albeola*), Canada goose (*Branta danadensis*), and mergansers (*Mergus* spp.).[724]

Tidal marshes. Marsh vegetation type is largely controlled by salinity and tidal regime (BBNEP, 2001). Low marsh, which is regularly inundated by the tide, is dominated by smooth cordgrass (*Spartina alterniflora*). Low marsh occurs in intertidal areas, especially along tidal creeks and channels.[725]

The high marsh, which is only irregularly flooded by saline waters, is dominated by salt meadow cordgrass (*S. patens*). The extensive salt

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[722]USFWS, 1997 (see note 172).
[723]Sogard and Able, 1991 (see note 94).

[724]USFWS, 1997 (see note 172).
[725]Ibid.

marshes along the mainland shoreline and salt marsh islands of Barnegat Bay are mostly high marsh.[726]

The invasive common reed (*Phragmites australis*) occurs in a narrow fringe along the upland edge of marshes where salinities are low because of less tidal flooding and greater freshwater runoff.[727]

Extensive networks of creeks ranging from small tidal rivulets to major subtidal tributaries occur throughout the *Spartina* marshes of New Jersey.[728] Marsh creeks support significantly higher densities of finfish than do SAV beds, whereas densities of decapod crustaceans such as blue crab tend to be higher in SAV.[729] The fish fauna of marsh creeks is dominated by small schooling species such as Atlantic silverside (*Menidia menidia*), mummichog (*Fundulus heteroclitus*), and bay anchovy (*Anchoa mitchilli*).

S. alterniflora marsh provides habitat for songbirds such as seaside sparrow (*Ammodramus maritimus*) and long-billed marsh wren (*Telmatodytes palustris*), and *S. patens* marsh provides habitat for sharp-tailed sparrow (*A. caudacutus*) and red-winged blackbird (*Agelaius phoeniceus*).[730]

Phragmites marshes support significantly fewer larval and small juvenile fish[731] and macroinvertebrates[732] than do *Spartina* marshes. *Spartina* marshes appear to have more standing water on the marsh surface and a more complex topography than do the generally drier and flatter *Phragmites* marshes.[733]

Sandy beaches. Beach nesting birds include black skimmer (*Rynchops niger)* and least tern (*Sterna antillarum*), both of which are state-listed endangered species, and piping plover (*Charadrius melodus*), a federally listed threatened species. According to surveys by the USFWS,[734] Holgate Beach within Barnegat Bay supported an average of 13 nesting pairs of piping plover from 1985 to 1995 and 1,500 black skimmers in 1993. In 1995, 570 nesting black skimmers were counted in Barnegat Bay. Holgate Beach and Barnegat Inlet had 400 and 307 adult least tern, respectively.

Beaches are also important spawning habitat for horseshoe crabs (*Limulus polyphemus*).[735] Horseshoe crab eggs are an important component of the diet for migratory shorebirds that use beaches as a feeding area.

Inundation Model

Model Algorithms

To predict habitat changes under various sea level rise and armoring scenarios, Stratus Consulting developed a GIS-based inundation model. The inundation model includes three integrated algorithms written in Arc Macro Language (AML) and run in the GRID module of ArcInfo software (v. 8.3).

The main algorithm predicts how current tidal wetland habitats (*S. alterniflora*, *S. patens*, and *Phragmites*) will change on an annual basis over 200 years based on the relationship of the habitat to the spring tide range and on estimated elevation changes relative to mean tide level (MTL) resulting from net sea level rise. Based on the available literature, net sea level rise is defined as the historical sea level rise rate plus the accelerated rate due to global warming minus

[726]Ibid.
[727]Ibid.
[728]Sogard and Able, 1991 (see note 94).
[729]Ibid.; Rountree and Able, 1992 (see note 22).
[730]BBNEP, 2001, *The Barnegat Bay Estuary Program Characterization Report*, available from the Barnegat Bay National Estuary Program at: http://www.bbep.org/char_rep.htm.
[731]Able, K.W. and S.M. Hagan, 2000, "Effects of common reed (*Phragmites australis*) invasion on marsh surface macrofauna: Response of fishes and decapod crustaceans," *Estuaries* 23:633–646.
[732]Angradi, T.R., S.M. Hagan, and K.W. Able, 2004, "Vegetation type and the intertidal macroinvertebrate fauna of a brackish marsh: *Phragmites* vs. *Spartina*," *Wetlands* 21:75–92.
[733]Able and Hagan, 2000 (see note 731).
[734]USFWS, 1997 (see note 172).
[735]Smith, D.R., P.S. Pooler, B.L. Swan, S.F. Michels, W.R. Hall, P.J. Minchak, and M.J. Millard, 2002, "Spatial and temporal distribution of horseshoe crab (*Limulus polyphemus*) spawning in Delaware Bay: Implications for monitoring," *Estuaries* 25:115–125.

the estimated accretion rate for each type of tidal wetland,[736] calculated annually over the 200 year time period.

Accretion rate estimates were developed for the project by Dr. Michael Kearney of the University of Maryland. He considered data from the literature and his own studies on vertical accretion rates in barrier lagoonal marshes with a similar tidal and physiographic setting. Accretion rates for *S. alterniflora* in the Virginia Barrier Islands determined by Pb-210 dating were about 2 mm/yr. Accretion rates of *S. patens* are expected to be somewhat less because *S. patens* is a planophile species (flatter and closer to the ground), and therefore less capable of trapping sediments. By contrast, *Phragmites australis* is a large plant with high biomass and effective sediment trapping, and therefore has a comparatively high accretion rate. On this basis, we modeled rates specific to each wetland type as follows:

- *Phragmites australis*: 10 mm/yr
- *S. patens*: 1.5 mm/yr
- *S. alterniflora*: 2 mm/yr

We recognize that accretion is a very complex process and that specific rates may vary significantly over space and time, but for modeling purposes these habitat-specific accretion rates were applied uniformly across the study area.

A second algorithm determines if non-nourished beach habitat will migrate inland or if migration will be impeded by an armoring structure, resulting in inundation. In this algorithm, the distance the beach would be expected to migrate inland is calculated using the Bruhn rule, which states that for each vertical unit of sea level rise, the beach will migrate 100 units inland.[737]

The third algorithm predicts the types and areal extent of tidal wetland habitat that would have existed in the study area if development had not occurred. This algorithm does not take sea level rise into account.

Data Layers

Several GIS layers were required as inputs to the inundation model. All data layers were in ArcInfo grid format (raster) with a resolution of 30 × 30 m pixel size. By working at a high spatial resolution, the model is able to address the spatial heterogeneity of the spring tide as well as the historical sea level rise rate.

The primary input layers included the following: current habitat (as of 1995), elevation relative to MTL (as of 1995), a layer delineating the historical rate of sea level rise, a layer delineating the spring tide range, and a separate layer for each of five armoring scenarios.

Two additional layers were created to delineate areas where no change in habitat was allowed to occur. The first of these "masks" covered two tidal deltas: Beach Haven Inlet and Barnegat Inlet (see Plate 21 in the appendix). The assumption was made that river- and tidal-borne sediments would replenish these areas. The second mask prevented any alteration of beaches on the eastern shore of the barrier island, because the assumption was made that beaches would be protected from inundation by nourishment with imported sand.

The "current" habitat layer was created by combining data from several source layers. The primary source was 1995 Landsat TM satellite data created by the Grant F. Walton Center for Remote Sensing and Spatial Analysis at Rutgers University.[738] The Landsat data were then combined with another layer from Rutgers of SAV that showed the extent of this vegetation as of 1999.[739] Data showing the extent of intertidal flats and subtidal pools, from NWI data,[740] were combined with the other two layers to produce a

[736]Titus and Narayanan, 1995 (see note 3); Huybrechts et al., 2001 (see note 1).
[737]Bruhn, P., 1962, "Sea level rise as a cause of shore erosion," American Society of Civil Engineers, *Journal of Waterways and Harbor Division* 88:117–130.

[738]CRSSA, 2000 (see note 721).
[739]CRSSA, 1999, Rutgers University, 19991118, Submerged Aquatic Vegetation in Barnegat Bay — 1999. Digital GIS data, Center for Remote Sensing and Spatial Analysis.
[740]USFWS, n.d., National Wetlands Inventory, accessed on December 28, 2001, at http://www.nwi.fws.gov.

Table 3.2. Habitat classifications and elevation ranges

Modeled habitat description	Elevation range[a]
Beach	na
Marine/estuarine unconsolidated shore: mud/organic	< = MTL
S. alterniflora	> MTL to LM
S. patens	> LM to HM
Phragmites australis[b]	> LM
Upland	> HM
Open water	MTL to –1 m
Upland	> HM
SAV beds	< = MTL
Marine/estuarine intertidal flats	< = MTL
Marine/estuarine subtidal pools	< = MTL
Intertidal mixed wetlands	na

[a] Upper elevations calculations:
HM = [MTL + (Spring tide range/2) + 0.3048 m]
LM = [0.666 * (Spring tide range/2)]
[b] *Phragmites* occurs both within the HM range and above HM range.

final composite habitat layer. One final modification was made to add a strip of wetlands where unarmored wetland abuts open water (intertidal mixed wetlands) to more realistically estimate the current habitat.

The elevation layer was created through interpolation of USGS DLG contours, U.S. Army Corps of Engineers point spot elevation data, and wetland boundaries created by the New Jersey Department of Environmental Quality. Elevations were relative to MTL and were adjusted from the 1969 tidal epoch to 1995 using the historical rate of sea level rise. Spring tide range and historical sea level rise rate layers were generated by interpolation of tide gauge data.

Modeled Habitats

The model evaluated potential changes in the areal extent of tidal wetland habitats (*Phragmites*, *S. alterniflora*, and *S. patens*), sandy beaches, SAV, and open water habitat. All upland habitats were modeled as a single "upland" category, intertidal habitats were not modeled, and it was assumed that beach loss would be minimal because of beach nourishment of the majority of beaches in the study area.

Using the set of input layers, the program determines for each 30 × 30 m pixel of habitat, elevation relative to MTL, spring tide range, and historical sea level rise rate. The elevation ranges for specific habitats are shown in Table 3.2. Changes in habitat type were based on elevation changes relative to MTL resulting from net sea level rise (historical sea level rise rate, plus acceleration rate, minus estimated accretion rate) over 200 years and the relation of each habitat to the spring tide range (see Figure 3.2).

Because the habitat and elevation data sets were derived independently, the initial 1995 habitat layer does not always correspond to the elevation range outlined in Table 3.2. These elevation/habitat "mismatches" are preprocessed by the model before any further processing by adjusting the elevation at that location to the elevation appropriate to the habitat found there.

Scenarios Evaluated

We used the model to examine habitat changes on an annual basis over a period of 200 years under various sea level rise rates and armoring scenarios. In addition, a historical scenario was developed to predict what type of wetland habitat would have existed in currently developed areas in the absence of development. Sea level rise was not taken into account for this scenario. For all scenarios, it was assumed that local communities would replenish beaches as needed.

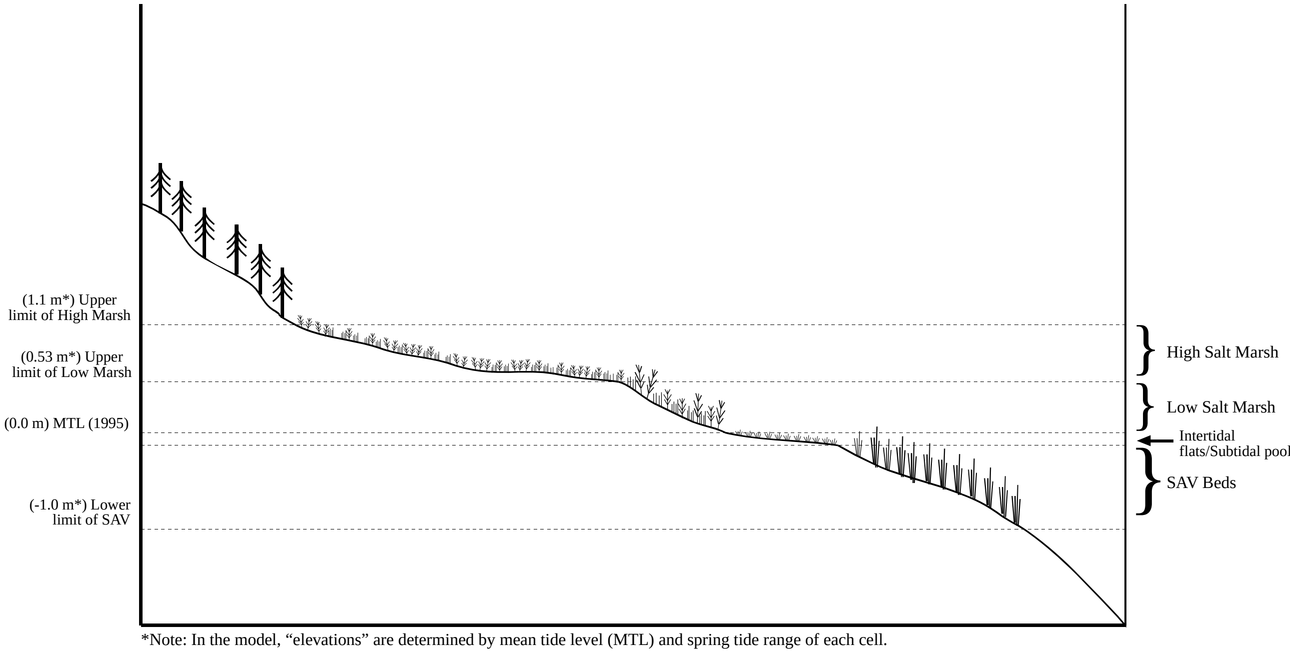

Figure 3.2. Hypothetical shoreline profile showing relationship between habitat type and elevation range relative to 1995 mean tide level (MTL).

The sea level rise and armoring scenarios were digitally mapped, and changes in the areal extent of various habitat classes under different scenarios were quantified. Two accelerated sea level rise rates were evaluated, 3 and 9 mm annual increases above the historical rate. For each sea level rise rate, six levels of response to sea level rise were evaluated: no armoring; current level of armoring; armoring scenario 1 (areas where there is a legal right to hold back the sea); armoring scenario 2 (areas that will probably be armored based on the best judgment of local planners); armoring scenario 3 (the same as scenario 2 except that no armoring is assumed in areas identified by planners where wetland migration might occur, because of increased environmental concerns or doubts about the cost-effectiveness of shore protection); and armoring scenario 4 (areas that should not be armored based on environmental considerations). The armoring scenarios were developed in consultation with local planners.

Armoring scenarios assumed placement of armored structures such as bulkheads on the landward side of mean high water (MHW)[741] or mean higher high water (MHHW).[742]

Methods for Quantifying Changes in Biota

Because the focus of our habitat analysis was on tidal marshes, SAV, and open water, estimates of changes in biota focused on species in these habitats, with a focus on avifauna, finfish, and nekton. Because of a general lack of data on the production of such species in these habitats, this version of the model makes the simplifying assumption that in most cases species losses will be proportional to habitat losses. This assumption can be modified as more data become available.

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[741]The average height of high waters (maximum height reached by a rising tide) over a 19 year period.
[742]The average height of the higher high waters (the higher of two high waters of a tidal day) over a 19 year period.

Table 3.3. Modeling assumptions for bird species

Species	Habitat	Modeling assumptions
Migrating waterfowl — dabbling ducks	SAV	Stable population until habitat loss exceeds 33%, then 1:1 decrease in abundance with loss of SAV
Migrating waterfowl — diving ducks	Open water	Increase in wintering habitat, but no increase in population, because limiting factors are probably not winter habitat
Loons, grebes	Open water	Increase in wintering habitat, but no increase in population, because limiting factors are probably not winter habitat
Mergansers, buffleheads	Open water	25% increase in abundance with increase in area of open water
Songbirds — marsh wrens	*Phragmites* marsh	1:1 decrease in abundance with loss of *Phragmites*
Songbirds — seaside sparrows	*S. alterniflora* marsh	1:1 decrease in abundance with loss of *S. alterniflora*
Songbirds — sharp-tailed sparrows	*S. patens* marsh	1:1 decrease in abundance with loss of *S. patens*

Table 3.4. Modeling assumptions for finfish in SAV and *Spartina* marshes

Species	Habitat	Modeling assumptions
Finfish: fourspine stickleback (*Apeltes quadracus*) naked goby (*Gobiosoma bosci*) northern pipefish (*Syngnathus fuscus*) rainwater killifish (*Lucania parva*)	SAV	1:1 decrease with loss of SAV
Finfish: Atlantic silverside (*Menidia menidia*) mummichog (*Fundulus heteroclitus*) bay anchovy (*Anchoa mitchilli*)	*Spartina* marsh	1:1 decrease with loss of *Spartina* marsh

Birds

Table 3.3 summarizes our assumptions about how the relative abundances of representative bird species in the study area will change with changes in the areal extent of different habitats. These assumptions are based on best professional judgment. The inundation model does not consider salt marsh islands or intertidal sand and mudflats, and assumes that there will be beach nourishment on the ocean side of the barrier island, which represents the majority of the beach habitat. Therefore, our analysis does not consider potential changes in migratory shorebirds, nesting shorebirds, or colonial nesting birds that depend on these habitats.

Estimations of changes in dabbling duck abundance in SAV are based on the assumption that current SAV can accommodate a 50 percent annual variation in bird abundance, but that loss of greater than 33 percent of SAV habitat will result in a 1:1 decrease in dabbling duck abundance. For birds using open water habitats in winter, increases in open water will provide increased habitat, but will not result in population increases, because the limiting factors on diving duck, loon, grebe, and merganser populations are not likely to be wintering habitat. For birds breeding in marsh habitats, the long-term percent change in bird abundance is assumed to be the same as the long-term habitat change.

Relative Abundances of Finfish in Spartina Marshes and SAV

Relative abundances of fish in SAV and tidal marsh were modeled on the basis of data from Great Bay-Little Egg Harbor, adjacent to the Barnegat Bay study area.[743] As indicated in Table 3.4, we assumed that there will be declines in the growth, survival, or reproduction of the

[743] Sogard and Able, 1991 (see note 94).

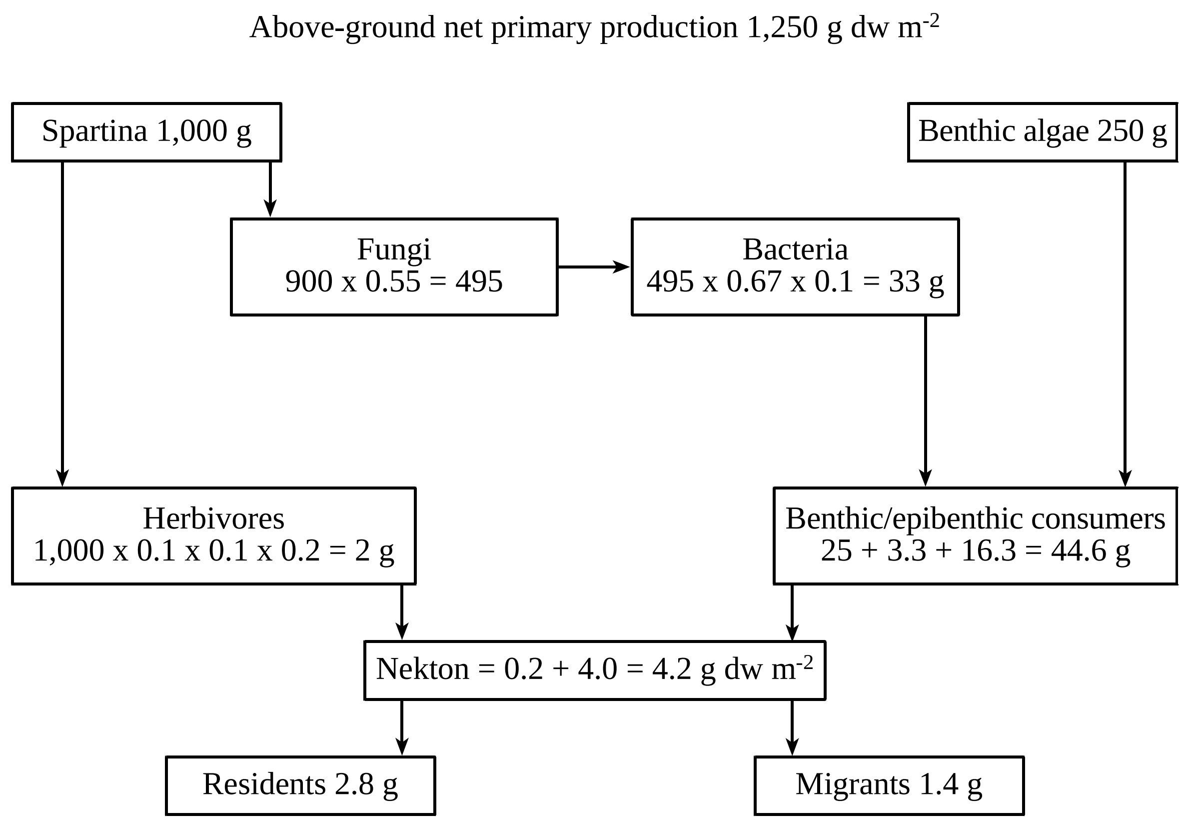

Figure 3.3. Production flows to nekton from net annual marsh primary production.
Source: After Figure 1 in Kneib (see text note 276).

dominant species in each habitat, resulting in declines in abundance proportional to habitat losses.

Annual Production of Nekton in Spartina Marshes

We estimated annual production of nekton (actively swimming fish and shrimp) in *Spartina* marshes based on consultation with a local expert (Dr. Michael Weinstein, Director, New Jersey Sea Marine Sciences Consortium) and data and methods in Kneib.[744] Kneib used two alternative methods to estimate the annual production of nekton in tidal wetlands. First, Kneib developed an estimate of annual nekton production by multiplying estimated mean annual standing stock biomass by a production:biomass (P:B) ratio. Based on a review of the scientific literature, Kneib used a P:B ratio of 2 for marsh fishes, 3 for penaeid shrimp, and 5 for caridean shrimp. On this basis, Kneib estimated that annual nekton production in *Spartina* marshes averages 1.5 g dry weight (g dw) m^{-2}.

Kneib also developed a simple trophic transfer model to estimate the annual production of nekton resulting from the annual above-ground production of *Spartina alterniflora*. The model is based on the premise that the primary production of salt marshes is linked to the secondary production of both resident and transient nekton.[745] Kneib's model is summarized in Figure 3.3.

[744]Kneib, 1997 (see note 17).

[745]Weinstein, 1979 (see note 361); Weinstein, M.P., 1983, "Population dynamics of an estuarine-dependent fish, the spot (*Leisotomus xanthurus*) along a tidal creek-seagrass meadow coenocline," *Canadian Journal of Fisheries and Aquatic Sciences* 40:1633–1638; Weigert, R.G. and L.R. Pomeroy, 1981, "The salt-marsh ecosystem: A synthesis," in *The Ecology of a Salt Marsh*, L.R. Pomeroy and R.G. Weigert (eds.), Springer Verlag, New York, pp. 219–230; Boesch and Turner (see note 318); Deegan, L.A., 1993, "Nutrient and

The model estimates that a total of 4.2 g dw m^{-2} of nekton is supported by the original 1,250 g dw m^{-2} of above-ground plant production. Of this total, Kneib assumed that two-thirds (2.8 g) are resident species (e.g., killifishes such as *Fundulus* spp.) and one-third (1.4 g) are estuarine migrants (e.g., juvenile white shrimp *Litopenoeus setiferus*).[746] Estimates in other studies of annual productivity of fish and shrimp in tidal marshes range from 9 to 16 g dw m^{-2} yr^{-1} for shrimp, from 10.2 to 16 g dw m^{-2} yr^{-1} for mummichog (*Fundulus heteroclitus*), and from 22.1 to 48.5 g dw m^{-2} yr^{-1} for total fish (review in Strange et al.[747]). Many of these studies estimate secondary productivity based on the total regional fisheries yield per unit area of supporting marsh. These results suggest that Kneib's estimate of 4.2 g dw m^{-2} may represent a lower bound estimate of marsh secondary productivity.

Results and Discussion

Results of the pilot study make clear that as armoring increases in response to anticipated sea level rise, there are likely to be substantial adverse impacts to certain coastal habitats and the species supported by those habitats. Even minimal armoring is predicted to substantially reduce the abundance and production of finfish and birds in coastal areas as critical habitats are lost or converted.

Habitat Changes

The appendix (map plates) and Table 3.5 show predicted changes in the distribution of the modeled coastal habitat types after 200 years under the different sea level rise and armoring scenarios. The predicted change in the areal extent of *S. alterniflora* is shown in Figure 3.4, *S. patens* in Figure 3.5, *Phragmites* in Figure 3.6, SAV in Figure 3.7, and open water in Figure 3.8.

Under all sea level rise and armoring scenarios, there are substantial declines in *Spartina* marshes, with more *S. patens* marsh lost compared to *S. alterniflora* marsh. This is to be expected given the lower accretion rate of *S. patens* marsh. The greatest declines in both *S. alterniflora* and *S. patens* occur under armoring scenario 1 for both 3 and 9 mm accelerated sea level rise rates.

Phragmites marsh, which is assumed to accrete at a rate that is five times higher than *S. alterniflora*, persists under a 3 mm accelerated sea level rise rate, but declines under a 9 mm increase.

SAV increases under armoring scenario 4, assuming a 3 mm accelerated rate of sea level rise. In contrast, SAV declines substantially under all 9 mm scenarios. The greatest decline in SAV occurs under the assumption of a 9 mm rate of sea level rise and armoring scenario 1.

Open water habitat increases under all sea level rise scenarios. The greatest increase occurs under the unarmored scenario and a 9 mm accelerated sea level rise rate. Note that because the model assumes that there will be beach nourishment for the majority of beaches in the study area, the extent of sandy beach habitat is relatively unchanged.

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energy transport between estuaries and coastal marine ecosystems by fish migration," *Canadian Journal of Fisheries and Aquatic Science* 50:74–79; Weinstein, M.P. and S.Y. Litvin, 2000, "The role of tidal salt marsh as an energy source for marine transient and resident finfishes: A stable isotope approach," *Transactions of the American Fisheries Society* 129:797–810; Kneib, 1997 (see note 17); Kneib, 2003 (see note 276); Deegan et al., 2000 (see note 428), in Weinstein and Kreeger, pp. 333–368 (see note 410).

[746] Kneib, 2003 (see note 276).

[747] Strange, E., H. Galbraith, S. Bickel, D. Mills, D. Beltman, and J. Lipton, 2002, "Determining ecological equivalence in service-to-service scaling of salt marsh restoration," *Environmental Management* 20:290–300.

Table 3.5. Area comparison of current (1995) coastal habitat (in hectares) to estimates modeled under six shoreline protection (armoring) scenarios and two accelerated sea level rise rates above the historical rate

	3 mm[a] accelerated sea level rise					9 mm[a] accelerated sea level rise				
Scenario	**Low salt marsh *S. alterniflora* dominant**	**High salt marsh *S. patens* dominant**	**High salt marsh *Phragmites australis* dominant**	**Marine/ estuarine open water**	**Sub-aquatic vegetation**	**Low salt marsh *S. alterniflora* dominant**	**High salt marsh *S. patens* dominant**	**High salt marsh *Phragmites australis* dominant**	**Marine/ estuarine open water**	**Sub-aquatic vegetation**
Current (1995)	5,036	3,875	1,507	42,903	5,591	5,036	3,875	1,507	42,903	5,591
Unarmored	3,206	966	1,507	52,744	7,433	2,893	739	95	63,077	4,492
Current armoring	1,996	366	1,507	52,740	5,054	2,160	463	95	59,357	2,088
Armoring scenario 1[b]	1,625	211	1,507	52,737	3,940	1,551	196	95	57,788	954
Armoring scenario 2[c]	1,951	339	1,507	52,746	4,947	1,990	401	95	59,175	1,729
Armoring scenario 3[d]	2,081	395	1,507	52,742	5,461	2,143	456	95	59,905	2,231
Armoring scenario 4[e]	3,000	894	1,507	52,724	6,761	2,741	678	95	62,178	4,114

[a] 3 mm and 9 mm represent annual accelerated rates of sea level rise above the historical rate.

[b] Armoring scenario 1 = areas where there is a legal right to hold back the sea;

[c] armoring scenario 2 = areas that will probably be armored based on the best judgment of local planners;

[d] armoring scenario 3 = the same as scenario 2 except that no armoring is assumed in areas identified by planners where wetland migration might occur due to increased environmental concerns, or doubts about the cost-effectiveness of shore protection);

[e] armoring scenario 4 = areas that should not be armored based on environmental considerations.

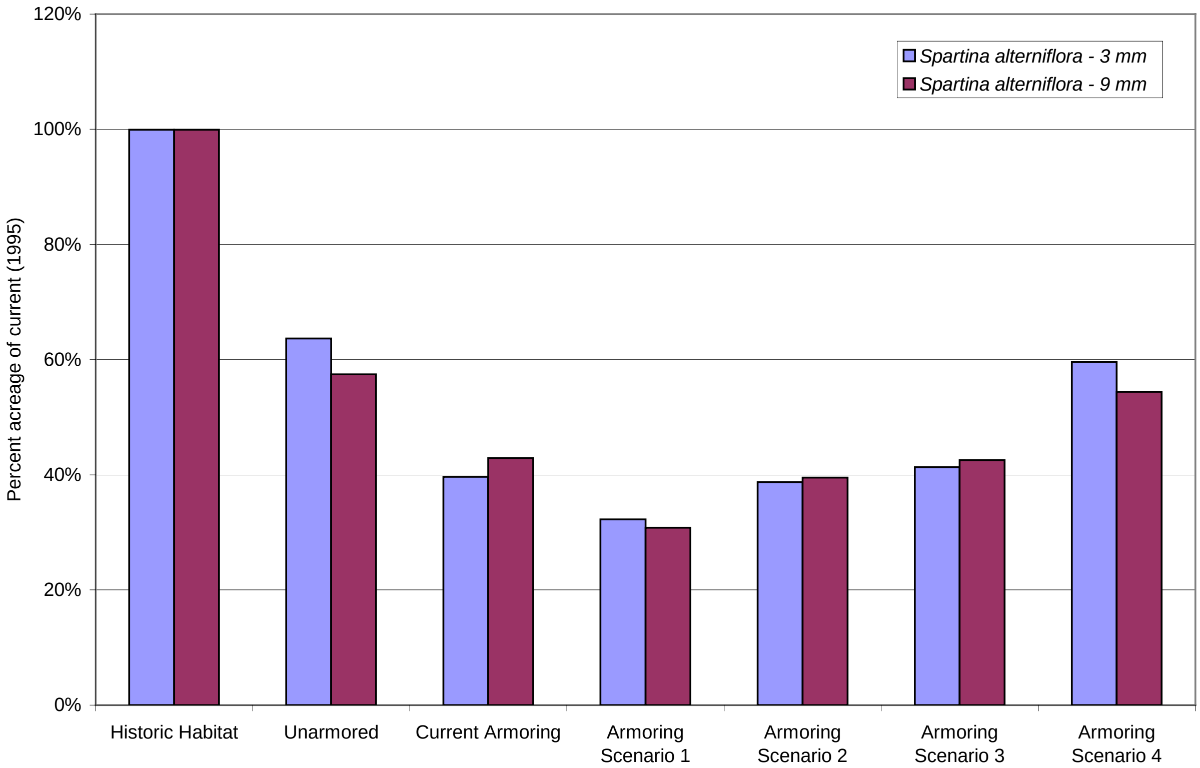

Figure 3.4. Under 3 and 9 mm accelerated sea level rise above historical levels by 2195 (200 years from 1995) and unarmored, current armoring, and four policy-derived armoring scenarios involving different degrees of armoring. (See notes in Table 3.5 for explanation of scenarios.)

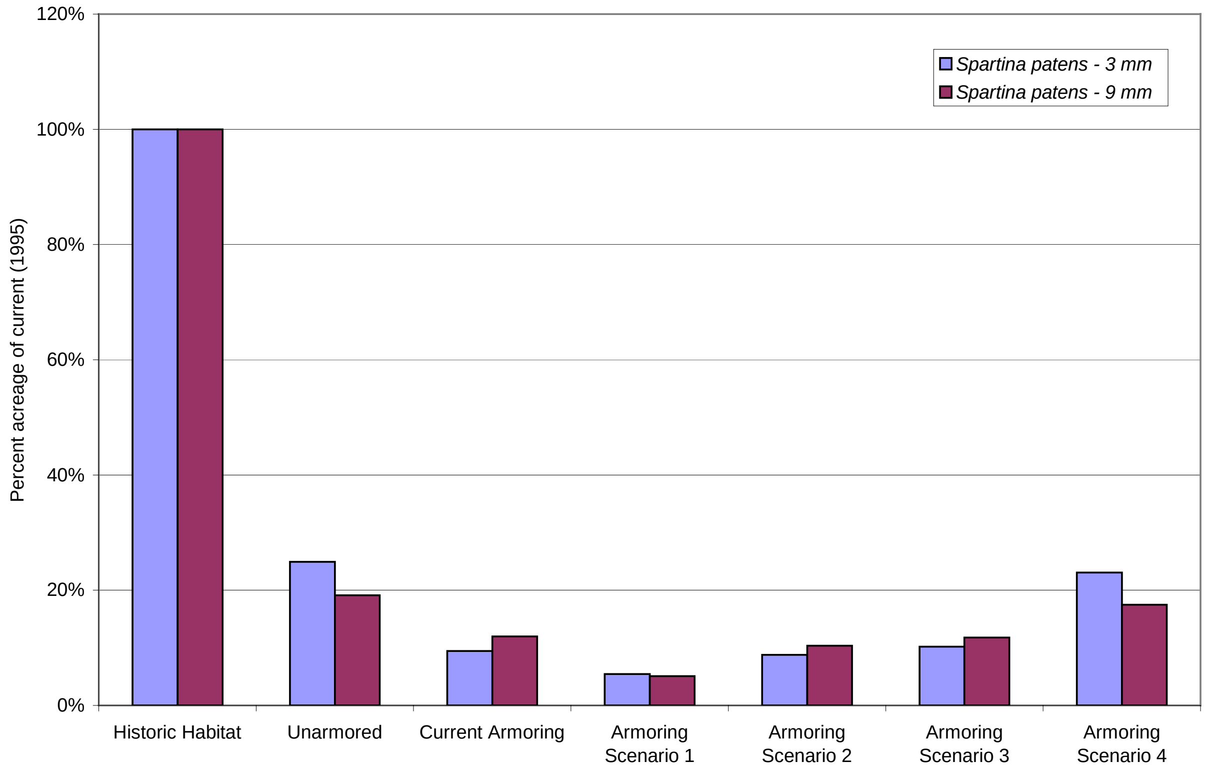

Figure 3.5. Comparison of current and historical acreages of *S. patens* high saltmarsh habitat to inundation-modeled acreages under 3 and 9 mm accelerated sea level rise above historical levels by 2195 (200 years from 1995) and unarmored, current armoring, and four policy-derived armoring scenarios involving different degrees of armoring. (See notes in Table 3.5 for explanation of scenarios.)

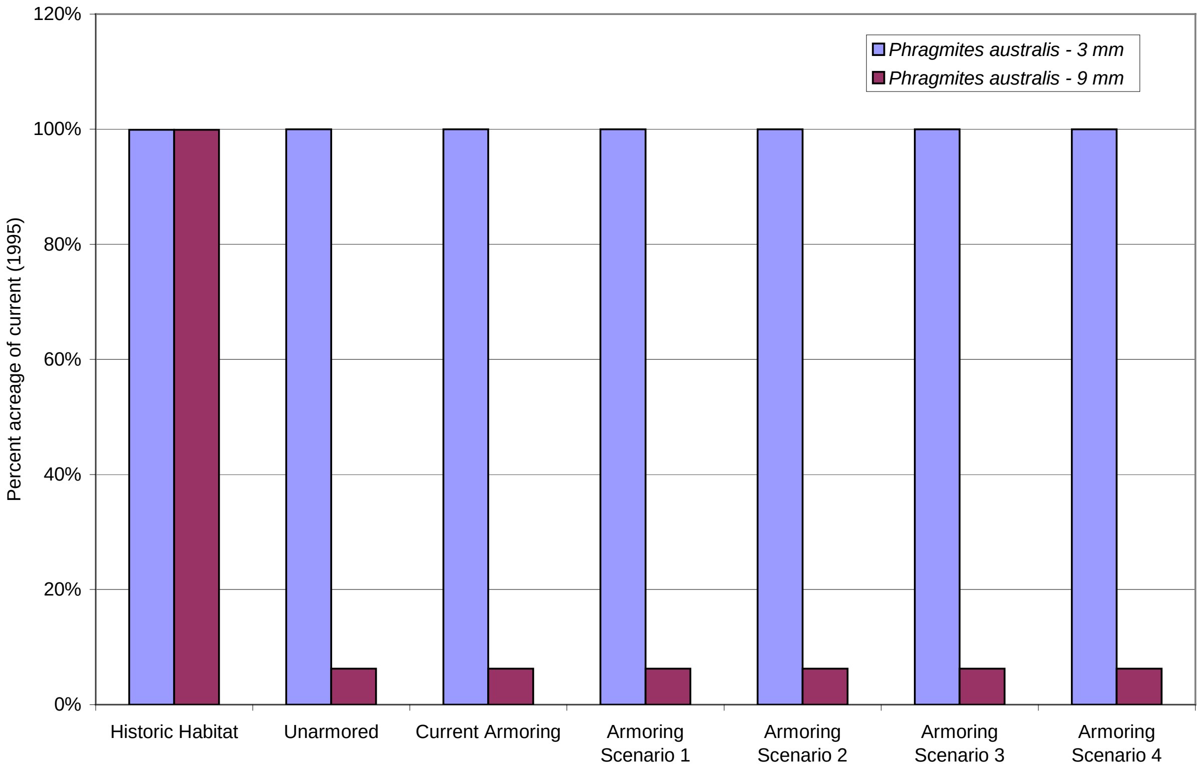

Figure 3.6. Comparison of current and historical acreages of *Phragmites australis* (high saltmarsh and upland) habitat to inundation-modeled acreages under 3 and 9 mm accelerated sea level rise above historical levels by 2195 (200 years from 1995) and unarmored, current armoring, and four policy-derived armoring scenarios involving different degrees of armoring. (See notes in Table 3.5 for explanation of scenarios.)

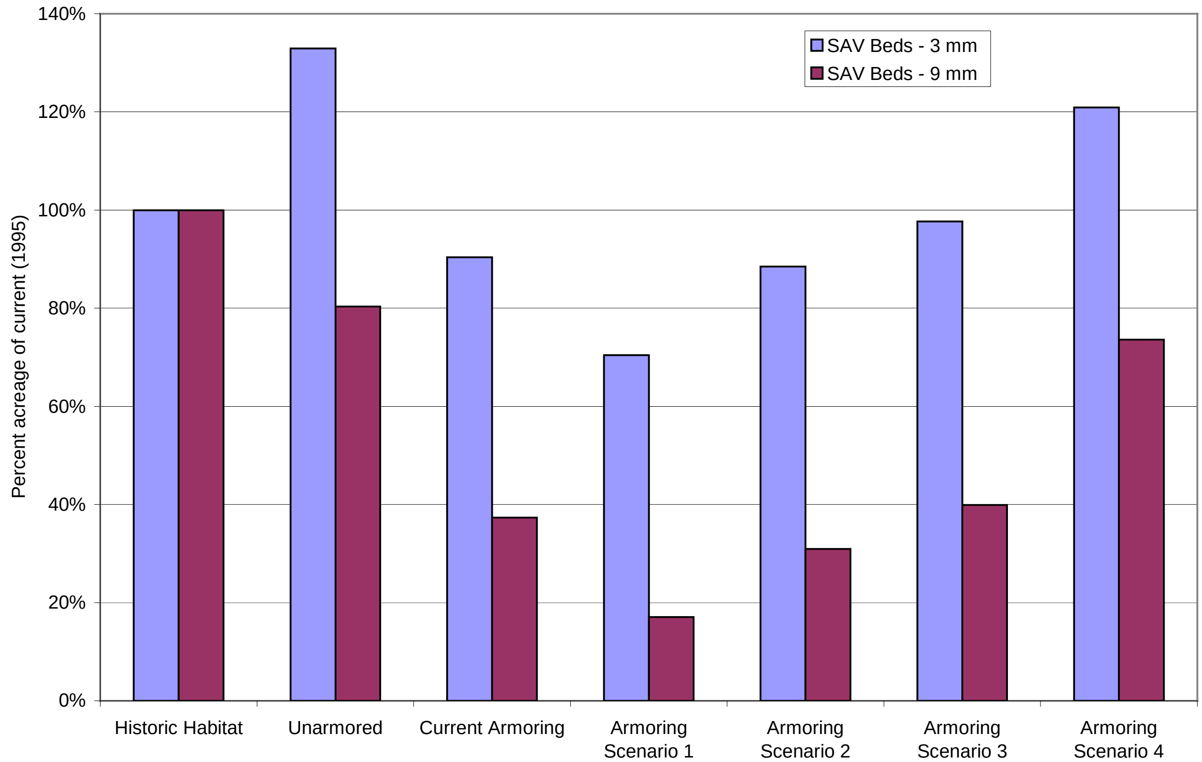

Figure 3.7. Comparison of current and historical acreages of SAV to inundation-modeled acreages under 3 and 9 mm accelerated sea level rise above historical levels by 2195 (200 years from 1995) and unarmored, current armoring, and four policy-derived armoring scenarios involving different degrees of armoring. (See notes in Table 3.5 for explanation of scenarios.)

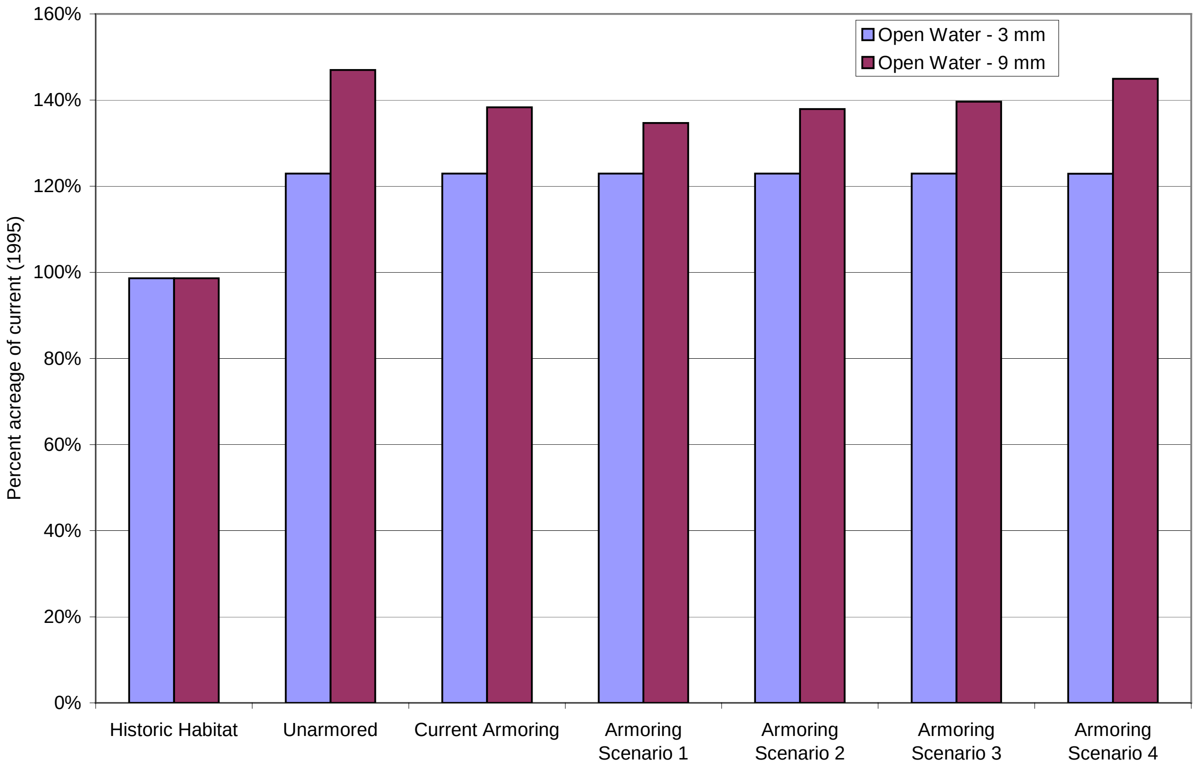

Figure 3.8. Comparison of current and historical acreages of open water to inundation-modeled acreages under 3 and 9 mm accelerated sea level rise above historical levels by 2195 (200 years from 1995) and unarmored, current armoring, and four policy-derived armoring scenarios involving different degrees of armoring. (See notes in Table 3.5 for explanation of scenarios.)

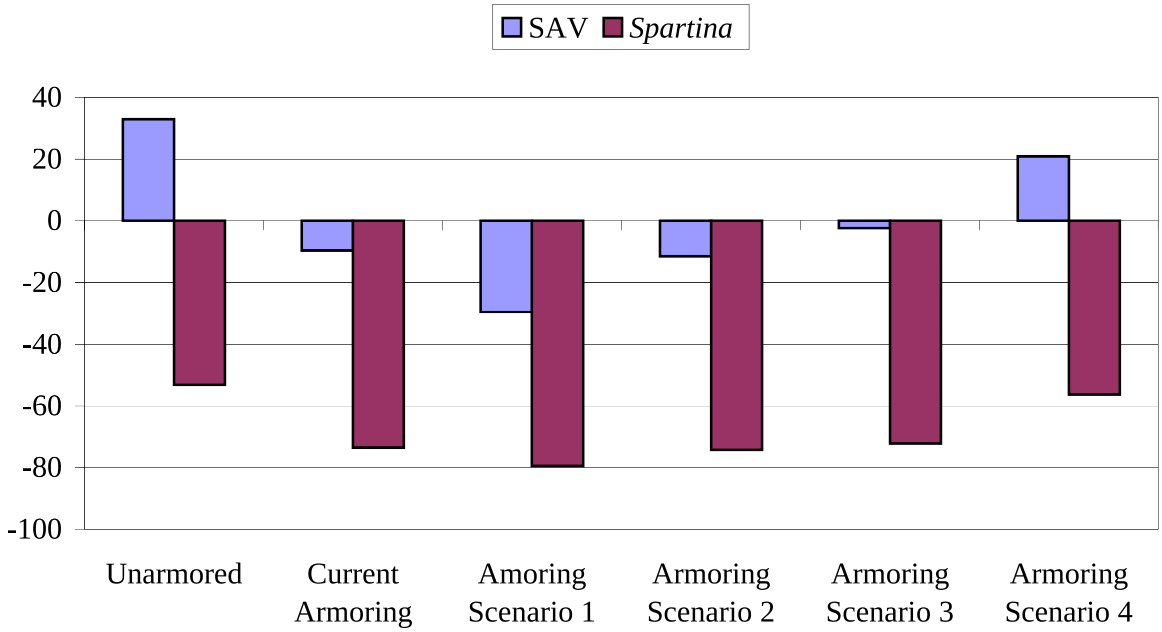

Figure 3.9. Percent change in relative abundances of fish species in *Spartina* and SAV by 2195 under 3 mm accelerated sea level rise. (See notes in Table 3.5 for explanation of scenarios.)

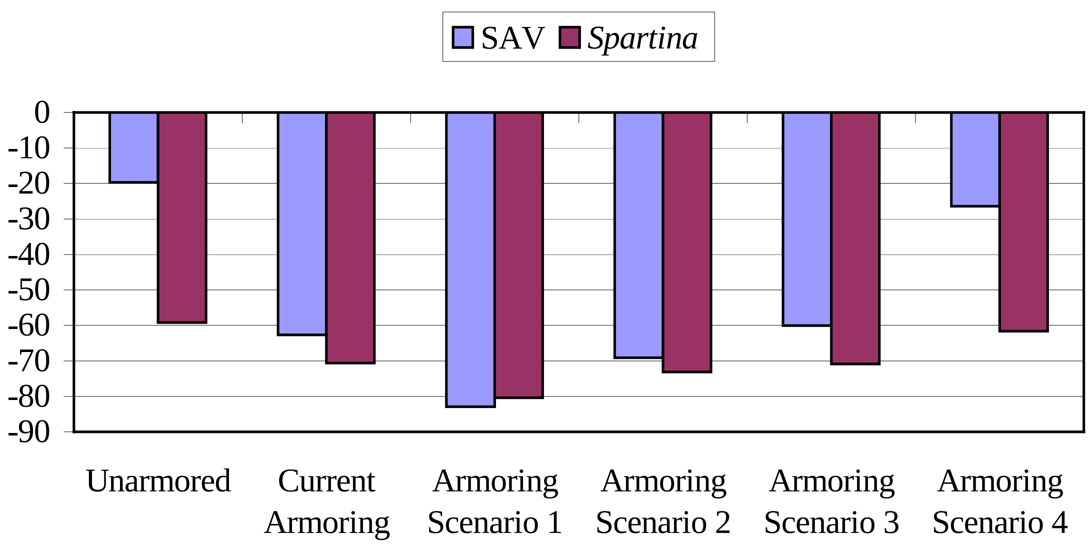

Figure 3.10. Percent changes in relative abundances of fish species in *Spartina* and SAV by 2195 under 9 mm accelerated sea level rise. (See notes in Table 3.5 for explanation of scenarios.)

Table 3.6. Current (1995) estimated annual production of nekton (in kg/ha/yr) in *Spartina* marsh in the study area

	Production under 3 mm accelerated sea level rise		Production under 9 mm accelerated sea level rise	
Scenario	Low estimate	High estimate	Low estimate	High estimate
Current (1995)	133,666	374,265	133,666	374,265

Table 3.7. Estimated annual production in 200 years of nekton (in kg/ha/yr) in *Spartina* marsh in the study area under different rates of accelerated sea level rise and alternative armoring scenarios[a]

	Production under 3 mm accelerated sea level rise		Production under 9 mm accelerated sea level rise	
Scenario	Low estimate	High estimate	Low estimate	High estimate
No armoring	62,575	175,211	54,491	152,576
Current level of armoring	35,432	99,210	39,353	110,187
Armoring scenario 1	27,533	77,093	26,206	73,377
Armoring scenario 2	34,348	96,175	35,876	100,454
Armoring scenario 3	37,134	103,976	38,983	109,151
Armoring scenario 4	58,413	163,557	51,280	143,583

[a] See notes in Table 3.5 for explanation of scenarios.

Changes in Relative Abundances of Finfish in Spartina *Marsh and SAV*

Figure 3.9 shows predicted percent changes in the relative abundances of resident finfish in SAV and *Spartina* marsh under 3 mm accelerated sea level rise and different degrees of armoring based on data in Sogard and Able.[748] Figure 3.10 provides results under 9 mm accelerated sea level rise. SAV-dependent fish species increase under the unarmored scenario and armoring scenario 4 assuming a 3 mm accelerated rate of sea level rise, but decline substantially under all scenarios with a 9 mm rise. By contrast, declines of *Spartina*-dependent fish species are substantial under all sea level rise and armoring scenarios.

Annual Production of Resident and Transient Marsh Nekton

As indicated in the previous section, results of Kneib indicate that production of nekton in *Spartina* marshes ranges from 15 kg/ha/yr (1.5 g m^{-2}) based on P:B ratios to 42 kg/ha/yr (4.2 g m^{-2}) based on trophic transfer of marsh primary production to nekton.[749] To account for uncertainty, these estimates were used as lower and upper bound estimates of production. On this basis, Table 3.6 presents estimated annual production in the study area under current (1995) conditions, and Table 3.7 presents predicted changes by 2195 under the different sea level rise and armoring scenarios.

Annual production of nekton declines substantially as *Spartina* marsh is lost, ranging from a decline of about 50–75 percent under a 3 mm accelerated sea level rise rate to about 60–80 percent under 9 mm. Such potentially dramatic declines in the annual production of nekton is of particular concern because many of these species, such as spot (*Leiostomus xanthurus*) and white perch (*Morone americana*), are important for commercial and recreational fisheries.

Changes in Relative Abundances of Birds in Spartina *Marshes, SAV, and Open Water*

Figure 3.11 shows predicted changes in the relative abundances of representative bird species in SAV, *S. alterniflora*, and *S. patens* under 3 mm accelerated sea level rise and

[748] Sogart and Able, 1991 (see note 94).

[749] Kneib, 2003 (see note 276).

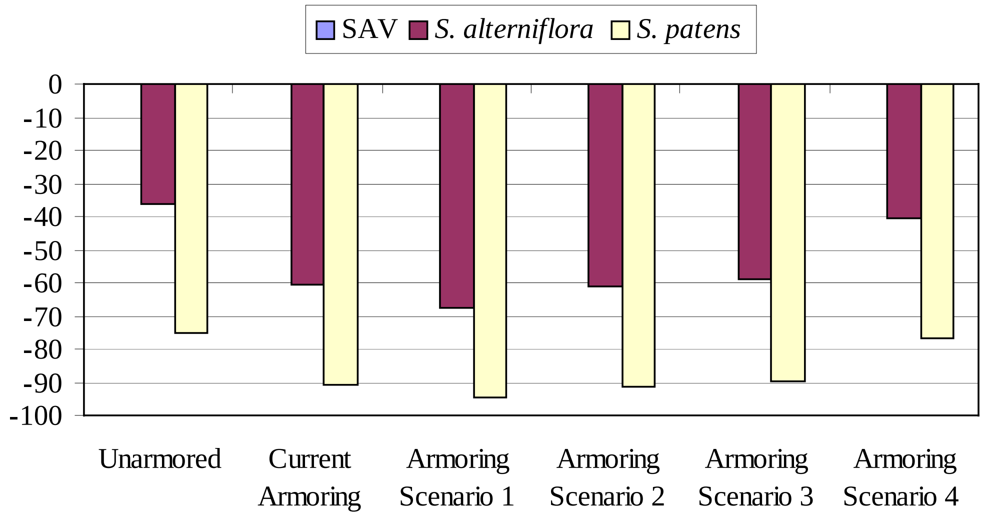

Figure 3.11. Percent changes in relative abundances of bird species by 2195 under 3 mm accelerated sea level rise. (See notes in Table 3.5 for explanation of scenarios.)

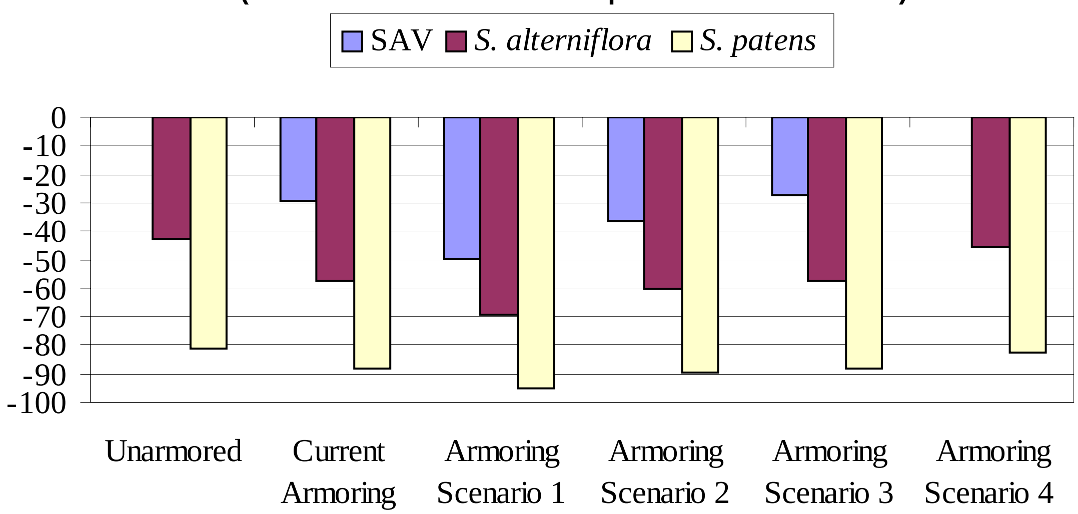

Figure 3.12. Percent changes in relative abundances of bird species by 2195 under 9 mm accelerated sea level rise. (See notes in Table 3.5 for explanation of scenarios.)

different degrees of armoring. Figure 3.12 provides results under 9 mm accelerated sea level rise. The greatest losses occur for songbirds

in *S. patens*, followed by songbirds in *S. alterniflora*. SAV-dependent species such as dabbling ducks show no change under a 3 mm accelerated sea level rise rate, and no change under a 9 mm accelerated sea level rise rate under the unarmored scenario and with minimal armoring (armoring scenario 4). However, under a 9 mm sea level rise, decreases in SAV-dependent bird species are significant with current armoring and armoring scenarios 1, 2, and 3. However, the percent change is still substantially less than for songbirds in *Spartina* marshes.

Conclusions and Directions for Future Research

The inundation and biological production models developed for this study function as intended and can be used to develop an order of magnitude approximation of changes in the production of birds, finfish, and shrimp under a variety of sea level rise and armoring scenarios. Such information can help guide stakeholders and decision-makers as they plan responses to anticipated sea level rise.

One of the unique features of this model is that it evaluates accretion, sea level rise, and habitat in a spatially explicit manner (i.e., on a cell by cell basis). This made it possible to use accretion rates specific to different marsh vegetation types

(1.5 mm/yr for *S. patens*, 2 mm/yr for *S. alterniflora*, and 10 mm/yr for *Phragmites*). Because *Phragmites* is assumed to accrete at such a relatively high rate, this vegetation type is able to keep pace with the 3 mm accelerated sea level rise rate.

In addition, our model is able to capture local variation in mean tide level and therefore sea level rise, rather than treating the entire area as a homogenous unit. This means the model was able to consider local tide levels related to subsidence, etc. The model can also be used to conduct a sensitivity analysis to examine the effects of different values of input parameters on model predictions. Model output can be generated for any time interval of interest.

The inundation model is flexible, and assumptions and mapping rules can be revised as needed for different study sites or to accommodate improved or additional physical and biological data. It is important to gather additional data to test the assumptions of this version of the model and to improve the accuracy and reliability of model predictions. This is particularly important because different scenarios of sea level rise rates and armoring may have different impacts on future coastal habitats than those predicted by our model based on current data and assumptions. This version of the inundation model examines potential changes in tidal marshes, SAV, sandy beaches, and open water habitats only, and makes a number of simplifying assumptions about how these habitats will change in response to sea level rise and shoreline armoring. Further analysis should examine other potentially important physical variables such as slope, overwash, fetch, and sediment inputs from the surrounding watershed to determine their relative influence on habitat predictions.

Future research should also address other habitats in addition to the four major habitat types considered here. For example, there are likely to be changes in the extent and distribution of intertidal mudflats. Loss of intertidal flats is expected to lead to declines in shorebirds such as semipalmated plover (*Charadrius semipalmatus*), red knot (*Calidris canutus*), and dunlin (*Calidris alpina*) that rely on these habitats for feeding during their migrations and over winter.[750]

Colonial nesting birds such as gulls and terns nest on salt marsh islands in the bay,[751] and loss of this habitat could also have important consequences. In 1989, more than 11,000 gulls, primarily laughing gulls (*Larus atricilla*), were observed in Barnegat Bay, and in 1995, 5,000 gulls, mostly herring gulls (*Larus argentatus*) and great black-backed gulls (*Larus marinus*), were observed. There were 5,000 terns observed in 1989 and 2,600 in 1995, mostly common tern (*Sterna hirundo*). In 1989 there was one colony of least tern (*Sterna antillarum*), a state-listed endangered species, and in 1989 there was one colony of Forster's tern (*Sterna forsteri*). Additional loss of the habitats that these species rely on from sea level rise may add significant stress to these populations that are already at risk.

For this analysis, we make the simplifying assumption that in most cases species losses will be proportional to habitat losses. Future versions of the model should examine other possible relationships between habitat loss and production of coastal biota. It will also be important to validate the assumptions of the trophic transfer model and the P:B ratio approach to estimating annual production of nekton. Other changes might include evaluation of the importance of the spatial configuration of habitat patches or patch size. It would also be useful to predict how sandy beach habitat and biota would change if no beach nourishment occurs. Beaches are essential for horseshoe crab spawning, and horseshoe crab eggs are a critical component of the diets of migratory birds. Therefore, losses of beaches could have important consequences for these species.

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[750]Galbraith et al., 2002 (see note 50); Galbraith, H., R. Jones, R. Park, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page, 2003, "Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds," in *Ecological Forecasting: New Tools for Coastal and Marine Ecosystem Management*, N. Valette-Silver and D. Scavia (eds.), NOAA technical memorandum NOS NCCOS 1, NOAA, Silver Spring, MD, pp. 19–22.

[751]USFWS, 1997 (see note 172).

Despite the limitations of the current version of the inundation and biological production models, results of this study make clear that there may be substantial changes in coastal habitats and biota in response to sea level rise and shoreline armoring, and that the model can be used to evaluate the potential effects of shoreline armoring on these resources. For this reason, it is imperative that tools such as these be refined to the extent possible to provide resource managers and stakeholders with the information necessary for planning responses consistent with resource goals.

The technical work that forms the basis for this report (this Section 3.20)was funded by the Global Programs Division of the U.S. Environmental Protection Agency's (EPA's) Office of Atmospheric Programs under Contract No. 68-W02-027. The report itself was prepared by Stratus Consulting with corporate development funds. James G. Titus, the EPA work assignment manager, developed the sea level rise and armoring scenarios that were evaluated as well as the habitat-elevation relationships used in the inundation model. Dr. Michael P. Weinstein of the New Jersey Marine Sciences Consortium, Sandy Hook Field Station provided valuable assistance with the analysis of effects on fish production of changes in marsh habitat. Dr. Michael Kearney of the University of Maryland developed accretion rates. ICF Consulting Inc. provided elevation data, and Industrial Economics developed the armoring scenarios in consultation with local planners. The conclusions presented in this report are those of the authors and do not represent the opinions of subcontractors or the official position of the EPA.

Appendix: GIS Maps of Modeled Habitat Changes

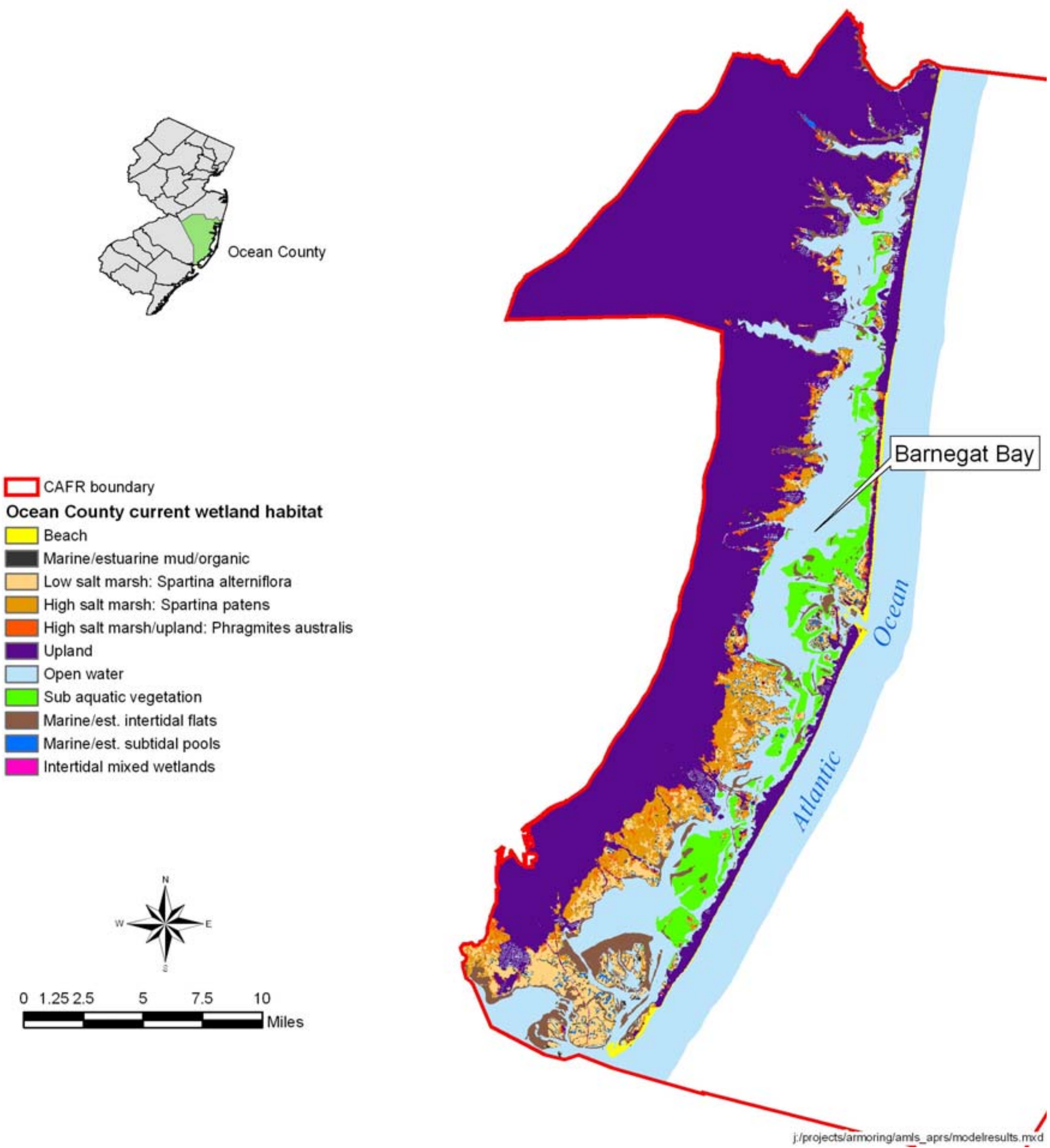


Plate 1. The study area along coastal Ocean County, New Jersey, including Barnegat Bay, inland to the boundary of the zone defined by New Jersey's Coastal Areas Facilities Review Act (CAFRA).

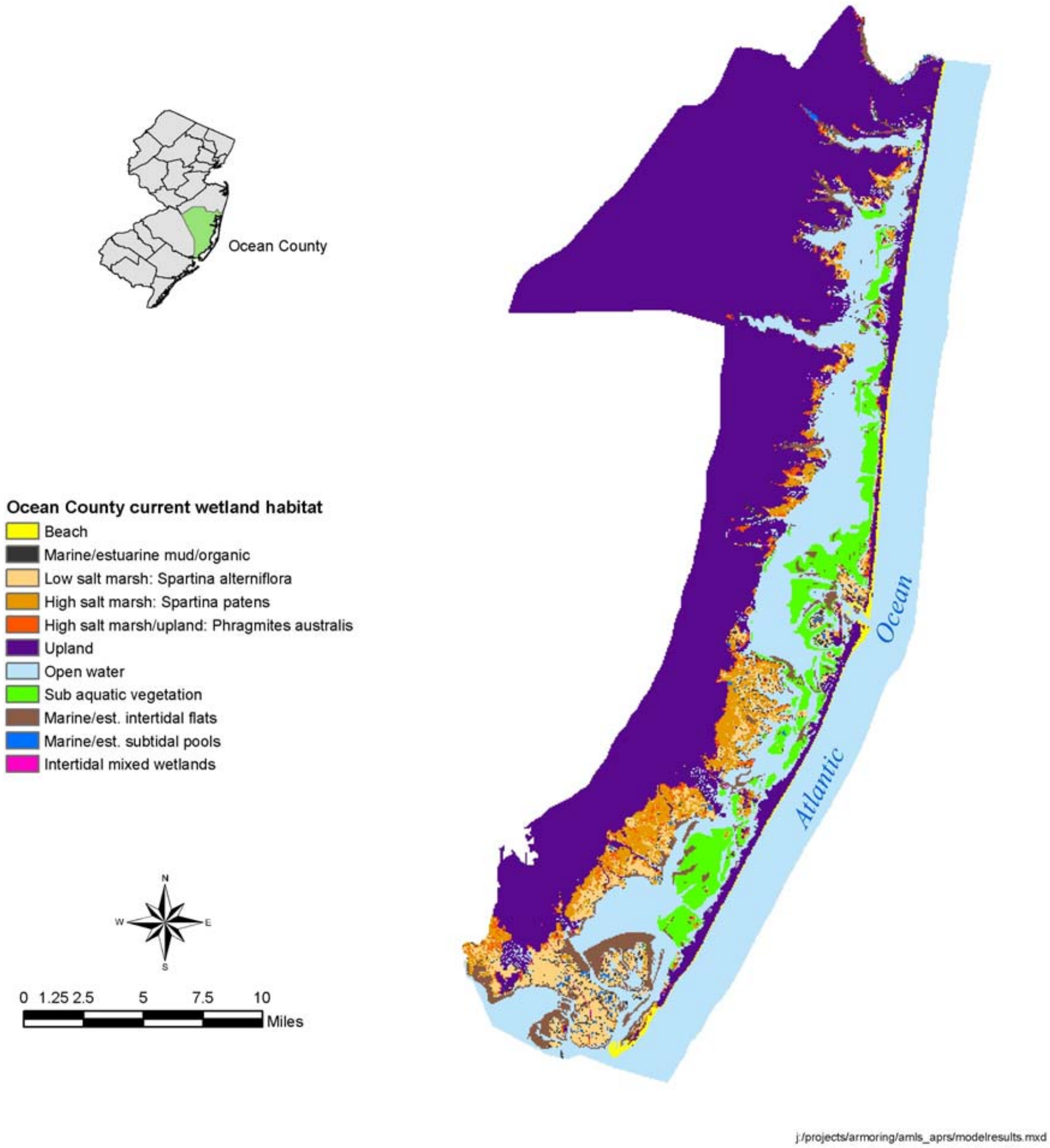


Plate 2. Distribution of wetland habitats as of 1995.

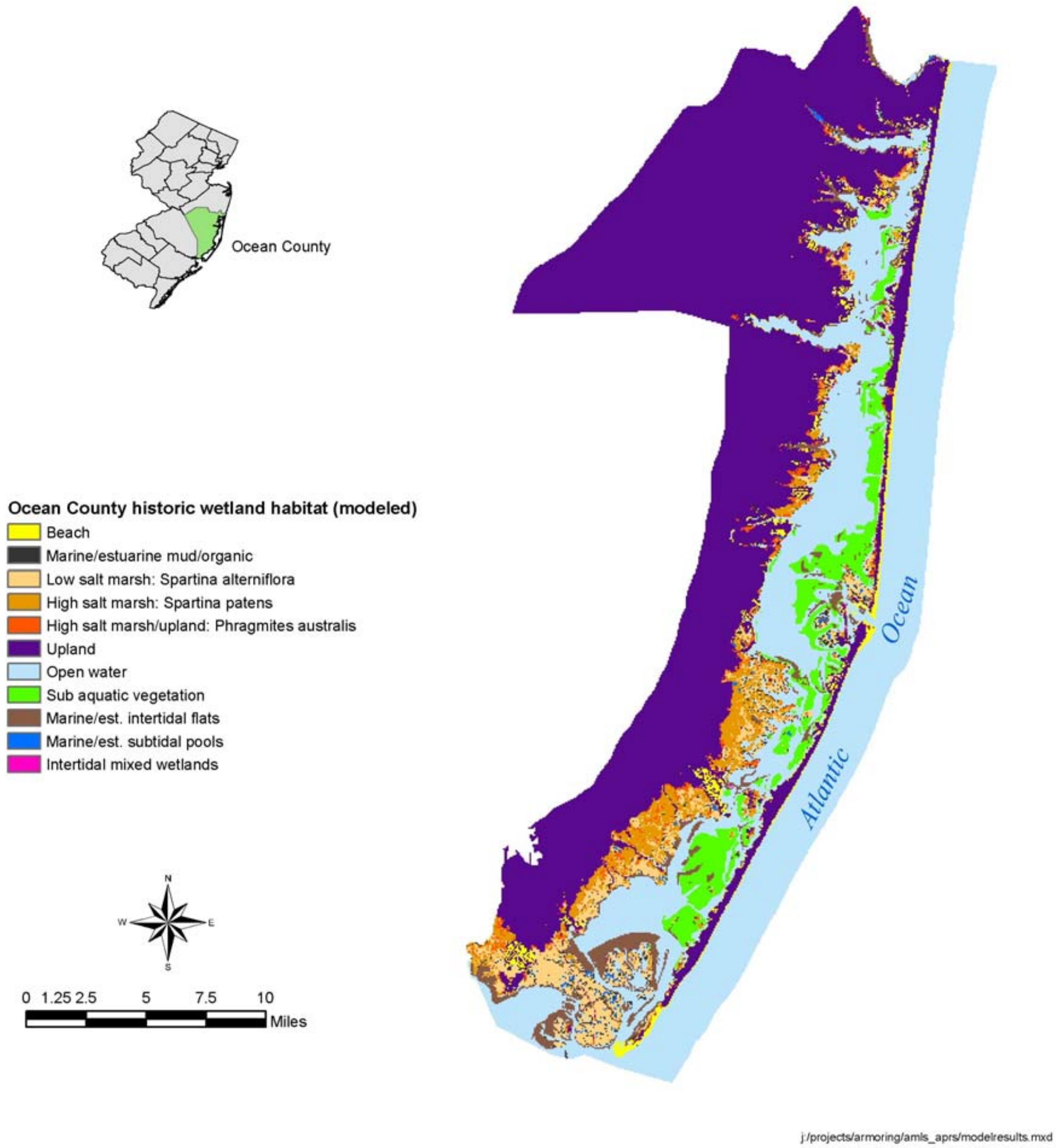


Plate 3. Distribution of wetland habitats estimated by conversion of developed lands into elevation-dependent wetland types.

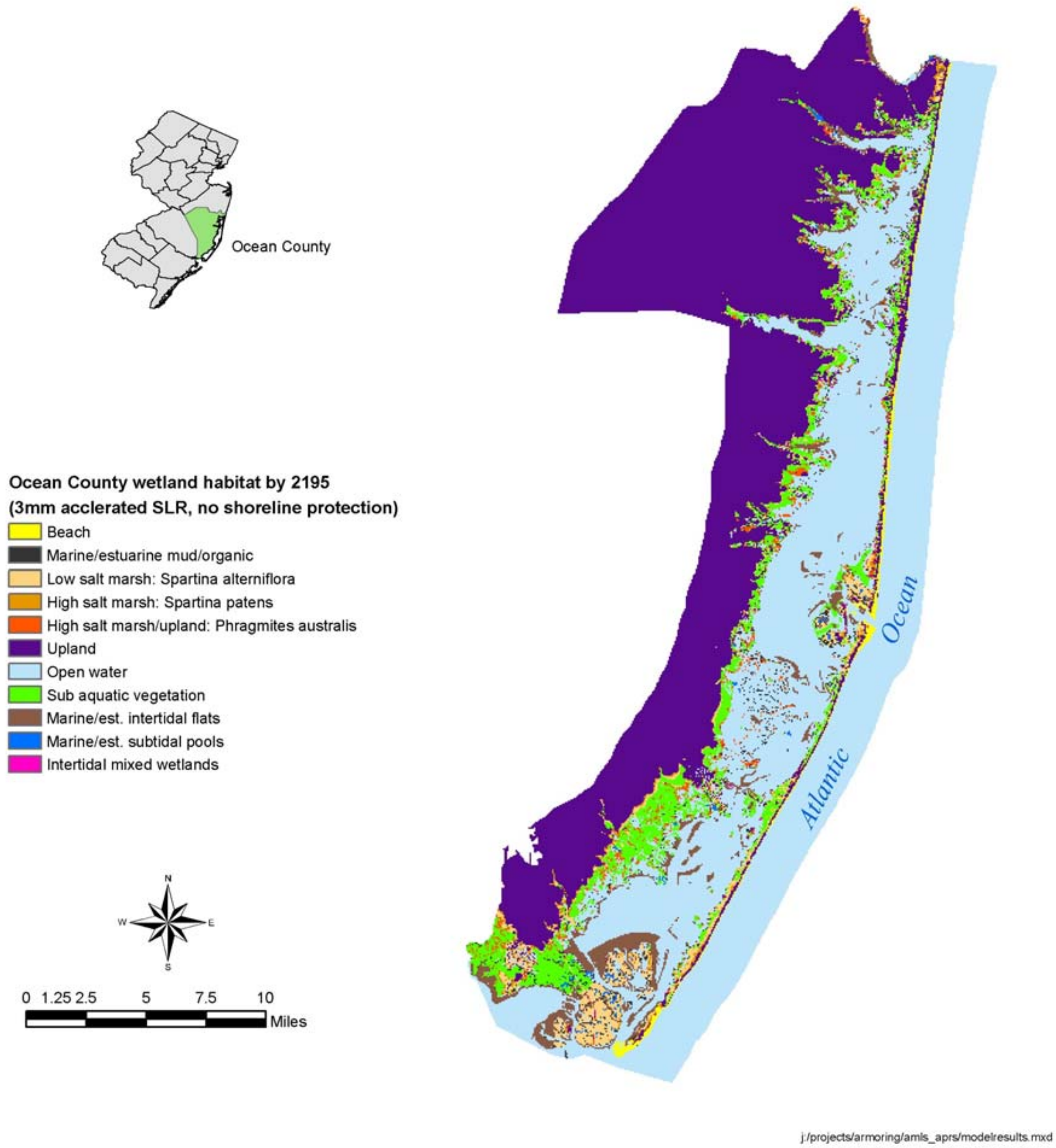


Plate 4. Distribution of wetland habitat types by 2195 modeled with no shoreline protection and 3 mm accelerated rate of SLR above the historic.

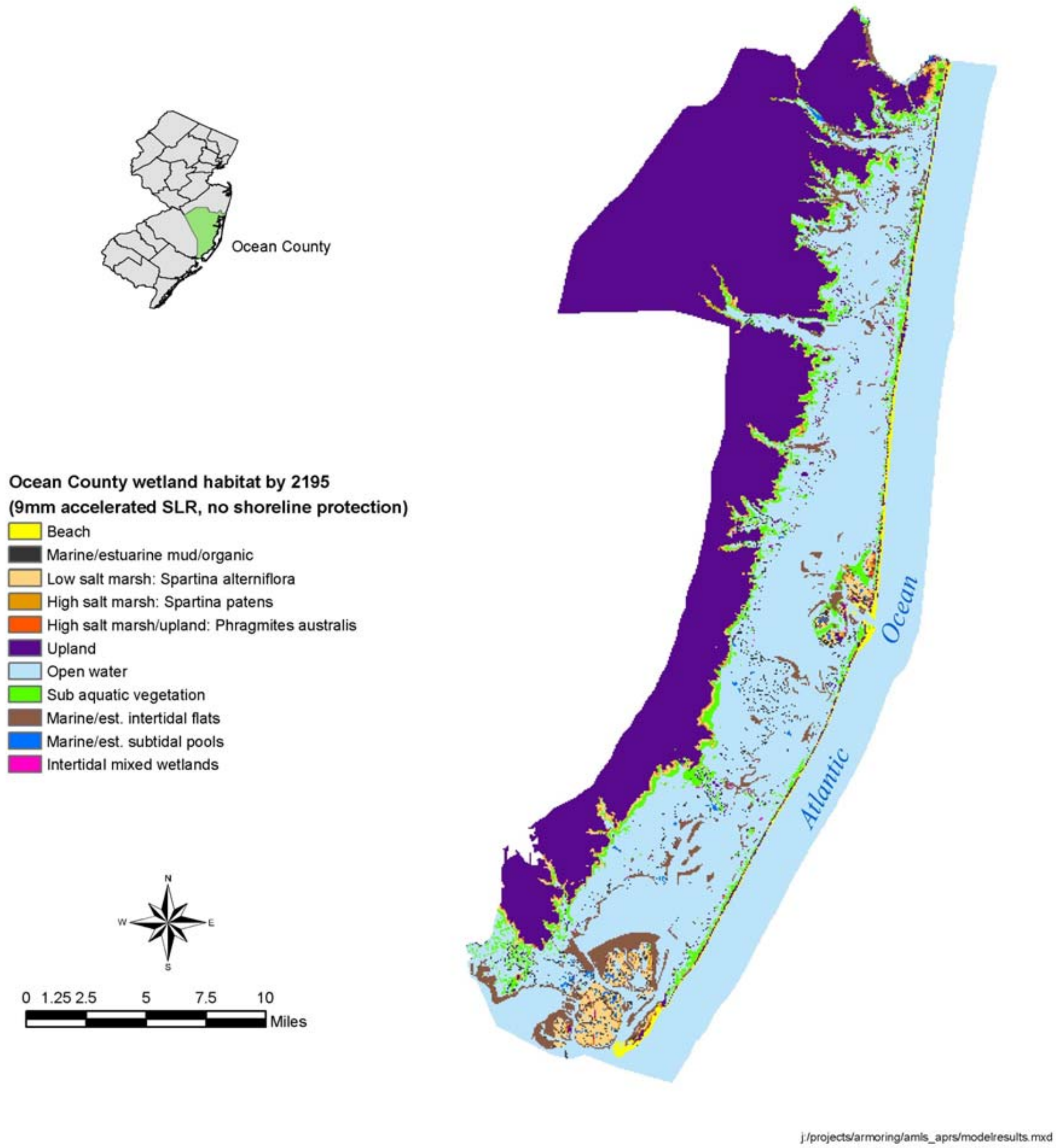


Plate 5. Distribution of wetland habitat types by 2195 modeled with no shoreline protection and 9 mm accelerated rate of SLR above the historic.

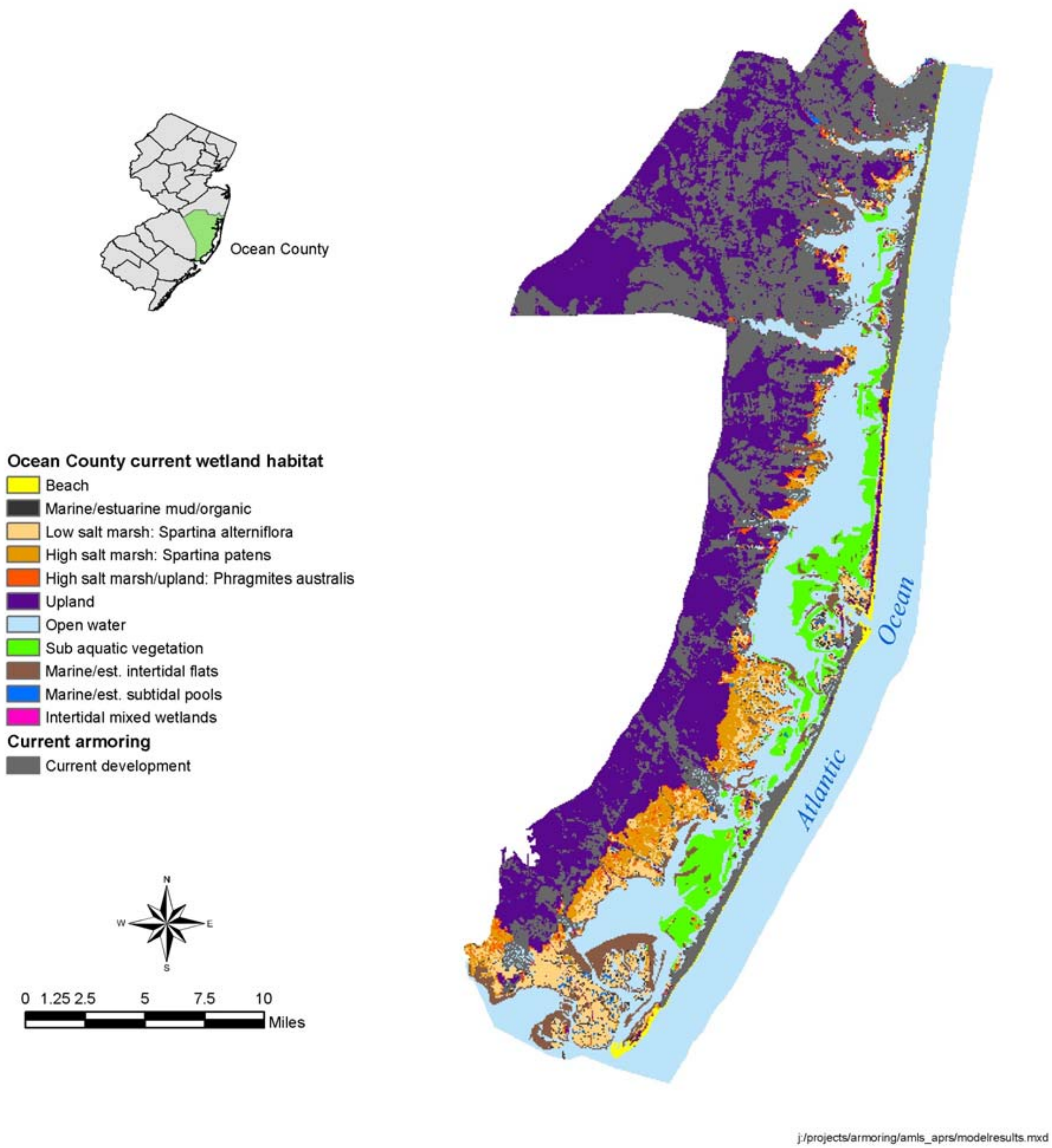


Plate 6. Current armoring scenario — currently developed lands shown on top of wetlands as of 1995.

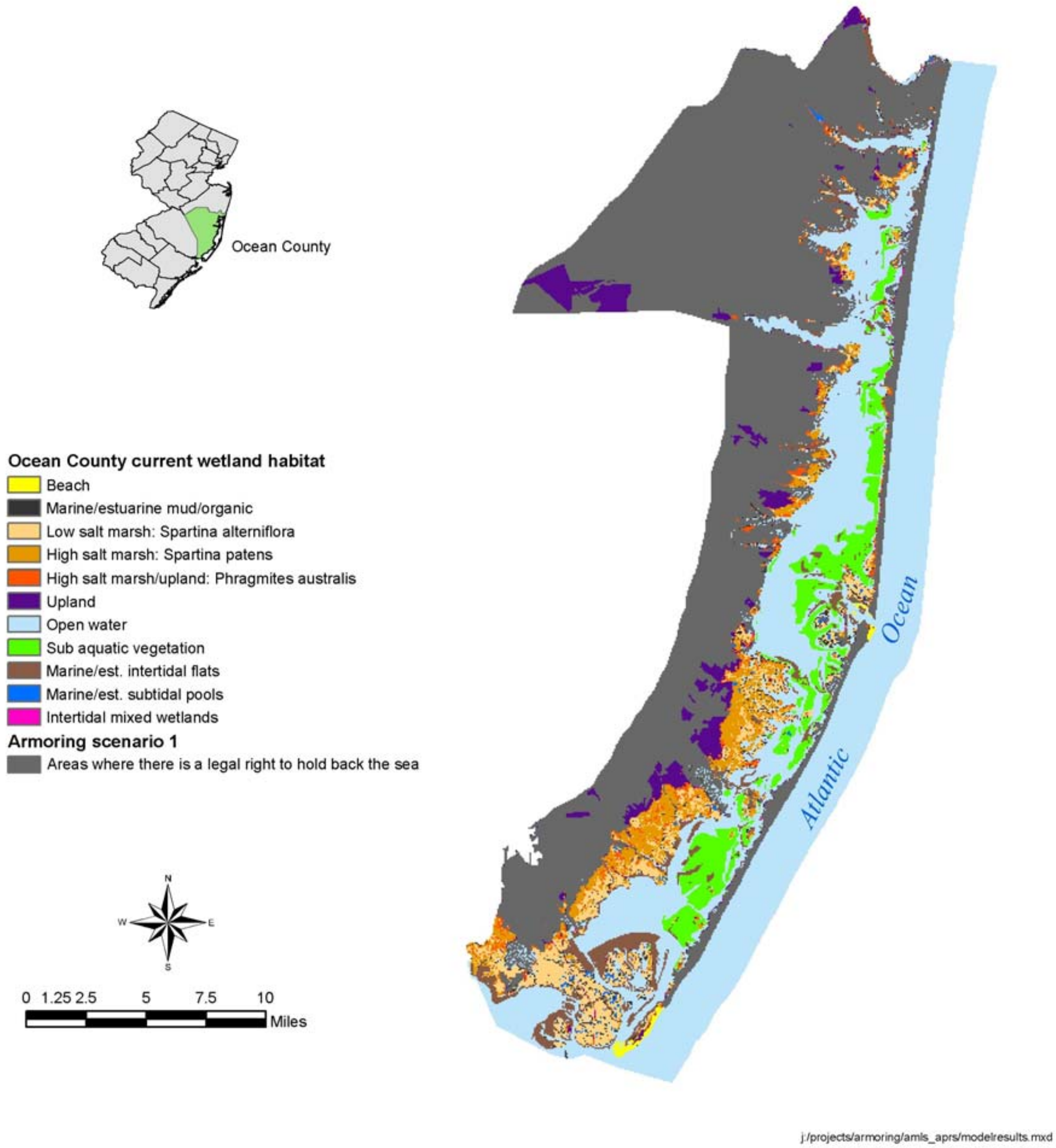


Plate 7. Armoring scenario 1 (areas where there is a legal right to hold back the sea) shown on top of wetlands as of 1995.

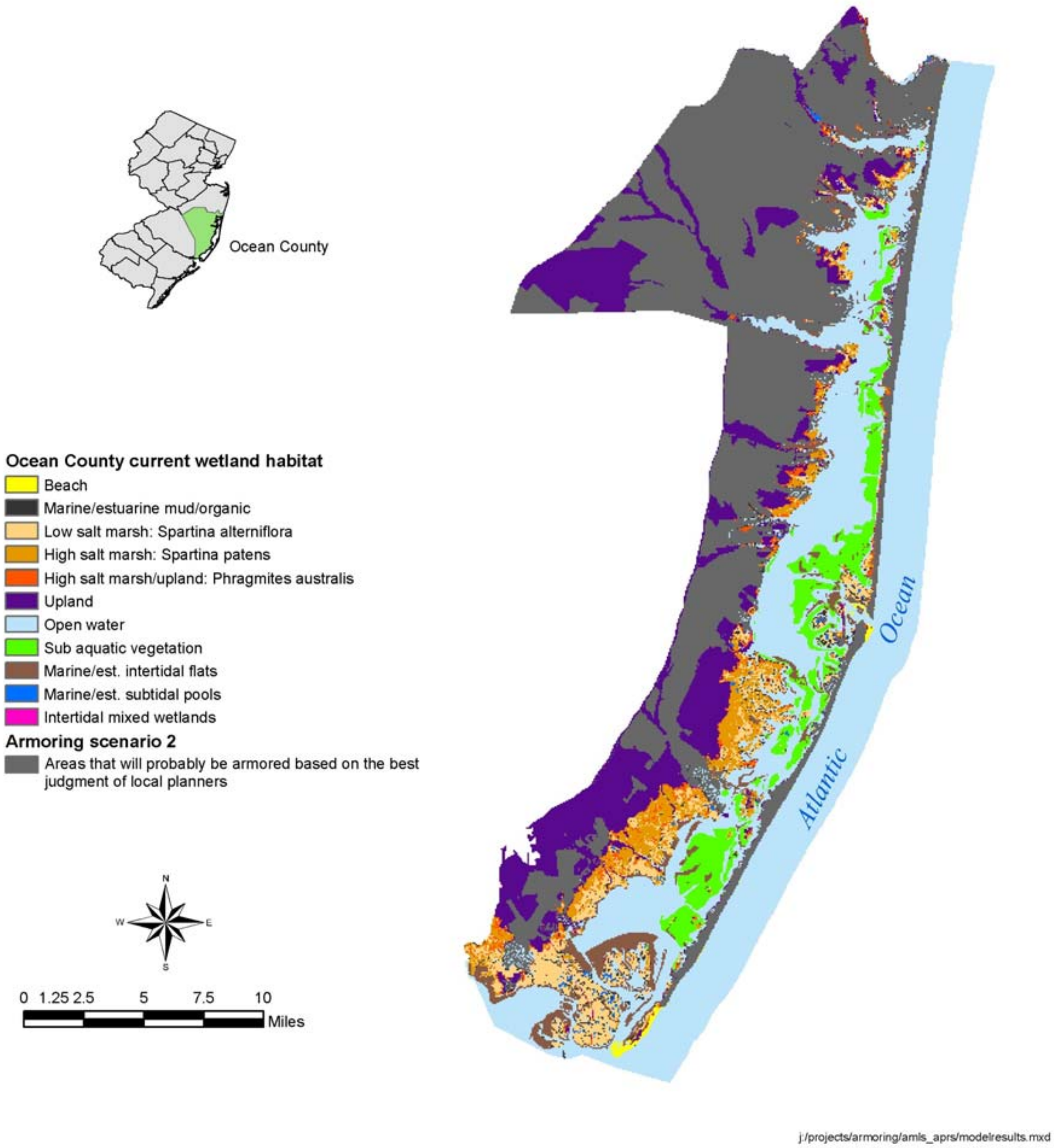


Plate 8. Armoring scenario 2 (areas that will probably be armored based on the best judgment of local planners) shown on top of wetlands as of 1995.

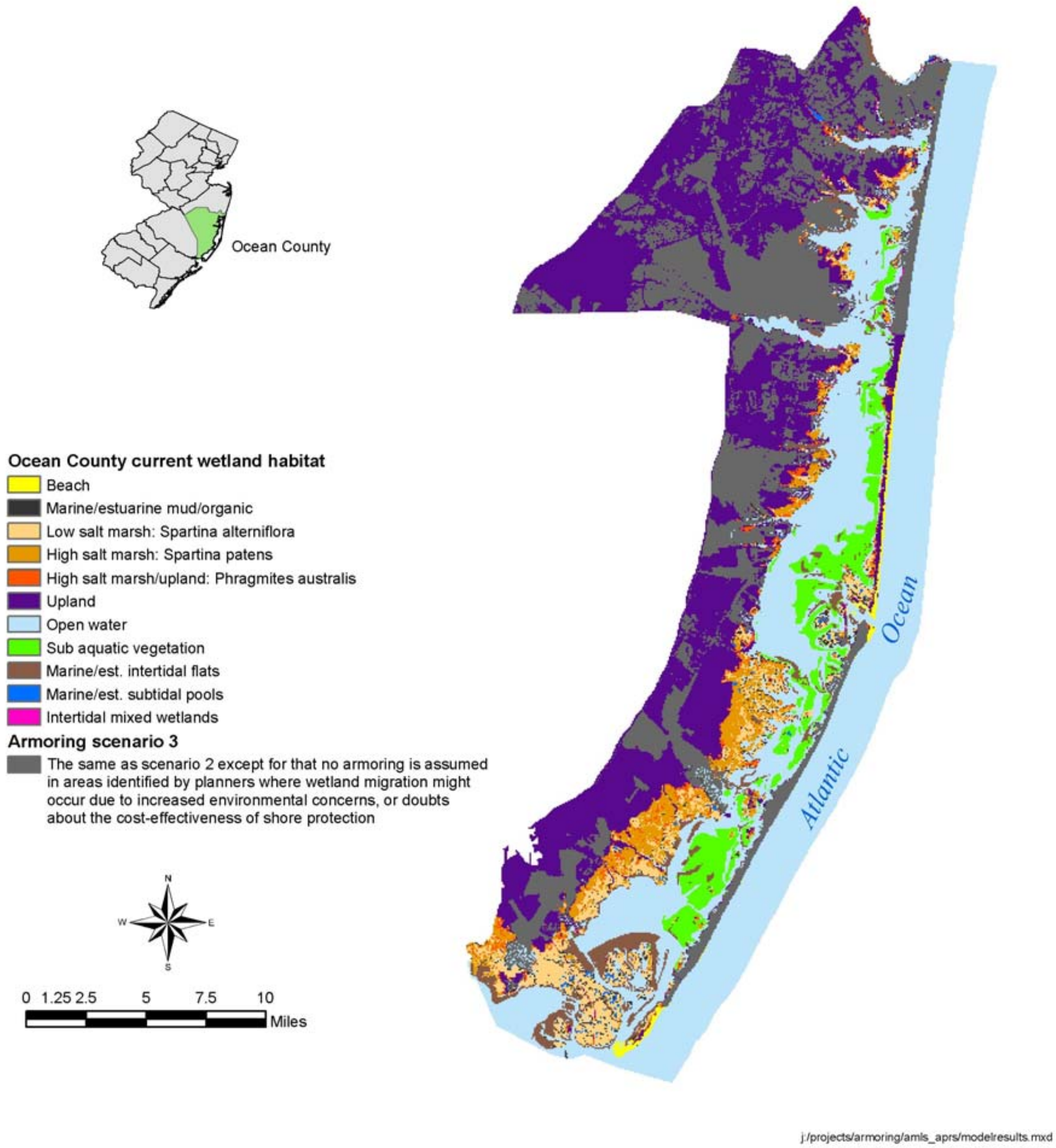


Plate 9. Armoring scenario 3 (the same as scenario 2 except that no armoring is assumed in areas identified by planners where wetland migration might occur due to increased environmental concerns, or doubts about the cost-effectiveness of shore protection) shown on top of wetlands as of 1995.

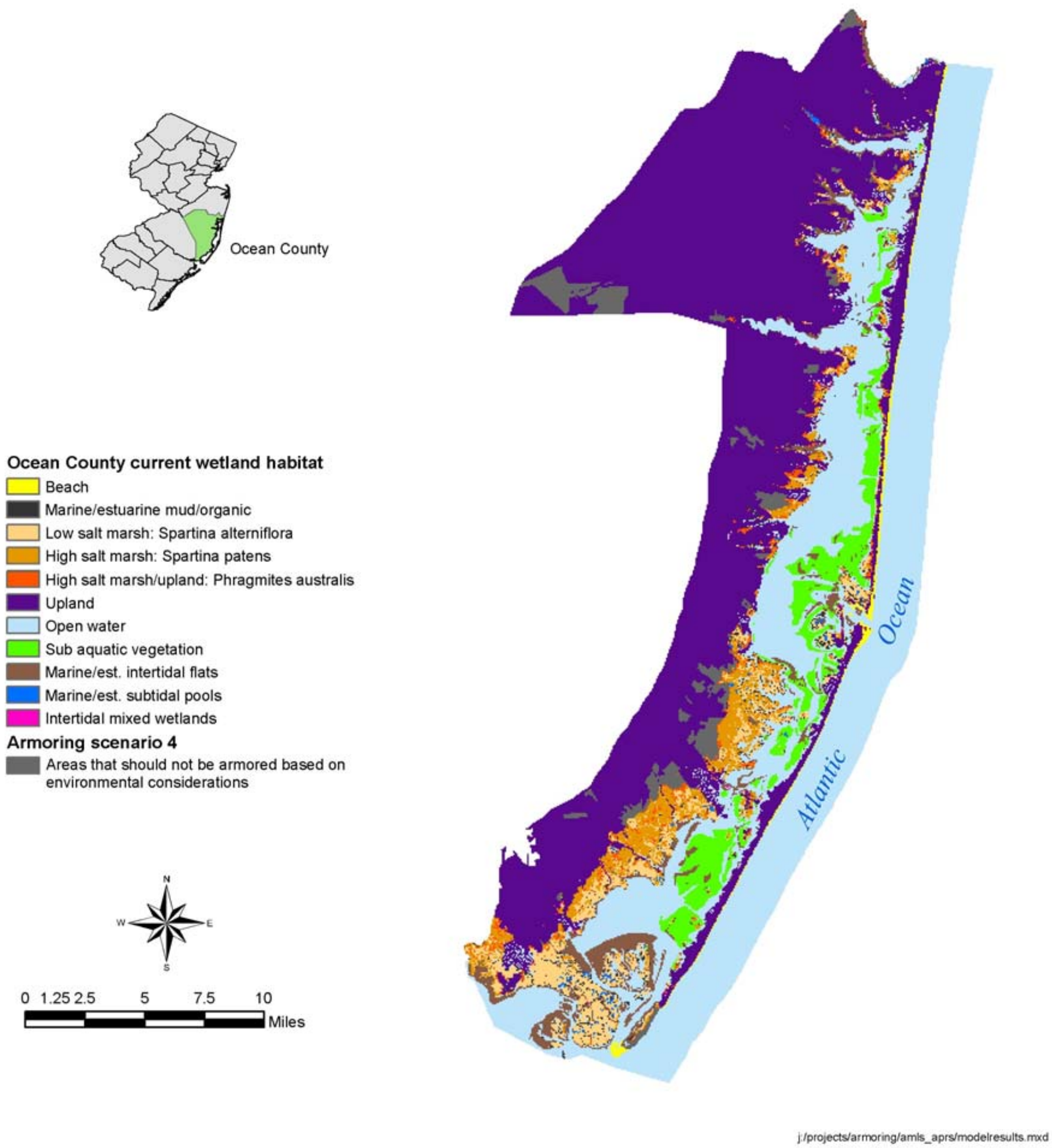


Plate 10. Armoring scenario 4 (areas that should not be armored based on environmental considerations) shown on top of wetlands as of 1995.

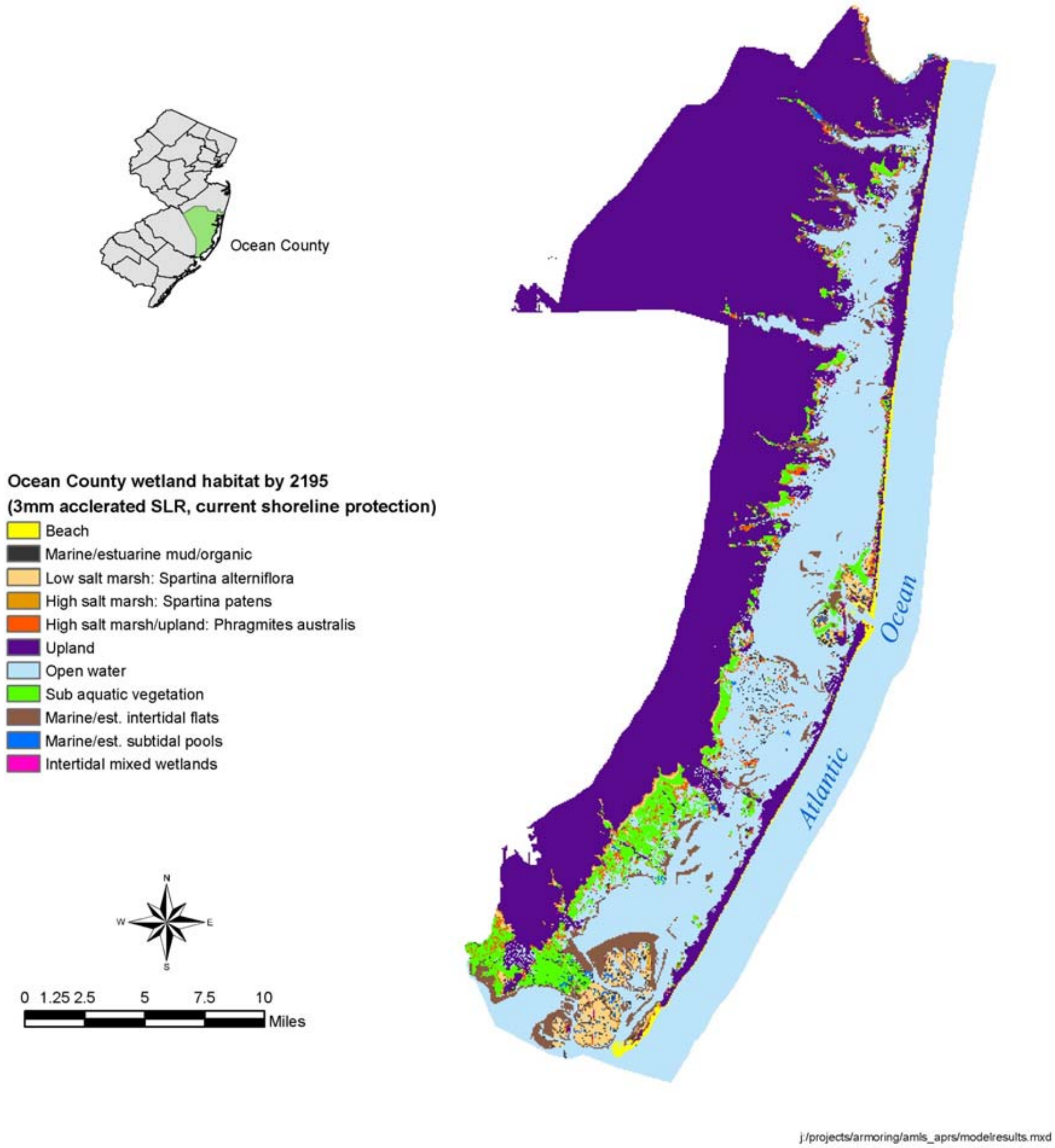


Plate 11. Distribution of wetland habitat types by 2195 modeled with current shoreline protection and 3 mm accelerated rate of SLR above the historic.

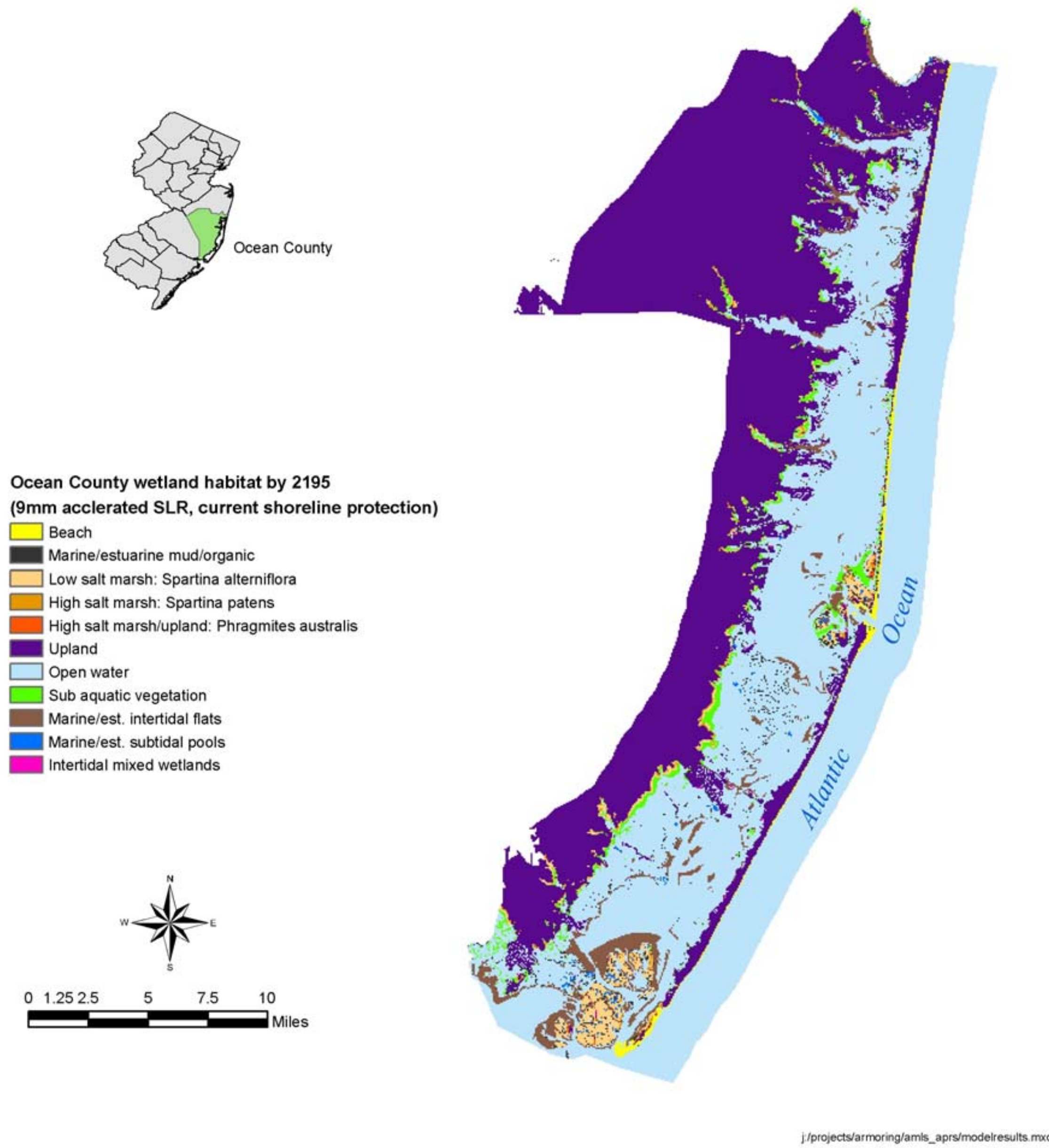


Plate 12. Distribution of wetland habitat types by 2195 modeled with current shoreline protection and 9 mm accelerated rate of SLR above the historic.

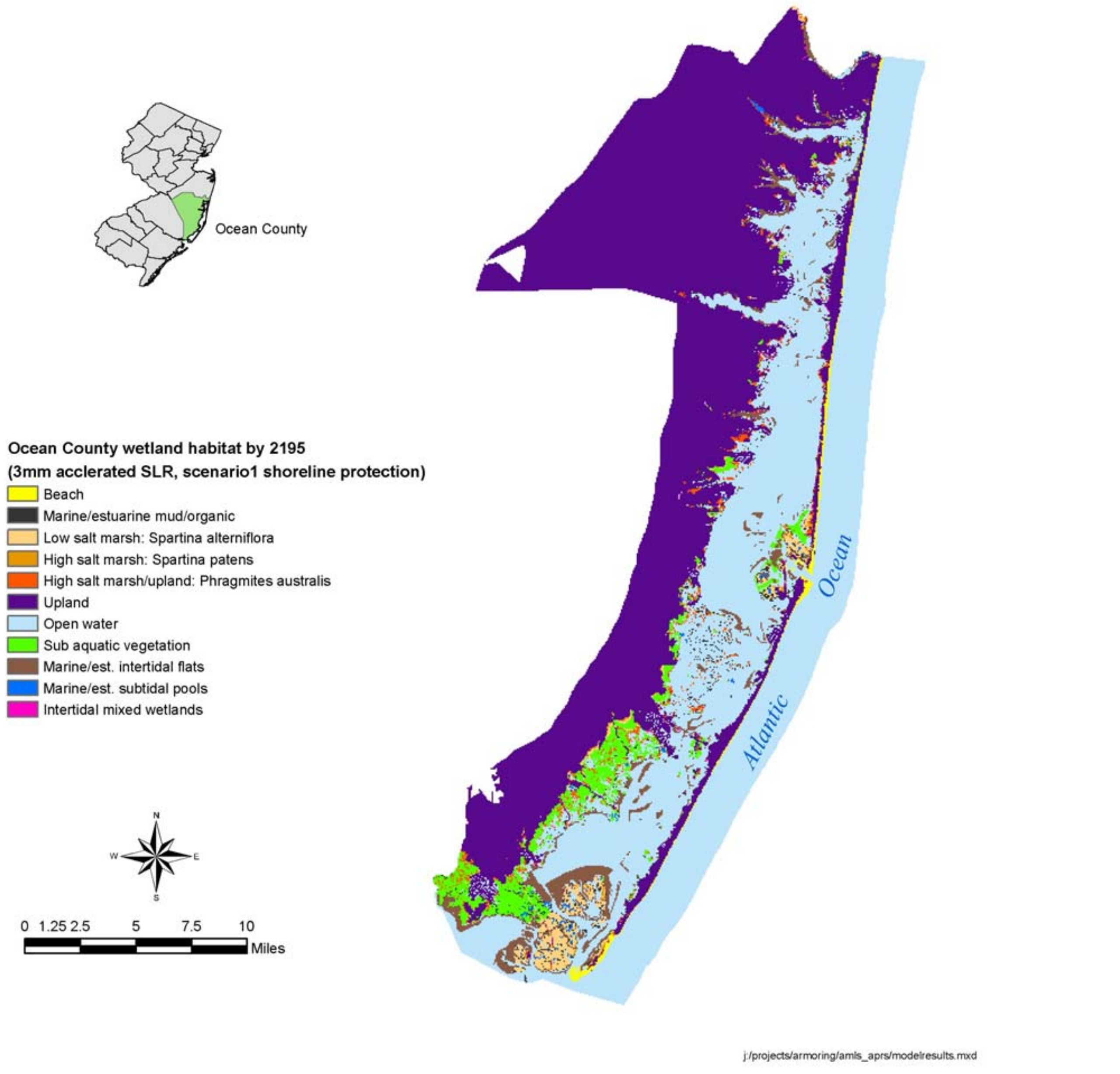


Plate 13. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 1 (areas where there is a legal right to hold back the sea) and 3 mm accelerated rate of SLR above the historic.

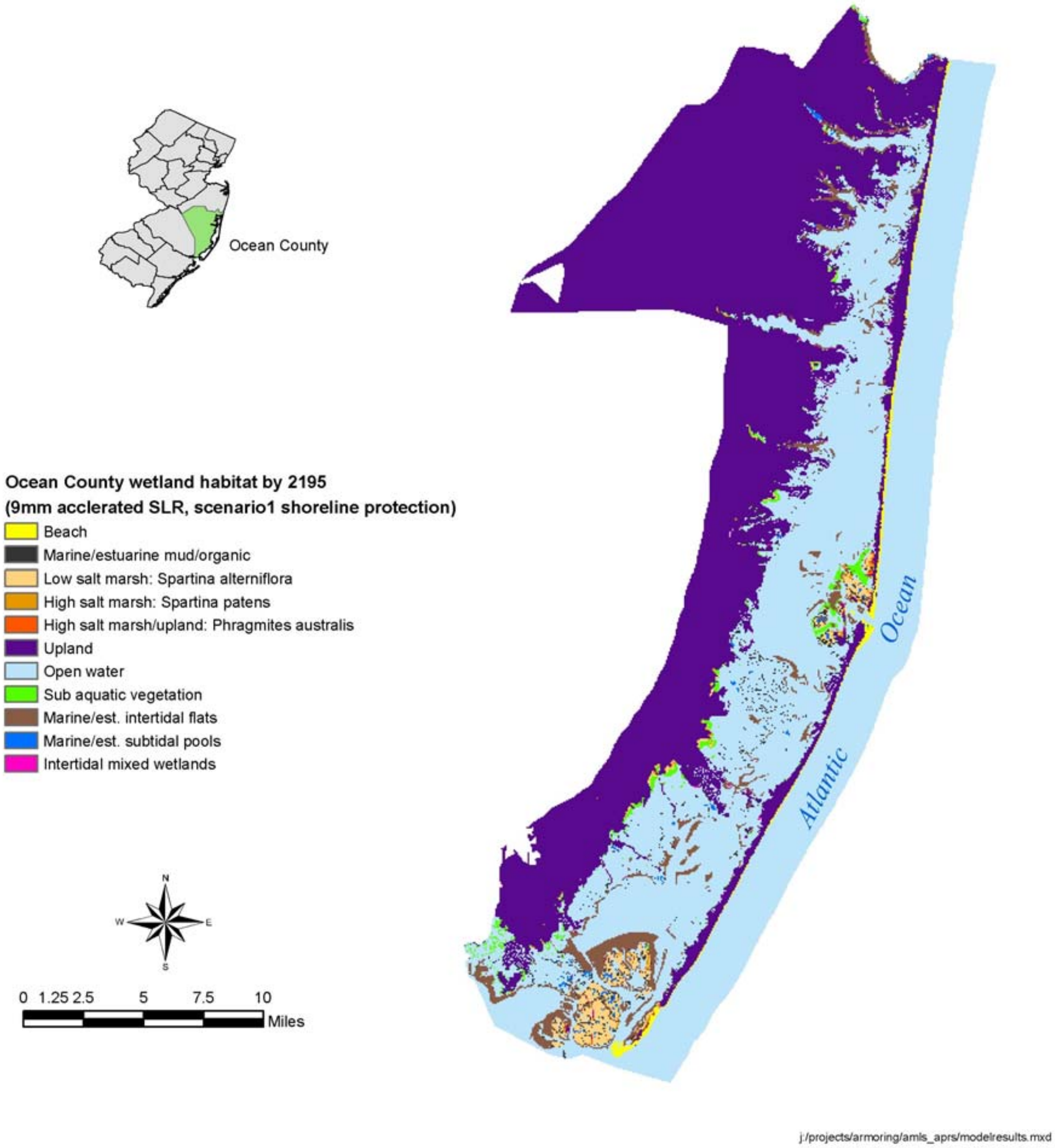
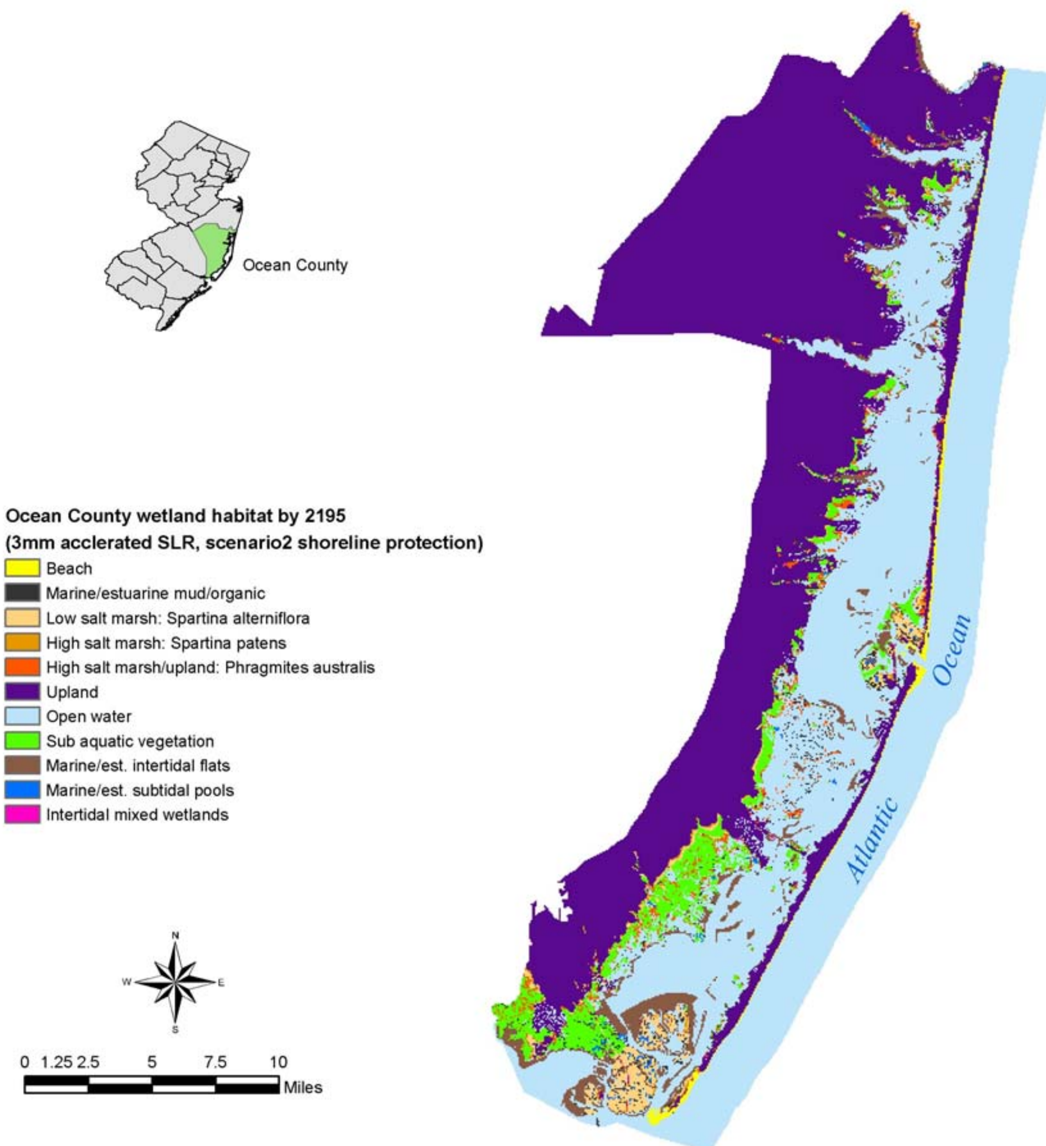


Plate 14. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 1 (areas where there is a legal right to hold back the sea) and 9 mm accelerated rate of SLR above the historic.



j:/projects/armoring/amls_aprs/modelresults.mxd

Plate 15. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 2 (areas that will probably be armored based on the best judgment of local planners) and 3 mm accelerated rate of SLR above the historic.

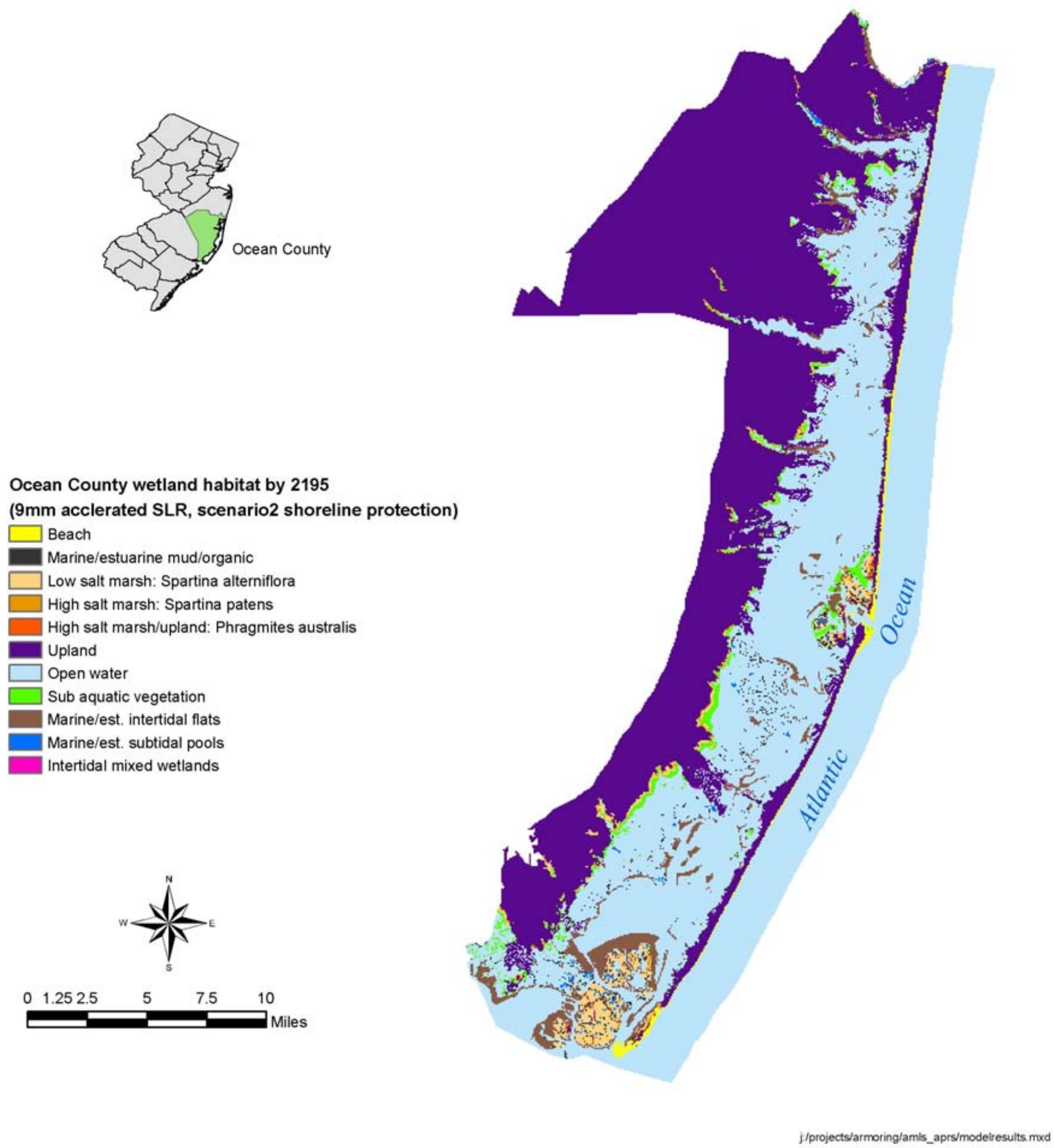


Plate 16. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 2 (areas that will probably be armored based on the best judgment of local planners) and 9 mm accelerated rate of SLR above the historic.

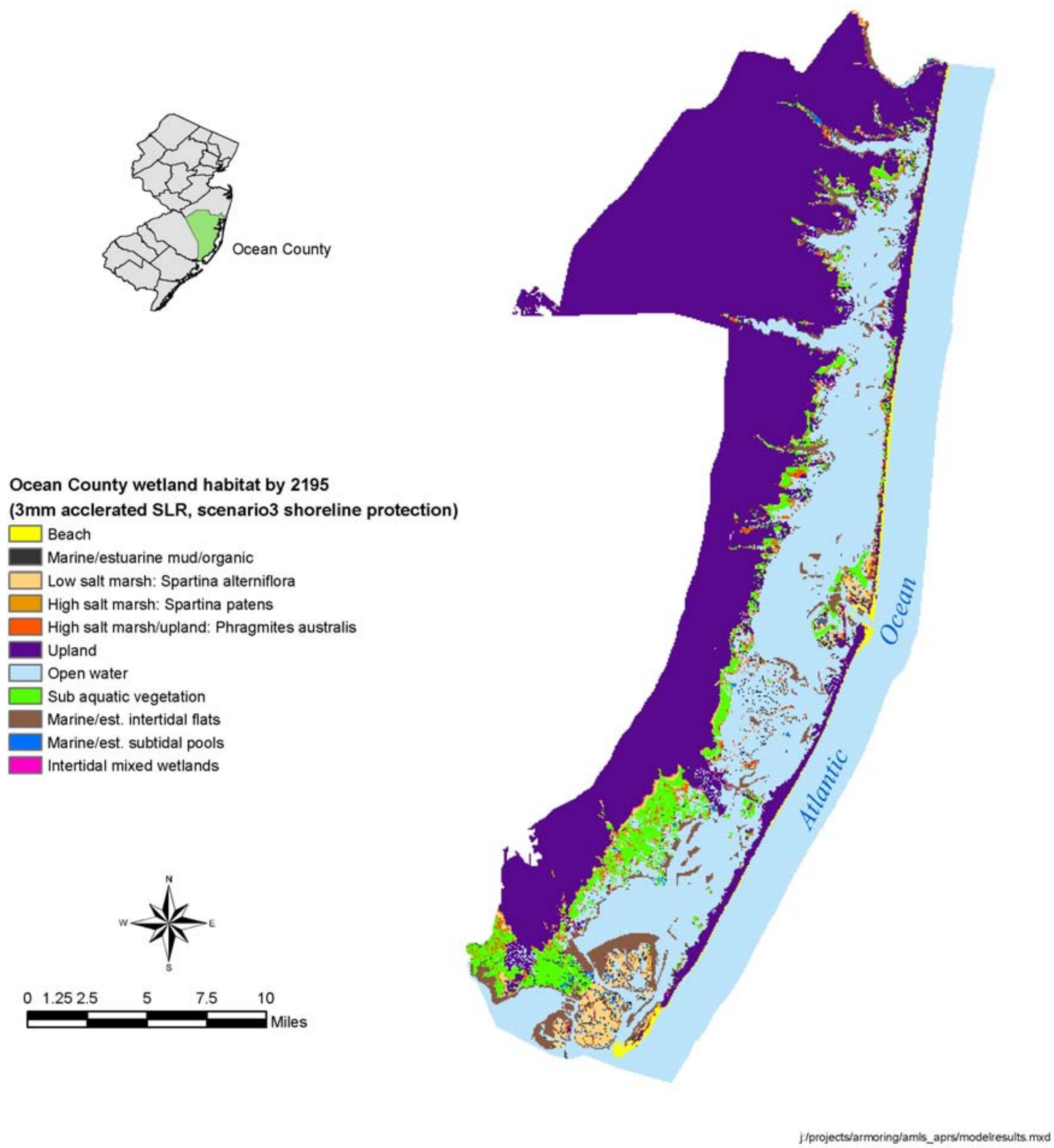


Plate 17. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 3 (the same as scenario 2 except that no armoring is assumed in areas identified by planners where wetland migration might occur due to increased environmental concerns, or doubts about the cost-effectiveness of shore protection) and 3 mm accelerated rate of SLR above the historic.

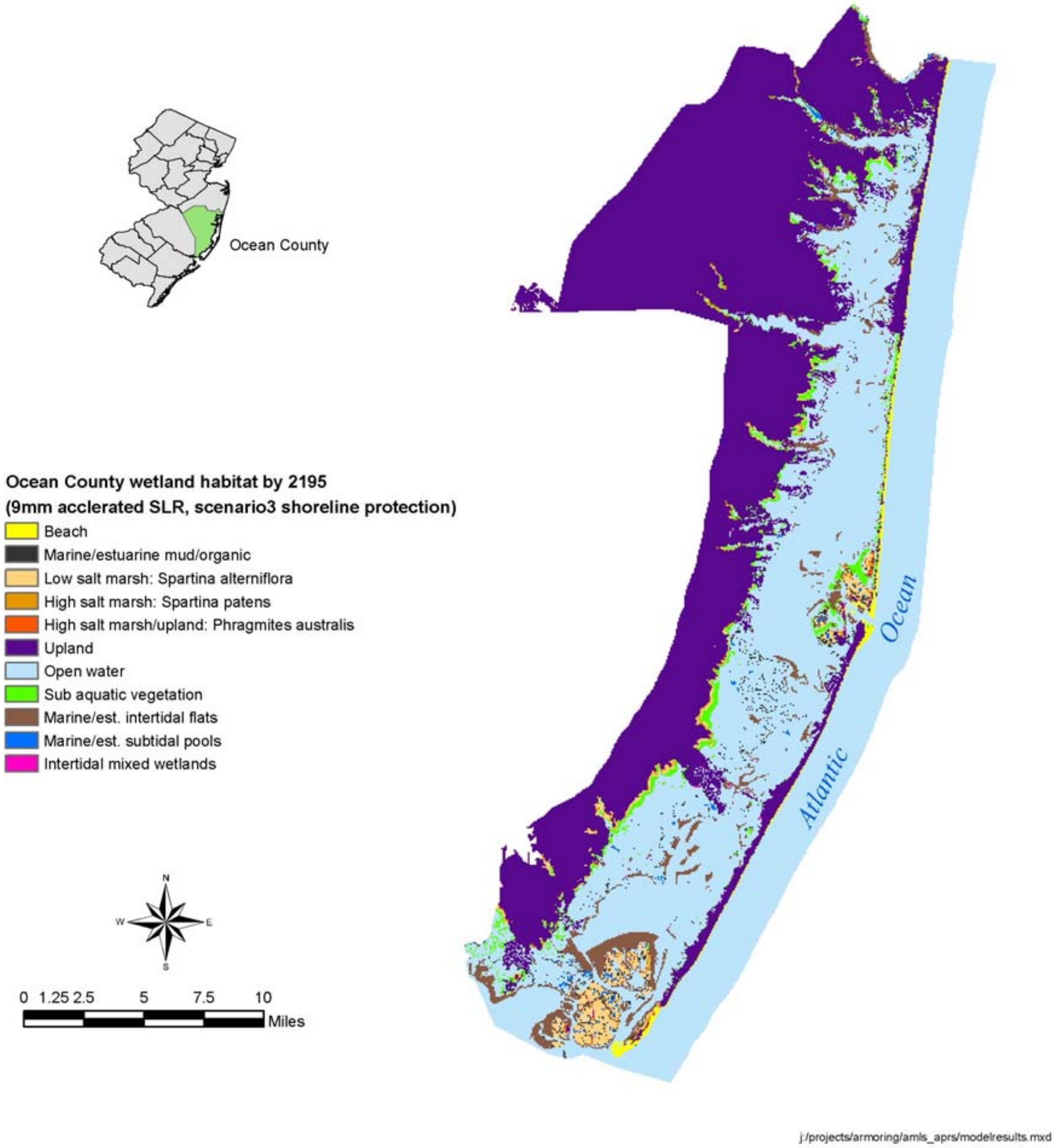


Plate 18. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 3 (the same as scenario 2 except that no armoring is assumed in areas identified by planners where wetland migration might occur due to increased environmental concerns, or doubts about the cost-effectiveness of shore protection) and 9 mm accelerated rate of SLR above the historic.

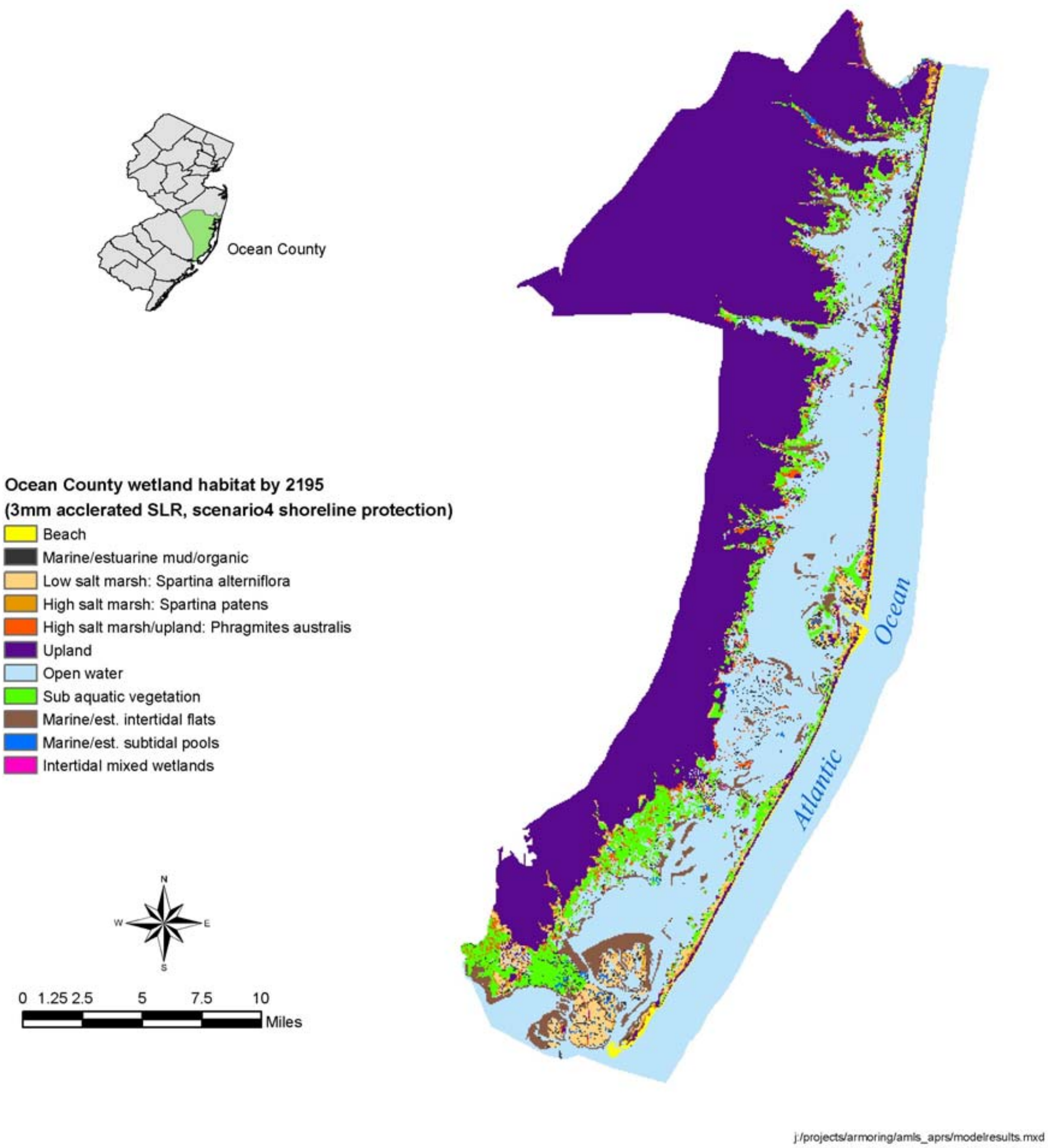


Plate 19. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 4 (areas that should not be armored based on environmental considerations) and 3 mm accelerated rate of SLR above the historic.

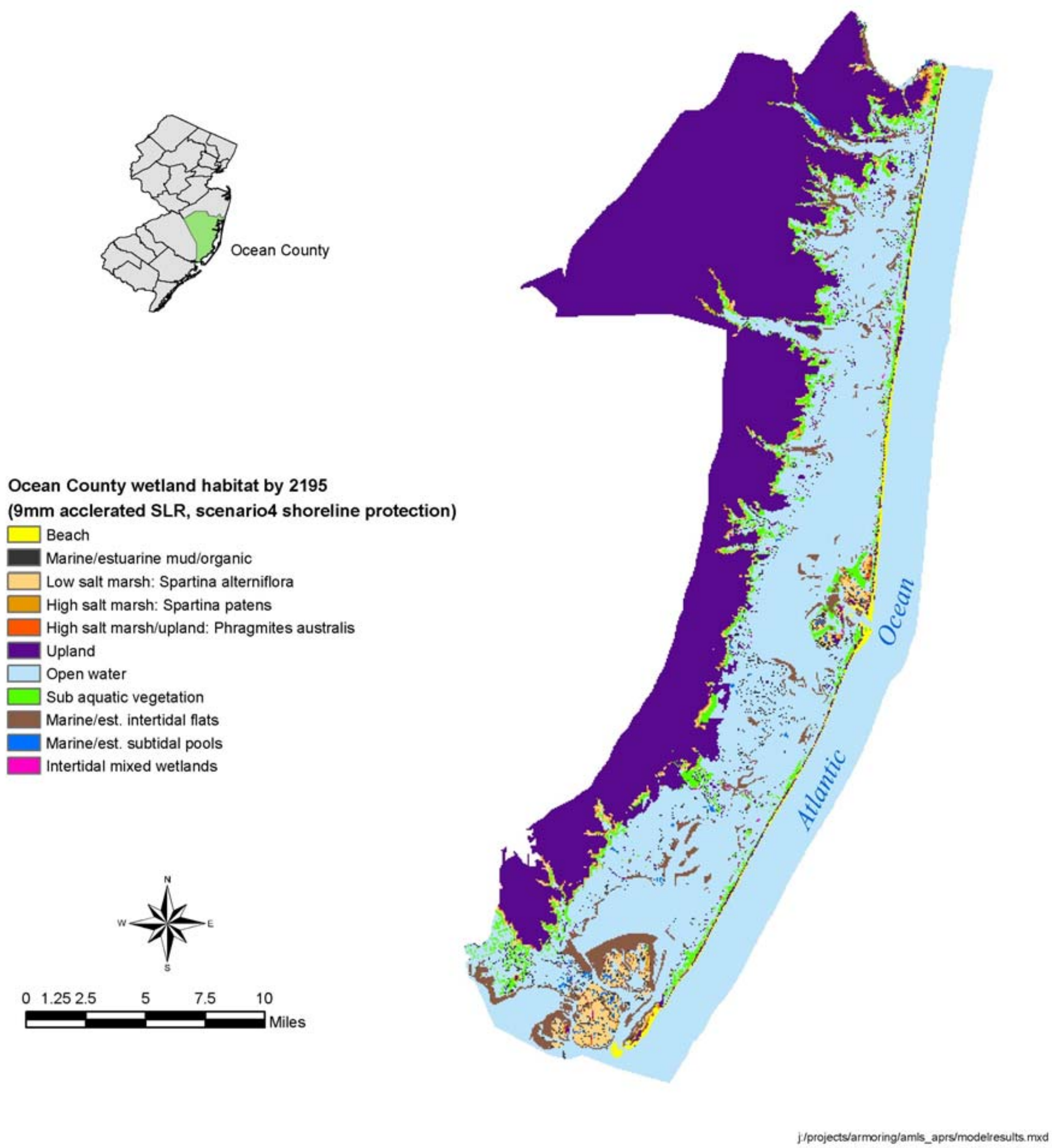


Plate 20. Distribution of wetland habitat types by 2195 modeled with shoreline protection scenario 4 (areas that should not be armored based on environmental considerations) and 9 mm accelerated rate of SLR above the historic.

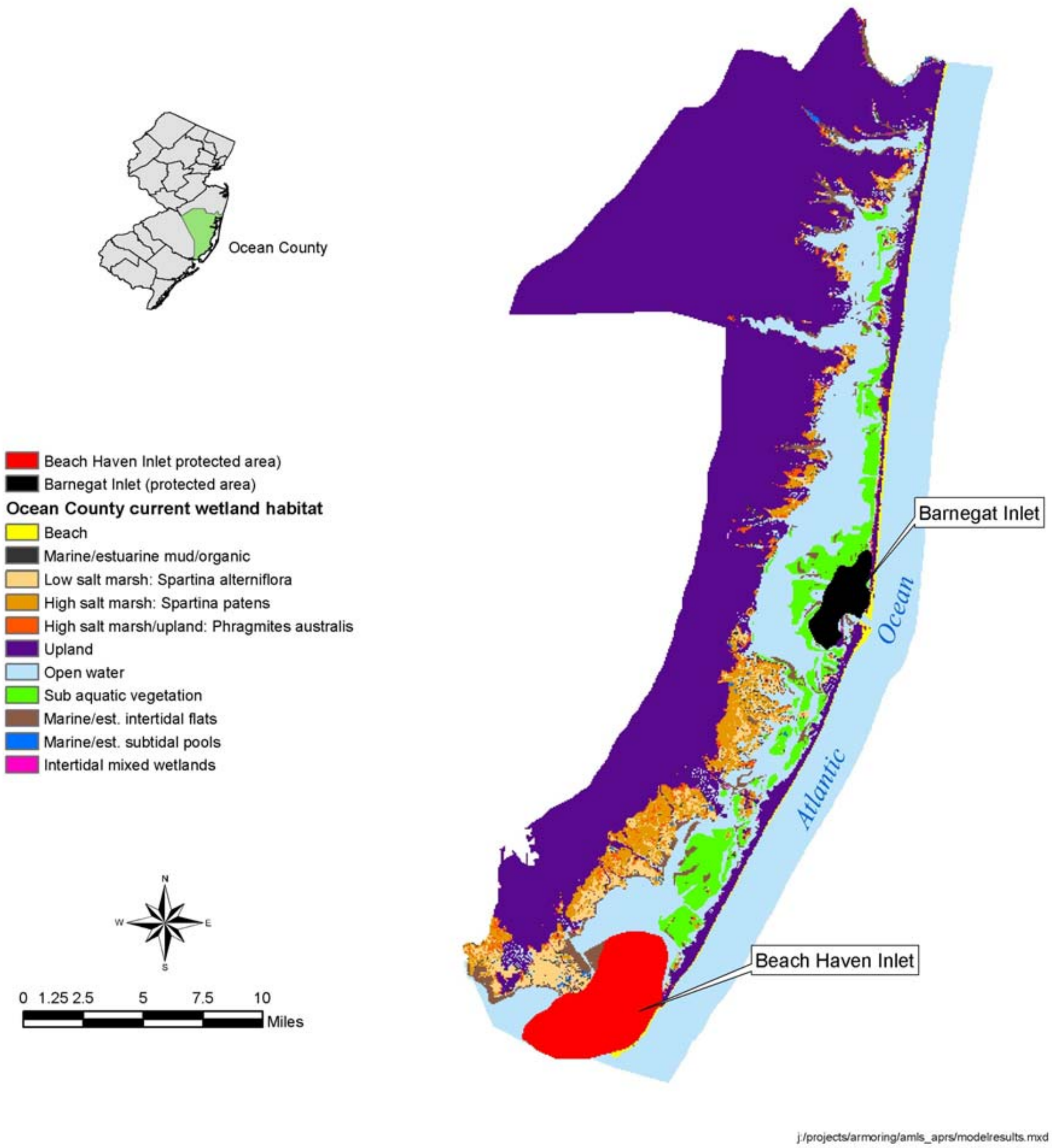


Plate 21. Distribution of wetland habitats as of 1995 with delta areas that were masked from model analysis shown in red and black.