3. MID-ATLANTIC COASTAL HABITATS AND ENVIRONMENTAL IMPLICATIONS OF SEA LEVEL RISE

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3.1 Overview

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This overview considers the species and habitats of the mid-Atlantic from Virginia to New York that are at risk from sea level rise. For different habitats in this region, the ecological implications of sea level rise vary in extent and certainty. Vegetation type, soil type, sediment inputs, and current ecological health can all affect the ecological response to sea level rise. In turn, the animal species that depend on these habitats for activities such as foraging or nesting will vary in their responses to habitat changes, depending on species-specific responses to changes in inundation, salinity, vegetation structure and composition, and other habitat characteristics. Where it is used, shoreline armoring will influence the ability of both habitats and biota to adapt to sea level rise. The following bullets summarize the assumptions on potential responses of mid-Atlantic habitats to increasing rates of sea level rise and shoreline armoring, based on answers to CCSP 4.1 Questions 2 and 3[1]:

- Rising sea level can cause *tidal marshes* (e.g., salt, brackish, and freshwater tidal marshes) to erode at the waterward boundary; drown in place and convert to open water; vertically keep pace with sea level rise through sedimentation and peat formation; and/or expand inland as areas just above the level of the tides become inundated. If sea level rise increases the salinity of an estuary, the vegetation composition of brackish and freshwater marshes may shift to more salt-tolerant species. In areas where habitat is lost or degraded, the myriad species dependent on marshes—birds, fish, invertebrates, and mammals—may show decreased growth, reproduction, or survival.

- *Tidal freshwater swamp forests,* like marshes, can retreat at the waterward boundary; drown in place; keep pace with sea level rise; and/or expand inland. In addition, saltwater can induce vegetation shifts or cause swamps to convert to open water by oxidizing organic soils or inducing subsidence. Within the study region, these swamp forests are found primarily in the tributaries of Chesapeake Bay. With inundation, an associated increase in salinity in the upper reaches of rivers will cause larger trees to die, opening space for germination, settlement, and establishment of marsh macrophytes.

- *Marsh and bay islands* are found throughout the mid-Atlantic study region. These isolated areas provide nesting sites that are protected from predators and human disturbance for various bird species, particularly colonial nesting water birds. Because of their limited migration ability, these islands are particularly susceptible to sea level rise.

- *Sea level fens* are an extremely rare type of coastal wetland. These fens grow only under unusual circumstances—where a natural seep from a nearby slope provides nutrient-poor groundwater to support their unique vegetation and where the fens are protected from nutrient-rich tidal flow. Sea level fens are present in Delaware's Sussex County Inland Bays watershed, on Long Island's South Shore, and on the eastern shore of Virginia's Accomack County. Because sea level fen vegetation needs nutrient-poor

[1]Question 2: How does sea level rise change the ocean coastline? Among those lands with sufficient elevation to avoid inundation, which land along the Atlantic Ocean could potentially erode in the next century? Which lands could be transformed by related coastal processes? Question 3: What is a plausible range for the ability of wetlands to vertically accrete, and how does this range depend on whether shores are developed and protected, if at all? In other words, will sea level rise cause the area of wetlands to increase or decrease?

waters, these unique wetlands might not survive inundation by sea level rise.

- In *nearshore waters*, rising sea levels and deepening waters will shade the deeper areas of submerged aquatic vegetation (SAV) beds, limiting photosynthesis. The landward edges of SAV may move inland onto areas that are currently tidal wetlands if the water bottoms have suitable sediments. Seagrasses (e.g., eelgrass and widgeon grass) provide food and shelter for a variety of fish and shellfish, food for the species that prey on those fish and shellfish, and physical protection from wave energy for shorelines. Scientists are not certain of the likely net change in SAV, which will depend on the balance between losses resulting from increasing depth in current beds and gains due to migration into inundated shoreline areas.

- *Tidal flats* may be readily lost with rising seas, but may also be created temporarily in areas where wetlands are inundated. Loss of tidal flats would eliminate a rich invertebrate food source for migrating birds.

- *Estuarine beaches* erode, but under natural conditions the landward and waterward boundaries usually retreat by about the same distance. In the built environment, structures can prevent the system from migrating inland, in effect causing the beaches to be squeezed between developed areas and the water. Society will preserve many beaches with sand replenishment (beach nourishment). In areas that do lose beaches, though, insects and other invertebrates such as sand diggers, sand fleas, and numerous crab species will lose their habitats. Shorebirds that rely on beaches for forage and nesting will also face more limited resources.[2]

- *Cliff areas* can experience increased erosion rates, or, if the cliff base is armored, the erosion rates can decrease. In the latter case, however, the armoring can eliminate habitat for species (e.g., Puritan tiger beetles and belted kingfishers) that depend on varying rates of cliff erosion.

This section gives a general description of vulnerable coastal habitats and potential ecological consequences of sea level rise and shoreline armoring in the U.S. mid-Atlantic region from Virginia to New York. The information presented here is based on current scientific understanding as well as the observations of local experts. In each section that follows this overview, we begin by describing the type of habitat (refer to the previous bulleted list), then discuss potential ecological responses to sea level rise and to shoreline armoring (if any) for that type of habitat, presenting case studies for specific bays, estuaries, and back barrier lagoons of the mid Atlantic from New York to Virginia.

Various general assumptions are made in this section based on other information from the CCSP and the scientific literature. Assumptions for marsh survival rely on the response to CCSP 4.1, Question 3 (Reed et al., Section 2.1), which describes accretion expectations under three sea level rise scenarios for marshes in the mid-Atlantic region. The three scenarios are (1) the current rate of sea level rise, (2) an increase of 2 mm/yr above the current rate, and (3) an increase of 7 mm/yr above the current rate. The accretion expectations take into account sediment inputs, marsh characteristics, and historical processes, among other considerations.

Changes in salinity are not directly considered in this section. In the absence of other factors, sea level rise is expected to drive the salt front farther upstream in estuaries and tributaries. For example, one estimate for the Delaware River is an 11 km movement upstream for the salt front.[3] More recent models, however, indicate that any concomitant changes in freshwater inputs to tributaries may negate the upstream drive of the

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[2] Lippson, A.J., and R.L. Lippson, 2006, *Life in the Chesapeake Bay*, 3rd ed., The Johns Hopkins University Press, Baltimore, MD, pp. 26–42. For more detail on beach habitats and the species that occur in them, see Section 3.1.7 of this section.

[3] Hull, C.H.J., and J.G. Titus, 1986, *Greenhouse Effect, Sea-Level Rise, and Salinity in the Delaware Estuary*, US EPA 230-05-86-010, U.S. EPA and Delaware River Basin Commission, Washington, DC, p. i.

salt wedge.[4] Although salinity change can have profound effects on both flora and fauna, we do not consider it in detail here because of the uncertainty associated with salinity.

Changes in water depth will be a function of the rate of sea level rise and the rate of sedimentation.[5] In embayments and estuaries where the tidal prism increases, increased water depth is likely.[6] In Chesapeake Bay, some researchers anticipate a water depth increase of almost 20 percent.[7] On the other hand, studies in England have indicated that estuarine channels might become both wider and shallower, which may be an effect of sedimentation and local geomorphology.[8] Increased tidal prism is also associated with an increase in interior ponding in marshes, along with tidal creek bank erosion, which can lead to catastrophic marsh loss (as in the Blackwater Wildlife Refuge on Maryland's Eastern Shore).[9] We assume that in areas where marshes are not expected to accrete sufficient sediment to remain in place, an increase in water depth will occur over any given area waterward of the marsh. Shoreline protections can further affect local water depths and are discussed in each section as necessary.

3.1.1 TIDAL MARSHES

Tidal marshes are characterized based on salinity. Freshwater marshes receive significant freshwater input and have waters that contain less than 0.5 parts per thousand (ppt) of ocean-derived salts. The waters of brackish (estuarine) marshes are less than 18 ppt. Salt marshes receive substantial inundation by ocean waters and have waters that can reach 30 ppt. As discussed in the following sections, numerous finfishes, birds, crustaceans, mollusks, reptiles, amphibians, and mammals rely on tidal marshes for at least part of their life cycle for resources such as food, shelter, nursery habitat, and nesting or spawning sites.

Salt marshes are among the most productive systems in the world, rivaling the productivity of agricultural lands. These marshes are the primary source of much of the organic matter and nutrients that form the basis of the estuarine food web.[10] Primary productivity includes both aboveground production (stalks and leaves) and belowground production (roots and tubers) by marsh plants as well as benthic algae. Much of the aboveground primary production is in the form of cellulose, which most animals cannot digest. Therefore, most vascular plant material is consumed by detritivores such as copepods, amphipods, annelids, snails, and insect larvae.[11] In turn, these organisms provide food for macroinvertebrates such as saltmarsh snails, ribbed mussels, and fiddler crabs, and small resident fishes such as mummichogs, sheepshead minnows, and Atlantic silversides.[12] The abundant invertebrates and small fishes of salt marshes are food for larger consumers. Bay anchovies, silversides, and other small schooling species use salt marshes as nursery grounds and are a food source for birds and piscivorous fish.[13,14]

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[4]Najjar, R.G., H.A. Walker, P.J. Anderson, E.J. Barron, R.J. Bord, J.R. Gibson, V.S. Kennedy, C.G. Knight, J.P. Megonigal, R.E. O'Connor, C.D. Polsky, N.P. Psuty, B.A. Richards, L.G. Sorenson, E.M. Steele, and R.S. Swanson, 2000, "The potential impacts of climate change on the mid-Atlantic Coastal Region," *Climate Research* 14: 219–233, pp. 224–225.

[5]National Research Council (U.S.), 1987, *Responding to Changes in Sea Level: Engineering Implications,* Committee on Engineering Implications of Changes in Relative Mean Sea Level, National Academy Press, Washington, DC, p. 36.

[6]Levin, D.R., 1995, "Occupation of a relict distributary system by a new tidal inlet, Quatre Bayou Pass, Louisiana," pp. 71–84 in *Tidal Signatures in Modern and Ancient Sediments,* B.W. Flemming and A. Bartoloma, eds., Special Publication of the International Association of Sedimentology (vol. 24.), Blackwell Science, Oxford, U.K.

[7]Stevenson, J.C., M.S. Kearney, and E.W. Koch, 2002, "Impacts of sea level rise on tidal wetlands and shallow water habitats: A case study from Chesapeake Bay," *American Fisheries Society Symposium* 32:23–36.

[8]Pethick, J., 1993, "Shoreline adjustments and coastal management: Physical and biological processes under accelerated sea-level rise," *The Geographical Journal* 159(2):162–168.

[9]National Research Council, 1987, p. 69 (see note 5).

[10]Teal, J.M., 1986, *The Ecology of Regularly Flooded Salt Marshes of New England: A Community Profile,* U.S. Fish and Wildlife Service Biological Reports 85 (7.4), 69 pp.

[11]Currin, C.A., S.Y. Newell, and H.W. Paerl, 1995, "The role of standing dead *Spartina alterniflora* and benthic macroalgae in salt marsh food webs: Considerations based on multiple stable isotope analysis," *Marine Ecology Progress Series* 121:99–116.

[12]Teal, 1986, pp. 21–25 (see note 10).

[13]McBride, R.S., 1995, "Marine forage fish," pp. 211–217 in Dove, L.E., and R.M. Nyman (eds.), *Living Resources of the Delaware Estuary.* The Delaware Estuary Program.

[14]Lippson and Lippson, 2006, p. 212 (see note 2).

Photo 3.1: Marsh and tidal creek, Mathews County, Virginia[15]

Salt marshes are characterized by distinct vegetation zones based on the degree of tidal flooding and the salinity tolerance of marsh plants. Because they are regularly flooded by daily tides, low marsh soils tend to be more waterlogged, saline, and anoxic than high marsh soils.[18] Low marsh is characterized by monospecific stands of smooth cordgrass. Characteristic bird species of low marsh include clapper rail, willet, marsh wren, seaside sparrow, and American black duck. Ribbed mussels form dense clumps on cordgrass roots and fertilize them by contributing phosphorous and nitrogen-rich pseudofeces.[19] Fiddler crabs enhance *Spartina* spp. survival by aerating the marsh soils.[20]

Birds that feed on crustaceans, mollusks, and fish within salt marshes include clapper rails, black rails, least bitterns, and many species of terns and gulls. Fiddler crabs are common in the diets of clapper rails, egrets, blue crabs, diamondback terrapins, and raccoons. Some of the birds are marsh-nesting obligates; others nest frequently, but not exclusively, in marshes. Three species of terns (including Forster's tern), several species of gulls, and the seaside and salt marsh sharp-tailed sparrows all nest in coastal salt marshes.[16]

In addition to secondary production within the marsh, some primary production may ultimately contribute to the surrounding estuarine food web. Kneib proposes that this occurs via "trophic relays," which consist of juvenile fauna that draw on the detrital food web of the marsh and then transfer marsh-produced organic matter to larger consumers as part of the estuarine food web.[17]

Tidal creeks and channels frequently cut through low marsh areas, functioning to drain the marsh surface and serving as conduits for nekton (small fish and decapod crustaceans) to enter the wetlands during high tides and for nutrient-rich plant detritus to be flushed out into deeper water with receding tides (see Photo 3.1).[21] Several fish species that are marsh residents and use the low marsh when it is flooded at high tide are found in tidal creeks at low tide, including Atlantic silversides, mummichogs, striped killifish, and sheepshead minnows. Marsh creeks support significantly higher densities of these species than other intertidal habitats.[22]

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[15]All photos are courtesy of Jim Titus, except for Photo 3.3a by Elizabeth Strange.

[16]Erwin, R.W., G. M. Sanders, and D. J. Prosser, 2004, "Changes in lagoonal marsh morphology at selected northeastern Atlantic Coast sites of significance to migratory waterbirds," *Wetlands* 24(4):891–903.

[17]Kneib, R.T., 1997, "Tidal marshes offer a different perspective on estuarine nekton," *Annual Review of Oceanography and Marine Biology* 35:1–120.

[18]LaBranche, J., M. McCoy, and D. Clearwater, 2003, p. 17 in *Maryland State Wetland Conservation Plan,* prepared by Nontidal Wetlands and Waterways Division, Maryland Department of the Environment.

[19]Kreamer, G.R., 1995, Saltmarsh invertebrate community. pp. 81–89 in Dove and Nyman, 1995 (see note 14).

[20]Dove and Nyman, 1995, pp. 81–89 (see note 14).

[21]Lippson and Lippson, 2006, pp. 202–203 (see note 2).

[22]Rountree, R.A., and K.W. Able, 1992, "Fauna of polyhaline subtidal marsh creeks in southern New Jersey: Composition, abundance and biomass," *Estuaries* 15:171–185.

Characteristic macroinvertebrates of salt marsh creeks include eastern mud snails, daggerblade grass shrimp, longwrist hermit crabs, common Atlantic slippershells, northern quahogs, softshell clams, razor clams, blue crabs, and horseshoe crabs. Great blue herons and egrets are among the many colonial wading birds and other waterbirds that commonly feed on the small fish and benthic invertebrates found in tidal creeks. If creeks deepen, these species will have increasing difficulty foraging for essential food supplies.

High marsh is briefly flooded once or twice daily on fewer than 10 days per month and is dominated by salt hay and spike grass. High marsh sediment contains more organic material than low marsh.[23,24] High marshes may include a scrub-shrub community at the upland edge. Salt shrubs often mark the limit of the highest spring and storm tides. Characteristic shrubs include groundsel, saltmarsh elder, and pasture rose. The marsh edge is typically dominated by salt marsh elder, whereas groundsel usually dominates the upland edge. Grasses include those typical of high salt marsh, including salt meadow grass, black grass, and switchgrass. The invasive common reed sometimes occurs in a narrow fringe along the upland edge of marshes where salinities are lower because of less tidal flooding and greater freshwater runoff.

Characteristic birds of high salt marsh include saltmarsh sharp-tailed sparrows, black rails, and northern harriers. Many of these high marsh species are adapted to nesting only in the short grasses of the high marsh, such as salt hay and spike grass, and may not thrive in the tall grasses of the low marsh.

Brackish or estuarine tidal marshes in estuaries of the mid-Atlantic are typically dominated by species such as Olney three-square, saltmarsh bulrush, switchgrass, dwarf spike grass, black needlerush, narrow-leaved cattail, big cordgrass, and the invasive common reed. In mixed communities, the vegetation occurs in zones. Big cordgrass is the most common near mean high tide (MHT), Olney three-square at MHT, and switchgrass near the spring tide line. Brackish marshes support many of the same species as salt marshes, with some notable exceptions. Bald eagles forage in brackish marshes and nest in nearby wooded areas. Because there are few resident mammalian predators, small herbivores such as meadow vole thrive in these marshes.[25]

Fish species common in the brackish waters of the mid-Atlantic include striped bass and white perch, which move in and out of brackish waters year-round. Anadromous fishes, including herring and shad, as well as marine transients such as Atlantic menhaden and drum species, are present in summer and fall. The most visible invertebrates of the brackish marshes include red-jointed fiddler crab, marsh periwinkle, Atlantic ribbed mussel, and common clam worm.[26]

Freshwater tidal marshes are characteristic of the upper reaches of tributaries of estuaries. They support a more diverse vegetation community than more saline marshes. Like salt and brackish marshes, freshwater tidal marshes can show three distinct vegetation zones, depending on the degree of tidal inundation. In general, the lower tidal zone, exposed only at low tide, consists of sparsely vegetated intertidal flats. The middle zone is dominated by wild rice, spatterdock, pickerelweed, and arrow arum. The upper tidal zone is dominated by cattails, often with a diversity of other species such as sensitive fern, river bulrush, and sweet flag, and sometimes the invasive common reed.[27]

In general, the species composition of freshwater marshes does not appear to be limited by seed availability. Instead, physical factors limit the species composition, especially through flooding. Some species germinate well when

[23]Brinson, M.M., R.R. Christian, and L.K. Blum, 1995, "Multiple states in the sea level induced transition from terrestrial forest to estuary," *Estuaries* 18(4):648–659.
[24]LaBranche et al., 2003, p.17 (see note 18).

[25]White, C.P., 1989, *Chesapeake Bay: Nature of the Estuary, A Field Guide,* Tidewater Publishers, Centreville, MD, pp. 107–123.
[26]White, 1989, p. 124 (see note 25).
[27]White, 1989, pp. 97–105 (see note 25).

completely submerged; others are relatively intolerant of flooding.[28]

Tidal freshwater marshes provide shelter, forage, and spawning habitat for numerous fish species, primarily cyprinids (minnow, shiner, carp); centrarchids (sunfish, crappie, bass); and ictalurids (catfish). Some estuarine fish and shellfish can also complete their life cycle in freshwater marshes.[29]

Freshwater tidal marshes are also important for a wide range of bird species, and some ecologists suggest that these marshes support the greatest diversity of bird species of any marsh type, including a variety of waterfowl; wading birds; rails and shorebirds; birds of prey; gulls, terns, kingfishers, and crows; arboreal birds; and ground and shrub species. [30] Perching birds such as red-winged blackbirds are common in stands of cattail. Tidal freshwater marshes support additional species that are rare in saline and brackish environments, such as frogs, turtles, and snakes.[31]

In addition to food and shelter for various species, marshes also improve water quality in the surrounding river or estuary. The marshes serve as filters for water draining from surrounding upland areas. In particular, marshes work to remove nutrients from runoff, process chemical and organic wastes, and reduce the terrigenous sediment load to the water column.[32] Marsh processes remove nitrogen and phosphorus compounds (e.g., nitrates, ammonia, and phosphates) from the water stream. The denitrification process (bacterial conversion of ammonia or nitrates from organic wastes and fertilizer into nitrogen gas) provides significant benefits to water quality. High levels of nutrients in coastal waters from nonpoint source runoff lead to algal blooms and hypoxia, which can kill large numbers of fish. Marsh vegetation also retains much of the terrigenous sediment load from runoff, which can interfere with photosynthesis in the water column (e.g., for SAV) and can cause siltation in nearshore areas (e.g., SAV or oyster beds).

Effects of Sea Level Rise on Tidal Marshes

The ability of tidal marshes to migrate in response to sea level rise depends on the supply of sediment and organic matter that is available to raise the marsh surface, the local tidal range, and the slope of nearby lowland. In addition, shoreline protection structures can block inland migration. The placement of hard structures reduces sediment inputs from upland sources and increases erosion waterward of a structure.

Tidal marshes may keep pace with sea level rise through vertical accretion and inland migration, as long as there is a dependable source of terrigenous sediment and the marsh can maintain the same elevation relative to the tidal range. In areas where neither sufficient accretion nor migration can occur, increased tidal flooding can stress marsh plants through waterlogging and changes in soil chemistry, leading to a change in species composition and vegetation zones. If marsh plants become too stressed and die, the marsh will eventually convert to open water or mudflats (see Photo 3.2).[33,34]

Steadily increasing relative sea levels may cause more frequent events such as saltwater flooding, storm overwash, and wrack deposition. These events, in turn, can trigger changes in wetland ecosystems.[35] The ability of marsh vegetation to accrete terrigenous sediment and migrate inland will determine marsh survival.[36] Marsh types,

[28]Mitsch, W.J., and J.G. Gosselink, 2000, *Wetlands*, 3rd ed., Van Nostrand Reinhold, New York, p. 275.
[29]Mitsch and Gosselink, 2000, p. 277 (see note 28).
[30]Mitsch and Gosselink, 2000, p. 279–280 (see note 28).
[31]White, 1989, pp. 107–109 (see note 25).
[32]Tiner, R.W., and D.G. Burke, 1995, *Wetlands of Maryland*, U.S. Fish and Wildlife Service, Region 5, Hadley, MA, pp. 146–147.

[33]Callaway, J.C., J.A. Nyman, and R.D. DeLaune, 1996, "Sediment accretion in coastal wetlands: A review and a simulation model of processes," *Current Topics in Wetland Biogeochemistry* 2:2–23.
[34]The Plum Tree Island National Wildlife Refuge is an example of a marsh deteriorating through lack of sediment input and migration capacity, due to development on its landward side. Extensive mudflats front the marsh. See Section 3.11 on Hampton Roads.
[35]Brinson et al., 1995, p. 655 (see note 23).
[36]Ward, L.G., M.S. Kearney, and J.C. Stevenson, 1998, "Variations in sedimentary environments and accretionary patterns in estuarine marshes undergoing rapid submergence, Chesapeake Bay." *Marine Geology* 151:111–134.

Photo 3.2: Fringing March and Bulkhead, Monmouth County, New Jersey

however, have differing capacities for sediment accretion. Facing increasing rates of sea level rise, high marshes may not be able to trap and accrete sufficient sediment, whereas low tidal marshes, both fresh and estuarine, are more likely to have this ability. Marshes without riverine sediment input, such as those that fringe islands, are at the greatest risk from sea level rise.[37] Sediment transport in low marsh areas is facilitated by tidal creeks, which frequently occur in networks throughout broad areas. These networks are absent in more mature marshes and in upland areas, limiting sediment input for high marshes.[38]

If accretion does not maintain the marsh in place, migration is also a possible mechanism for marsh survival. In addition to artificial and natural barriers (e.g., armoring structures), sediment requirements also impede wetland migration. Bare patches and a more mineral sandy substrate are necessary for lower marsh vegetation species to migrate onto areas that once were high marsh. For successful transition, a variety of factors, including localized topographic changes, erosion, deposition of wrack on high marsh plants, and ponding, can contribute to deterioration of the high marsh organic-rich peat and allow for colonization by low-marsh *Spartina alterniflora*.[39] *S. alterniflora* can aggressively colonize high marsh areas that have been devegetated by wrack deposition from a storm or overwash event. Even though *S. alterniflora* can colonize deteriorated high marsh areas with suitable sediment types, factors that reduce wetland vegetation's ability to trap sediments (e.g., construction of roads across them or reductions in sediment supply) and the processes that drive deterioration (described previously) can continue even in the absence of further sea level rise, resulting in total marsh loss.[40]

Local variation in rates of terrigenous sedimentation and other processes such as erosion will determine accretion and migration at specific sites.[41] In addition to anthropogenic or natural physical barriers, storm-induced erosion and sediment deficits can preclude migration. In Chesapeake Bay, scientists estimate that "the influx of particulates is not high enough to keep pace with relative sea level rise" on a bay-wide scale.[42] A trend of decreasing sediment inputs from major mid-Atlantic rivers because of farmland abandonment in the mid-Atlantic

[37]Najjar et al., 2000, p. 223 (see note 4).
[38]Stevenson, J.C., and M.S. Kearney, 1996, "Shoreline dynamics on the windward and leeward shores of a large temperate estuary," pp. 233–259 in *Estuarine Shores: Evolution, Environments, and Human Alterations*, K.F. Nordstrom and C.T. Roman (eds.), John Wiley & Sons, New York; and Najjar et al., 2000, p. 223 (see note 4).

[39]Brinson et al., 1995, p. 655 (see note 23).
[40]Stevenson and Kearney, 1996, p. 238 (see note 38).
[41]Ward et al. (1998) (see note 36) found that accretion rates tend to decrease down-estuary in the Nanticoke, an eastern Bay tributary. Overall, rates in embayment marshes were close to or less than the local sea level rise and not as spatially patterned as the tributary marshes. A 0.24 cm/year accretion rate at the mouth of an estuarine tributary (the Nanticoke) compared to a 0.19 cm/year accretion rate for an interior marsh area ("Variations in sedimentary environments," p. 125). In Monie Bay, a low organic content was found, indicating a higher level of mineral soils and suggesting that accretion rates are lower than relative sea level rise ("Variations in sedimentary environments," p. 127).
[42]Stevenson and Kearney, 1996, p. 236 (see note 38).

region suggests that a lack of sediment may also affect wetlands outside of Chesapeake Bay.[43] Similarly, lagoonal marshes, areas within embayments or larger marsh systems, and marshes migrating inland that are remote from tributary sediment inputs may not be able to keep pace with sea level rise.[44] In areas without sufficient sediment, wetlands may transition to tidal flat or open water.

Vegetation type can also affect the ability of a marsh to accrete sediment. Greater rates of mineral and organic sediment trapping have been associated with common reed (as compared to *Spartina* spp.) in both a subsiding creek bank marsh and a laterally eroding marsh.[45] Researchers indicate that belowground productivity most likely plays a key role in the ability of the common reed to rapidly increase substrate level.[46] Given the greater ability of marshes dominated by common reed to meet increased rates of sea level rise, expected ecological effects are lower in these areas.[47]

Effects of Armoring on Tidal Marshes

Shoreline protection can affect both migration and accretion for wetlands. Increases in wave energy generated by armoring structures can eliminate marsh areas waterward of the structures.[48] Sediment scoured from bulkhead bases in estuaries can "cover spawning habitats formerly used by forage fish that spawn in the upper intertidal zone."[49] Marsh and tidal areas reinforced with armoring that prevents habitat migration will suffer the greatest loss of habitat.[50,51] Elimination of these wetland areas will also reduce the shoreline's ability to buffer the effects of erosion and floods and to filter nutrient and contaminant loads in runoff.

Ecological Effects on Tidal Marshes

Where tidal wetlands are lost, the myriad species that depend on marshes—birds, fish, invertebrates, amphibians, reptiles, and mammals—can show decreased growth, reproduction, or survival resulting from a decrease in habitat quantity or quality. If salt marsh areas are lost, avian marsh-nesting obligates such as Forster's terns, black rails, clapper rails, northern harriers, American black ducks, seaside sparrows, and sharp-tailed sparrows will lose habitat and are likely to suffer reproductive stress.[52] Lagoonal marshes and mid-embayment areas are particularly susceptible to changes induced by sea level rise. Tidal flats will be inundated, and although changes in extent might be localized at first, scientists anticipate an overall reduction in forage habitat for shorebirds.

Sea level rise is also advancing the salinity gradient upstream in some rivers, leading to shifts in vegetation composition and the conversion of some tidal freshwater marshes into oligohaline marshes.[53] High brackish marshes can deteriorate as a result of ponding and wrack-smothering of vegetation as salinity increases with rising seas and storms accentuate the fragmentation of the marshes.[54] This process may allow colonization by lower marsh species, but

[43]Najjar et al., 2000, p. 223 (see note 4).
[44]Erwin et al., 2004, p. 892 (see note 16).
[45]Rooth, J.E. and J.C. Stevenson, 2000, "Sediment deposition patterns in *Phragmites australis* communities: Implications for coastal areas threatened by rising sea-level," *Wetlands Ecology and Management* 8:173–183.
[46]Ibid.
[47]At Eastern Neck National Wildlife Refuge, Maryland, managers are leaving phragmites stands in place as a strategic action against erosion. See Section 3.17, Chesapeake Bay's Upper Bay, of this section.
[48]U.S. Geological Survey (USGS), 2003, "A summary report of sediment processes in Chesapeake Bay and watershed," p. 55 in *Water-Resources Investigations Report 03-4123,* USGS, Reston, VA.
[49]Small, D., and R. Carman, 2005, "Marine shoreline armoring in Puget Sound and the Washington State Hydraulic Code," p. 1 in *Proceedings of the 2005 Puget Sound Georgia Basin Research Conference, March 29-31, 2005.* Available at: http://www.engr.washington.edu/epp/psgb/2005psgb/2005proceedings/index.html from the University of Washington, College of Engineering.
[50]Galbraith, H., R. Jones, P. Park, J. Clough, S. Herrod-Julius, B. Harrington, and G. Page, 2002, "Global climate change and sea level rise: Potential losses of intertidal habitat for shorebirds, *Waterbirds* 25(2):173–183.
[51]Oyster Bay, New York, has experienced extensive marsh loss as a result of bulkheading. See Section 3.3, Long Island South Shore.
[52]For example, seaside and sharp-tailed sparrows are both prevalent in at-risk marshes on Virginia's Eastern Shore. See Section 3.19.
[53]Maryland Department of Natural Resources (DNR), 2005, Chapter 4, Part 2, p. 49 in *Wildlife Diversity Conservation Plan—Final Draft,* available at: http://www.dnr.state.md.us/wildlife/divplan_wdcp.asp (accessed February 28, 2007).
[54]Along the Patuxent River, Maryland, refuge managers have noted marsh deterioration and ponding with sea level rise. See Section 3.16 on the Western Shore.

that outcome is not certain.[55] Low brackish marshes may change dynamically in area and composition as sea level rises. If they are lost, forage fish and invertebrates of the low marsh—such as fiddler crabs, grass shrimp, and ribbed mussels—will no longer be available to the predators that consume them. Even though more ponding and "pannes" might provide some additional foraging areas as marshes deteriorate, the associated increase in salinity due to evaporative loss will drive vegetation changes to less diverse assemblages of salt-tolerant species.[56] In fact, high salt conditions will be lethal for many species.

If marshes can migrate, changes in vegetation assemblages will in turn affect the faunal species that forage, nest, spawn, and seek shelter in tidal marshes. Factors affecting fauna include reduced available oxygen, structural changes in vegetation, and reduction of foraging areas in tidal flats. In these hypoxic conditions, more salt-tolerant fishes such as mummichogs and killifishes become prevalent.[57]

In areas where marshes are reduced, remnant marshes might provide lower quality habitat and pose greater predation risk for a number of bird species that are marsh specialists and are also important components of marsh food webs. These species include the clapper rail, black rail, least bittern, Forster's tern, willet, and laughing gull.[58] Scientists estimate that as much as 80 percent of the Atlantic Coast breeding population of Forster's tern and 70 percent of laughing gull

are at risk because of habitat loss due to sea level rise.[59] Populations of some noncolonial species are also at risk because of their already-low population sizes, estimated at about 142,000 for the clapper rail, 102,000 for the willet, and as little as 13,000

[55]Stevenson and Kearney, 1996, p. 236 (see note 38).
[56]Maryland DNR, 2005, p. 49 (see note 53).
[57]Stevenson et al., 2002, pp. 25–26 (see note 7).
[58]Erwin, R.M., G.M. Sanders, D.J. Prosser, and D.R. Cahoon, 2006, "High tides and rising seas: potential effects on estuarine waterbirds," pp. 214–228 in *Terrestrial Vertebrates of Tidal Marshes: Evolution, Ecology, and Conservation* (R. Greenberg, J. Maldonado, S. Droege, and M.V. McDonald, eds.). Studies in Avian Biology No. 32, Cooper Ornithological Society.
[59]Ibid.

to 14,000 for the American black duck.[60] The number of bird species in Virginia marshes was found to be directly related to marsh size; the minimum marsh size found to support significant marsh bird communities ranged from 4.1 to 6.7 ha.[61] Particular species may require even larger marsh sizes; minimum marsh sizes for successful communities of the saltmarsh sharp-tailed sparrow and the seaside sparrow, both on the Partners in Flight WatchList, are estimated at 10 and 67 ha, respectively.[62]

Effects of marsh inundation on fish and shellfish species are likely to be complex. In the short term, inundation could make the marsh surface more accessible, increasing production.

The benefits, however, will decrease as submergence decreases total marsh habitat.[63] A marsh loss model, coupled with shrimp survey data from the National Marine Fisheries Service, suggests that losses in yields due to marsh loss could be as high as 50 percent.[64]

Deterioration and mobilization of marsh peat sediments increase the biological oxygen demand in the immediate vicinity and deplete oxygen levels to below requirement thresholds for many game fish such as striped bass. In these hypoxic conditions, more tolerant fish assemblages ,including mummichogs and killifish, become prevalent.[65]

[60]Ibid.
[61]Watts, B.D., 1993, *Effects of Marsh Size on Incidence Rates and Avian Community Organization within the Lower Chesapeake Bay*, Center for Conservation Biology Technical Report CCBTR-93-03, The College of William and Mary, Williamsburg, VA, 53 pp.
[62]Benoit, L.K., and R.A. Askins, 2002, "Relationship between habitat area and the distribution of tidal marsh birds," *The Wilson Bulletin* 114(3):314–323.

[63]Rozas, L.P., and D.J. Reed, 1993, "Nekton use of marsh-surface habitats in Louisiana (USA) deltaic salt marshes undergoing submergence," *Marine Ecology Progress Series* 96:147–157.
[64]Zimmerman, R.J., 1992, "Global warming: effects of sea level rise on shrimp fisheries," pp. 58–73 in *Proceedings of the Southeast Fisheries Science Center Shrimp Resource Review*, K.N. Baxter and L. Scott-Denton (eds.), NOAA Technical Memorandum, NMFS-SESC-299.
[65]Stevenson et al., 2002, pp. 25–26 (see note 7).

3.1.2 FRESHWATER SWAMP FORESTS

Limited by their requirements for low salinity water and high sediment inputs, tidal swamp forests occur primarily in the upper regions of tidal tributaries in Virginia, Maryland, Delaware, New Jersey, and New York.[66] Tidal hardwood swamps occur in all of Virginia's major eastern rivers, and are particularly pristine in the Pamunkey and Mattaponi rivers. In these rivers, pumpkin ash and swamp tupelo are the primary overstory species. In the Potomac River and farther north, green ash replaces pumpkin ash as the dominant species.[67] Parts of the Pocomoke River tidal floodplain forests are dominated by bald cypress. At the upland edges of tidal river floodplains, loblolly pine, sweetgum, and oaks can be present.[68] Farther north (into New Jersey and New York), varying tree species are present, and the habitat is classified as northern Atlantic coastal plain tidal swamp.[69] North Carolina contains large stands of forested wetlands, particularly cypress swamps, as discussed in the review of ecological impacts in North Carolina (see, for example, Photo 3.3b).[70]

Throughout the forested swamps, "hummock-and-hollow microtopography" dictates where trees can establish themselves on small elevated areas above the highest tide levels.[71] A species-rich herb vegetation layer includes a variety of species such as jewelweed, arrow arum, and sedges in the regularly flooded areas; marsh blue violet, water hemlock, greenfruit clearweed, false nettle, and ferns are found on the hummocks (vegetated mounds that rise above the adjacent wetland area).[72] Tidal swamps support a variety of wildlife, including the prothonotary warbler, the two-toed amphiuma salamander, and the bald eagle. Forested wetlands with thick understories provide shelter and food for an abundance of breeding songbirds.[73] Various rare and greatest conservation need (GCN) species reside in tidal swamps, including the Delmarva fox squirrel (federally listed as endangered), the eastern red bat, bobcats, bog turtles, and the red-bellied watersnake.[74]

Effects of Sea Level Rise on Tidal Freshwater Swamp Forests

Tidal freshwater swamp forests are considered globally uncommon to rare, and face a variety of threats, including sea level rise. According to Fleming and colleagues, "Crown dieback and tree mortality are visible and nearly ubiquitous phenomena in these communities and are generally attributed to sea level rise and an upstream shift in the salinity gradient in estuarine rivers" (see also Photo 3.3a).[75] Ecologists in Virginia note that where tree death is present, the topography is limiting inland migration of the hardwood swamp and the understory is being infilled with marsh species such as *Spartina*.[76]

Ecological Effects on Tidal Freshwater Swamp Forests

This pattern of crown dieback and marsh species migration is likely to continue with sea level rise acceleration. Salinity may increase as areas are inundated, eliminating vegetation that relies on the diluting effect of freshwater inputs. Loss of

[66]NatureServe, 2006, "NatureServe Explorer: An online encyclopedia of life" [Web application], Version 5.0, NatureServe, Arlington, Virginia, available at: http://www.natureserve.org/explorer, accessed September 1, 2006, and "Northern Atlantic coastal plain tidal swamp," CES203.282, accessed on September 1, 2006 at: http://www.natureserve.org/explorer/servlet/NatureServe?searchSystemUid=ELEMENT_GLOBAL.2.723205.

[67]Fleming, G.P., P.P. Coulling, K.D. Patterson, and K. Taverna, 2006, "The natural communities of Virginia: Classification of ecological community groups. Second approximation. Version 2.2," Virginia Department of Conservation and Recreation, Division of Natural Heritage, Richmond, VA, available at: http://www.dcr.virginia.gov/dnh/ncintro.htm, accessed June 19, 2007.

[68]Maryland DNR, 2005, *Wildlife Diversity Conservation Plan*, p. 1 (see note 53).

[69]Westervelt, K., E. Largay, R. Coxe, W. McAvoy, S. Perles, G. Podniesinski, L. Sneddon, and K. Strakosch Walz, 2006, *A Guide to the Natural Communities of the Delaware Estuary: Version 1*, NatureServe, Arlington, VA, pp. 270–273.

[70]Mark Brinson of East Carolina University is providing CCSP and USGS with an analysis of these wetlands. We hope to work with him to fully reflect these important wetlands.

[71]Fleming et al., 2006 (see note 67).

[72]Maryland DNR, 2005, p. 1 (see note 53).

[73]Lippson and Lippson, 2006, p. 218 (see note 2).

[74]Maryland DNR, 2005, p. 4 (see note 53).

[75]Fleming et al., 2006 (see note 67).

[76]Written communication, Gary Fleming, vegetation ecologist, Virginia Department of Conservation and Recreation, Division of Natural Heritage. Via email to Christina Bosch, Industrial Economics, September 11, 2006. Subject: Re: Sea level rise report wrap-up - please respond.

tidal swamp forests would detrimentally affect the varied fauna that reside there.

3.1.3 MARSH AND BAY ISLANDS

Islands are common features of salt marshes, and some estuaries and back barrier bays have islands formed by deposits of dredge spoil. Many islands are a mix of habitat types, with vegetated and unvegetated wetlands in combination with upland areas.[77] Shorelines can be composed of marsh or rocky or sandy beaches. These islands are important habitats for birds because they provide protection from terrestrial predators such as the red fox. Birds such as gull-billed terns, common terns, black skimmers, and American oystercatchers nest on marsh islands.[78] Many islands provide secluded areas for important bird colonies (e.g., the colonies of the rare black-crowned night heron on North and South Brother islands in New York; see Section 3.2 on Long Island Sound). Salt marsh islands in the New Jersey back-barrier bays are feeding and/or nesting sites for a variety of birds and turtles, including several species of tern, oystercatchers, plovers, and diamondback terrapins (see Section 3.6 on New Jersey Shore). Artificially enhanced islands, generally created through dredge spoil, can provide similar benefits (e.g., Hart-Miller Island near Baltimore, Maryland); however, dredge spoil islands can be particularly susceptible to erosion (see Section 3.16, Chesapeake Bay's Western Shore, and discussion of Poplar Island in Section 3.18, Chesapeake Bay's Central Eastern Shore). Hummocks can also be considered a type of island (see Photo 3.4).

Photo 3.3a: Inundation and tree mortality in tidal freshwater swamp at Swan's Point, Lower Potomac River

Photo 3.3b. Cypress along Roanoke River, North Carolina

[77]Thompson's Island in Rehoboth Bay, Delaware, is a good example of a mature forested upland with substantial marsh and beach area. The island hosts a large population of migratory birds. See Section 3.8 of this section.

[78]Rounds, R.A., R.M. Erwin, and J.H. Porter, 2004, "Nest-site selection and hatching success of waterbirds in coastal Virginia: Some results of habitat manipulation," *Journal of Field Ornithology* 75:317–329; Eyler, T.B., R.M. Erwin, D.B. Stotts, and J.S. Hatfield, 1999, "Aspects of hatching success and chick survival in gull-billed terns in coastal Virginia," *Waterbirds* 22:54–59; and Lauro, B., and J. Burger, 1989, "Nest-site selection of American oystercatchers (*Haematopus palliatus*) in salt marshes," *Auk* 106:185–192.

Photo 3.4: Marsh Drowning and Hummock in Blackwater Wildlife Refuge, Maryland

Barrier islands form where sand accumulates along sandy coasts with small or medium tide ranges and wide continental shelves.[79] They contain many fragile habitats such as sand dunes, maritime forests, and back-barrier marshes that provide critical habitat for many coastal species. Barrier islands are a common feature of the U.S. Atlantic Coast.

Effects of Sea Level Rise on Islands

Depending on their current elevations, sediment supply, and rates of erosion, wetland islands could become the first habitats to be eliminated as a result of sea level rise. Sea level rise poses a unique threat to islands, in that migration is not an option and sediment inputs may be limited. Some scientists believe that salt marsh islands in large coastal lagoons will be more vulnerable to inundation as sea level rises than fringing marshes because the lagoons lack inorganic sediments.[80] In some cases, rising sea level may cause additional islands to form, as portions of peninsulas erode and higher water levels separate high ground from the mainland. Many islands along the mid-Atlantic Coast, and particularly in Chesapeake Bay, have been lost or severely degraded because of sea level rise. Although armoring can be used to protect these islands, it is not generally employed because the islands are undeveloped.

Without human interference, barrier islands often maintain a state of dynamic equilibrium between sediment exchange, wave energy, and sea level, migrating inland through a process often called "overwash" or "barrier island rollover." Under some circumstances, however, rising sea level can increase the frequency of inlets, and under extreme circumstances, sea level rise can cause the islands to disintegrate or reform several kilometers inland. The relatively slow rise in sea level during the last several centuries has enabled many barrier islands to widen far beyond their critical width; it follows that accelerated sea level rise would tend to cause most barrier islands to narrow.

Ecological Effects on Islands

For island-nesting bird species, the loss of wetland islands to flooding and erosion is a serious problem. A shift to mainland marshes is generally not an option for these species because of predators present in those marshes. Numerous species of special concern, including the piping plover, nest in the protected back-dune areas of barrier islands. Loss of these habitats could have a serious effect on such rare species. To the extent that estuarine and riverine beaches, particularly on islands, survive better than barrier islands, shorebirds like oystercatchers might be able to migrate to these shores.[81]

[79] The information presented here on barrier islands is very limited because CCSP4.1 has at least two nationally recognized barrier-island experts from USGS; hence this background report is unlikely to be used for the CCSP discussions of barrier islands.

[80] Erwin et al., 2004, pp. 891–903 (see note 16).

[81] McGowan, C.P., T.R. Simons, W. Golder, and J. Cordes, 2005, "A comparison of American oystercatcher reproductive success on barrier beach and river island habitats in coastal North Carolina," *Waterbirds* 28:150–155.

3.1.4 SEA LEVEL FENS

The mid-Atlantic region contains a few areas of the globally rare sea level fen habitat. These fens are unique combinations of plant species, present in Delaware's Sussex County Inland Bays watershed, on Long Island's South Shore, and on the eastern shore of Virginia's Accomack County.[82] Sea level fens generally occur just above the upper high tide mark, at the bases of slopes.[83] Groundwater seepage from the slopes provides sea level fens with nutrient-poor fresh water. The fens occur only where they are protected from nutrient-rich tidal flow by a barrier such as a fronting tidal marsh.

The nutrient-poor environment and acidic soils support a unique mix of vegetation species, including both freshwater tidal species and northern bog species, in sea level fens.[84] Red maple, blackgum, sweetbay, and southern bayberry form the overstory; the herb layer typically includes twig rushes, beaked spikerushes, and beakrushes. Carnivorous plants, including sundew and bladderworts, are also present.[85] The eastern mud turtle and the smallest northeastern dragonfly (*Nanothemis bella*) are two faunal species known to occur in the fens.[86] The animal and plant species listed here are not exclusive to sea level fens, but many are rare species.

Effect of Sea Level Rise on Sea Level Fens

Because these fens are located at the bases of slopes, they are likely to be inundated by sea level rise. The Virginia Natural Heritage Program identifies sea level rise as a primary threat to sea level fens because of the increase in salinity and nutrient-rich water inputs.[87] The location of fens below slopes limits the possibility for migration. During the development of this report, no studies of the effects of armoring on sea level fens were identified.

Ecological Effects on Sea Level Fens

The unique vegetation assemblages and little-studied animal communities of sea level fens are likely to be eliminated by sea level rise. The plant assemblages are unique, but the animal species identified are present in other habitats. The habitat is likely to convert to more usual tidal marsh vegetation and faunal assemblages following the increased incursion of higher salinity waters. However, given the slopes at the landward edges of the fens, migration will be restricted and survival of any marsh areas will depend on accretion rates.

3.1.5 NEARSHORE WATERS AND SUBMERGED AQUATIC VEGETATION (SAV)

Nearshore shallow water habitats perform a variety of roles in the aquatic ecosystem. Key ecological features of the nearshore shallow water habitat include SAV, oyster reefs, and nektonic (e.g., fish and decapod crustaceans) and planktonic inhabitants. In areas without SAV or oyster reefs, muddy and sandy substrates similar to those found on tidal flats are present.[88] Oyster reefs are a key resource in intertidal and nearshore waters; however, they are not addressed in detail here because many factors currently affect their success. Over harvest, nutrient levels, and disease have all significantly affected oyster reefs.. Changes related to sea level rise may additionally affect the resource. For example, if salinity were to increase, oysters might be able to successfully colonize farther up estuaries, but in their current areas they would suffer greater losses from predators and disease. These possibilities, though, are difficult to estimate in the presence of annual variability. This section therefore focuses on SAV, which provides a wide array of ecological services and

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[82] For additional discussion, see Sections 3.8, Maryland and Delaware Coastal Bays; 3.3, Long Island's South Shore; and 3.19, Virginia's Eastern Shore.

[83] Virginia Natural Heritage Program, Virginia Department of Conservation and Recreation. Natural Heritage Resources Fact Sheet: Virginia's rare natural environments: Sea-level fens. Accessed on July 17, 2007 at: http://www.dcr.virginia.gov/natural_heritage/documents/fsslfen.pdf.

[84] Ibid.

[85] Fleming et al., 2006 (see note 67).

[86] Virginia Natural Heritage Program (see note 83).

[87] Fleming et al., 2006 (see note 67).

[88] Lippson and Lippson, 2006, pp. 126–127 (see note 2).

is very sensitive to water depth and substrate. SAV includes submerged, vascular rooted plants found in the subtidal and, occasionally, in the intertidal zone.[89] SAV can occur as isolated patches or form extensive beds. Aquatic vegetation is distributed throughout the mid-Atlantic region, dominated by eelgrass in the higher salinity areas and a large number of brackish and freshwater species elsewhere (e.g., widgeon grass and sea lettuce). During low tides, SAV can be exposed on estuarine beaches and tidal flats.[90]

Nearshore vegetation plays a strong role in estuarine and bay ecology, regulating dissolved oxygen, reducing suspended sediments and nutrients, stabilizing bottom sediments, and reducing wave energy.[91] SAV communities regulate the production, uptake, and storage of nitrogen, carbon, and oxygen in the ecosystem.[92] Optimum growing conditions for SAV are highly dependent on light levels for photosynthesis. Various interferences—such as increased turbidity, epiphyte growth on leaves, and increased water depth—can decrease the light available to the plants for photosynthesis. Plants at either end of the growing zone are stressed by overexposure or sunlight limits. Nutrient runoff (which boosts algal growth that shades the SAV) as well as boating and mollusk dredging (which cause physical disturbance to the beds) can all have detrimental effects on SAV.[93]

Except for a high predominance of sea lettuce in New York's Jamaica Bay and the subtidal reaches stretching from Little Egg Harbor south to Cape May in New Jersey, the more northerly SAV beds are largely eelgrass. Research in New Jersey's coastal bays found a reduced habitat quality of SAV in areas dominated by sea lettuce.[94]

Seagrasses (e.g., eelgrass and widgeon grass) provide food and shelter for a variety of fish and shellfish, food for the species that prey on them, and physical protection from wave energy for shorelines. Organisms that forage in seagrass beds feed on the plants themselves, on the detritus and the epiphytes on plant leaves, or on the small organisms found within the SAV bed.[95] Invertebrates that are common in eelgrass meadows include polychaetes such as the common clam worm; mollusks such as bay scallop and northern quahog; crustaceans such as blue crabs, hermit crabs, and mud crabs; and amphipods such as *Lysianopsis alba* and the small, shrimp-like *Ampelisca abdita*. The commercially valuable blue crab hides in eelgrass during its molting periods, when it is more vulnerable to predation. Blue crabs in the postlarval phase (megalopae) preferentially inhabit eelgrass beds.[96]

These invertebrates are in turn consumed by fish and other predators.[97,98] In Chesapeake Bay, summering sea turtles frequent eelgrass beds. The endangered Kemp's Ridley sea turtle forages in eelgrass beds and flats, feeding on

[89]Hurley, L.M., 1990, *Field Guide to the Submerged Aquatic Vegetation of Chesapeake Bay*, U.S. Fish and Wildlife Service, Chesapeake Bay Estuary Program, Annapolis, MD, 48 pp.
[90]Maryland DNR, 2005, pp. 22–23 (see note 53).
[91]Short, F.T., and H.A. Neckles, 1999, "The effects of global climate change on seagrasses." *Aquatic Botany* 63(1999):169–196.
[92]Buzzelli, C.P., 1998, "Dynamic simulation of littoral zone habitats in lower Chesapeake Bay. I. Ecosystem characterization related to model development," *Estuaries* 21(48):659–672; Buzzelli, C.P., R.L. Wetzel, and M.B. Meyers, 1998, "Dynamic simulation of littoral zone habitats in lower Chesapeake Bay. II. Seagrass habitat primary production and water quality relationships," *Estuaries* 21(48):673–689.
[93]Orth, R.J., J.R. Fishman, A. Tillman, S. Everett, and K.A. Moore, 2001, *Boat Scarring Effects on Submerged Aquatic Vegetation in Virginia (Year 1),* Final Report to the Virginia Saltwater Recreational Fishing Development Fund; Moore, K.A., and R.J. Orth. 1997, *Evidence of Widespread Destruction of Submersed Aquatic Vegetation (SAV) from Clam Dredging in Chincoteague Bay, Virginia,* Report to the Virginia Marine Resources Commission. Both reports are available from VIMS at: http://www.vims.edu/bio/sav/savreports.html (Accessed October 16, 2007).
[94]Sogard, S.M., and K.W. Able, 1991, "A comparison of eelgrass, sea lettuce macroalgae, and marsh creeks as habitats for epibenthic fishes and decapods," *Estuarine, Coastal and Shelf Science* 33:501–519.
[95]For blue crabs, see Stockhausen, W.T., and R.N. Lipcius, 2003, "Simulated effects of seagrass loss and restoration on settlement and recruitment of blue crab postlarvae and juveniles in the York River, Chesapeake Bay," *Bulletin of Marine Science* 72(2):409–422. For fish, see Wyda, J.C., L.A. Deegan, J.E. Hughes, and M.J. Weaver, 2002, "The response of fishes to submerged aquatic vegetation complexity in two ecoregions of the mid-Atlantic Bight: Buzzards Bay and Chesapeake Bay," *Estuaries* 25:86–100.
[96]van Montfrans, J., C.H. Ryer, and R.J. Orth, 2003, "Substrate selection by blue crab *Callinectes sapidus* megalopae and first juvenile instars," *Marine Ecology Progress Series* 260:209–217.
[97]USEPA, 1982, *Chesapeake Bay: Introduction to an Ecosystem,* USEPA, Washington, DC, , 33 pp.
[98]Lippson and Lippson, 2006, p. 181 (see note 2).

blue crabs in particular.[99] Various water birds feed on SAV, including brant, canvas back duck, and American black duck, which is a U.S. Fish and Wildlife Service species of concern.[100] Forage for piscivorous birds and fish is provided by a number of small fishes that are residents of nearby marshes and move in and out of seagrass beds with the tides, including mummichog, Atlantic silverside, naked goby, northern pipefish, and threespine and fourspine sticklebacks. Juveniles of many commercially and recreationally important estuarine and marine fishes (including menhaden, herring, shad, spot, croaker, weakfish, red drum, striped bass, and white perch) and smaller adult fish (such as bay and striped anchovies) use SAV beds as nurseries that provide both food and protection from predators.[101] Adults of estuarine and marine species such as sea trout, bluefish, perch, pickerel, and drum search for prey in the SAV beds.

Effect of Sea Level Rise on Nearshore Waters and SAV

Sea level rise may harm seagrass beds through inundation, increased turbidity, and saltwater intrusion.[102] In subtidal areas, rising sea levels and deepening waters will shade seagrass and limit photosynthesis. Extensive armoring coupled with areas of limited natural migration could significantly decrease seagrass abundance. Although plants in some portion of a seagrass bed could decline as a result of such factors, landward edges may migrate inland depending on shoreline slope and substrate suitability. The extent of ecological effects is uncertain because most changes in seagrass beds occur on a significantly shorter time scale than can be attributed to sea level rise.[103]

Under optimal conditions, seagrasses could migrate into deteriorating marshes. For example, populations of widgeon grass were observed in marsh potholes that developed as canals formed through organic marsh deposits.[104] Kentula and McIntire documented eelgrass expansion into a basin created by sand deposition.[105] Preliminary studies of eelgrass in marsh areas being inundated by relative sea level rise have, however, shown that the sediment composition of the low marsh areas may not be suitable for eelgrass colonization. In areas where inundation exposed underlying sand, eelgrass beds extended into the areas, but areas of exposed peat were not colonized. The difficulty in colonization was tied to the impermeability of the substrate (prohibiting seed settlement and germination) and the high levels of nutrients in the sediment, particularly nitrogen. These factors changed the morphology of the eelgrass, making it less suited to the energy level of its environment.[106] Unlike most wetland plants, seagrasses generally require a low organic content for optimal growth.[107] When tidal marshes, which have a high organic content, are submerged, SAV such as *Ruppia maritima* can have difficulty revegetating the substrate. SAV grows significantly better in areas where erosion provides sandy substrates rather than fine-grained or high-organic-matter substrates.[108]

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[99]Chesapeake Bay Program sea turtles guide, 2003, available at: http://www.chesapeakebay.net/seaturtle.htm, accessed February 27, 2007.
[100]Perry, M.C. and A.S. Deller, 1996, “Review of factors affecting the distribution and abundance of waterfowl in shallow-water habitats of Chesapeake Bay,” *Estuaries* 19:272–278.
[101]NOAA Chesapeake Bay Office, 2007, “Underwater grasses and submerged aquatic vegetation,” accessed June 19, 2007 at: http://noaa.chesapeakebay.net/HabitatSav.aspx; Wyda et al., 2002, pp. 86–100 (see note 95).
[102]Short and Neckles, 1999, pp. 169–196 (see note 91).
[103]USFWS Chesapeake Bay Field Office, n.d., “Nutrient pollution,” accessed on July 20, 2006 at: http://www.fws.gov/chesapeakebay/nutrient.htm.
[104]Christian, R.R., 1981, referenced in Brinson et al. 1995, p. 654 (see note 23).
[105]Kentula, M.E., and C.D. McIntire, 1986, “The autecology and production dynamics of eelgrass (L. *Zostera marina*) in Netarts Bay, Oregon,” *Estuaries* 9(3):188–193.
[106]Wicks, E.C., 2005, *The Effect of Sea Level Rise on Sea Grasses: Is Sediment Adjacent to Retreating Marshes Suitable for Seagrass Growth?* Thesis, Marine, Estuarine, and Environmental Science Program, University of Maryland, College Park; and preliminary research by Koch.
[107]Kemp, W.M., R. Batuik, R. Bartleson, P. Bergstrom, V. Carter, G. Gallegos, W. Hunley, L. Karrh, E. Koch, J. Landwehr, K. Moore, L. Murray, M. Naylor, N. Rybicki, J.C. Stevenson, and D. Wilcox, 2004, “Habitat requirements for submerged aquatic vegetation in Chesapeake Bay: Water quality, light regime, and physical-chemical factors,” *Estuaries* 27:363–377.
[108]Stevenson et al. 2002, pp. 26, 32 (see note 7).

The effect of sea level rise on the tidal range will also have an impact on seagrass, although it may be detrimental or beneficial. In areas where the tidal range increases, plants at the lower edge of the bed will receive less light at high tide, which will increase plant stress.[109] In areas where the tidal range decreases, the decrease in intertidal exposure at low tide on the upper edge of the bed will reduce plant stress.[110]

Effects of Armoring on Nearshore Waters and SAV

Areas of shoreline armoring are likely to experience the biggest losses of seagrass. Movement of seagrass beds shoreward will be impeded by shoreline construction and armoring in developed areas.[111] Where inland migration is not possible, seagrass will decline or be eliminated as a result of inundation and increased salinity as seas rise. Nearshore fishes have been found to be significantly less abundant at bulkheaded sites, in part because seagrass is not present.[112] Bulkheads and other hard structures tend to affect the geomorphology of their locations as well as any adjacent seagrass habitats. Particularly during storm events, wave reflection off of revetments can increase water depth and magnify swash runup on downcoast beaches.[113] A USGS sedimentation study notes that these structures tend to increase erosion at their bases by reflecting wave energy across the nearshore bottom.[114] Similarly, a study of armoring in estuaries found that "wave energy reflected from bulkheads causes an increase in turbulence and erosional energy waterward of the structure that can result in substrate coarsening and lowering of the beach profile."[115] These physical changes in turn affect the habitats.

As sea level rises in armored areas, accompanied by erosional energy at the bottom, the nearshore area deepens with no ability to migrate. In addition to the effects of increased reflectional wave energy, which can be dissipated to a large degree by healthy seagrass communities, light attenuation increases with the deepening water, restricting and finally eliminating seagrass growth. Optimum growing conditions for most SAV require light levels typically found at up to 1 to 2 meters in depth, generally starting below the mean lower low watermark.[116] Light reductions from water clarity and epiphyte growth in most SAV beds are now at 1 meter or less in depth.[117]

In addition to the effects of light quantity and turbulence, high nutrient levels in the water are also a limiting factor. Despite the protection from wave energy provided in their interior, breakwaters appear to be detrimental to seagrass in the long term. Sediment trapping behind the breakwater, which increases the organic content, can limit eelgrass success. Low-profile armoring, including stone sills and other "living shoreline" projects, have a more limited impact on seagrass growth.[118] New designs for seagrass-friendly breakwaters that allow rollover at high tide might serve to flush out the interior of the breakwater and eliminate excess nutrient buildup.[119]

Ecological Effects on Nearshore Waters and SAV

The extent of ecological effects is uncertain, because most changes in SAV beds occur on a significantly shorter time scale than can be attributed to sea level rise.[120] Some species of seagrass could survive the effects of sea level

[109]Koch and Beer, 1996, referenced in Short and Neckles, 1999, p. 179 (see note 91).
[110]Short and Neckles, 1999, pp. 179–180 (see note 91).
[111]Short and Neckles, 1999, p. 178 (see note 91).
[112]Byrne, D.M., 1995, "The effect of bulkheads on estuarine fauna: a comparison of littoral fish and macroinvertebrate assemblages at bulkheaded and non-bulkheaded shorelines in a Barnegat Bay Lagoon," *Second Annual Marine Estuarine Shallow Water Science and Management Conference*: 53–56.
[113]Plant, N.G. and G.B. Griggs, 1992, "Interactions between nearshore processes and beach morphology near a seawall." *Journal of Coastal Research* 8: 183–200, p. 190.
[114]USGS, 2003, p. 50 (see note 48).
[115]Small and Carman, 2005, p. 1 (see note 49).
[116]Kemp et al., 2004 (see note 107).
[117]Orth, R.J., and K.A. Moore, 1984, "Distribution and abundance of submerged aquatic vegetation in Chesapeake Bay: An historical perspective," *Estuaries* 7:531–540; Kemp et al., 2004, p. 365 (see note 107).
[118]See, for example, National Academy of Sciences, 2006, *Mitigating Shore Erosion along Sheltered Shores*, The National Academies Press. Washington, DC, pp. 46, 57.
[119]Koch, E.W., L.P. Sanford, S.-N. Chen, D.J. Shafer, and J.M. Smith, 2006, Waves in Seagrass Systems: Review and Technical Recommendations. Final Report prepared for the U.S. Army Corps of Engineers, System-Wide Water Resources Research Program and Submerged Aquatic Vegetation Restoration Research Program, ERDC TR-06-15, p. 16.
[120]USFWS, n.d., Nutrient pollution (see note 103).

rise by expanding inland. Submerged vegetation cannot grow and survive, however, where increased water depth or increased turbidity severely restrict the amount of light available for photosynthesis. Short and Neckles estimate that, in general, a 50 cm increase in water depth as a result of sea level rise could reduce the available light in coastal areas by 50 percent, reducing seagrass growth in current bed areas by 30 to 40 percent.[121] Such reductions in seagrass could have a significant effect on the many fauna found in seagrass beds. For example, research indicates that the abundance, biomass, and diversity of fishes are higher near seagrass beds than in unvegetated areas.[122]

In areas where seagrass is lost, the primary productivity, the habitat provided to key species, and the shoreline protection benefits will all be affected.[123] The extent of primary productivity impact is unknown; autotrophs like phytoplankton and sediment microalgae are generally not considered capable of providing the extent of primary production contributed by SAV.[124] In Chesapeake Bay, the microbenthic algal community comprises between 3 and 5 percent of the total annual primary production from all sources.[125] Vegetation also increases the dissolved oxygen content of the water; low dissolved oxygen in summer (common in many Atlantic waterways) is a major stressor on biota such as the blue crab, Atlantic sturgeon, and striped bass.[126] Wrack from submerged aquatic vegetation also plays an important role in beach communities, providing cover and food to a variety of amphipods, isopods, and insects, which are in turn fed on by shorebirds such as plovers.[127]

Loss of SAV affects the large number of species that depend on the vegetation beds for protection and food. As noted previously, blue crabs are particularly dependent on seagrass beds, although some types of shoreline structures (e.g., riprap and jetties) can provide similar protective cover to juvenile crabs.[128] By one estimate, a 50 percent reduction in SAV results in a roughly 25 percent reduction in striped bass production.[129] Fish abundance and species richness are also affected by degradation of SAV habitat. A decline in SAV also affects larger predators, including shorebirds and sea turtles. Birds that are primarily herbivorous are directly affected by the loss of SAV. For diving and dabbling ducks, researchers have noted a decrease in SAV in their diets since the 1960s. With the decline of SAV, the diet of geese and swans has shifted to agricultural field wastes. For canvasback ducks, SAV consumption has been replaced by a diet high in invertebrates and crustaceans. Such diet shifts have not been possible for all SAV-reliant species. The decreased SAV in Chesapeake Bay is cited as a major factor in the substantial reduction in wintering waterfowl such as redhead ducks.[130]

3.1.6 TIDAL FLATS

Tidal flats are found in the intertidal zone. They have muddy substrates, typically composed of silt and clay, that support sparse or no vegetation. In brackish area flats, vegetation is rare, consisting of occasional clumps of

[121]Short and Neckles, 1999, p. 178 (see note 91).
[122]Wyda et al., 2002, pp. 86–100 (see note 95).
[123]Duarte, C.M., 2002, "The future of seagrass meadows," *Environmental Conservation* 29(2):192–206.
[124]Borum, 1996, in Duarte, 2002, p. 199 (see note 123); reviewed in Buzzelli 1998, p. 659 (see note 92).
[125]Wendker, S., H.G. Marshall, and K.K. Nesius, 1997, "Benthic primary production within shallow water sites in Chesapeake Bay," pp. 148–151 in *Proceedings of the Second Marine and Estuarine Shallow Water Science and Management Conference, U.S. Environmental Protection Agency, Philadelphia, PA,* EPA 903/R/97009, USEPA, Washington, DC.
[126]For blue crabs, see Mistiaen, J.A., I.E. Strand, and D. Lipton, 2003, "Effects of environmental stress on blue crab (*Callinectes sapidus*) harvests in Chesapeake Bay tributaries," *Estuaries* 26(2A):316–322. For Atlantic sturgeon, see Niklitschek, E.J., and D.H. Secor, 2005, "Modeling spatial and temporal variation of suitable nursery habitats for Atlantic sturgeon in the Chesapeake Bay," *Estuarine, Coastal, and Shelf Science* 64(2005):135–148. For striped bass, see Coutant, C.C., and D.L. Benson, 1990, "Summer habitat suitability for striped bass in Chesapeake Bay: Reflections on a population decline," *Transactions of the American Fisheries Society* 119:757–778.
[127]Dugan, J.E., D.M. Hubbard, M.D. McCrary, and M.O. Pierson, 2003, "The response of macrofauna communities and shorebirds to macrophyte wrack subsidies on exposed sandy beaches of southern California," *Estuarine, Coastal and Shelf Science* 58S:25–40.
[128]Maryland Sea Grant, 2001, p. 10 in *Research Needs for Sustainable Blue Crab Production in Maryland, A Workshop Report*, publication number UM-SG-TS-2001-01, prepared by Maryland Sea Grant College, College Park.
[129]Kahn, J.R., and W.M. Kemp, 1985, "Economic losses associated with the degradation of an ecosystem: The case of submerged aquatic vegetation in Chesapeake Bay," *Journal of Environmental Economics and Management* 12:246–263.
[130]Perry and Deller, 1996, p. 273, 276 (see note 100).

Photo 3.5: Estuarine beach and bulkhead along Arthur Kills, New Jersey

saltmarsh cordgrass. Freshwater flats, common in Chesapeake Bay tributaries, can support herbaceous species. Tidal flats are critical foraging areas for numerous birds, including wading birds, migrating shorebirds, and dabbling ducks such as mallards and the American black duck.

Effects of Sea Level Rise on Tidal Flats

In areas with low sediment supplies, marsh will revert to unvegetated flats and eventually to open water.[131] For example, in New York's Jamaica Bay, several hundred acres of low salt marsh have converted to open shoals (see Section 3.4). Except in high-sediment supply areas and in locations where migration is possible, tidal flats will gradually become inundated as sea levels rise.

Effects of Armoring on Tidal Flats

In areas where sediments accumulate in shallow waters and shoreline protection prevents landward migration of salt marshes, flats could become vegetated as low marsh encroaches waterward, accelerating sediment deposition at the waterward edge of the vegetated area and leading to an increase in low marsh at the expense of tidal flats.[132] If sediment inputs are insufficient, tidal flats will convert to subtidal habitats.

Ecological Effects on Tidal Flats

Loss of tidal flats would eliminate a rich invertebrate food source for migrating birds. Shorebirds feed on all trophic levels of beach invertebrate communities, including primary consumers (herbivorous insects, amphipods, and isopods as well as suspension-feeding crabs and bivalves) and the secondary consumers that feed on them (crabs, isopods, polychaetes, and beetles).[133] As tidal flat area declines, increased crowding in remaining areas will lead to exclusion and mortality of many shorebirds.[134] In some cases, reversion of *Spartina* marsh to unvegetated flats could benefit foraging by wading birds and dabbling ducks. As the flats become more deeply inundated, however, they will become unavailable to short-legged shorebirds.[135] Modeling by Galbraith and colleagues predicted that under a 2°C global warming scenario, sea level rise could inundate significant areas of intertidal flats in some regions.[136] Although this may initially lead only to crowding of remaining

[131]Brinson et al. 1995, p. 650 (see note 23).
[132]Redfield, A.C., 1972, "Development of a New England salt marsh," *Ecological Monographs* 42:201–237.

[133]See, for example, M.D. Bertness, 1999, Chapter 6, "Soft sediment habitats," pp. 249–312 in *The Ecology of Atlantic Shorelines*, Sinauer Associates, Inc., Sunderland, MA.
[134]Galbraith et al., 2002, p. 173 (see note 50).
[135]Erwin et al., 2004, p. 902 (see note 16); and Erwin, R.W., n.d., Atlantic Sea Level Rise, Lagoonal Marsh Loss, and Wildlife Habitat Implications. Accessed at: http://www.pwrc.usgs.gov/reshow/erwin1rs/erwin1rs.htm on March 16, 2006.
[136]Galbraith et al., 2002, p. 178 (see note 50).

tidal flat forage areas, Galbraith and coinvestigators further noted that increased crowding will lead to the exclusion and mortality of shorebirds.[137] Ponds within marshes might become more important foraging sites for these birds as mudflats are inundated by sea level rise.[138]

3.1.7 ESTUARINE BEACHES

Estuarine beaches are unconsolidated sandy shores that are inundated by the tidal cycle. Throughout most of the mid-Atlantic region and its tributaries, these beaches front the base of low bluffs and high cliffs as well as bulkheads and revetments. The beaches are characterized by steep foreshores and broad, flat, low tide terraces (see Photo 3.5).[139] Beaches can also occur in front of marshes, sometimes retreating back over them through storm-driven overwash processes. Plants are typically sparse in beach areas, surviving only above the high tide line with adaptations for the harsh beach environment, such as waxy leaves or strong root systems. In Chesapeake Bay, such plant species include seabeach and marsh orach (*Atriplex cristata*), sea rocket (*Cakile edentula*), Russian thistle (*Salsola kali*), and sea blite.[140]
The most abundant beach organisms are microscopic invertebrates (meiofauna) that live between sand grains, feeding on bacteria and single-celled protozoans. It is estimated that more than 2 billion of these organisms can be found in a single square meter of sand. [141] The meiofauna play a critical role in beach food webs as a link between bacteria and larger consumers.

The most conspicuous invertebrates of beaches are the macroinvertebrates that burrow in sediments or hide under rocks. These include hermit crabs, beach fleas, worms, beach amphipods, bivalves, and snails. Various rare and endangered beetles also live on sandy shores. Diamondback terrapins and horseshoe crabs bury their eggs in beach sands. Piping plover (federally listed as threatened), American oystercatcher, and sandpipers feed on beetles, larvae, marine worms, mollusks, and other insects and crustaceans, as well as on horseshoe crab eggs.[142] In mid-Atlantic bays, particularly Delaware Bay and southern Chesapeake Bay, horseshoe crabs rely on estuarine beaches for spawning during high spring tides.[143] Migrating shorebirds and resident gulls and terns feed on the horseshoe crab eggs. The diamondback terrapin nests in sandy areas above the high tide mark and may hibernate along embankments on muddier shorelines.[144]

Eggs of species that nest on estuarine beaches and invertebrate infauna provide forage for numerous bird species, including migratory shorebirds and species that nest on nearby barrier islands, such as the piping plover (federally listed as threatened). Shorebirds feed on all trophic levels of beach invertebrate communities (see Photo 3.6).[145] The insects, isopods, and amphipods found in wrack deposits on estuarine beaches are also an important source of forage for birds (see Photo 3.7).[146] The abundance of these organisms has been shown to be highest at sites with greater wrack. In addition, the abundance of shorebird species is positively correlated with the abundance of wrack and wrack-associated invertebrates.[147]

[137] Galbraith et al., 2002, p. 173 (see note 50).
[138] Erwin et al., 2004, p. 902 (see note 16).
[139] Jackson, N.L., K.F. Nordstrom, and D.R. Smith, 2002, "Geomorphic-biotic interactions on beach foreshores in estuaries," *Journal of Coastal Research Special Issue* 36:414–424.
[140] Lippson and Lippson, 2006, p. 28 (see note 2).
[141] Bertness, 1999, 256–257 (see note 133).
[142] USFWS, 1988, *Endangered Species Information Booklet: Piping Plover*, USFWS, Arlington, VA.
[143] Lippson and Lippson, 2006, p. 32 (see note 2); Dove and Nyman, 1995 (see note 14).
[144] Chesapeake Bay Program, 2006, Diamondback terrapin, available at: http://www.chesapeakebay.net/diamondback_terrapin.htm, accessed June 13, 2006.
[145] Dugan et al., 2003, p. 26 (see note 127).
[146] Jackson et al., 2002 (see note 139).
[147] Dugan et al., 2003, pp. 32–33 (see note 127).

Photo 3.6. Dinnertime along Peconic Estuary Beach, Long Island, New York

Photo 3.7: Beach with beach wrack and marsh in New Jersey

Effects of Sea Level Rise on Estuarine Beaches

As with vegetated tidal wetlands, the fate of estuarine beaches depends on their ability to migrate or on the presence of sufficient sediment to allow accretion. Beaches can migrate through marshes, generally through a process of overwash and dune building, as exhibited by barrier islands.[148,149] The general lack of vegetation on the beaches, however, frequently limits the ability to retain sediment. In front of shoreline protection structures, or where the land behind the existing beach has too little sand to sustain it, beaches that are not nourished will erode and eventually drown as sea level rises. If impediments to migration exist or natural sediment inputs decline, beaches will be lost. Through nourishment efforts, society will preserve many beaches at risk of erosion. But in many areas where homes are built on the shoreline, beach loss will be inevitable.

Effects of Armoring on Estuarine Beaches

Many shoreline protections interfere with the survival of estuarine beaches by both blocking migration and affecting sediment retention. Because of the sediment trapping effects of many shore protections, armoring that traps sand in one area can limit or eliminate longshore transport. This, in turn, diminishes the constant replenishment of sand necessary for beach retention in nearby locations. Areas with bulkheads frequently have artificially

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[148]Jackson et al., 2002, p. 418 (see note 139).
[149]The overwash process is also observed on peninsulas (e.g., the migration of Bethel Beach over marsh area in Mathews County, Virginia). See Section 3.12, Chesapeake Bay's Middle Peninsula.

elevated land areas, or headlands, because not all structures are built in a straight line. In areas with sufficient sediment input relative to sea level rise (e.g., upper tributaries and upper Chesapeake Bay), accretion may keep beaches in place in front of armoring.

In armored areas between headlands, the beach is likely to become steeper and the sediments coarser. Waterward of the bulkheaded headlands, the foreshore habitat will be lost, often even without sea level rise.[150] If the areas between these headlands are not armored, in most cases sediment input will be reduced and inundation will occur with rising sea level.

In many developed areas, estuarine beaches may be maintained with beach nourishment, although the ecological effects of nourishment remain uncertain.[151] Beach nourishment will allow retention in areas with a sediment deficit, but could reduce habitat value through effects on sediment characteristics and beach slope.[152] Some think that benthic organisms on the shallow, low tide terrace of estuarine beaches are less tolerant of burial as a result of beach nourishment than organisms of the subtidal zone of more energetic beaches.[153] The viability of horseshoe crab eggs depends on sediment characteristics that promote drainage and aeration, and therefore some coastal geomorphologists predict that egg survival could be low on beaches that are modified through beach nourishment. [154] On the other hand, Delaware plans to nourish beaches that lie in front of marsh for the purpose of preserving horseshoe crab habitat.[155]

Ecological Effects on Estuarine Beaches

Where beaches are lost, the many invertebrates that burrow in the sand and species that spawn on beaches will lose critical habitat. Using high-precision elevation data from nest sites, researchers are beginning to carefully examine the effects that sea level rise will have on oystercatchers and other shore birds.[156] To the extent that estuarine and riverine beaches, particularly on islands, survive better than barrier islands, shorebirds like oystercatchers might be able to migrate to these shores.[157] Loss of beach will also cause local elimination of beach-dependent species such as the rare beetles found in Calvert County, Maryland. Although the northeastern beach tiger beetle is able to migrate in response to changing conditions, suitable beach habitat must be available nearby.[158]

The degree to which horseshoe crab populations will decline as beaches are lost is currently unclear. Early results of ongoing research funded by New Jersey Sea Grant indicate that horseshoe crabs also lay eggs in other intertidal habitats in addition to estuarine beaches, such as sandbars and the sandy banks of tidal creeks.[159] Nonetheless, if these habitats are also inundated, they will provide only temporary refuges for horseshoe crabs.

Where horseshoe crabs decline because of loss of suitable habitat for egg deposition, there can be significant implications for migrating shorebirds, particularly the red knot, which is a candidate for the federal endangered species list. The red knot feeds almost exclusively on horseshoe crab eggs, and, to continue its migration, the bird nearly doubles its weight by feeding on crab eggs. Researchers from Virginia Tech and the New

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[150] Jackson et al., 2002, p. 420 (see note 139).
[151] Peterson, C.H. and M.J. Bishop, 2005, "Assessing the environmental impacts of beach nourishment," *BioScience* 55:887–896.
[152] Peterson and Bishop, 2005 (see note 151).
[153] Nordstrom, K.F., 2005, "Beach nourishment and coastal habitats: Research needs to improve compatibility," *Restoration Ecology* 13:215–222, p. 217.
[154] Jackson et al., 2002, p. 421 (see note 139).
[155] See, for example, Smith, D., N. Jackson, S. Love, K. Nordstrom, R. Weber, and D. Carter, 2002, *Beach Nourishment on Delaware Shore Beaches to Restore Habitat for Horseshoe Crab Spawning and Shorebird Foraging*, prepared for The Nature Conservancy, Delaware Bayshores Office, Wilmington, DE, accessed on June 19, 2007 at: http://www.dnrec.state.de.us/fw/hcrabs/FINAL%20Beach%20Habitat%20Restoration%20Report.pdf.
[156] Rounds, R. and R.M. Erwin, 2002, "Flooding and sea level rise at waterbird colonies in Virginia," presented at Waterbird Society Meeting, November 2002, accessed on June 19, 2007 at: http://www.vcrlter.virginia.edu/presentations/rounds0211/rounds0211.pdf.
[157] McGowan et al., 2005, p. 150 (see note 81).
[158] USFWS, 1994, Recovery Plan for the Northeastern Beach Tiger Beetle (*Cicindela dorsalis dorsalis*), USFWS, Hadley, MA.
[159] Research by Dr. Mark Botton of Fordham College and Dr. Bob Loveland of Rutgers University, funded by New Jersey Sea Grant; summarized online and accessed on June 19, 2007 at: http://www.njmsc.org/Sea_Grant/Research_News/The_Importance_Of_Marginal_and_Restored_Habitats.htm.

Jersey Division of Fish and Wildlife report that the number of horseshoe crab eggs is the most important factor determining the use of mid-Atlantic back-barrier beaches by red knots, and documented a reduction in the number of red knots throughout the Delaware Bay correlated with a decline in horseshoe crabs (see also Section 3.9 on Maryland and Delaware Coastal Bays.[160]

3.1.8 CLIFFS

Cliffs and the sandy beaches sometimes present at their bases are constantly reworked by wave action, providing a dynamic habitat for cliff beetles and birds. Little vegetation exists on the cliff face because of constant erosion. Eroding sediment augments nearby beaches. Cliffs are present on Chesapeake Bay's western shore and tributaries and its northern tributaries (see Photo 3.8), as well as in Hempstead Harbor on Long Island's North Shore.

Erosion is driven by two key processes: freeze/thaw and wave undercutting. Recession rates for cliffs are higher in areas where undercutting is the dominant erosion method; for example, Wilcock and coworkers reported historical erosion rates between 0.3 and 1 ft/yr for freeze/thaw areas of Maryland's Calvert Cliffs and rates between 2 and 3 ft/yr for wave undercut areas.[161] On the Sassafras, near its entrance at the north end of Chesapeake Bay, the cliffs are receding at rates of 0.9 to 1.4 ft/yr.[162] Areas dominated by the freeze/thaw mechanism frequently have beaches at their base (a higher toe elevation) that protect the bottom of the slope from wave energy.[163]

Effect of Sea Level Rise on Cliffs

Sea level rise may increase rates of cliff erosion by decreasing the toe elevation, but ecological impacts of such an increase in erosion rate are uncertain. If erosion rates are too high, sudden losses of the cliff face can endanger species that depend on unvegetated cliffs (e.g., Puritan tiger beetles). The armoring that is in place, or that might be increased in response to accelerated sea level rise, poses more evident threats to the cliff ecology.

[160] Karpanty, S., J. Fraser, J. Berkson, L. Niles, A. Dey, and E. Smith, 2006, "Horseshoe crab eggs determine red knot distribution in Delaware Bay habitats," *Journal of Wildlife Management,* 70:1704–1710.

[161] Wilcock, P.R., D.S. Miller, R.H. Shea, and R.T. Kerhin, 1998, "Frequency of effective wave activity and the recession of coastal bluffs: Calvert Cliffs, Maryland," *Journal of Coastal Research* 14(1):256–268.

[162] Maryland DNR, 2002, *Sassafras Natural Resources Management Area Land Unit Plan,* Maryland DNR Resource Planning Program, accessed on June 19, 2007 at http://www.dnr.state.md.us/resourceplanning/sassafras.pdf.

[163] Toe elevation is the height of the beach before the bluff/cliff begins.

Photo 3.8. Emerald Beach along the Elk River in Maryland

Effects of Armoring on Cliffs

Cliffs and headlands could experience increased erosion rates resulting from disruption in longshore sediment transport as a result of nearby sediment-trapping shoreline protections (e.g., groinfields).[164] Alternatively, if the cliff base is armored, the erosion rates could decrease. Either outcome could eliminate habitat for endangered species that depend on varying rates of erosion. According to the Maryland Department of Natural Resource's wildlife diversity conservation plan, naturally eroding cliffs are "severely threatened by shoreline erosion control practices."[165] Because of the sediment-trapping effects of many types of shore protection, armoring in one area can diminish the constant replenishment of sand necessary for beach retention in nearby locations. Introducing shoreline protections can subject adjacent cliff areas to wave undercutting and higher recession rates. Development and shoreline stabilization structures that interfere with natural erosional processes are cited as threats to bank-nesting birds (e.g., bank swallows and belted kingfishers) as well as two species of tiger beetles (federally listed as threatened) at Maryland's Calvert Cliffs.[166,167] The majority of the identified Puritan tiger beetles live in the Calvert Cliffs, particularly in Calvert Cliffs State Park on Chesapeake Bay's western shore.

[164]Wilcock et al., 1998, p. 259 (see note 161).
[165]Maryland DNR, 2005, p. 13 (see note 53).

[166]USFWS, 1993, Puritan Tiger Beetle (*Cicindela puritana* G. Horn) Recovery Plan, Hadley, MA; USFWS, 1994 (see note 158).
[167]The Center for Conservation Biology at William & Mary, 1996, "Fieldwork concluded on bank-nesting bird study," in *Cornerstone Magazine*, accessed on June 21, 2006, at https://www.denix.osd.mil/denix/Public/ES-Programs/Conservation/Legacy/Cornerstone/corner.html.