Chapter 3
Sea Level Rise in Delaware Bay, U.S.A.: Adaptations of Spawning Horseshoe Crabs (*Limulus polyphemus*) to the Glacial Past, and the Rapidly Changing Shoreline of the Bay

Robert E. Loveland and Mark L. Botton

Abstract Horseshoe crabs have proven adept at locating suitable areas of sandy beach spawning habitat throughout their long geological history. Paleogeographic studies have shown that the most recent period of sea level rise (SLR) has been occurring in Delaware Bay for at least 6,000 years. Comparison of aerial photographs from the 1930s with contemporary satellite imagery clearly indicates a landward movement of the shoreline along the New Jersey coastline of Delaware Bay. Habitat for horseshoe crab spawning has been adversely impacted over this period of time by the loss or degradation of spawning beaches, which to some extent has been offset by the deposition of this sand in "marginal habitats" such as tidal creeks and sandy deltas. The well-documented natural landward movement of a beach-marsh system in a time of SLR has been compromised in some locations by the hardening of the coastline through construction of bulkheads, groins and jetties. This directly reduces the productivity of these beaches for horseshoe crabs, and, consequently, their use by shorebirds. The response to SLR and storms in the recent past has emphasized the protection of coastal property; however, there has been some effort to restore beach ecosystems through nourishment. Given that SLR is an ongoing process, beach nourishment projects to protect a developed shoreline will require a long-term commitment at considerable cost. From the perspective of horseshoe crab conservation and habitat preservation, we suggest that consideration be given to the strategy of property buy-outs and abandonment, thus enabling a more natural beach response to SLR.

Keywords Delaware Bay • Limulus • Sea level rise • Beach erosion • Paleogeology • Geomorphology • Spawning habitat

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3.1 Introduction

An elevated chunk of salt marsh cordgrass (*Spartina alterniflora*) once formed a circular mini-marsh of approximately one acre (ca. 4,000 m^2), just off the beach of the Rutgers University Cape Shore Laboratory on the Delaware Bay in Cape May County. Beginning in the early 1960s, the marsh became noticeably smaller over the years. Eventually one summer, it was gone – not a trace of the marsh could be found. By the beginning of the 1980s, it was indeed rare to find any remnants of a salt marsh sitting on the flats of Delaware Bay along the coast of the Cape May peninsula in New Jersey. After the demise of the mini-marsh, a gently sloping beach became important spawning habitat for the American horseshoe crab *Limulus polyphemus*. Although both of the authors studied the population biology of horseshoe crabs along the East coast of North America since the 1970s, and conducted research at the very site where the mini-marsh once stood, it never dawned on us until recently that we had witnessed an event which has become commonplace along the coast of Delaware Bay. At about that same time, we started to observe dying stands of forests near the banks of the small creeks along Delsea Drive (New Jersey Route 47), the main road connecting small towns that dot the New Jersey shore of Delaware Bay. Not only are salt marshes being fractured and "pushed" further upland, but salt water is now intruding farther into the creeks, leading to the demise of the trees. The very beach itself is being eroded, overwashed and moved inland; areas of peat – remnants of earlier salt marsh vegetation – are being exposed for the first time in thousands of years. Although not discussed much in the early 1980s, we now realize that a global phenomenon known as Sea Level Rise (SLR) continues to impact our study sites. It has become common knowledge that SLR can be observed across the world's oceans, posing a potential threat to coastal communities everywhere.

When we began our collaborative research on *Limulus polyphemus* in the mid-1980s, horseshoe crabs were extremely abundant along the New Jersey coast of Delaware Bay. However, it was not always that way. The Delaware Bay population of horseshoe crabs was decimated for fertilizer and animal feed in the late 1880s (Shuster 2003; Kreamer and Michels 2009); populations declined until the beginning of the Great Depression. A period of harvesting of such magnitude, just to sustain the fertilizer industry, nearly extirpated the local horseshoe crabs of lower Delaware Bay. That near-extinction event created a bottleneck that lasted for over four decades, from the early 1880s to the middle of the 1930s (Shuster and Botton 1985). With the development of chemical fertilizers, harvesting of horseshoe crabs ceased, and the population began a slow comeback. However, the crabs were no longer "useful"; in fact, during the summer spawning season many local residents along the beachfront considered the crabs to be a nuisance.

In the backwaters of Delaware Bay, around 1990 the local fishermen discovered that horseshoe crabs were an excellent bait for catching eels. Although most Americans do not eat eels, they are in great demand in Asia. The commercial value of horseshoe crabs soared as the market value for eels and conchs increased (Kreamer and Michels 2009). The race was on to harvest as many horseshoe crabs as possible for the bait industry. Unregulated harvesting has contributed to further reduction in population size, and although the fishery is now regulated by the Atlantic States Marine Fisheries Commission (ASMFC 1998), the bait fishery continues to be a contentious factor in protecting *Limulus polyphemus*.

How human activity affects the population level and distribution of horseshoe crabs is important because *Limulus polyphemus* plays a central role in the dynamics of shorebird migration in Delaware Bay (Mizrahi and Peters 2009), and because blood of the horseshoe crab is used to produce LAL (*Limulus* amoebocyte lysate), necessary for the US Food and Drug Administration (FDA) approved deterministic test for pyrogenic infections and contamination (Levin et al. 2003). Current decisions which relate to beach maintenance and erosion directly influence the quality of the beach as spawning habitat for *Limulus polyphemus*. How horseshoe crabs respond to the rapidly changing environment of Delaware Bay is the subject of this chapter. Knowledge of the geologic history and a contemporary view of SLR are necessary to understand the challenge for survival in a somewhat chaotic and entropic environment. Fortunately, *Limulus polyphemus* has confronted such elements in the past, and has done reasonably well, given that we can now trace this species back to the upper-Jurassic (148 million years ago).

3.2 A Brief Geological History of South Jersey and Delaware Bay

In 1925, it was Alfred Wegener who first described and documented the phenomenon of "continental drift" (Wegener 1929). A belt of Cretaceous fossils stretching from the Highlands of Sandy Hook to Camden in New Jersey has a remarkable similarity to Cretaceous fossils found north of London, England. There was no doubt in Wegener's mind that the only explanation for the distribution of such Cretaceous fossils is that New Jersey must have been adjacent to what is now Western Europe, since the European Plate was once in contact with the North American Plate. An explanation of *how* the continents drifted apart emerged only after geophysicists discovered alternating bands of extruded magma along the Mid-Atlantic Ridge. Although Wegener, at the beginning of the twentieth Century, was not able to explain the mechanism of Continental Drift, he explained an incredible amount of the findings of the other Alfred, namely Alfred Wallace, and incidentally Charles Darwin (Winchester 2003). The scientific community in the early 1960s *finally* accepted his evidence for the concept of continental drift. We now understand that it is Plate Tectonics which is the driving force, causing continents to move as they float on a semi-liquid mantle beneath individual plates.

Now, why is the above brief synopsis very important in a contemporary discussion of horseshoe crabs? *Limulus polyphemus* is abundant and the only species of horseshoe crab in the Western Atlantic, presently distributed along the East Coast of North America from Maine to the Yucatan peninsula. In Asia, illustrations of horseshoe crabs can be found dated as early as 800 AD (Sekiguchi 1988). In fact, a species of "kingcrab" was first mentioned by Rudyard Kipling (1902) in his "Just So" stories; since Kipling had lived in India, it is likely that he was referring to *Tachypleus gigas*. Although there are few early references to the American horseshoe crab, there is some indication that Native Americans and early European settlers may have used horseshoe crabs for food and a variety of other purposes (reviewed by Kreamer and Michels 2009). The sharp, spiny telsons may have been used as spear tips, while dried horseshoe crabs were used to fertilize corn and other farm crops. The famous painting (ca. 1590) by John White, entitled "The Method of Fishing of the Inhabitants of Virginia" (reproduced as Fig. 3.2 in Kreamer and Michels 2009) clearly depicts Native Americans in the process of harvesting horseshoe crabs with long spears from a dugout canoe.

We are very aware of the modern American horseshoe crab, even though not much documentation exists about *Limulus polyphemus* prior to its widespread use as fertilizer in the nineteenth century (Shuster 2003). Thus, we must look further back in time.

3.2.1 Importance of the Fossil Record

Recent fossil evidence suggests that horseshoe crabs have always lived in shallow coastal areas (reviewed by Rudkin and Young 2009), and may even have spawned intertidally in a manner similar to living horseshoe crabs (Diedrich 2011). Curiously, fossils of *Limulus polyphemus* have never been found in North America, largely because the type of lithographic rock where horseshoe crab fossils occur is not found along the Northeast coast of the US. So, how long ago did *Limulus polyphemus* arrive on the shores of North America? *Mesolimulus*, found in Triassic limestone deposits in Germany, used to be considered the closest relative of the American horseshoe crab. That species was of rather small size relative to *Limulus polyphemus*; adult American horseshoe crabs are large, especially the female (Delaware Bay females: 25 cm; males: 20 cm). Even today there are remnants of a population in which both males and females are rather small – namely the horseshoe crabs that are resident in embayments at the northern extent of the range, such as Great Bay, New Hampshire. The fact that most horseshoe crab fossils are small simply suggests that it was the young and smaller individuals that fossilized, not the adults. While most discussion of the fossil record of horseshoe crabs has been largely speculative relative to *Limulus polyphemus* (Shuster and Anderson 2003), a most amazing discovery was recently reported by the young paleontologist from Poland, Blazej Blazejowski. While digging in a lithographic Owadow-Brzezinki Quarry for ancient clams and microfossils, Blazej and his colleagues came across a small collection of extremely rare horseshoe crab fossils, so well preserved that he was able to reconstruct three-dimensional models of the specimens (Kin et al. 2013; see also Chap. 1 by Blazejowski in this book). The fossils were small and strongly resembled *Limulus polyphemus*, so Blazej decided to compare his upper-Jurassic fossils (148 million years old) with extant juvenile specimens of New Jersey horseshoe crabs. Analysis of many morphological features of the fossils matched the extant exuviae (the molted carapace) of *Limulus polyphemus* (Fig. 3.1).

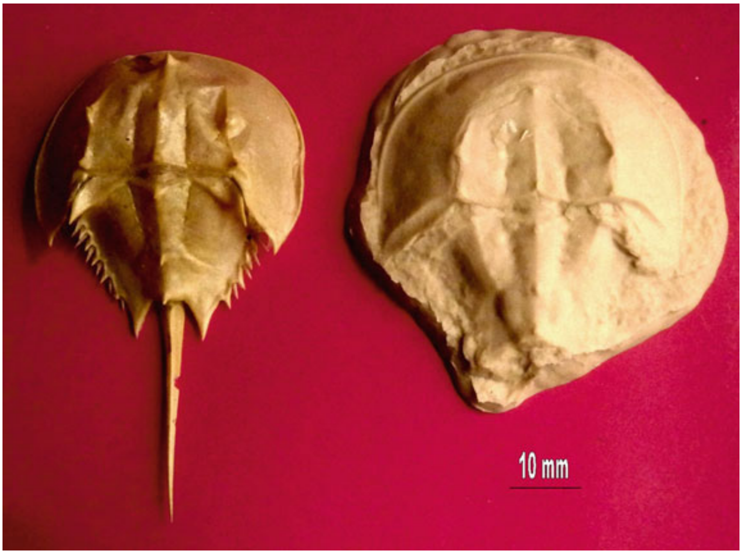

Fig. 3.1 Comparison of cast of juvenile *Limulus polyphemus* with Upper-Jurassic fossil of *Limulus darwini* (Courtesy of B. Blazejowski)

The external appearance of the Polish fossils was similar enough to suggest that they were ancestral to *Limulus polyphemus*. A few minor differences in spination led Blazej to assign the species *Limulus darwini* to the newly discovered fossil. Blazejowski and Kin have proposed a new concept which explains the incredible similarity of *Limulus polyphemus* to a creature that moved among the calcareous silty inlets of the Jurassic Sea. That is, the American horseshoe crab is a stabilomorph, not a "living fossil" as it is so commonly referred to in the literature (Kin and Blazejowski 2014). Błażejowski (2015) would attribute the constancy in external appearance of *Limulus* for at least the last 148 million years as an indicator of extreme stabilomorphy. As also argued by Shuster and Anderson (2003), the morphology of *Limulus polyphemus* needs not respond to an entropic world because it has proven itself to be completely adapted to whatever environment it exploits. So, even though the absolute position of sandy shorelines changes over time as a function of sea level, horseshoe crabs have proven to be quite capable of tracking this habitat, behavior that may strongly relate to the morphology of *Limulus*.

3.2.2 Limulus polyphemus *Took a Ride*

How long ago did *Limulus polyphemus* arrive on the shores of North America? Thanks to Alfred Wegener, we now know that there was a time when the European Plate and the North American Plate were contiguous (e.g. Fig. 3.13 in Garrison 1993). About 200 million years ago, roughly at the beginning of the Triassic, the tectonic plates began to separate due to the advent of sea floor spreading along the mid-Atlantic rift. Most of the European Plate drifted to the east, and what was to become the North American Plate drifted west – but the cleavage was not exact. It is known that due to a bit of randomness in Continental Drift, chunks of the European Plate drifted to the coast of North America. Several examples come to mind: it has been shown that parts of two very famous islands are of European origin in the nature of their country rock, namely Mt. Desert Island in Maine, and Staten Island in New York (McPhee 1982). Wegener had already pointed out that certain rocks of Scotland and Ireland were very similar to those that can be found in New Brunswick and Newfoundland, Canada. Well, if entire blocks of country rock were transported to what is now Eastern North America, couldn't an early version of *Limulus polyphemus* also be moved from the waters of Europe, albeit slowly?

3.2.3 Why Did **Limulus polyphemus** *"Prefer" North America to Europe?*

If we examine the current distribution of *Limulus polyphemus*, we find that it is most abundant in the mid-Atlantic states. Although there are populations of horseshoe crabs along the coast of Long Island, and even along the coast of Cape Cod, those were regions that were heavily impacted by recurrent glacial periods. North of Long Island, New York, there are few estuaries that become wide, shallow bays near the ocean, which also are characterized by extensive sandy beaches. But south of Long Island, there are many estuaries that terminate in shallow, sandy bays with well-developed beaches such as Raritan Bay, Delaware Bay, and Chesapeake Bay. Why did horseshoe crabs not remain in European waters? Simply put, there are few if any estuaries in Europe that have the requisite topography necessary for horseshoe crab spawning habitat. Clearly, such habitat must have existed in the Jurassic, but it may have disappeared once continental drift created a completely different world by the time of the Cretaceous. The truth is, we simply do not know why *Limulus polyphemus* moved to the mid-Atlantic states of North America. But we do know that *Limulus* went extinct in Europe.

As the Atlantic Ocean continued to expand, continental drift largely settled down to a snail's pace (it still exists, moving New Jersey to the west by a few centimeters per year). New Jersey was roughly where it is now, but the ocean was not. During the Cretaceous, which ended about 60 million years ago, much of the eastern part of North America was an inland sea. Somewhere in the middle of the Miocene, the ocean was retreating from the land; however, most of southern New Jersey was still under water. As illustrated in the very fine work of David P. Harper (2013, p. 154), the Atlantic coastline was roughly along the current boundary of the Cretaceous deposits. We assume that *Limulus polyphemus* was around then, and most likely was adapted to the retreating coastline. After all, horseshoe crabs belong to an extremely old group of Arthropods, dating back to mid-Ordovician, about 450 million years ago. About two million years ago, during the beginning of the Pleistocene

Ice Ages, continental glaciers came down from the north and covered much of what is now Canada and the northern United States. With a periodicity of about 80,000 years (US Army Corps of Engineers 2004), the glaciers cycled between their southernmost transgression, and their retreat back toward the North Pole. Of the many transgressions, only three glaciers moved as far south as New Jersey. Their influence on coastal geomorphology and ocean level was profound. Each time the glaciers advanced to their terminal moraine, the level of the ocean dropped to an unfathomable depth relative to the level seen along the coast today. In fact, land was 'created' during the advance of a glacier and the shoreline was many kilometers east of the present coastline of South Jersey. We suspect that *Limulus polyphemus* simply adjusted to the dropping level of the ocean, as did the Lenape natives who were around at least during the last glacial transgression and the subsequent regression.

3.3 Sandy Beach Habitat in Delaware Bay: Reconstructing the Past and Predicting the Future

As shown in a seminal paper by Knebel et al. (1988), Delaware Bay has undergone a remarkable geological transformation within the past 18,000 years. At that time, with sea level much lower than at present, the long stretches of sandy beach that now comprise the main horseshoe crab spawning areas along the lower bay were completely absent (Fig. 3.2a). Sea level began rising at the end of the Pleistocene (Fig. 3.2b) and small areas of beach began to develop near the present bay mouth, though most of the shoreline still consisted of tidal wetlands. The main channel widened, and the extent of sandy beach continued to increase as sea level rose (Fig. 3.2c, d), presumably giving horseshoe crabs access to more suitable spawning locations within the estuary. Were there horseshoe crabs in Delaware Bay 18,000 years ago, before there were extensive sandy beaches? Unfortunately, direct evidence is unobtainable as this predates historical records, and no archaeological evidence has yet been uncovered. We would suggest, however, that the numerous small tidal creek areas (Fig. 3.2a) could well have had sand bar systems, and these sites could well have been refugia for spawning horseshoe crabs at times when expansive beaches were scarce.

Contemporary rates of SLR have been the subject of much discussion. As noted earlier, we first became aware of the local effects of SLR through some of our own casual observations of salt marsh loss, beach erosion and peat exposure, and salt water intrusion into uplands. There is now voluminous evidence linking SLR to global climate change. Since 1900, the rate of global SLR is some 1.7 mm/year, with the most rapid rate of increase (3.2 mm/year) occurring from 1993 to 2010 (IPCC 2013). Sea level is rising because warming temperatures contribute to the melting of glaciers and the thermal expansion of sea water. It is not only the increase in ocean volume that is significant, because land subsidence in southern New Jersey exacerbates the increase in relative sea level. NOAA records for the past 100 years

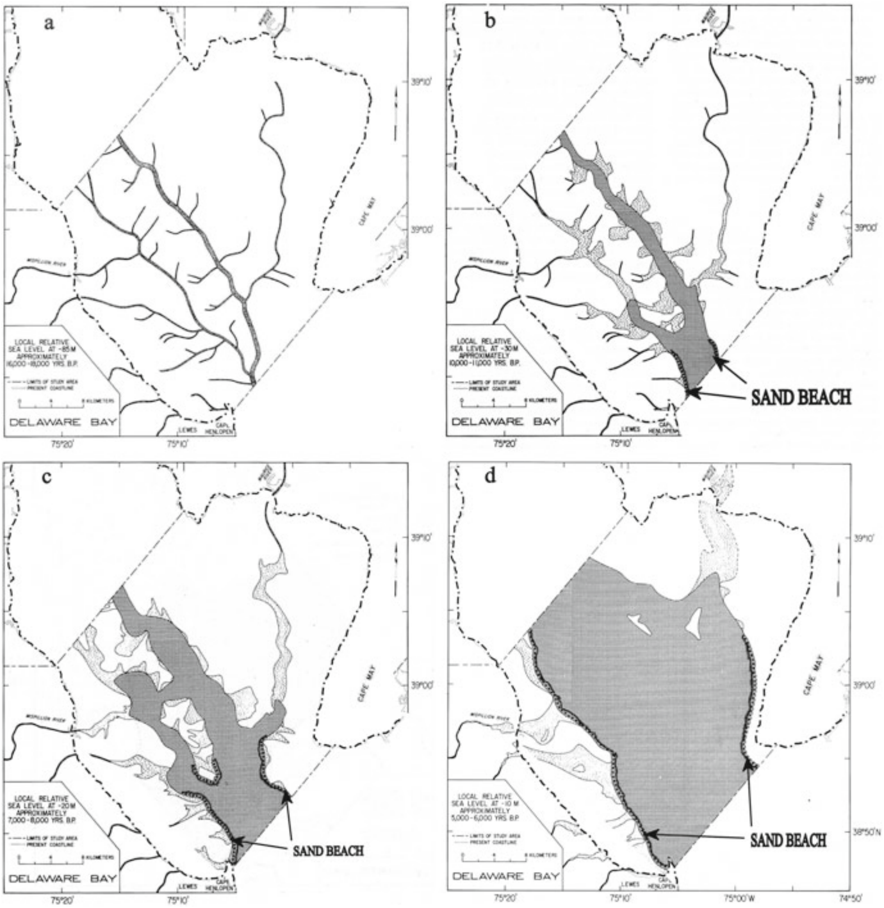

Fig. 3.2 Paleogeographic reconstruction of Delaware Bay (Modified from Knebel et al. 1988). (**a**) Delaware Bay at 16,000–18,000 years before present (bp); note the absence of sandy beaches and the lack of a well-defined main channel. The *dot-dashed* outlines show the approximate position of the current shorelines of New Jersey and Delaware, (**b**) Delaware Bay at 10,000–11,000 years bp, near the end of the Pleistocene glaciation; note the increased areas of open water (shown in *gray*) and the limited area of sandy beach (shown by *heavy border*) near the bay mouth, (**c**) Delaware Bay at 7,000–8,000 years bp showing further development of sandy beaches, (**d**) Delaware Bay at 5,000–6,000 years bp showing further widening of the bay and the development of sandy beaches along the New Jersey and Delaware shores

show that sea level in the region has risen at an average rate of 3.99 mm/year (Fig. 3.3), much higher than the global average (IPCC 2013).

Direct evidence of the effects of SLR on the Delaware Bay can be seen by comparing aerial photographs taken in 1933 and 1990 (Fig. 3.4). We show three different locations for purposes of illustration. At East Point, New Jersey, the sandy beach was completely lost in less than 60 years (Fig. 3.4a1, a2), and the shoreline was hardened to protect homes (Fig. 3.4a3). The only suitable spawning habitat in the

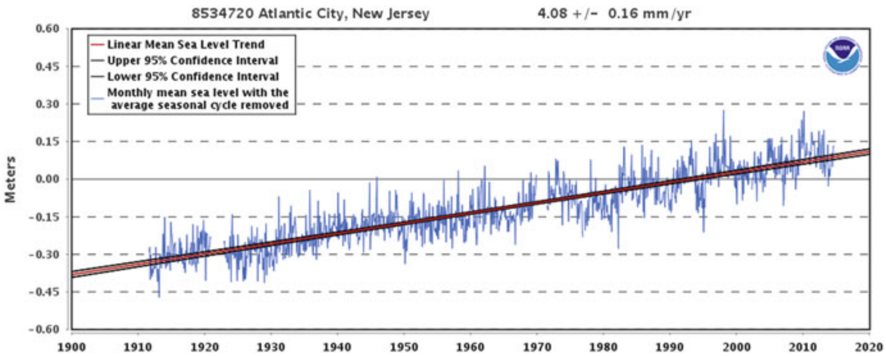

Fig. 3.3 Changes in sea level at station Atlantic City, New Jersey during the past century as recorded by National Oceanic and Atmospheric Administration (NOAA) (http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=8534720). The mean sea level trend is 3.99 mm/year with a 95 % confidence interval of ±0.18 mm/year

immediate vicinity consists of a few pocket beaches, which may be found between areas of salt marsh and/or peat (Fig. 3.4a4). At Kimbles Beach, New Jersey, part of the Cape May National Wildlife Refuge, there are no houses on the shoreline so the beach has been “allowed” to migrate landward in a more natural way (Fig. 3.4b1, b2). Areas of overwashed sand are now common along the open bay shore, while a system of sand bars and spits (Fig. 3.4b3) has developed into a locally important horseshoe crab spawning and shorebird feeding location (Botton et al. 1994). Lastly, Reeds Beach demonstrates the combined effects of SLR and jetty construction on the movement of sand (Fig. 3.4c1, c2). The jetty traps sand moving northward with the longshore drift; consequently sand is accreting near the jetty (Fig. 3.4c3) while the southern portion of town is severely eroded (Fig. 3.4c4). It is important to emphasize that these are long-term changes in SLR that can be documented since (at least) the early 1900s. It is simply disingenuous to attribute the erosion of beaches and loss of property along the Delaware Bay shore of New Jersey to rare and catastrophic events such as Hurricane Sandy. This distinction must be kept in mind when we consider how best to respond to the situation.

3.3.1 Sea Level Rise and Horseshoe Crab Habitat

There is abundant evidence that the level of the ocean along New Jersey stopped dropping for the “last time” around 10,000 years ago. As the ocean retreated, landward sediments washed down and over the salt marshes, onto the mudflats, and eventually covered both the marshes and beaches. So what happened to the sandy beaches, which are necessary as spawning habitat for horseshoe crabs? The answer comes from the fact that quartzite (the major component of beach sand) has always been around, even in some of the oldest deposits ever found. Sand is a product of the

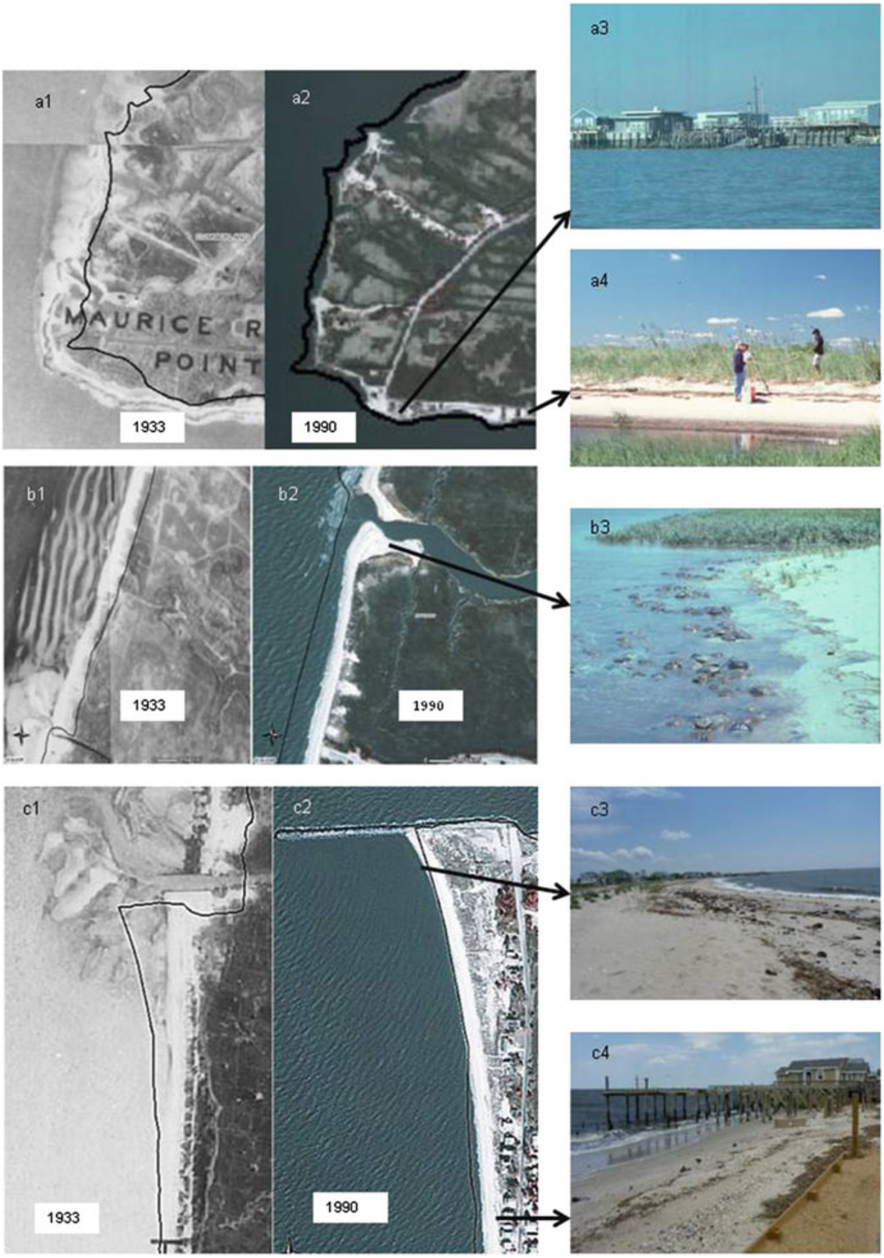

Fig. 3.4 Comparison of aerial photographs of Delaware Bay in 1933 and 1990, with ground truth photographs of selected regions. The *black line* superimposed on the coastline is a fixed contour giving perspective to the extent of beach erosion along the bay shore. (**a**) East Point in 1993 (**a1**) and 1990 (**a2**); (**a3**) shows the armored portion of the town of East Point, (**a4**) is a typical "pocket beach" to the east of town, (**b**) Kimbles Beach in 1933 (**b1**) and 1990 (**b2**); note the extensive

slow destruction of mountains and the erosion which follows. Sand is readily moved by water currents, and is deposited downstream of where it originated. Given enough time, sand can cover vast areas both on the land and the sea. Thus, sand was never a limiting factor in the movement of the coastline of New Jersey, particularly in the region of the coastal plain. Some beaches were no doubt covered by advancing terrestrial sediments. Much of the sand seems to have moved seaward as the level of the water dropped. But what happened when the ocean began to rise, as it did when the Wisconsin Glacier (the last to reach New Jersey) started its journey back to the Arctic? Simply put, the East Coast began to experience a period of Sea Level Rise (SLR), where the edge of the ocean advanced landward at an inexorable pace about 10,000 years ago. Glaciers, of course, begin their retrenchment when the average temperature of the earth's surface increased. The many cycles of advance and retreat of glaciers are highly correlated with changing temperature. With the loss of glacial mass, the amount of water in the ocean increased. With the rising temperature, the volume of the ocean increased, and consequently the land adjacent to the ocean was inundated.

But there are other factors which change the rate of relative SLR, not the least of which is subsidence, or sinking of the land. South Jersey is an example of a sinking coastline. One of the reasons relates to the work of Alfred Wegener done so long ago, but given little regard until recently. He proposed the concept of isostatic adjustment. This phenomenon is easy to understand from the point of view of compression. As an example, consider the rising coastline of Alaska, which requires that piers and bulkheads be moved seaward periodically. The land is actually rebounding from a time when the sheer mass of the glaciers, which covered that land, literally pushed the land downward. When the Wisconsin Glacier retreated, the land referred to as New England arose. What is now understood is that isostasy requires that for every mass of land that sinks, some other land must rise! Thus, land that was compressed under the glacier had to sink below its previous level, and the land adjacent (south) of the glacier actually elevated in order to balance the distribution of continental landmass. As glaciers retreat, the once elevated land to the south of the glacier sinks. There are many reasons why land sinks, but it is a fact that the shores of Delaware Bay are sinking.

The rate of SLR is not constant. The rate is influenced by both geophysical and climatological changes (both up and down). It turns out that recent evidence of samples taken from the exposed marshes along the shore of Delaware Bay indicates that SLR took a statistical turn upward around 6,000 years ago. The people of the Lenape tribe must have recognized this change, since they were forced to move inland, again, by the rising waters. In fact, if one digs deeply in the marshes or beaches of today, one might encounter artifacts of that ancient civilization.

Fig. 3.4 (continued) setback of the beach and the areas of sand overwash in 1990; (**b3**) demonstrates the intensive spawning by horseshoe crabs on sandy tidal creek delta areas along Delaware Bay, (**c**) Reeds Beach in 1993 (**c1**) and 1990 (**c2**). The long jetty seen at the top of (**c2**) was constructed to maintain the navigational channel at Bidwell's Ditch; it has resulted in sand accretion at the northern section of town near the jetty (**c3**) and the loss of sand from the southern section (**c4**)

Eventually, those deposits and artifacts will once again see the light of day. We are not sure why the rate of SLR changed 6,000 years ago, but based on the fossil foraminifera preserved in cores, it appears that temperature began to increase slightly faster than previously. After all, the glaciers were in retreat and the influence of the tropical waters of the Gulf Stream may have begun to affect the coast, much as the Gulf Stream off the coast of New Jersey still does today. We know enough about the coastal geology of southern New Jersey, including land subsidence as well as contemporary rates of SLR (Fig. 3.3) that it is possible to model the advance of the coast with rising sea level (Cooper et al. 2008).

What did the coast look like as the ocean moved onto the shelf and into river valleys? Beside the fact that the coast was further out on the continental shelf, its appearance was not much different than today. There were mudflats and marshes, and yes, there were sandy beaches. Ancient beaches are not too difficult to validate in the geological deposits of the past. As an expert in fossil conodonts, the geopaleontologist Anita Harris was able to identify ancient sand beaches in the sediments of the Delaware Water Gap (McPhee 1982). Some of the eroded ancient sands of the Gap may have moved far down the Delaware River becoming the contemporary beaches of Cape May, also giving rise to the famous Cape May "diamonds" so abundant on Sunset Beach. How did SLR influence the spawning behavior of horseshoe crabs? Probably not much. As SLR advances, so do the marshes and the beaches. Adjacent upland forests are lost as sea water invades the land, causing major changes in the types of vegetation along the coast. In light of the apparent 'destruction' of habitat, one sees a balance in the 'creation' of new habitat. As the authors have publically suggested, new habitats resulting from SLR may appear initially as being "marginal." With time, these new habitats become the status quo of the coast. Accordingly, we hypothesize that shifting habitat for horseshoe crab spawning has always been a hallmark of the advancing coastline. Under most conditions, *Limulus polyphemus* is able to find the new habitat and exploit it for the purpose of reproduction.

What do we mean by "marginal habitat"? This term has both temporal and spatial implications. As an ecosystem, coastal marshes and beaches are notoriously dynamic – they can be created, or destroyed, by overnight storms. At some locations such as East Point, New Jersey, the sandy beach was completely lost in less than 60 years due to the combined effects of erosion, sea level rise and hurricanes such as Gloria in 1985. Large portions of a beach may transmute into a mudflat if the sand is removed during an onshore storm. Nearshore sandbars may appear suddenly if an erosion event deposits sand parallel to the beach. Sandy beaches may develop at the mouth of tidal creeks, replacing peaty banks. These are examples of rapidly changing habitats. On a slower scale, SLR may contribute to the transgression of a sandy beach, exposing ancient peat bogs and former salt marsh. Wind may literally blow sand from a beach onto the adjacent, higher elevated salt marsh, thus creating an overwash beach; such an event may form the basis of a future, more stable sandy beach which constantly moves to higher, inland ground. Our research indicates that horseshoe crabs seem to exploit new habitats, while at the same time abandoning former high-quality, sandy beaches that were deeper but are now eroding at a fast pace. As we found in the late 1980s, horseshoe crabs are repelled by toxic materials emanating from exposed ancient peaty bogs on eroding beaches, particularly hydrogen sulfide which is a byproduct of anaerobic decomposition of marsh material (Botton et al. 1988; Draxler 1993). On the other hand, horseshoe crabs are strongly attracted to newly formed offshore sandbars. While *Limulus polyphemus* successfully spawns on beaches where the sand is deep (greater than 25 cm) and somewhat intertidal, this species seems prone to spawn in great numbers on sandbars and spits that are largely submerged by the tide most of the day. Periodically, when the bar is exposed at low tide, one can observe many spawning “nests” where the horseshoe crabs laid their eggs. One also can observe great flocks of shorebirds feeding on the green eggs of horseshoe crabs; these are washed out of the nest by wave action and are an important part of the diet of many species of migratory shorebirds (Botton et al. 1994).

On a larger, spatial scale, habitat formation is relatively infra-dispersed in Delaware Bay. This presents a problem for spawning horseshoe crabs – they must locate small patches of sand which might provide a place to reproduce. *Limulus polyphemus* has an uncanny sense of finding a nesting habitat. We have observed spawning crabs at the base of upland forests, in tidal sloughs, on the surface of salt marshes, on newly formed overwash beaches and on small “pocket beaches”. The crabs make nests along tidal creeks, under houses propped up by pilings, and among rocky fill areas with pockets of sand even within highly disturbed estuaries (Botton et al. 2006). Over the course of time, sand accumulates along the front of salt marshes and constitutes an emerging spawning beach. However, *Limulus polyphemus* appears to abandon highly erosional beaches, particularly where human activity has armored the beach with debris, bulkheads, or houses (Botton et al. 1988; Jackson and Nordstrom 2009). There is a simple explanation for this, which is spatially related. We previously alluded to the fact that SLR is responsible for the movement of the entire coastal system landward. This includes the beaches of Delaware Bay, as well as the barrier island system on the Atlantic side of the coastal plain of New Jersey. However, humans cannot seem to tolerate the advancing beaches. This advancement is slow and progressive, but it is a geophysical reality. The placement of barriers may temporarily stop the ocean from progressing landward, but the cost of developing a fixed coastline is extraordinary in time, space and resources. Are horseshoe crabs affected? Yes, but only to the extent that a barrier to the movement of a beach, or the loss of sand from a developed beach, will reduce the net habitat available to the crabs for the purpose of spawning. Irrespective of the existence of horseshoe crabs, socioeconomic reasons often trump environmental issues. During the past four decades that we have been doing research on horseshoe crabs in Delaware Bay, we have witnessed the demise of the small towns of Moores Beach, Thompsons Beach, and Seabreeze, which were formally viable communities of summer residents, local fishermen, vacationers, boaters, and beach walkers. SLR ultimately ‘won out’ because the roads (often through elevated berms on the surface of a salt marsh) that led to the towns became impassable, particularly at high tide and storms. The towns became isolated from their necessary infrastructural needs. Eventually, local and state resources helped the residents to abandon the town, and the buildings were removed. Beach rubble, used to stabilize the encroaching bay water, was removed; in time, the beaches were restored by natural forces of tides, currents, and storms. Now these once rough-hewn beaches have reverted to spawning habitat for horseshoe crabs. Of particular interest is Moores Beach where through the efforts of many conservation groups the beach has been completely restored, and appears to attract both horseshoe crabs and shorebirds (discussed in Sect. 3.4.4).

As of this writing, there are towns along Delaware Bay that are experiencing severe impacts from both SLR and coastal storms such as Hurricanes Irene in 2011 and Sandy in 2012. In the following section, we describe some of the changes that have taken place in four of our study sites along the Delaware Bay and summarize our observations on habitat quality for horseshoe crabs in these locations.

3.4 Case Studies of SLR Along the New Jersey Coast of Delaware Bay

3.4.1 Norburys Landing

Norburys Landing has been one of our southern-most sampling stations since 1985. The landing is a minor promontory into the bay at the end of Millmann Road (County Road 642). The beach to the north is sand-starved and has been eroding for a long time. In the mid-1980s, we used to observe enormous numbers of horseshoe crabs spawning, and numerous migratory shorebirds were to be seen, particularly at high tide when horseshoe crabs were spawning. We sampled the beach at Norburys Landing from the late 1980s until 2001. Our data for egg abundance both in the surface sediments and at a depth of 20–25 cm indicate a severe drop in egg density over time. In other words, *Limulus polyphemus* was no longer using this beach for spawning, largely due to the lack of deep sand and the increase of muddy sediments along the present narrow beach. Total live horseshoe crab eggs dropped from 553,998 eggs/m^2 in June of 1990 to 104,712 eggs/m^2 in June of 2001. Norburys Landing went from a relatively robust site for spawning and egg development, to a place that horseshoe crabs no longer visited – all a result of beach erosion. No attempt has been made to restore this beach.

3.4.2 Kimbles Beach

Kimbles Beach is several miles up-bay from Norburys Landing; it includes an open bay beach and three tidal creek systems (Fig. 3.4b). When we first sampled Kimbles, the open beach was wide, gently sloped and of excellent quality sand for the development of horseshoe crab eggs. Prior to 2001, the density of horseshoe crab eggs was always quite high; it was not unusual to find densities of 10^6 eggs/m^2 (see

Table 3.1 Mean densities of horseshoe crab eggs/m^2 at three habitats in the vicinity of Kimbles Beach, New Jersey

Date	Open beach	Tidal creek	Sand bar
15 May 1997	488,689	149,821	948,079
29 May 1997	879,832	1,284,051	873,348
12 June 2001	0	172,653	80,327

Eggs were sampled using a series of replicate 5 cm cores to a depth of 20 cm (See Smith et al. 2002 for detailed description of sampling procedure)

Table 3.1 for 1997). Consequently, there were large numbers of migratory shorebirds feeding on the eggs at the water's edge. Ruddy Turnstones (*Arenaria interpres*) would dig up the nests of horseshoe crabs in search of eggs. Great Black Backed Gulls (*Larus fuscus*) could be seen feeding on overturned or stranded mated pairs of *Limulus polyphemus*. By the end of the 1990s, we noticed that the beach was not only losing sand due to erosion, but the beach was moving inland. Emerging marshes contained the roots and rhizomes of *Phragmites* and *Spartina* that had been buried for nearly 5,000 years. By 2001, we found many mated pairs of horseshoe crabs spawning, not on the beach, but on a sand bar that had formed off the mouth of the creek. We also found that mated pairs were entering the tidal creek from the bay, making their way to the newly formed sandy plots along the edge of the tidal creek. Samples taken from the open beach, the sandbar, and the tidal creek indicated that the crabs showed preference for the newly formed "marginal" habitats (see Table 3.1 for 2001).

We conclude, therefore, that the loss of pristine beach habitat over a short period may result in the development of a very rich habitat elsewhere. From the perspective of a mated pair of horseshoe crabs, not all is lost if a particular beach is no longer suitable for spawning due to beach erosion.

3.4.3 Reeds Beach

Reeds Beach, about a half mile north of Kimbles Beach, is probably the best known beach in the world for observing spawning horseshoe crabs and large flocks of migratory shorebirds, which feed on the abundant eggs of the crabs. The beach at Reeds is relatively narrow to non-existent in the south, but very expansive to the north (Fig. 3.4c). Why? Because there is a navigable creek at the north end of town, called Bidwells Ditch. To prevent the silting in of the creek, a large jetty was constructed that parallels the creek well out into the bay. The jetty has also acted as a block to the natural movement of sand from the south. Thus, at Reeds the southern beaches are eroding landward and the northern beaches are expanding bayward. Recently, fewer horseshoe crabs use Reeds Beach for spawning. The beach profile at the north end of Reeds has remained constant for many years; similarly, the composition of the sand is the same now as it was during the height of migratory

Table 3.2 Mean and maximum densities of horseshoe crab eggs/m^2 at the open beach at Reeds Beach, New Jersey

Date	Mean	Maximum
8 May 1986	516,956	1,197,720
21 May 1986	1,282,517	2,563,862
5 Jun 1986	1,913,395	3,979,886
14 Jun 1986	2,630,165	10,709,594
9 May 2001	325,716	708,373
23 May 2001	584,781	1,045,542
6 Jun 2001	278,489	720,128
20 Jun 2001	58,497	169,977

shorebirds and mating horseshoe crabs. It is improbable that beach quality has resulted in reduced spawning. More likely, there are simply fewer horseshoe crabs around due to a severe reduction in population density since the early 1990s. One of our earliest sampling forays onto the beach at the jetty yielded incredibly high counts of eggs in the sand (see Table 3.2 for 1986). By 2001, we found that egg density has dropped by at least one order of magnitude (see Table 3.2 for 2001). Observations of Reeds beach near the jetty in 2014 suggest that there are simply not enough crabs spawning there to sustain the level of eggs to attract shorebirds.

3.4.4 Moores Beach

Moores Beach, located about 1.5 miles (2.4 km) from the town on Route 47 in Cumberland County, was once a thriving community. During the mid-1980s, over 25 cottages (including double wide trailers) were resident on the beach. Over time, the occupants began to protect the cottages from the ravages of the encroaching bay. Our observations and sampling of the beach began before 1990; it was apparent even then that erosion was systematically destroying the town, first by damaging the most bayward cottages, then destroying the paved road, then eroding a temporary dirt road, then finally washing the most landward cottages onto the marsh (Fig. 3.5a–c). Sometime in the late 1990s to early 2000s, Moores Beach was abandoned and inaccessible. The loss of Moores Beach parallels the abandonment of other beachfront towns along the New Jersey shoreline of Delaware Bay, including Thompsons Beach and Sea Breeze, since the late 1980s.

Due to the effort of a number of agencies, and inspired by the leadership of Dr. Larry Niles, Moores Beach is in the process of being restored, with the use of funds that were recently appropriated for Superstorm Sandy recovery. The results have been striking – a person standing on today's beach (Fig. 3.5d) would see no evidence that the beach was once home to numerous summertime dwellers. Much of the added sand appears to have moved north toward the entrance of the tidal creek at the north end of Moores Beach, thereby forming sandbars and a larger beach along the creek. In the summer of 2014, we observed a fair number of horseshoe

Fig. 3.5 Composite images of Moores Beach, New Jersey showing changes between 1987 and 2014. (**a**) October 1987, showing the extensive amount of rubble fill used to protect dwellings. The trailer with the red roof seen here is the same as the one in the backgrounds of Fig. 3.5b, c, (**b**) May 1992, note the pilings in the bay where houses once stood; also note in the foreground a remnant of the older blacktopped road which was washed away, and the reddish colored earthen road to the left which became inundated and impassable, (**c**) June 1995, the town was essentially abandoned; note the extensive peat formations, a further indicator of beach erosion, (**d**) July 2014, after the removal of all debris followed by beach nourishment

crabs on the upper beach along the tidal creek. Small flocks of returning shorebirds were seen in the shallows adjacent to the sandbars. It appears that the effort to restore Moores Beach to a *natural* beach has merit. Even without beach nourishment, it is likely that some aspect of the beach will prevail even as the level of the bay rises inexorably.

3.5 Responding to Future SLR

As we have shown in the preceding sections, horseshoe crabs have successfully tracked the available shallow water marine habitats throughout geological time. Sea level rise is nothing new, and in our view, SLR itself is not a threat to horseshoe crabs. They have adapted and found suitable spawning habitats wherever they are, regardless of the position of the shoreline. Problems for horseshoe crabs are caused by man-made alterations of the coast that are engineered to "stabilize" beaches and protect coastal properties (Botton et al. 1988; Botton 2001; Berkson et al. 2009; Hsieh and Chen 2009).

By combining sea level rise scenarios with a digital elevation model, Cooper et al. (2008) showed that virtually all of the Delaware Bay coastline of New Jersey would be susceptible to inundation with as little as 0.61 m of sea level rise. Moreover, there are only very slight differences in elevation between beaches, marshes, and uplands. The amount of landward shoreline retreat is much greater than the vertical rise in sea level (Bruun 1962), and shorelines along the east coast of the US have moved inland some 23.8 m for each 0.3 m of sea level rise over the last century (Zhang et al. 2004). These studies suggest that the narrow sandy beaches on Delaware Bay, particularly those which are inhabited, are at great risk from sea level rise, even without factoring in the possible impacts of catastrophic storm events.

Moving forward, what can be done to best conserve beaches that are of importance to horseshoe crabs? There are three basic strategies that can be considered:

1. Armoring – harden the shoreline through the use of structures such as bulkheads, revetments, or groins;
2. Beach nourishment – maintain the present position of coastal dwellings through the periodic addition of massive quantities of sand;
3. Shoreline retreat – either abandon coastal property and infrastructure, or move it landward in anticipation of future SLR.

Shoreline armoring is probably most viable when the coastal zone is very highly developed and economically valuable, and where retreat is not practical, e.g. New York City. Seawalls and other such structures tend to give property owners a false sense of security, encouraging further development and artificially lowering the perceived risks of living in the coastal zone (Kousky 2014). Once in place, armored shorelines generally have less ecological functionality than the sandy beaches that they replace (e.g. Dugan et al. 2011), and in the specific case of horseshoe crabs, bulkheads or revetments may limit access to portions of the intertidal spawning habitat (Jackson and Nordstrom 2009; Jackson et al. 2010) and reduce the amount of suitable habitat (Botton et al. 1988; Lathrop et al. 2006). Given the relatively modest economic value of Delaware Bay beach front communities, when balanced against their ecological value for horseshoe crabs and shorebirds, we would not recommend this method of shore protection.

Beach nourishment is used throughout the coastal US for shore protection. It is expensive and must be done regularly in order to maintain its effectiveness. For example, the beach at Cape May, New Jersey was nourished 12 times between 1962 and 1999 at a total cost of over US $119 million; in the most recent project, over US $102 million was spent to nourish 3.06 km of beach (http://beachnourishment.wcu.edu/). The region from Cape May Inlet to Lower Township (along the Cape May Peninsula) has been nourished 14 times from 1991 to 2012 at a total cost of over US $74 million. The most recent project added sand to 4.1 km of beach at a cost of US $9.1 million, or about US $2.2 million per km (http://beachnourishment.wcu.edu/). As with shoreline armoring, beach nourishment encourages development in vulnerable coastal areas and requires enormous public subsidies when the systems fail; the cost is absorbed through Federal Emergency Management Agency (FEMA) grants and other government programs (Maly and Ishikawa 2013). And while beach nourishment may provide protection under current conditions, it is prudent to factor in SLR in any future cost/benefit scenarios (McGuire and Lynch 2013). When considering the potential benefits of beach nourishment for horseshoe crabs, it is important to choose source sediments that have the proper texture and organic carbon content (Avissar 2006) because it may prove difficult to modify the sediments once they are in place (Jackson et al. 2007). An ongoing effort to nourish several Delaware Bay beaches in the aftermath of Hurricane Sandy (Bauers 2014) employs sand trucked in from nearby sand quarries rather than beach sand; the long term suitability of these sediments for horseshoe crab spawning and egg development is not yet known. These nourished beaches may contribute sand to the mouths of nearby tidal creeks and create suitable habitat for spawning.

As sea level rises, it may become increasingly prudent to consider the third option, retreat from the coastline. Certainly, this poses numerous challenges. Many owners of coastal property will be reluctant to leave; they have come to expect that publically funded beach nourishment and/or armoring projects will continue to maintain their property values, and that flood insurance policies will be made available to them at rates that do not truly reflect the risks of living in the coastal zone (Kousky 2014). When their property is damaged, the homeowner's response is often to rebuild-in-place rather than to consider moving away from the coast. The developed Delaware Bay shoreline of New Jersey could serve as a model for considering the coastal retreat option because it has very high ecological value and is rather sparsely settled with modest property values when compared to houses along the Atlantic coast barrier beaches.

As an illustration of the comparative economics of beach nourishment and buyouts, we examined the southern section of Reeds Beach, New Jersey (Table 3.3). In order to approximate the one-time costs of a buyout, we used the most recent tax assessment data from the township to estimate of the value of the land and property, and we also factored in the demolition costs. In estimating the costs of beach nourishment, we assumed that costs would be comparable to a recent project in Lower Township-Cape May, US $2.2 million per km (http://beachnourishment.wcu.edu/) and that nourishment of the 907 m of beach would need to take place once per decade. Maintaining the existing housing would also require continued services, including roads, electricity and telephone services, but we did not include these in our analysis. Based on our estimates, the one-time costs of a buyout would be

Table 3.3 Comparison of the costs (in US $) of beach nourishment and buyout scenarios for South Reeds Beach

Category	Total land value[a]	Total dwelling value[a]	Total value[a]
1. Buyout scenario			
All lots (n=30)	$2,862,100	$1,309,600	$4,171,700
Occupied lots (n=22)	$2,848,700	$1,309,600	$4,158,300
Vacant lots (n=8)	$13,400	$0	$13,400
Demolition and removal of debris[b]			$250,000
Total costs			$4,421,700
2. Nourishment scenario			
Length of beach = 907 km			
Cost per km = $2,200,000[c]			
Cost = $2,000,000 per event, repeated at 5–10 year intervals for an indefinite period of time			
Additional costs: maintain roads, electricity, telephone lines, etc.			

[a]Data on property values is taken from Middle Township, New Jersey for tax year 2013 (http://www.middletownship.com/Assessor/yearly%20assessment%20listing%202013.pdf, accessed 6 July 2014)
[b]Estimated at $10,000 for demolition and removal of debris from existing homes, plus $30,000 for removal of pilings and bulkheads from vacant lots
[c]Estimated at $2,200,000 per km for the most recent nourishment project at Cape May, New Jersey (http://beachnourishment.wcu.edu/, accessed 6 July 2014)

approximately US $4.4 million, versus approximately US $2.0 million for the first nourishment project, and approximately US $2.4 million for the second nourishment project 10 years later (assuming an inflation rate of 2 % per annum). In other words, beyond 10 years, the economics shift in favor of a buyout. Interestingly, there is renewed interests on the part of residents of Delaware Bay shore communities to consider buyouts due to the damage caused by Hurricane Sandy in 2012 (Nutt 2013).

3.6 Summary and Conclusions

The geological record informs us that there have been many fluctuations of sea level during the 445 million years that horseshoe crabs have existed. We suggest that these animals have always been able to track the available sandy beaches which they then used for spawning. Today, concern for the state of coastal beaches in Delaware Bay is a contentious issue because humans, horseshoe crabs and migratory shorebirds co-occur. Many beachfront communities that are now experiencing SLR (whether they believe it or not!) are in trouble due to the inexorable landward movement of the intertidal zone. Recent storms, such as Hurricane Sandy, have certainly accelerated the problem, but the erosion of Delaware Beaches has been occurring for a much longer period of time (Fig. 3.4). Several options, among many, are most common to temporarily stabilize the land where dwellings occur. The most popular, and expensive, method is to stay put and restore the dwelling by rebuilding and/or elevating the building to conform to federal standards. Another method of protection is to build higher berms or vegetated dunes, often in association with beach nourishment. A third solution, but not final, is to remove the dwellings from the beach and then restore habitat through a beach nourishment program. It is a costly procedure to “buy out” an entire community, or even a portion thereof. After the community is abandoned, infra-structural elements must be removed and sand must be brought to the beach by truck or dredge. None of these approaches provides a lasting buffer against SLR. However, we also are aware that horseshoe crabs can benefit by the third solution above. The case of Moores Beach is a good example of returning a beach area to its original state, before it was occupied by settlers. The reason that we are cautious regarding any of the above actions is that *the beach will still move inland as SLR proceeds*, *and sand will have to be periodically renewed on the restored area*. Over extensive coastal regions of Delaware Bay, new habitat in the form of overwash beaches, sandbars, and sand beaches along tidal creeks is emerging in areas that are not at all influenced by human activity. This is the condition that has challenged spawning horseshoe crabs for thousands of years, and they have readily adapted to the changing environment spurred on by SLR.

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