Direct and indirect effects of urbanization on Diamondback terrapins of the Big Apple: Distribution and predation of terrapin nests in a human-modified estuary

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ABSTRACT**:** Populations of Diamondback terrapins, *Malaclemys terrapin*, are declining throughout their range as a result of habitat degradation, urbanization, incidental trapping, and predation. Large populations of terrapins still live in the Hudson River Bight (HRB), a large estuary mostly within the political borders of New York City, the second largest city in the world. Two centuries of intensive urbanization, pollution, and ocean dredging have resulted in dramatic changes to HRB shorelines and marshes. Proximity to the city has also resulted in high terrapin harvest rates in the past, and high levels of subsidized predators now.

Gateway National Recreation Area (GNRA) is a relatively new national park comprised of land and ocean properties within HRB, thus protecting essential terrapin habitat. We studied distribution of and predation rates on terrapin nests at the three management units of the GNRA:

heavily urbanized Staten Island Unit (SIU), less urbanized Jamaica Bay Unit (JBU), and least urbanized Sandy Hook Unit (SHU). The terrapin population at SIU appears to be effectively extinct. Terrapins nest on the mainland coast and on three islands in JBU. On two of these islands, approximately 20 nests are deposited annually, predation is low, and about 318 hatchlings are produced. Approximately 2000 terrapin nests are laid annually on the largest JBU island (Ruler's Bar Hassock), and 95% of these are predated by raccoons (*Procyon lotor*). Thus the smaller islands may be important recruitment sources of the JBU terrapin population, whereas Ruler's Bar Hassock may now be a sink population. Despite lower levels of human disturbance at SHU, predation rates were high. We conclude that human-induced habitat changes affect terrapin nesting success even at low levels of urbanization because these changes result in high levels of subsidized predators such as raccoons, Norway rats (*Rattus norvegicus*), and gulls (*Larus atricilla* and *L. argentatus*).

Key words: Urbanization, diamondback terrapin, *Malaclemys*, reproduction, habitat, GIS

INTRODUCTION

Diamondback terrapins (*Malaclemys terrapin*) are medium-sized, brackish water North American turtles whose range is a narrow strip approximately 5764km long along the Atlantic coast from Cape Cod to the Gulf Coast of Texas (Fig. 1, Conant and Collins 1998). Terrapins are the only American turtles that regularly inhabit tidal creeks, bays, estuaries, and salt marshes, where the salinity ranges from fresh water to almost full salt water. Their diet consists mainly of invertebrates such as crabs, snails, shrimps, and clams (Ernst et al. 1994). Terrapins may be important components of estuarine food webs (Hurd et al. 1979), but more research is needed to clarify their role in estuarine ecosystems.

Other than for rare terrestrial basking, terrapins only come on land to nest. During their late May - early August nesting season, female terrapins cross the intertidal zone to oviposit in nearby upland areas (Ernst et al. 1994). In much of their range terrapins are dependent on tidal salt marshes, dominated by smooth cordgrass (*Spartina alterniflora*), within which terrapins feed, hibernate, and thermoregulate (Ernst et al. 1994).

It is difficult to quantify the effects that urbanization has had on terrapins, mostly because few data are available on terrapin population levels prior to high levels of human disturbance. However, there is reason to suggest that terrapin populations were formerly enormous, as they commonly shared habitat with oysters, which only 300 years ago formed vast reefs all along the shallow coasts of eastern United States (Jackson et al. 2001, Jackson 2001). Once terrapins were so inexpensive that they were provided as a monotonously common food for slaves (Carr 1952), and so abundant that they regularly clogged the nets of fishermen (Coker 1920). Terrapins were still numerous throughout their range until, due to a change in culinary fashions, large-scale terrapin harvest began in the mid 1800's (Carr 1952, Hay 1904, McCauley 1945). Heavy harvest of terrapins continued into the early 1900s; by then many populations had been reduced to low levels (Babcock 1926, Carr 1952, Conant 1952, De Sola 1931) and imminent extinction was feared (Hay 1904). Although no firm data are available, harvest range-wide has dropped considerably since the early 1900's and terrapin populations have managed a partial comeback (Burke et al. 2000, Carr 1952, Klemens 1993).

In addition to harvest, terrapins have been directly impacted by other human activities. Currently, terrapins face threats from habitat degradation, pollution, road and boat traffic, drowning in crab pots (Roosenburg et al. 1997), and predation. Many sections of the terrapin range are heavily urbanized (Fig 1) and thus subject to massive amounts of pollution of many types, from multiple sources, both large and small (Daskalakis and O'Connor 1995, O'Connor and Huggett 1988). The effects of pollutants on terrapins are poorly studied, but are likely to be severe (e.g., Bishop et al. 1991; 1998).

Two indirect ways that humans and urbanization affect terrapins are through subsidized predators and destruction of salt marshes. Although many species are known to prey on terrapins and their eggs, raccoons *(Procyon lotor)* are by far the most important overall. Raccoon predation on nests is common in many North American turtle populations (Mitchell and Klemens 2000), but this may be a recent phenomenon. United States raccoon populations generally grew 15-20 times larger in the 20th century, and spread into many new areas of North America (Obbard et al. 1987, Sanderson 1987). The reasons for these increases are not well understood, but urbanization is certainly a contributing factor (Prange and Gehrt 2004). Raccoons adapt well to urbanization and urban areas have some of the highest raccoon densities known (Larivière 2004, Riley et al. 1998). Raccoon predation is a potentially limiting factor for terrapin populations not only because raccoons eat turtle eggs, but because raccoons also eat adults (Feinberg and Burke 2003, Seigel 1980). Predation on adults can have severe impacts on turtle populations (Congdon et al. 1993), for example, terrapin populations can be eliminated by raccoon predation on reproductive females (e.g., Seigel 1980).

Besides subsidizing predators, urbanization has also impacted terrapins indirectly through damage to salt marshes. Many of the world's largest cities are located near estuaries, because such sites provide commercially and militarily valuable linkages between ocean travel and rivers. As a result, over one-third of the population of the United States lives close to salt marshes (McLusky and Elliot 2004). Beginning in the 1700's, the impacts of such urbanization were primarily through increased loads of sediments and sewage and through intensive resource use, but with increased industrialization pollutants changed rapidly to more complex chemicals and greater movement of surface material (Ehrenfeld 2001, Hanson and Lindh 1993, Odum et al. 1984). Wide-scale diking, dredging, and filling of urban salt marshes became common around cities beginning in the mid-1800's with the advent of appropriate machinery, often associated with the maintenance of shipping channels and development of industrial sites. Dredging has continued; development and fill deposition accounted for 73% of estuarine losses in the United States 1986-1997 (Dahl 2000). Four of the five states with the highest levels of estuarine wetland losses are found within the range of the diamondback terrapin: Florida, Louisiana, New Jersey, and Texas (Tiner 1984), and the coastlines of these four states together comprise 67% of terrapin range. Three of the five largest cities in the United States, New York City, Houston, and Philadelphia, are located on estuaries within terrapin range—clearly terrapins and their habitat have been strongly impacted by urbanization.

We investigated the distribution of terrapin nesting activity and associated nest success along a gradient of human disturbance within the boundaries of Gateway National Recreation Area, a national park in New York and New Jersey. Urbanization has had an important effect on terrapins in this region. Prior to initial urbanization, shallow reefs spread across much of New York Harbor (Waldman 2000), and the *Spartina* marshes of New York Harbor and neighboring Long Island probably supported extremely large terrapin populations. Terrapins of the New York/New Jersey area appear to have been especially heavily affected by the trade in terrapin meat because of their proximity to major food markets in, New York City and Philadelphia, and their reputation as the best-flavored meat (Murphy 1916). Subsequent development of New York City led to the loss of most regional *Spartina* marshes (Waldman 2000). We studied nest characteristics because they are relatively easily surveyed and they may serve as good proxies for recruitment rates. Because we expected that human impact would be seen indirectly through presence and abundance of nest predators, we also censused nest predators at these sites.

MATERIALS AND METHODS

Study Sites

Gateway National Recreation Area (GNRA) is a relatively new park consisting of uplands, salt water marshes, and ocean, mostly within the political borders of New York City, the second largest city in the world (20 million residents). Established in 1972 by the National Park Service (NPS) as America's first urban national park, GNRA is responsible for providing recreational opportunities for 8.5 million visitors annually (NPS, unpublished data) and for supplying habitat for wildlife.

GNRA spans the mouth of the Hudson River, an area known as the Hudson River Bight (HRB). HRB has a 250-year history of development and pollution, including a complex mix of organic and inorganic toxins (Waldman 2000). The lower Hudson River currently absorbs treated sewage from most of New York City's 14 wastewater treatment plants, which emit 1-2 billion gallons of treated sewage per day. The plume is mostly inorganic nitrogen, but also carries a long list of heavy metals and chemicals, mostly in trace amounts. Other active sources of pollution include industrial discharge and leaks from landfills. While levels of many of these pollutants, such as mercury, PCBs, and DDTs, have dropped in recent decades (Steinberg et al. 2004), dioxin levels in Hudson River Bight sediments have risen steadily since measurements were begun in the 1960’s. Thus the waters of GNRA have a complex and changing history of pollution.

GNRA is divided into three management units (Fig. 2). The most urbanized, Staten Island Unit (SIU), is located in the New York City borough of Staten Island. SIU consists of several properties, including Miller Field, Great Kills Park (GKP), and Hoffman and Swinburne Islands (Fig 2, 3). The lack of *Spartina* marshes at Miller Field, and Hoffman and Swinburne Islands probably precludes terrapins there, but small *Spartina* marshes still exist within GKP. GKP was dramatically altered by dredging and land fill activity, especially in the 1940s (Barlow 1971, Tanacredi and Badger 1995, Wrenn 1975). As a result, nearly all of the *Spartina* marsh that once existed in SIU has been eliminated.

Jamaica Bay Unit (JBU) is located in the boroughs of Brooklyn and Queens and includes mainland coast, parts of a barrier island, and seven upland islands ("upland" here means habitat that is not flooded by high tides, and therefore utilizable by terrapins for nesting): Ruler's Bar Hassock (RBH) the largest island, Canarsie Pol (CP), Ruffle Bar (RB), Little Egg Marsh (LEM), Subway Island (SI), Pumpkin Patch (PP), and Elder's Point (EP). Jamaica Bay was relatively unaffected by urbanization until the mid-1800's (Black 1981), and was known for abundant fish, oysters, and clams supporting a substantial harvest industry throughout the 1800's. In 1904, household sewage and industrial pollution from rapidly expanding New York City resulted in serious human illness in people who ate shellfish from Jamaica Bay, and the shellfish industry was closed. The *Spartina* marshes, islands, and ocean floor of Jamaica Bay were greatly altered by dredging operations in the early 1900's in order to provide greater ocean access to urban areas of New York City. Most coastal marshes in Jamaica Bay were covered with dredge material, and the freshwater streams into the bay were largely eliminated (Black 1981). CP was created in the 1930's by the dumping of ocean dredge material onto a tiny marsh. Ocean gaps that separated most of the original upland islands were filled, so these islands became connected to the mainland, providing direct access for potential terrestrial nest predators. A roadway bridge was built connecting the mainland to RBH in 1923, similarly providing a potential corridor for dispersing wildlife. Two large freshwater ponds were excavated on RBH in the 1950's, providing the only permanent fresh water source for wildlife on any of the Jamaica Bay islands. Several smaller islands were eliminated, and dredge material was dumped on a central group of marshes, creating one big upland island (RBH) where none had existed before. The only upland island existing today that existed prior to this period of dredging is RB (Black 1981). Loss of terrapin habitat in JBU continues because the *Spartina* marshes are currently deteriorating, due to combined effects of the changes in sediment deposition patterns and recent ocean level increases (Gornitz et al. 2002, Hartig et al. 2002, NPS 2001).

Sandy Hook Unit (SHU) is a barrier beach peninsula located at the northern tip of the New Jersey shore (Fig. 2, 5), and is the only GNRA unit outside of New York City political boundaries. The west side of the peninsula faces the Hudson River Bight and includes significant *Spartina* marshes. SHU has undergone intense military use from the early 1800s until 1972, which resulted in significant upland alterations (Tanacredi and Badger 1995). One result of the military activities has been dramatic efforts to protect the peninsula from erosion, using a series of sand groins and beach refurbishment. Although approximately 2.3 million people visit SHU annually, the SHU coastline is mostly undeveloped.

Measuring wetlands loss at the three GNRA management units

As a measure of the effects of urbanization of terrapin habitat, we measured the loss of estuarine wetlands in the three GNRA management units since major urbanization of New York City. We digitized the earliest maps that we could find that contained relevant information for each of the GNRA management units, to measure the area of estuarine habitat before large-scale modification occurred (before the mid 1800s, see above). We assumed that all coastal habitat labeled as wetlands or marsh was *Spartina* marsh. We compared the amount of *Spartina* in these maps to surveys done in the mid-1970s, which is after major modification and after the area was protected as a national park (NPS 1979).

Identifying Potential Nesting Areas

We located potential terrapin nesting areas in two ways, using previous reports (Cook 1989 and Feinberg 2000) and analyzing GIS data. The latter was accomplished for SIU and JBU using 1994 aerial imagery obtained from NPS, including 1976 vegetation maps. We used the ArcView GIS program to find possible terrapin nesting grounds with suitable habitat. Terrapins nest in a variety of upland habitats (Roosenburg 1994); we defined suitable nesting habitat for diamondback terrapins as "bare sand", "beach", "beachgrass dune", "mixed grassland", "open shrubland", "sand flat", "sand dunes", "sparsely vegetated dune areas", "low thicket", "lawn", and "flat sand areas with low vegetation cover," as defined on the vegetation maps.

To identify possible terrapin nesting areas in the SHU, we rectified a time series of historical, 2001 aerial photographs and 1996 vegetation maps from Monmouth County, New Jersey provided by NPS. As described above, we categorized sites into habitat types based on the same vegetation categories. In 2001 we also made a preliminary visit to SHU and located nesting areas based on where we found evidence of predated nests.

Surveys of potential nesting areas

We could not get access to the potential terrapin nesting areas we identified for SIU. In 2000, we trained a NPS employee working on the site to survey (see protocol below) the potential terrapin nesting areas daily in May, June, and July.

In 2000 with the assistance of volunteers we surveyed all suitable island nesting areas at JBU (CP, EP, LEM, PP, RB, and SI) and SIU for any sign of nesting terrapins. We recorded observations of available habitat and compared it with the vegetation maps and aerial photoimagery.

In 2001 we focused on the areas where we found evidence of nesting in 2000. We spent little time on RBH because it was already well studied (Feinberg 2000), instead we concentrated our work on LEM and RB because nesting had been reported there previously (Feinberg and Burke 2002) and we found predated eggshells there in 2000. Volunteers were posted on LEM and RB each day of the nesting season (June - July 2001) to watch for nesting activity. When a nesting female was detected, we let her nest, recorded nest location and captured the terrapin to obtain measurements and uniquely mark her. Upon first capture each female was marked by cutting a unique pattern of notches into marginal scutes and injecting a transponder (PIT). The location of each nest was marked by an orange polyvinyl flag and monitored until predation or hatching. Such marking probably does not affect predation rates (Burke et al. 2005), and we did not protect JBU nests from predators.

The remaining islands (CP, EP, and PP) were visited once each week in June - July 2001 for turtle tracks or predated nests. SI was visited biweekly. In early August, after the nesting season, CP, EP, LEM, PP, and RB were visited twice weekly to observe either evidence of predation or signs of hatchling emergence. Hatchling signs include post-emergence holes, which are small openings in the ground from which hatchlings have emerged. June 9 - October 26, 2001, we spent 521 total person hours on LEM, RB, PP, EP and CP waiting for nesting females, looking for nests, searching for evidence of predation, and signs of hatchling emergence on possible terrapin nesting beaches.

We visited SHU briefly in 2001 and performed an intensive study there in 2002. In 2001 we searched all feasible areas for evidence of nesting and performed counts of predated nests. In

2002, we visited nesting areas daily and monitored for nesting females. Each nesting female and nest was treated as described above for LEM and RB, except we also protected 19 nests to determine mean clutch size and measure egg viability. 1 June – 1 August, 2002, we spent 518 total person hours at SHU looking for terrapin nests and nesters. As described above for LEM and RB, we surveyed all feasible nesting areas for predation or signs of hatchling emergence during August and September. In some cases post-emergence holes allowed us to find nests that we had missed during the nesting period and we excavated these to count eggs, eggshells, and remaining hatchlings. At SHU we spent 164 hours searching for post-emergence holes.

Measuring Mortality of Nests and Adults

We surveyed SIU in 2000 for predated nests, dead terrapins, and nesting females, as described above. Similarly, we searched for predated nests and dead terrapins on CP, EP, LEM, RB, PP and SI, from 1 June - 31 July and sporadically in August 2000. In 2001, volunteers who were stationed on LEM, RB and CP to observe nesting also monitored unprotected nests and searched for predated nests. We searched SHU for predated nests and dead terrapins briefly in 2001 and more intensively 1 June - 30 October, 2002. During all these surveys we only counted a nest as predated if the excavated hole had eggshells associated with it, in order not to inflate our count with other holes that had not been nests. We identified nest predators by species, where possible, based on tracks, nest scars or scat.

Measuring Egg Viability

We defined "egg viability" as the number of eggs that resulted in emergent hatchlings, excluding eggs that were predated, flooded, died while hatching, or eaten by fly larva. We determined this by excavating nests either upon hatchling emergence or in the late fall. We counted the number of unhatched eggs, eggs infested with fly larva, egg shells (indicating successful hatching), and dead hatchlings. We assumed eggs were killed by flooding when nests were below the tide line and no eggs hatched. At SHU, in order to improve the probability that some nests would survive predation and could be used to measure egg viability, we protected 19 nests with hardware cloth predator excluders (Feinberg and Burke 2003).

Predator Surveys

In addition to casual observations of mammals made during all visits to terrapin nesting areas, we surveyed LEM and RB more intensively for potential predators. September 3–17, 2001 we set mammal traps on these two islands. We used Tomahawk live-traps (80 X 30 X 30 cm), baited with marshmallows, donuts, and cat food to capture mammals such as rats, raccoons, and opossums. Three Tomahawk traps were placed on LEM (18.3 hectares) and five Tomahawk traps on RB (56.8 hectares). We also used Sherman traps baited with peanut butter and a seed mixture to live-trap smaller mammals, such as mice, meadow voles, and shrews. We set 40 Sherman traps on LEM and 20 traps on RB for the same time periods as the Tomahawk traps.

RESULTS

Measuring wetlands loss at the three GNRA management units

The best pre-major-modification estuarine marsh coverage data showed that 84% of the marsh was within what is now JBU, 16% was within what is now SIU, and 2% was within what is now SHU (Table 1). By the time of the creation of GNRA in the 1972, JBU contained 92% of GNRA’s total estaurine marsh, SHU contained 6.5%, and SIU contained 1.5%. SIU had experienced nearly complete loss of its original salt marsh, while JBU lost more than half of its original salt marsh, and SHU has gained salt marsh.

Identification of Potential Nesting Areas

Based on GIS analysis of the vegetation maps and surveys of the SIU, JBU (1976), and SHU (1986), all appeared to have at least some suitable nesting habitat (Table 2, Figs. 3, 4, 5). SIU and SHU had about the same amount of potential nesting habitat as RBH. Most islands in JBU had little potential nesting habitat, but CP and RBH had large amounts of potential nesting habitat, together comprising 65% of the potential nesting habitat on JBU islands.

Surveys of Potential Nesting Area

Despite the availability of nesting areas, we did not find any evidence of terrapins in SIU, at either Great Kills or Miller's Field. However, in summer 2002 one terrapin hatchling was found in a parking lot in Great Kills (Cook, pers. comm.).

Results were more varied in the JBU. We observed 43 terrapin nests (29 in 2000, 14 in 2001) on LEM and RB; both are fairly small islands (Table 2). Seven of these nests were found during oviposition, 14 were found after predation, and 20 were found as post-emergence holes. Despite having more potential nesting habitat than any other island in JBU, we found little evidence of nesting terrapins on CP; in 2000 and again in 2001 a single terrapin crawl trail led from the beach into a nesting area, but no nests were found. We found no evidence of nesting on the tiny islands of PP or EP, however we observed nine turtles swimming near EP. Nesting density was highest at RBH, where nearly 6% of available nesting habitat was used for nesting (Table 2).

In 2002 we found 202 nests at SHU, all cases in which we either observed oviposition, we found the nest after predation, or we found the nest by means of a post-emergence hatchling signs. Nesting density was nearly as high as at RBH: 4% of available nesting habitat was used for nesting (Table 2).

Mortality of Nests and Adults

At SIU, we could not measure nest mortality due to the absence of terrapin nests. At JBU during the 2000 and 2001 nesting seasons, nest mortality rates on LEM and RB were low. Predation accounted for the loss of 33% of nests, whereas flooding accounted for the loss of another 8% of the nests (Table 3). All predation events were discovered post facto; we did not directly observe any predation on these islands on either terrapins or their nests. All but one of these nests appeared to have been predated by rats and/or birds; the eggshells were scattered 3-4 meters away, and rat tracks were found around the nests. The exception to this pattern was a RB nest in 2000, which appeared to have been raccoon predated (see Aresco 1996 for description of field sign). Predated and flooded nests were always completely destroyed. Other sources of mortality accounted for partial loss of nests (Table 3).

At SHU we found 139 nests after predation; almost all predation was by raccoons. Fifty nests were discovered during oviposition, all 31 that were left unprotected were predated. Fourteen emergence holes were discovered in SHU, leading to nests that had survived raccoon predation and successfully produced hatchlings. Raccoons predated eight of the 19 SHU nests that had been protected with predator excluders. Predation occurred after the protection had been removed, 63 days post-oviposition.

In 2001 we found a terrapin carcass, unidentified sex, on the RB beach; cause of death could not be determined. In 2002 we found carcasses of seven nesting terrapins killed by raccoons at SHU.

Egg Viability

At SIU, we could not measure egg viability due to the absence of terrapin nests. Overall egg viability on LEM and RB in 2000 and 2001 combined was 95% (322/340 eggs). At SHU egg viability from protected nests was 73.3% (85/116 eggs, 11 nests). This low rate was partially due to one terrapin that laid two clutches (n = 15, 16 eggs) that had 0% survivorship. If nests from this female are excluded from the egg viability calculations, viability at SHU was 97.6% (83/85).

Surveys for potential terrapin predators

Mammal Trap Results – Three meadow voles *(Microtus pennsylvanicus)* and eight Norway rats *(Rattus norvegicus)* were captured on LEM and RB in 14 trap-nights. Voles were captured only on RB, at an overall rate of three captures per 980 trap-nights (0.003 captures/trap night) using Sherman traps. Rats were captured on both LEM and RB, at an overall rate of eight per 112 trap-nights (0.071 captures/trap night) using Tomahawk traps.

No raccoons were captured at either island, perhaps because human visitors to the islands tampered with the Tomahawk traps on LEM and RB. The donuts and marshmallows were missing from the trap and the door of the trap was placed on the top of the cage.

Casual Observations – Because of the absence of terrapin nesting at SIU, we did not survey for predators there. Large nesting colonies of common terns *(Sterna hirundo)* and herring gulls *(Larus argentatus)* were found on LEM and CP. RB had a large breeding colony of herring gulls on the side of the island opposite from where the terrapins nested.

Although raccoon and muskrat were never captured in traps, their tracks were observed on both LEM and RB, and in 2001 we found a raccoon skull on RB. We also found one terrapin nest on RB that appeared to have been predated by a raccoon (see above). Otherwise, a lack of footprints throughout the area and bite patterns in the eggshells suggested that raccoons were not the main predators on LEM and RB.

At SHU raccoons were observed at dusk searching the terrapin nesting areas. We did not directly observe predation, but evidence of raccoon predation on nests and adults was commonly observed. We observed foxes and their prints in the area, but none of the nests showed evidence of fox predation.

Discussion

Diamondback Terrapins are restricted to a narrow strip of near offshore salt marsh habitat along the heavily urbanized east coast of the United States. Results of this urbanization include pollution, subsidization of raccoon populations, deliberate and accidental terrapin harvest, and damage to salt marshes, all of which can be important to local terrapin populations. We examined some of these factors associated with urbanization at Gateway National Recreation Area, a new national park near one of the world's largest cities.

We are unable to estimate past terrapin population sizes in this area because no appropriate records are available. Terrapins were too unimportant as a commercial food source to be recorded along with the accounts of the vast oyster beds and fisheries of this area through the 1800's. However, we found that the salt marshes upon which terrapins depend for food and shelter were once far more extensive than they are currently, and that marsh loss can be primarily attributed to development due to urbanization. Nearly all of the salt marshes of SIU were covered with landfill during the rapid urbanization of Staten Island. Many of the salt marshes of JBU were either dredged or covered with dredge spoil, partly to develop a major airport and in an attempt to develop the area as a sea port. Only the salt marshes of SHU, those farthest from New York City, remain largely intact.

Although foraging habitat is greatly reduced, we found that substantial nesting habitat remains. Some parts of SIU may have more dune habitat now than in the past, as marshes were converted to uplands. While much of the shoreline of Jamaica Bay has been made inaccessible to nesting terrapins through bulkheading, new nesting areas were created when dredged material was dumped high enough to make upland islands. For example, CP, a large human-made island in Jamaica Bay, now provides substantial potential nesting habitat. However, it is rarely used by nesting terrapins. It may take more time for terrapins to colonize new nesting beaches. The availability of nesting habitat in the upland areas of SHU appears to be much the same as it has been for the last few centuries.

In addition to habitat degradation, urbanization affects terrapins by facilitating populations of nest predators. In most of North America, raccoons are the most important predators on turtle nests, and generally benefit from all levels of urbanization (Mitchell and Klemens 2000, Larivière 2004, Riley et al. 1998). It is not surprising that we detected a dense raccoon population even at SHU, the least urbanized of our study sites, because it is heavily used by beach visitors throughout the year, supplying ample refuse as a food resource.

The major source of egg mortality throughout GNRA was predation by raccoons, and not surprisingly, we found a close relationship between the presence of nest predators, primarily raccoons, and levels of nest predation. On the two Jamaica Bay islands where raccoons occurred only sporadically and then in low numbers, egg predation levels were relatively low. We note that in the 1980's, before raccoons occurred on the island of Ruler's Bar Hassock, egg predation was very low there as well (Cook 1989). Raccoon populations on RBH increased with urbanization of the island, and a large raccoon population occurs there now. RBH predation rates now match those of SHU—ca. 90-95% (Feinberg and Burke 2003).

The possible effect of other egg and nest predators is unclear, however two other subsidized predators, herring gulls and Norway rats, are also common in GNRA. We found

Norway rats on the Jamaica Bay islands LEM and RB, and they also occur on RBH (Burke, pers. obs.). We never found unambiguous evidence that birds predated eggs or hatchlings. We did not measure predation on hatchlings, however Draud et al. (2004) found that Norway rats can be important predators on hatchling terrapins.

We did not measure pollution or pollution effects directly, but we did measure egg viability. We assumed that if pollutants, such as the organochlorines and heavy metals known to occur in GNRA, were currently having a dramatic effect on the terrapins, this effect would be evident in reproductive failure, as has been seen elsewhere (Guillette et al. 1994, 1999). Instead, we found relatively high levels of egg viability at both JBU (as did Giambanco 2003) and SHU. However, pollutants could express their effects in a more subtle ways, for example, we have noted high levels of scute abnormalities in many hatchlings from all three units (Ner unpub. data, Widrig, unpub. data).

Because of the near complete loss of salt marshes in SIU, we conclude that the terrapin population there is effectively extinct, despite the fact that not long ago terrapins were common on Staten Island (Kieran 1959). Terrapins are not likely to be found in any significant numbers in SIU again until salt marshes are restored. Terrapin numbers at JBU appear to be very high and numerically stable currently (Burke, unpub. data), but it is unclear whether this will continue under the impacts of new, high levels of egg predation on RBH (Feinberg and Burke 2003) and current high levels of marsh loss (Gornitz et al. 2002, Hartig et al. 2002). Because of lower egg predation rates on the smaller islands of JBU, they may be an important recruitment source of Jamaica Bay's terrapin population, whereas RBH now may be a sink population. Despite much lower levels of human disturbance at SHU, predation rates there were similar to those in RBH. It is unclear whether the terrapin population at SHU is already in equilibrium with high levels of egg and nest predation, because it is unknown whether raccoon densities have changed in recent years.

Our results indicate that the relationships between urbanization and factors affecting terrapin populations are complex. Factors that may have been important in the past, such as terrapin harvest and dredging, may still be influencing the terrapin habitat and terrapin numbers today, both directly and indirectly. Air pollution affects the amount of terrapin habitat, because among the effects of global climate change is ocean level rise, and rising ocean levels are reducing the size of JBU salt marshes (Gornitz et al. 2002) and likely other marshes throughout terrapin range (Kennish 2001). In addition, even relatively subtle human-induced upland habitat changes, such as the light urbanization at SHU, can affect terrapin nesting success because these changes result in high levels of subsidized predators (e.g., raccoons and Norway rats).

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Table 1. Salt marshes in the three GNRA units, comparing coverage before major development beginning in the mid-1800s to coverage in the mid 1970s, when they were protected by the National Park Service. The estimates of early coverage are from our digitization of maps and from NPS (2001), modern coverage is from NPS (1979).

	pre-modification (ha)	1979 (ha)	% change
JBU	930.8 (1857-1924)	354.1	-62%
SHU	2.5 (1889-1900)	24.7	+888%
SIU	179.9 (1781)	5.7	-97%
total	1113.2	384.5	-65%

Table 2. Total size, quantity of appropriate nesting habitat, and actual nesting habitat in different areas of Gateway National Recreation Area.

Unit	Site	Total uplands (ha)	GIS Potential Suitable Nesting Areas Size (ha)	Actual Nesting Areas Size (ha)
JBU	Canarsie Pol	117.6	58.1	0.2
	Pumpkin Patch	5.1	0.7	0
	Little Egg Marsh	18.3	12.1	0.5
	Elder's Point	7.1	1.3	0
	Ruffle Bar	56.9	19.7	0.2
	Ruler's Bar Hassock	361.5	26.5	1.5
	Subway Island	19.9	11.7	0
Total JBU islands		586.4	130.1	2.4
SIU	Great Kills Park	480	27.4	0
	Miller Field	90.4		
	Fort Wadsworth	4.0		
SHU		666	36.9	1.5

Table 3. Terrapin nest and egg survivorship on Ruffle Bar and Little Egg Marsh (both in JBU) and Sandy Hook Unit (SHU). All nests were found through direct observation of nesting females, following adult tracks on land, discovery of predated nests, or post-emergence holes. For SHU, calculations of the % predated nests does not include the 19 nests that we protected from predators, and data on the fate of individual eggs comes from the 11 nests we protected successfully.

	2000				2001				2000 + 2001		2003	
	LEM		RB		LEM		RB		LEM and RB		SHU	
	Number	%	Number	%	Number	%	Number	%	Number	%	Number	%
Total number of nests found	14		15		7		7		43		203	
Predated nests	2	14%	10	67%	0	0%	2	29%	14	33%	170	92%
Fate of unpredated eggs: hatched	114	77%	62	95%	85	86%	57	95%	318	85%	104	66%
Fate of unpredated eggs: undeveloped	5	3%	2	3%	8	8%	3	5%	18	5%	37	23%
Fate of unpredated eggs: died while hatching	1	1%	1	2%	2	2%	0	0%	4	1%	5	3%

Fate of unpredated eggs: flooded	29	20%	0	0%	0	0%	0	0%	29	8%	0	0%
Fate of unpredated eggs: dipteran larva	0	0%	0	0%	4	4%	0	0%	4	1%	0	0%
Fate of unpredated eggs: plant roots	0	0%	0	0%	0	0%	0	0%	0	0%	11	7%
Total mortality other than predation	35	24%	3	5%	14	14%	3	5%	55	15%	53	34%

Figure captions

Figure 1. Range map of diamondback terrapins with major river and estuaries indicated and combined with photograph created using satellite images of the light United States east coast cities generate at night. The brightest areas are the most urbanized. Data and photograph produced by Imhoff et al. (2005).

Figure 2. Gateway National Recreation Area. Most of this park is within the political boundaries of New York City. Image courtesy of United States Park Service.

Figure 3. Staten Island Unit of Gateway National Recreation Area. Habitat identified as suitable for nesting terrapins (see text for details) is shaded gray. Photo inset is of current condition of landfill placed over the major *Spartina* marsh of this unit. Images courtesy of United States Park Service and G. Frame.

Figure 4. Jamaica Bay Unit of Gateway National Recreation Area. Habitat coded as for figure 3, and actual habitat used for nesting is shaded black. Photo inset is of current condition of the major *Spartina* marshes of this unit. Images courtesy of United States Park Service and G. Frame.

Figure 5. Sandy Hook Unit of Gateway National Recreation Area. Habitat coded as for figure 4. Photo inset is of current condition of the major *Spartina* marshes of this unit. Images courtesy of United States Park Service.