

RESEARCH ARTICLE

Nesting Habitat Creation Enhances Recruitment in a Predator-Free Environment: *Malaclemys* Nesting at the Paul S. Sarbanes Ecosystem Restoration Project

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Abstract

Aquatic turtles worldwide are plagued with habitat loss due to development and shoreline alteration that destroys the terrestrial–aquatic linkage which they must cross to reproduce successfully. Furthermore, nesting habitat loss can concentrate nesting, increasing nest predator efficiency. We describe how the Paul S. Sarbanes Ecosystem Restoration Project at Poplar Island created nesting habitat for *Malaclemys terrapin* (Diamondback Terrapin), and document nesting success in response to construction progress and the absence of raccoons and foxes, the primary nest predators. We monitored terrapin nests throughout the nesting seasons from 2002 to 2011 to determine overall and within-nest survivorship. Female terrapins began nesting on the restoration project within 1 year but planned construction during the study eliminated some nesting areas and opened previously inaccessible areas. Overall, nest survivorship was considerably higher than mainland nesting areas due to the absence

of raccoons and foxes on the island and within-nest survivorship was similar. Egg size, hatchling size, and the frequency of shell scute anomalies were similar to other terrapin populations, suggesting normal developmental conditions on the island. We documented annual variation in hatchling size that correlated negatively with mean air temperature during the incubation season. Our results indicate that restored or created isolated island habitat can be located rapidly by terrapins and can become an important source of recruitment in regions where nesting habitat is limited and predation is high. Poplar Island illustrates how habitat loss and restoration can affect turtle populations by revealing the changes in nesting patterns and success in newly created, predator-free habitat.

Key words: island restoration, *Malaclemys*, nesting habitat, nesting success, Poplar Island, predator exclusion, terrestrial–aquatic linkage, turtles.

Introduction

The interface between land and water is important habitat for terrestrial and aquatic species. Alteration or destruction that severs the terrestrial–aquatic linkage (Bilkovic & Roggero 2008) can be particularly problematic for species that require aquatic and terrestrial habitats to complete their life cycle. Estuary and river shoreline is dynamic and experiences high rates of erosion and accretion. Shoreline erosion causes economic loss that

landowners frequently prevent with shoreline hardening, rigid structures of stone (rip-rap), wood, or metal (bulkheads) that deflect wave action and reduce erosion. Shoreline hardening also destroys the terrestrial–aquatic linkage. Depending on the hardening structure and the locomotor capability of the affected species, hardening may prevent certain species from accessing their critical terrestrial habitats. Shoreline hardening also may affect species behavior, forcing species to move away from hardened areas, which increases species density in remaining habitat patches. Increased density may facilitate predation, disease, and other detrimental density-dependent processes (Currin et al. 2010). Habitat construction or restoration can ameliorate density-dependent losses by increasing available habitat. However, successful use or colonization of the new habitat is dependent on the target species' ability to locate that habitat and whether the new habitat meets the organism's niche requirements (Scott et al. 2001).

The Paul S. Sarbanes Ecosystem Restoration Project at Poplar Island (hereafter Poplar Island) uses dredge material

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from the Baltimore Harbor approach channel to rebuild an island in Chesapeake Bay with a goal of restoring and creating habitat native to the area including wetlands and the aquatic–terrestrial interface. Transportation and disposal of dredged material are costly and environmentally challenging (Lund 1991) due to the potential for dredge material to be laden with toxic materials and high nutrient loads (Jones & Lee 1988). Poplar Island’s restoration attempts to restore critical habitat lost through erosion and subsidence using dredge material. The original 27-year construction project combines soft shoreline (maintains terrestrial–aquatic linkage) and hardened shoreline to create both protected wildlife habitat and a dredge material repository. A primary goal of the project is to attract nesting shorebirds and other wildlife that have diminished in the region due to development, shoreline stabilization, and high nest predator densities.

Rip-rap and bulkheading create barriers that break the terrestrial–aquatic linkage for aquatic turtles that must nest on terrestrial habitats (Roosenburg 1991). Aquatic turtles must cross the terrestrial–aquatic interface to complete their life cycle: juveniles and adults are aquatic, but the eggs must incubate above mean high water in areas without prolonged inundation. Bulkheads and rip-rap can also result in oviposition below mean high tide where nests wash out or embryos drown (Fowler 1979; Whitmore & Dutton 1985). Furthermore, nesting density can increase in the remaining intact sites and thereby increase nest predation rates. Human-subsidized predators (Soulé 1988) and their effects on turtle populations are well known (Eskew et al. 2010; Esque et al. 2010) and, in developed coastal areas, *Procyon lotor* (raccoons) consume most *Malaclemys terrapin* (diamondback terrapin) nests within 24 hours of oviposition (Roosenburg & Place 1995; Feinberg & Burke 2003; Butler et al. 2004). Studies documenting how turtles might respond to the creation or alteration of nesting habitat are mostly limited to sea turtles. Beach “nourishment” (substrate supplementation) can alter substrate bulk density, albedo, teratogens, and slope that all can affect nest success (reviewed in Crain et al. 1995).

Malaclemys terrapin (diamondback terrapins) are an exclusively estuarine turtle found throughout the eastern seaboard and Gulf Coast region of the United States. Commercial fisheries-induced mortality and habitat loss threaten terrapins throughout their range (Roosenburg 1991; 2004). In the northeastern and mid-Atlantic region, development and shoreline hardening have significantly reduced terrapin nesting habitat and juvenile salt marsh habitat (Seigel & Gibbons 1995; Butler et al. 2006). Poplar Island provides a unique opportunity to evaluate the efficacy of nesting habitat creation for diamondback terrapins and the effects of using dredge material as the foundation for such habitat. Furthermore, the absence of *Procyon lotor* (raccoons) and *Vulpes* sp. (foxes) on Poplar Island could result in increased nest survival and hatchling recruitment relative to sites where these nest predators are present. Herein, we present and analyze a 10-year dataset of terrapin nesting success on Poplar Island and ask if the island has created nesting habitat that contributes long-term to terrapin recruitment. We evaluate egg size, hatchling phenotype, and the frequency of shell scute anomalies

as potential indicators of the suitability of substrates used in nesting site construction. Furthermore, we evaluate the potential of isolated nesting sites devoid of raccoons and foxes to maintain and restore turtle populations through increased recruitment.

Methods

The Paul S. Sarbanes Ecosystem Restoration Project at Poplar Island is a 478 hectare restoration of a middle Chesapeake Bay island near Sherwood, MD (Figure 1). Poplar Island occupied more than 450 hectares 150 years ago, but by 1998, erosion and subsidence had resulted in three remnant islands that totaled less than 4 hectares. In 2000, the rebuilding of Poplar Island began on a footprint reflecting the original island of 1850. The U.S. Army Corps of Engineers completed a perimeter dike in 2002 using imported stone and sand harvested from the site and began filling the interior of the island with dredge material. When completed in 2027, the island will consist of approximately 50% wetland cells comprising *Spartina* spp. salt marshes and 50% upland cells of mid-Atlantic coastal plain forest. The 13 salt marsh cells are separated by sand dikes that isolate filling and construction. Most of the perimeter dike is protected by stone revetment, rip-rap; however, no stone armoring exists in sheltered areas of the Notch and outside Cell 5 (Figure 1). From 2002 to 2007, an opening in the perimeter dike allowed access to open sandy areas within Cell 6, but closure of the perimeter dike in late 2007 isolated these areas (Figure 2). However, culverts installed in completed wetland cells to establish tidal flow breached the perimeter dike and provided new access routes to the island interior.

We monitored nesting areas daily and located terrapin nests during the 2002–2011 nesting seasons, documenting both depredated and intact nests. Intact nests > 24 hours old were marked and left undisturbed. Nests < 24 hours old were excavated and all eggs were counted. We weighed (± 0.1 g) each egg on a jeweler’s balance and then carefully reburied the nest. Four survey flags marked the nest (known not to attract mammalian predators [Tuberville & Burke 1985; Burke et al. 2005]) and after 2006, we also anchored hardware cloth (1.25 cm² mesh) flushed with the soil surface over the nest to prevent crow predation. We recorded nest latitude and longitude using a Garmin Etrex GPS (Garmin International Inc, Olathe, KS, U.S.A.) and mapped all nests for each year using ArcGIS (Esri, Redlands, CA, U.S.A.). We monitored nests daily for predation and other disturbances, such as washout.

After 45–50 days of incubation, we removed the hardware cloth and placed a metal flashing ring buried ~10 cm around the nest to catch emerging hatchlings. Hardware cloth (1.25 cm² mesh) placed over the ring prevented hatchling predation. Because access to the island is limited to weekdays, during the weekends we placed plywood over rings from July to September to provide shade for emerged hatchlings. We transported hatchlings to a laboratory facility on the island in small mesh bags. We weighed (± 0.1 g) and measured plastron and carapace length, shell height, and width (± 0.1 mm) of all hatchlings and noted shell anomalies or other developmental abnormalities. Hatchlings were released

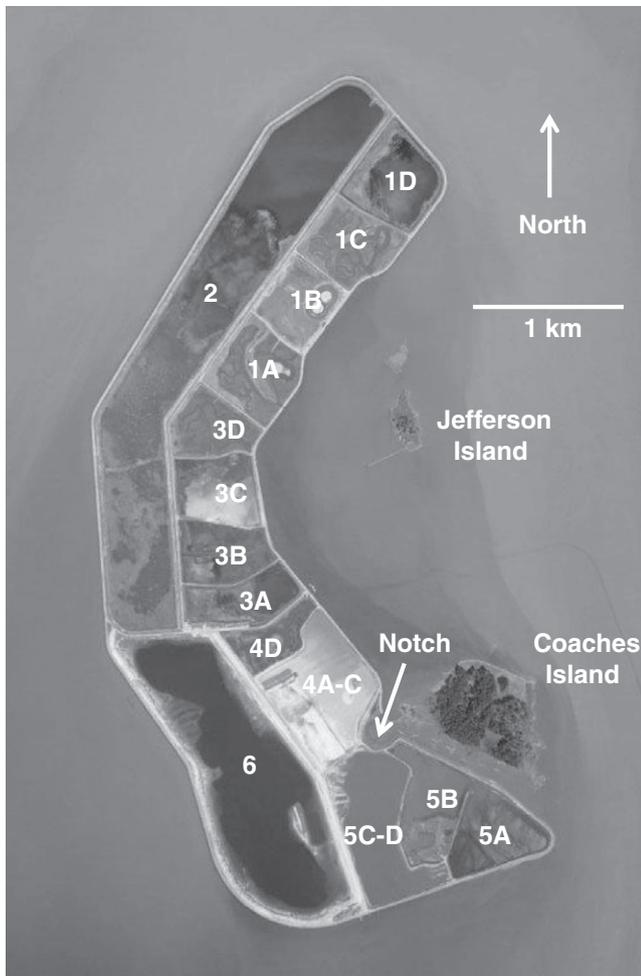


Figure 1. Map of the Poplar Island Environmental Restoration Project in Talbot County, MD. Cells 2 and 6 when completed will be upland cells made of eastern coastal plain forest and Cells 1, 3, 4, and 5 will be wetland cells of *Spartina* salt marsh habitat. Terrapin access to nesting areas occurs along the dike of Cell 5 and the Notch (the semicircle area between Poplar and Coaches Island), outside Cell 3, and along the inside of completed wetland cells (as of 2011 Cells 4D, 3D, 1A and 1B).

after processing in either the Notch or in completed wetland cells.

We calculated annual nest survival rate as the number of nests that produced hatchlings divided by the total number of nests found on the island; nest survival also was calculated for each of the main nesting areas (the Notch, Cells 3, 5, and 6). Within-nest survivorship was calculated as the number of surviving hatchlings divided by the total number of eggs within each clutch; nests of unknown clutch size were excluded. We used the mean clutch values for comparisons of egg and hatchling metrics across years to avoid pseudoreplication (Hurlbert 1984) in comparisons among years.

We downloaded weather data from the NOAA Thomas Point weather station 9.5 km north-northwest (NNW) of Poplar Island and calculated mean daily temperature and mean daily maximum temperature for June 1–August 15 of each year.

Most terrapin nests are in their critical stages of development during this time period. These summary weather data were correlated with the frequency of shell anomalies, mean hatchling metrics, and within-nest survivorship values using a Pearson Product Moment Correlation. We analyzed data using SAS 9.2 for Windows (SAS Institute Inc, Cary, NC, U.S.A.).

Results

The restoration of Poplar Island provided terrapin nesting habitat, with a mean of 208 nests per year since 2004 when daily surveys began. Nesting has become widespread on Poplar Island, but nesting locations have changed during construction of the island (Figure 2). Because the majority of the perimeter dike is stone rip-rap, access for terrapins is limited to areas where the dike is constructed of sand or where terrapins have access to interior sand dikes. The hardening and closure of the perimeter dike on Cell 6 in October 2007 resulted in the elimination of 20–40 nests per year in that area (Figures 2 and 3). However, the installation of culverts to establish tidal flow in completed wetland cells provided access to nesting sites in Cells 4D, 3D, and 1A (Figures 1 and 2), particularly in Cell 4D, which is the oldest and most established wetland cell. The area of sand accretion outside Cell 3 was a major nesting area in 2004, but continued erosion has substantially reduced the size of the nesting area outside Cell 3, resulting in fewer nests (Figures 2 and 3). Finally, nest numbers in the Notch and Cell 5 have changed over the years (Figure 2) as vegetation growth and wind erosion of sand have altered the location and availability of high-quality nesting habitat.

Terrapin nests on Poplar Island have high annual nest survival and high within-nest survivorship (Figures 2 and 3; Table 1). The high nest success (mean = 73.3%) on the island relative to mainland sites was due to the absence of raccoons and foxes that are efficient terrapin nest predators. We observed a decline in nest survivorship during 2005 (62.4%) and 2006 (58.6%) that was caused by *Corvus ossifragus* (fish crow) predation of our marked nests. The hardware cloth successfully protected nests beginning in 2007, which eliminated the crow predation of marked nests and increased nest survival back above 70%. The absence of raccoons and foxes and the elimination of crow predation allowed us to identify other novel nest predators including *Lampropeltis getula* (Eastern kingsnakes), *Triunga semipalmata* (willet), and *Peromyscus leucopus* (white-footed deer mice). Additionally, some nests were depredated by *Panicum virgatum* (switchgrass) both dehydrating eggs and entrapping hatchlings. Within-nest survivorship averaged 62.5% but varied among years (Kruskal–Wallis, degrees of freedom [df] = 7, $\chi^2 = 40.515$, $p < 0.0001$; Figure 4) and tended to decrease with increasing ambient air temperatures (Pearson product moment correlation, $\tau = -0.618$, $p > 0.102$). The year with warmest ambient air temperatures (2010; Figure 5) had the lowest within-nest survivorship (42.9%).

Clutch size, total clutch mass, and mean within-clutch egg size differed among years (multivariate analysis of variance [MANOVA], Wilk's Lambda = 0.942, $df = 21$, 2217.3,

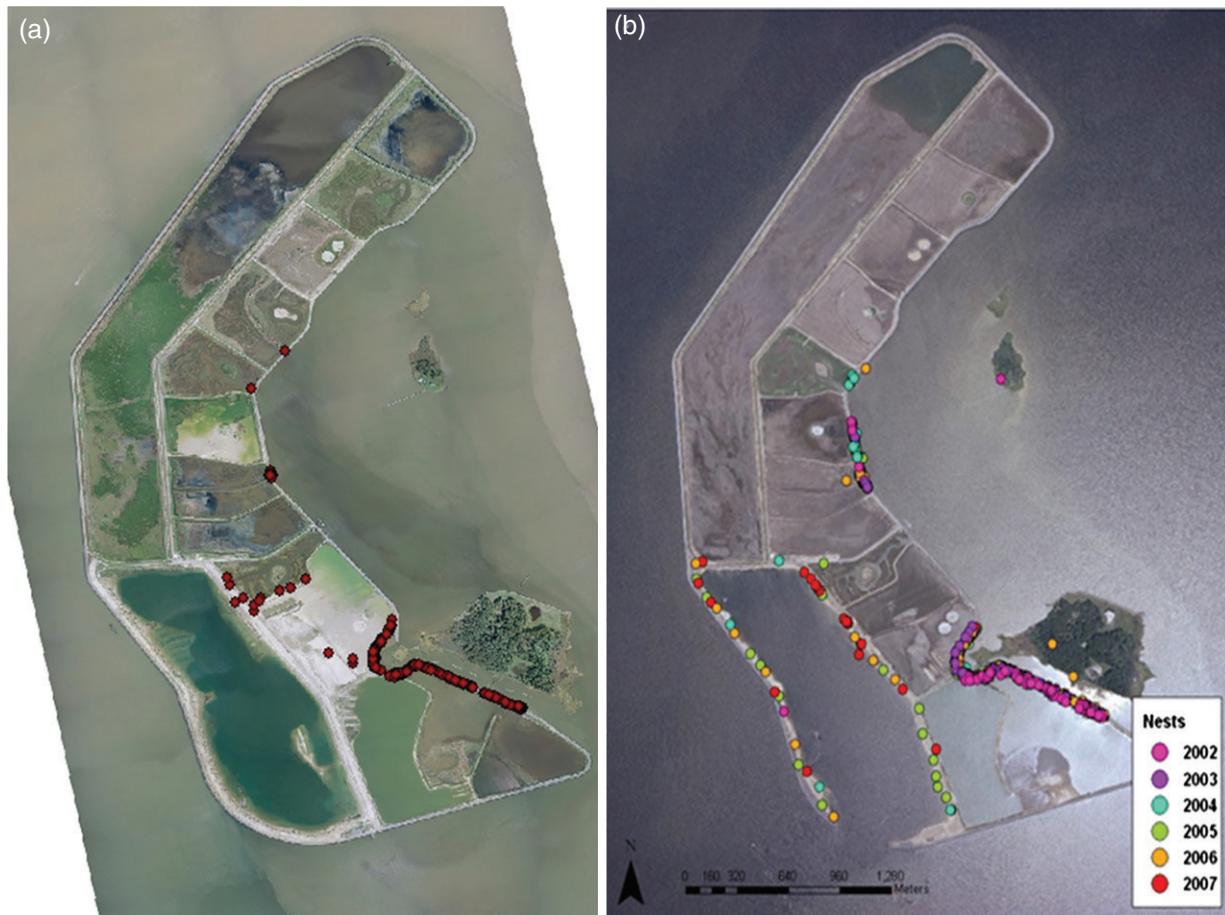


Figure 2. Nest site locations on Poplar Island from (a) 2002 to 2007 and (b) during 2010. Note that the completion of the dike at the southwest corner of the island eliminated nesting inside of Cell 6. The dike was completed in fall 2007. Also note the increase in nesting along the perimeter of wetland cells in the south-central section of the island.

$p > .001$; Table 2). Tukey's post hoc univariate test (analysis of variance [ANOVA], $F_{7,784} = 2.03$, $p < 0.05$) found differences in clutch size between 2008 and 2011 only and differences in average egg mass (ANOVA, $F_{7,786} = 3.10$, $p < 0.05$) among 2011 and 2010, 2009, 2008, 2006 (Table 2). These results indicate that there was a dramatic drop in egg size and a concomitant increase in clutch size in 2011 that drove the differences observed. Interestingly, total clutch mass (ANOVA, $F_{7,786} = 1.54$, $p > 0.05$) did not differ among years. Hatchling size varied among years of the study. Mean hatchling mass and mean carapace length differed among years (Table 3; ANOVA; mass $F_{8,1058} = 2.48$, $p < 0.012$; carapace length $F_{8,1061} = 22.54$, $p < 0.001$). Both mean hatchling mass and carapace length correlated negatively with mean daily air temperature (Pearson product moment correlation for mass $\tau = -0.767$, $p < 0.016$, carapace length $\tau = -0.867$, $p < 0.004$), suggesting that warmer years resulted in smaller hatchlings.

Shell anomalies varied from 11.5 to 32.4% among years (Table 4). During 2004, we identified 14 hatchlings with cranial deformities (cleft palate, incomplete development of the parietals, and missing heads) but since 2004 we found only one hatchling with a cranial abnormality. We observed cranial

deformities in hatchlings from all nesting areas in 2004 and four nests had two affected hatchlings. No correlation was found between the annual frequency of shell anomalies and mean daily air temperature, air temperature standard deviation, and mean daily maximum temperature (Pearson product moment correlation, $p > 0.05$). However, during 2010 shell anomalies were high, corresponding with the high temperatures during that year.

Discussion

As human impact rapidly decreases available habitat for many species, habitat creation or restoration offers a solution for waning populations but depends on the arrival of colonizing individuals (Scott et al. 2001). Interestingly, the dynamic nature of restoration warrants an adaptive strategy to maintain habitat critical for species as that habitat goes through successional stages initiated through restoration (Scott et al. 2001). Poplar Island exemplifies this principle through both the anthropogenic and natural changes to the habitat that have altered nest site use. Although restoration of Poplar Island targeted habitat creation for colonial nesting wetland birds, it also created nesting

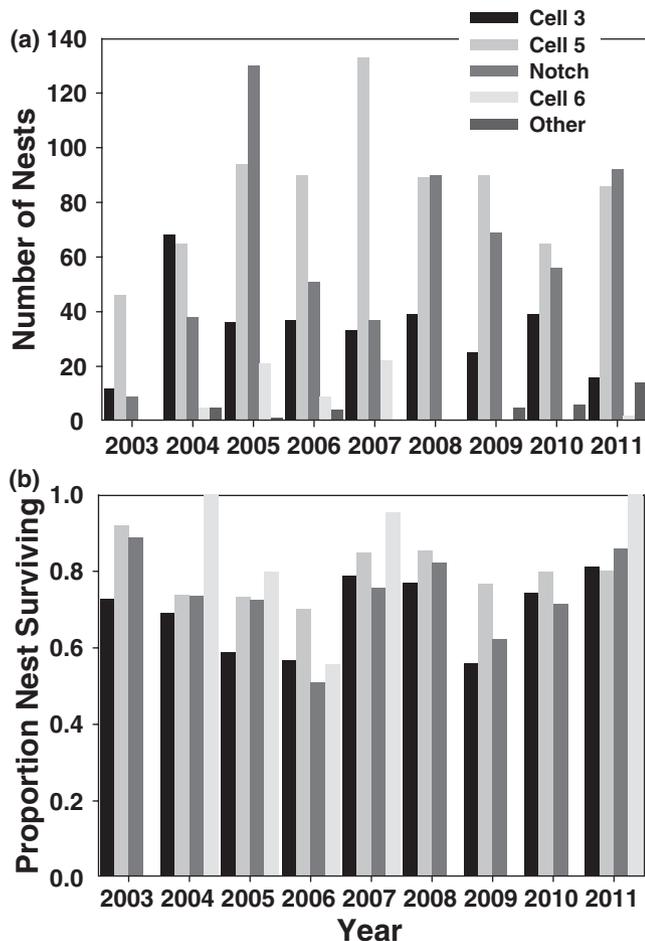


Figure 3. Number of nests and nest survival among the main nest locations on Poplar Island. Most nesting occurs in the Notch and on the dike outside Cell 5. Note the absence of nesting in Cell 6 beginning in 2008 and an increase in nesting in other areas.

habitat that was discovered and used by diamondback terrapins (a nontarget species) in the first nesting season it was available. However, the absence of nesting along hardened portions of the perimeter dike and the closure of the Cell 6 perimeter dike in 2007 illustrates how stone rip-rap barriers can eliminate access

to nesting sites. The completion of wetland Cells 1A, 3D, and 4D, and the installation of culverts that breached the perimeter dike, established routes into the island that facilitated nesting in the island interior. Although the terrestrial–aquatic interface on the exterior of Poplar Island is limited because of the stone rip-rap, the completion of wetland cells and breaching of the barrier increased the available aquatic–terrestrial interface inside the cells through which terrapins accessed nesting sites. Maximizing the aquatic–terrestrial linkage should be an important goal of island and wetland restoration and the creation of turtle nesting habitat.

Natural succession and growth of vegetation combined with wind-driven movement of sand have also shifted concentrations of nesting activity on Poplar Island. Terrapins nest in open sandy areas in Chesapeake Bay (Roosenburg 1996) and the increasing vegetation has reduced nesting in some areas (Cell 5), whereas the open areas created and maintained by windblown sand have increased nesting in other areas (Notch) over the years. Vegetation planted to prevent erosion of the perimeter dike in the Notch and Cell 5, particularly *Panicum virgatum* (switchgrass), which reaches a stature in excess of 1 m, created shade and dense vegetation that reduced terrapin nesting there. We also have observed predation of eggs and entrapment of hatchlings by grasses that also occur in natural nesting areas (Lazell & Auger 1981; Stegmann et al. 1988). Maintaining open sandy areas along portions of the perimeter dike is an important component of an adaptive management strategy to maintain terrapin nesting habitat on Poplar Island.

The absence of raccoons and foxes created nesting habitat with high recruitment and the potential for terrapin population growth. Nest survivorship is comparatively high on Poplar Island primarily due to low predation rates and the absence of raccoons contributed substantially to the recruitment of more than 11,000 hatchlings during this study. Mainland nesting areas in Chesapeake Bay have high nest predation rates that range from 70 to 100% (Roosenburg 1991). Throughout the terrapin's range, 81.9 (FL, Butler et al. 2004) to 94.8% (NY, Feinberg & Burke 2003) of nests are depredated by raccoons and their removal dramatically increased nest survivorship in a Florida terrapin population (Munscher et al. 2012). Long-term removal of 50% of the raccoons on sea turtle nesting beaches did not increase nest success but did alter the demographic

Table 1. Summary and fate of nests discovered on Poplar Island from 2002 to 2011.

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Total nests	68	67	182	282	191	225	218	189	166	211
Nests producing hatchlings	38	50	129	176	112	166	180	145	124	180
Nest survival	–	0.746	0.709	0.624	0.586	0.738	0.826	0.767	0.747	0.853
Depredated (roots or animal)	0	0	12	46	54	18	12	10	9	24
Washed out	1	6	3	11	13	2	6	3	4	3
Undeveloped eggs, weak shelled eggs, or dead embryos	0	1	0	12	1	19	10	12	11	5
Destroyed by another turtle or nest was in rocks	0	0	2	0	0	3	0	0	2	0
Dead hatchlings	0	0	0	0	1	2	0	2	6	3
Fate of nest unknown	29	10	36	37	10	19	10	10	17	11

In 2004, nest surveys were completed daily contributing to the increase in nesting at that time. Since 2004, nesting activity has fluctuated but averaged 208 nests per year. Depredated nests include nests with complete and partial predation.

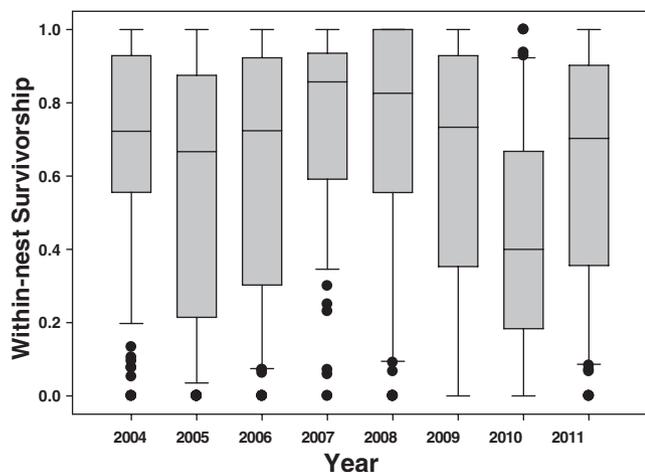


Figure 4. Box plot of within-nest survivorship among years on Poplar Island.

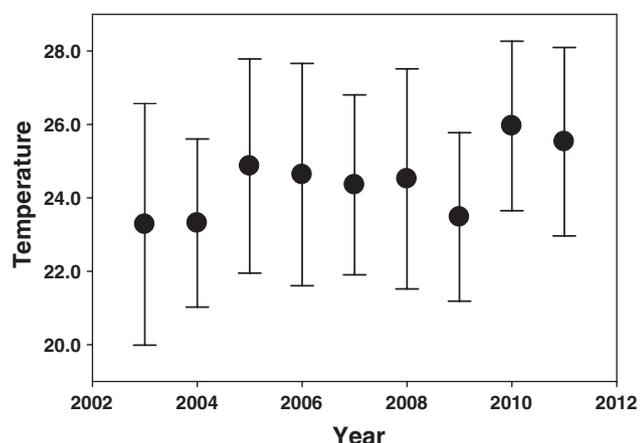


Figure 5. Mean daily temperature, ± 1 standard deviation, from 1 June to 15 August at the NOAA Thomas Point Light House weather station in Chesapeake Bay. The weather station is approximately 9.5 km NNW of Poplar Island.

structure of the raccoon population (Ratnaswamy et al. 1997; Burton & Roth 1997) and may have had other unforeseen ecological consequences (Ratnaswamy & Warren 1998). We suggest that isolated islands that lack nest predators, whether anthropogenic or naturally occurring, may function as sources that maintain turtle populations in adjacent mainland areas and thus can be important contributors to turtle restoration and recovery.

The absence of raccoons on Poplar Island allows the identification of additional nest predators. Snakes eat turtle eggs (Iverson 1990; Bowen & Janzen 2005) and we have observed Eastern kingsnakes eating terrapin nests since 2006. During 2005, we observed *Triunga semipalmata* (willet) probing terrapin nests and puncturing eggs. *Corvus ossifragus* (fish crows) and *Peromyscus leucopus* (white-footed deer mice) have also been identified eating terrapin eggs. Fish crows accounted for the large increase in predation of marked nests during 2005–2006,

Table 2. Average and standard error of diamondback terrapin clutch size, clutch mass, and egg mass from 2004–2010 on the Poplar Island.

Year	Clutch Size	Clutch mass (g)	Egg mass (g)
2004	13.69 (0.379)	127.55 (4.372)	9.80 (0.110)
2005	13.62 (0.245)	133.11 (2.541)	9.92 (0.087)
2006	13.48 (0.248)	133.28 (2.570)	9.97 (0.081)
2007	13.11 (0.241)	127.4 (2.502)	9.86 (0.086)
2008	12.90 (0.260)	128.0 (2.890)	10.06 (0.092)
2009	13.87 (0.242)	136.8 (2.329)	9.98 (0.091)
2010	13.33 (0.364)	133.1 (3.850)	10.10 (0.198)
2011	14.08 (0.290)	131.5 (2.688)	9.46 (0.142)

Table 3. Number of hatchlings found on Poplar Island for each year of the study and hatchling means of clutch mean carapace length (standard error) and of clutch mean mass (standard error) of terrapin hatchlings caught on Poplar Island from 2002 to 2011.

Year	Number of hatchlings	Mean carapace length (mm)	Mean mass (g)
2002	565	31.28 (0.07)	7.53 (0.04)
2003	387	31.11 (0.20)	7.61 (0.14)
2004	1,337	31.51 (0.10)	7.56 (0.07)
2005	1,526	30.77 (0.14)	7.34 (0.08)
2006	855	30.94 (0.14)	7.34 (0.08)
2007	1,616	31.15 (0.11)	7.53 (0.07)
2008	1,443	30.69 (0.15)	7.27 (0.08)
2009	1,430	30.81 (0.14)	7.33 (0.07)
2010	785	30.22 (0.15)	7.22 (0.10)
2011	1,382	30.15 (0.15)	7.26 (0.09)

Values for 2002 are means and standard errors of all hatchlings captured.

but this predation decreased with the use of hardware cloth laid over the nest after excavation. Crows learn and depredate marked nests (Baker 1978; Yahner & Wright 1985; Rollinson & Brooks 2007) and our conspicuous nest marking technique that we used on Poplar Island queued crows to nests. Predation of unmarked nests by crows was rare and thus our decision to protect our marked nests using hardware cloth. Because crows located nests by watching and following females, crow predation of unmarked nests was considerably lower without identifying flags. Predation by kingsnakes and deer mice increased because these predator populations appear to be increasing on Poplar Island, perhaps facilitated by the succession of vegetation on nesting areas (W. M. Roosenburg 2013, Ohio University, personal observation). Partial predation of nests by kingsnakes and deer mice reduces within-nest survivorship and can kill all eggs in the nest if the predator’s excavation results in exposing the remaining eggs to increased temperatures and dehydration.

We did not detect any abnormal effects on survivorship, egg, and hatchling metrics, or the frequency of hatchling shell anomalies on Poplar Island suggesting that the nesting area substrate is suitable. The nesting areas on Poplar Island were created from sand mined from the site and not from the dredge material that is used to fill and create the cells. However, we

Table 4. Frequency of hatchling terrapin shell scute anomalies on Poplar Island.

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011
Marginals (M)	0.023	0.016	0.027	0.044	0.020	0.020	0.017	0.019	0.017
Vertebrales (V)	0.126	0.042	0.164	0.049	0.064	0.052	0.105	0.149	0.073
Costals (C)	0.013	0.028	0.029	0.001	0.074	0.015	0.013	0.037	0.030
Plastron	0.003	0.001	0.009	0.001	0.019	0.001	0.003	0.000	0.007
M and V	0.031	0.004	0.043	0.011	0.016	0.006	0.014	0.028	0.009
V and C	0.013	0.020	0.031	0.005	0.048	0.008	0.013	0.066	0.029
C and M	0.000	0.004	0.001	0.000	0.014	0.007	0.003	0.001	0.003
C and M and V	0.005	0.007	0.007	0.000	0.021	0.003	0.004	0.010	0.014
Plastron and Carapace	0.000	0.000	0.013	0.001	0.021	0.001	0.005	0.001	0.010
Kyophotic	0.000	0.000	0.000	0.004	0.000	0.001	0.000	0.004	0.000
Totals	0.213	0.123	0.324	0.116	0.296	0.115	0.177	0.316	0.192

Frequencies are within the ranges described for other terrapin populations.

cannot rule out exposure to environmental pathogens during development. Within-nest survivorship for nests that avoided predation on Poplar Island was over 60% and each year ranged from 0 to 100%. Wnek et al. (2013) noticed a decrease in survival of terrapin nests on dredge sediments immediately after deposition, but nest survivorship increased on these materials in the second year of their study. The only other published natural within-nest survivorship for the turtle *Kinosternon baurii* (striped mud turtle), ranged from almost 10 to 80%, depending on the habitat type (Wilson 1998). Egg and hatchling metrics from Poplar Island are comparable to other terrapin populations in Chesapeake Bay. In the Patuxent River of Chesapeake Bay, annual mean terrapin egg size ranged from 9.69 to 10.10 g among years, clutch size varied from 12.7 to 13.7 among years, and total clutch mass varied between 124 and 131 g (Roosenburg & Dunham 1997), which is similar to the metrics for Poplar Island. Hatchlings from Poplar Island also were similar to the Patuxent population where mean hatchling carapace length was 30.2 mm and mean hatchling mass was 7.5 g (Roosenburg unpublished data). These metrics are similar to what we present for Poplar Island (Table 3) and suggest normal reproductive output and development of the hatchling phenotype. Hatchling shell anomalies varied considerably among years and was similar to those observed in two locations in New Jersey (Herlands et al. 2004). Exposure to high incubation temperatures (Herlands et al. 2004) and environmental pathogens during development can increase the frequency of shell anomalies (Bishop et al. 1991; 1994; 1998). We detected a trend of increasing air temperature and decreasing hatchling size among years. The warmest year (2010) had the lowest within-nest survivorship and a high frequency of shell anomalies. These findings hint that temperature may be a more important contributing factor affecting hatchling development than the quality of the incubation substrate. However, the air temperature metrics may not accurately reflect nest temperatures experienced by developing embryos because soil temperatures are a function of soil moisture, incoming solar radiation, slope, and aspect (Roosenburg & Place 1995).

The restoration of Poplar Island altered nesting habitat that is used by diamondback terrapins, and the absence of

mammalian nest predators combined with high within-nest survivorship resulted in high hatchling recruitment. Although the long-term survival of the hatchlings remains to be determined, we have recaptured several hatchlings and in 2012 had our first 2004 hatchling return as an adult to nest on Poplar Island. The movement of sand either through natural processes or by anthropogenic practices such as dredging can thus create nesting habitat for turtles and potentially be a means of population enhancement via restoring the terrestrial–aquatic linkage that is essential for aquatic turtles. This study indicates that projects like Poplar Island can illustrate how to create nesting habitat successfully and rebuild the terrestrial–aquatic linkage that can serve as an effective management tool for restoring turtle populations.

Implications for Practice

- Hardening of shoreline and barriers on the aquatic–terrestrial interface can block access to high-quality nesting sites for aquatic turtles, which should be considered when evaluating the environmental impact of shoreline stabilization strategies.
- Island restoration can restore and create habitat with a terrestrial–aquatic linkage and high nest survival and recruitment. Island building should minimize the hardening of shoreline, and particularly in protected areas build the terrestrial–aquatic interface similar to natural shorelines.
- Nest predator-free islands, whether natural or man-made, can have high recruitment and potentially serve as a population source in the source–sink continuum.
- Avian nest predators can detect nests marked by researchers that may require additional protection but unmarked nests have low avian predation rates.
- Dredge material can be a feasible substrate for island restoration and the creation of turtle habitat, but should be evaluated on a per project basis depending on the source of the material.

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