

DIAMONDBACK TERRAPIN BYCATCH REDUCTION STRATEGIES FOR COMMERCIAL
AND RECREATIONAL BLUE CRAB FISHERIES



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ABSTRACT

Diamondback terrapin (*Malaclemys terrapin*) is considered a keystone species for its influence on community structure of tidal marshes. Terrapins exhibit strong habitat and nest site fidelity, and have relatively small home ranges (< 2 km), so that sub-populations tend to be spatially discrete. Terrapins rely on open water, wetlands, and adjacent uplands at various stages of their life-cycle, so the quality and connectivity of these habitat patches is critical to population persistence. Terrapin is listed in Virginia as a species of "Very High Conservation Need" based on threats due to nest predation and drowning of adults in crab pots. Terrapin population declines, reduced growth, and changes in sex ratios have been directly attributed to bycatch mortality in commercial crab pots. Our overall project goal was to characterize essential terrapin habitats toward development of bycatch reduction strategies for managing commercial and recreational blue crab fisheries. In a pilot study area surrounding the mouth of the York River, Virginia, our approach was to 1) geospatially define suitable terrapin habitat based on natural features, 2) integrate spatial datasets to develop a "Vulnerability Index" of terrapin habitats and define potential resource conflict areas where crab pots correspond to essential terrapin habitat, and 3) conduct terrapin and crab pot counts in habitats with varying suitability to test predictions. Suitable terrapin habitat (full connectivity among habitat metrics) accounted for over 50% of all terrapin observations, and another 45% of observations occurred in areas where only one habitat metric was absent. In 96% of these cases, the absent metric was SAV presence. In contrast, full habitat connectivity was determined for only 5% of areas where terrapins were absent. Within the pilot study area during a two year retrieval program, 2872 derelict pots were removed. Of these, 22% were within shallow waters (≤ 2 m) where terrapins typically reside. Of the suitable terrapin habitat (70km²), 21% (15 km²) was considered vulnerable to crabbing pressures (10% highly and 11% moderately vulnerable). Approximately 15% of the study area was considered to be potential resource conflict areas for terrapin and crabbing. Candidate zones for the targeted application of blue crab fishery management actions to reduce terrapin bycatch include the Severn River, Perrin River, Guinea Marshes, and south of Gwynn Island. The integration of spatial information on terrapin habitat and crabbing pressure in a single framework will allow managers to identify areas where terrapins are most likely to encounter threats and target conservation efforts in those areas. In resource conflict areas, there are several management options that can be used in combination

- 1) Require use of bycatch reduction devices (BRDs) on commercial & recreational crab pots
- 2) Avoid particular habitats (e.g. small tidal creeks) or establish fishing exclusion zones
- 3) Educate – design public education programs to
 - promote the voluntary use of BRDs, and
 - communicate to recreational boaters the ramifications of severing buoy lines of active crab pots
- 4) Promote proper use of gear (e.g. retrieving pots regularly to minimize terrapin mortality).

With further refinement to improve the predictability of terrapin occupancy, the terrapin habitat vulnerability model is transferable to all coastal areas where diamondback terrapins occur and where blue crabs are commercially and recreationally fished—from southern New England to Texas.

BACKGROUND AND RATIONALE

Over the last three decades, the diamondback terrapin (*Malaclemys terrapin*), the only fully estuarine turtle in North America, has experienced population declines throughout its range (Massachusetts to the Gulf Coast of Texas), provoking some states to list the terrapin as threatened, endangered, or a species of special concern. Within the framework of Virginia's comprehensive wildlife conservation strategy, the Virginia Department of Game and Inland Fisheries lists the diamondback terrapin as a Tier II species of "Very High Conservation Need" (VDGIF 2005). The terrapin is considered a keystone species for its influence on community structure of intertidal marshes (Silliman and Bertness 2002). Terrapins exhibit strong habitat fidelity (Roosenburg et al. 1999; Gibbons et al. 2001), nest site fidelity (Mitro 2003), and have relatively small home ranges (typically < 2 km: Sheridan et al. 2010), so that sub-populations tend to be spatially discrete. Further, terrapins rely on open water, intertidal wetlands, and adjacent uplands at various stages of their life-cycle, so the quality and connectivity of these habitat patches is critical to population persistence. Foremost among threats to terrapin populations are losses due to nest predation and adult mortality by drowning in commercial-style crab pots. Nest predation by human subsidized predators, such as raccoons *Procyon lotor* (Prange et al. 2003), is postulated to be high in areas where human land-use patterns increase densities of these predators near terrapin nesting areas. Recent studies have attributed terrapin population declines and changes in sex ratios directly to bycatch mortality in commercial crab pots (Roosenburg et al. 1997; Dorcas et al. 2007; Grosse et al. 2009). In Virginia waters, the blue crab fishery has exerted sufficient selection pressure on the terrapin bycatch to affect the growth rate and average size of female terrapins (Wolak et al. 2010).



One conservation option for terrapins currently being explored in Virginia is the use of bycatch reduction devices (BRDs: Rook et al. 2010; Morris et al. 2011). The overriding concern for terrapin population management is the potential for adverse economic impacts on the blue crab fishery. Recently, Virginia Marine Resources Commission (VMRC), faced with concerns from commercial waterman, supported the shorter-term promotion of voluntary use of BRDs on recreational crab pots (as opposed to imposing mandatory requirements), with the longer-term goal of determining BRD effectiveness in reducing bycatch of terrapins in

crab pots. VMRC also noted the need for better, more comprehensive information on terrapin populations in Virginia and their susceptibility to potential threats such as drowning in commercial crab pots.

For this pilot study, we constructed an ecosystem-based management approach that evaluates potential use-conflict within essential terrapin habitat. This approach will support the eventual

development of necessary bay-wide population estimates and ecosystem-based conservation plans for terrapins, as well as provide blue crab fishery management recommendations. To date, no studies have completed detailed examination of the spatial overlap of the blue crab fishery and diamondback terrapin habitat, but this is an essential step toward the development of bycatch reduction strategies for the commercial and recreational blue crab fishery. In the absence of any reliable determination of factors influencing the potential and realized distribution of terrapins in Virginia waters, regulatory initiatives for the crab fishery cannot be developed effectively. Clearly, approaches that preserve terrapin populations while minimally affecting the commercial and recreational crab fishery are desired.

Our overall goal was to characterize essential terrapin habitats toward development of bycatch reduction strategies for managing commercial and recreational blue crab fisheries.

Available strategies include the use of bycatch reduction devices (BRD), fishing exclusion zones, and conservation measures (protection of essential habitats). Research results support the Virginia Sea Grant (VASG) strategic plan focus of development of sustainable fishing practices and management for commercial and recreational blue crab fisheries, with implications for terrapin populations.

RESEARCH METHODS

We hypothesize that effective and economically feasible bycatch reduction strategies can be determined with spatially explicit ecosystem-based models of essential terrapin habitat and attendant stressors. This research will develop a framework for assessing suitable terrapin habitat in relation to anthropogenic stressors with applications for blue crab fishery management (**Fig.1**).

To accomplish this, our specific objectives were to 1) geospatially define suitable terrapin habitat based on natural features, and 2) quantify anthropogenic stressors that have the potential to influence terrapin mortality within terrapin habitat (cf., Roosenburg 1991), in particular blue crab fishing pressure. Field measurements (e.g. terrapin observations and crab pot counts) were used to refine and evaluate modeled predictions. In future iterations, additional data input can be used to modify initial model components, such as habitat suitability predictions (i.e. adaptive management). The resulting model output (*Habitat Vulnerability Index*) was the integration of model components that define terrapin habitat quality and vulnerability within a spatial framework that can be examined at multiple spatial scales and applied in additional regions. Model applications include recommendations for targeted application of conservation measures or restricted fishing activities.

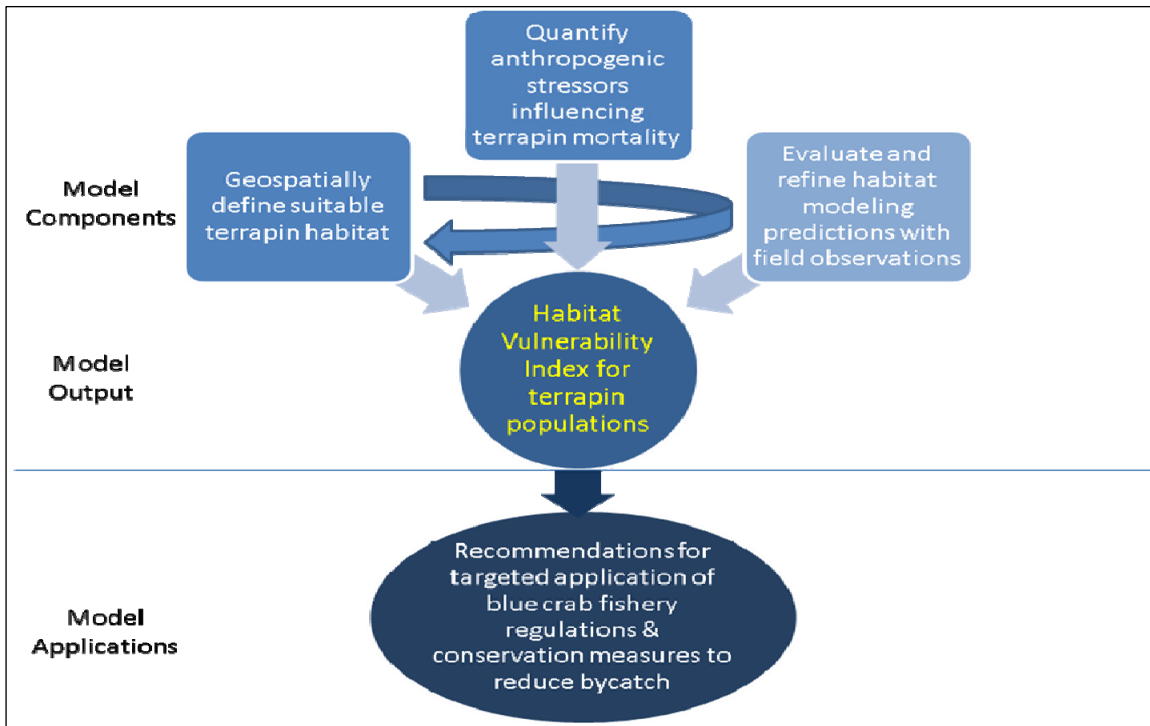


Figure 1. Framework for the development of an ecosystem-based approach for terrapin conservation with fishery management applications

Figure 2.

Pilot Study Area

For the proposed pilot study, we worked with a subset of wetlands in the Chesapeake Bay estuary (**Fig. 2**), chosen for ease of access and for their anticipated range in habitat suitability for terrapins. The Virginia study area encompassed the lower York River and Mobjack Bay and tributaries.








Terrapin Habitat Suitability

Diamondback terrapins live in mesohaline to polyhaline tidal wetlands that provide adequate forage and protection from potential predators. These marshes typically are dominated by *Spartina* grasses. Terrapins consume snails, crabs, bivalves, barnacles, and other invertebrate species they encounter in marshes, in tidal creeks dissecting marshes, and in adjacent subtidal areas that could be sandy bottom, mudflat, or vegetated by seagrass. In addition, terrapins overwinter buried in shallow subtidal mudflats or tidal creeks. Both intertidal marshes and adjacent subtidal areas are used by terrapins throughout their lives.

As a third habitat requirement, mature female terrapins emerge from the water to nest, and prefer sandy substrates above the level of the highest tides (Palmer and Cordes 1988). In the absence of open, sandy beaches, however, terrapins will nest in poorer substrates. Nesting success is mostly dependent on accessibility, the quality of substrate, and the density of nest predators, some of which are subsidized by anthropogenic activity such as residential developed land use.

A number of habitat metrics were used to identify and characterize suitable terrapin habitat in Chesapeake Bay (**Table 1**). First, the distribution of shallow subtidal waters (< 2m depth) was quantified because terrapin predominantly occupy shallow water habitats. Second, the occurrence and distribution of essential shoreline characteristics: mesohaline to polyhaline tidal marshes and potential nesting beaches were quantified to determine preferred terrapin habitat. Third, access to high marsh and high-quality, adjacent upland habitat was estimated on the basis of riparian land use. Forested lands within 10 m of the shore were considered to preclude access to high marsh and upland nesting habitats, and diminish land-water connectivity. Lastly, submerged aquatic vegetation was included as a measure of supplementary feeding habitats that may support growth and survivability of terrapin.

Table 1. Explanatory variables and associated spatial datasets used for the characterization of suitable terrapin habitat in Chesapeake Bay

Variable	Rationale	Metrics	Source
Bathymetry 	Primary critical habitats occur in shallow waters	Waters \leq 2m depth	NOAA - National Ocean Service
Tidal Marsh 	Essential terrapin habitat: mesohaline to polyhaline distribution	Presence of extensive or embayed marshes	Shoreline Inventory (CCRM-VIMS)
Nesting Beach 	Nesting success influenced by nest site suitability	Presence of subaerial unconsolidated sands	Shoreline Inventory (CCRM-VIMS)
Riparian land use 	Access to high marsh, land-water connectivity diminished	Forested land use within 10 m of the shore	Southeast Gap Analysis Project (SEGAP) Land Cover Dataset
Submerged Aquatic Vegetation 	Supplementary feeding habitats	Presence/area of seagrasses	10 year composite of annual VIMS SAV aerial survey

All spatial analyses were performed in ArcMap 9.3.1 and 10 (ESRI). Spatial datasets were initially resampled (land use imagery resolution = 30 m pixels) and standardized to a cell size of 5 m (shore line spatial data set) to preserve enough detail to accurately predict terrapin habitat preferences. We developed scores of habitat suitability ranging from 0 to 1 for each metric in the table above. A combined habitat suitability index was derived by summing metric scores for water depth, shoreline characters (tidal marsh or nesting beach), riparian lands, and submerged aquatic vegetation (HSI scale: 1 – 4).

Bathymetry

Bathymetric data were obtained from the NOAA's National Ocean Service Hydrographic Database maintained by the National Geophysical Data Center. We converted the bathymetric water polygon into a raster dataset (5 m cell size) with bathymetric values. This became our baseline raster grid to which all other data were aligned. We reclassified the bathymetric grid values of 1 – 2 meters depth as suitable for terrapins (score = 1) and all other depths as unsuitable (score = 0).

Shoreline Characteristics: tidal marsh and nesting beach

Beach and tidal marsh shoreline characteristics were extracted from a comprehensive inventory of shoreline condition available for much of Virginia's tidal waters (VIMS-CCRM Shoreline Inventory, Berman and others 2007). The shoreline inventory employs a continuous tiered field shoreline assessment approach, dividing the shorezone into three regions 1) immediate riparian zone, evaluated for land use; 2) bank, evaluated for height, stability, cover, natural protection, beach and marsh type; and 3) shoreline, describing the presence of shoreline structures for shore protection and recreational purposes. Geographically referenced shoreline data are acquired in the field using a pre-programmed data-dictionary in a handheld Trimble GPS GeoExplorer receiver accurate to within 10 cm of true position with extended observations and differential correction. GPS field data are converted to GIS spatial datasets which are corrected to reflect true shoreline geometry (for additional details see Berman and others 2007).

Within the Shoreline Inventory, tidal marsh is currently classed as extensive, embayed or fringe. Older surveys did not distinguish marsh type, such as those in Gloucester County which encompasses the lower York River and Mobjack Bay regions. When available 'extensive' and 'embayed' marsh were considered suitable terrapin habitat while narrow fringe marsh was considered suboptimal feeding habitats. Shoreline reaches delineated as 'beach' are unconsolidated sand shores that are subaerial during mean high water. Shorelines with marsh or beach were designated as suitable terrapin habitat (score = 1), all other shorelines, such as hardened, were scored as unsuitable (score = 0). These features were then individually buffered by a 200 m circular radius to represent the extent that terrapins may travel terrestrially from shore. We unioned all three buffers, preserving their ranking, and converted to a raster snapped to the bathymetry raster. We reclassified the grid values of beach or marsh as suitable for terrapins = 1 and all others as unsuitable = 0. In this manner, the anthropogenic stressors developed lands (high and low intensity) and hardened shorelines were integrated into the index as unsuitable habitat due to their potential negative influence on terrapin nesting through habitat loss/fragmentation and/or enhanced raccoon predation.

Adjacent Uplands

One natural terrestrial feature—forest—that may negatively impact terrapins by precluding access to high marsh and upland nesting habitats, and diminishing land-water connectivity was incorporated into the index. With 5 m raster cell size, we extracted riparian forest information

from the Southeast Gap Analysis Project (SEGAP) Land Cover Dataset (2001). We classified forested lands presence within 10 m of the shoreline as unsuitable terrapin habitat.

Submerged aquatic vegetation (SAV)

Submerged aquatic vegetation was included as a modifying habitat which potentially enhances or supports the growth and survivability of terrapin. Submerged aquatic vegetation was considered to be underwater grasses inclusive of vascular macrophyte families. Annual survey data from the SAV Program at VIMS (1998–2007) were merged to represent a composite of current potential SAV distribution. SAV distribution data were converted to a 5 m cell raster and SAV presence was coded as suitable for terrapins (score = 1) and SAV absence was designated as a score of 0.

Anthropogenic Stressors – Commercial and Recreational crabbing

Derelict blue crab pot density and fishing effort were used as proxies for pot-based mortality that has been attributed to terrapin population declines (e.g., Dorcas et al. 2007). The Marine Debris Location and Removal Program (under the direction of VIMS and VMRC) involved the employment of commercial fishers directly affected by the closure of the winter dredge fishery to locate and remove lost or derelict blue crab pots from Virginia waters in 2008–2012 (http://ccrm.vims.edu/marine_debris_removal/index.html). To date, approximately 30,000 derelict crab pots have been located, removed and bycatch information recorded. Abundance and distribution of derelict pots can be indicative of relative fishing pressure experienced by terrapins. Derelict pots were removed in the winter months when terrapins are in brumation and buried in shallow sub-tidal mud; however, ~38 terrapin mortalities were reported in the first 2 years of the program. Incidental bycatch of terrapins in derelict pots likely increases in spring months when terrapin activity, and potential pot interaction, resume. The pilot study area contains tidal creeks with both high and low derelict pot density for comparative analysis and terrapin captures have been observed in the area.

We converted the derelict pot point data to a raster with 5 m cells. We modeled neighborhood effects of crabbing pressure on habitat suitability using focal functions in ArcGIS. Focal functions (or Neighborhood Statistics), produce a raster result having for each cell, a summary of data that occurs within a defined neighborhood around each cell. In our case we defined our neighborhood as a circle having a radius of 200 m.

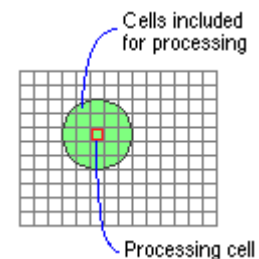


Image Source: Environmental Systems Research Institute (ESRI)

We used a circular moving window analysis with a 200 m radius (remaining consistent with other layers) to calculate the sum per cell. Our values ranged from 0–82 pots. Within suitable terrapin habitat, terrapin in areas with an excess of 3 derelict crab pots were considered highly vulnerable to crab pot capture and mortality on the basis of the average distance between deployed commercial crab pots (150 m), annual crab pot loss rates (20%) (Havens et al. 2008). The average distance between crab pots was divided by two to determine a radius to make a sphere of influence around each crab pot (75 m). We calculated the area of our circular moving window (200 m radius) divided by the area around each crab pot (75 m radius) and multiplied the product by the estimated annual crab pot loss (20%) for a resulting value of 1.4 pots. We then created a density grid (200 m radius) and reclassified crabbing pressure as low (pot density ranging from 1–2 pots) and high (pot density greater than 3; range 3–82 pots).

Within a GIS framework, we placed the composite HSI values into two categories: HSI values of 1–2 were attributed as unsuitable habitat and HSI values of 3–4 were attributed as suitable

habitat. We then classified the vulnerability of terrapins to crabbing pressures in designated suitable terrapin habitat. Terrapin habitat vulnerability was initially depicted as high, moderate or no/low based on the underlying structure of pilot study data. Suitable terrapin habitat associated with crab pot densities *a)* between 1 and 2 pots was considered to have a low vulnerability, and *b)* greater than 3 pots was considered to have high vulnerability to fishing pressures. Crab pot distribution and abundance metrics was used to describe potential resource conflict areas where crab pots correspond to zones of terrapin activity. These zones become candidates for the application of blue crab fishery regulations to reduce terrapin bycatch.

Table 2. Anthropogenic stressors evaluated as influences on terrapin population demographics

Variable	Rationale	Metric	Source
Derelict Crab Pots	Negative impact to terrapin population. Crab pots represent a potential source of mortality, particularly to males and juvenile females	Density of derelict crab pots	VIMS Marine Debris Removal Dataset (2008–2010)
Crab Fishing Effort	Negative impact to terrapin population (as above).	Density of Crab Pots fished. Secondary measure to be used to corroborate derelict crab pot density.	Field survey 2010, 2011 (VIMS & W&M)

Model Validation

Based on the habitat suitability index, we identified a predicted space that represents the potential habitat niche for diamondback terrapins, and also space that explicitly is NOT suitable for terrapins. To test our predictions, we conducted small vessel-based surveys during May – July 2011 in habitats of varying conditions and completed head counts for terrapins. This method has been shown to yield population estimates strongly correlated with independent estimates based on mark and recapture (Harden et al. 2009). Field observations were collected and digitized into a GIS format. We did not plan to assess absolute sizes of populations; however, we were more interested in the relative occupancy of terrapins in different habitat types. This first-order modeling and assessment of terrapin habitat was appropriate for the first phase of the current study. In conjunction with terrapin counts, we enumerated active crab pots (buoy counts and counts of pots on residential piers) focusing on nearshore waters which can be neglected during derelict pot retrieval activities.

For model outcomes assessment, four results were possible: 1) terrapins are present where the habitat suitability index score is high; 2) terrapins are absent where the habitat suitability index score is low; 3) terrapins are present where the habitat suitability index scores are low; 4) terrapins are absent where the habitat suitability index scores are high. Habitats with outcomes 1) and 2) support the predictive model. Habitats with outcome 3) were not anticipated; but their presence would suggest additional model refinement was necessary (e.g., adjustment of index metric scores). Finally, outcome 4) represents habitats where terrapins should occur but do not, an outcome that may be the result of anthropogenic stressors that have reduced habitat quality for terrapins or imprecise habitat suitability indices.

RESULTS

Terrapin Habitat Suitability

- **The location of important coastal habitats for terrapins**

During field-based occupancy surveys, terrapins were present at 175 positions. Since absences were continually noted over the surveyed area, we generated a positional database for terrapin absence (650 positions) and randomly selected 175 points for spatial analysis of habitat associations with absence data. (**Fig. 3**)

Seventy-five percent of the total survey area (94 km²) was classified as suitable terrapin habitat (HSI scores of 3 or 4) and suitable habitat was delineated throughout the study area (i.e., not clustered in a single location). Suitable terrapin habitat (full connectivity among habitat metrics) accounted for over 50% of all terrapin observations, and another 45% of observations occurred in areas where only one habitat metric was absent. In 96% of these cases, the absent metric was SAV presence. In contrast, full habitat connectivity was determined for only 5% of areas where terrapins were absent. Unfortunately, 56% of the areas without terrapins had just one habitat metric absent (predominantly SAV), indicating our initial model is too simplistic.

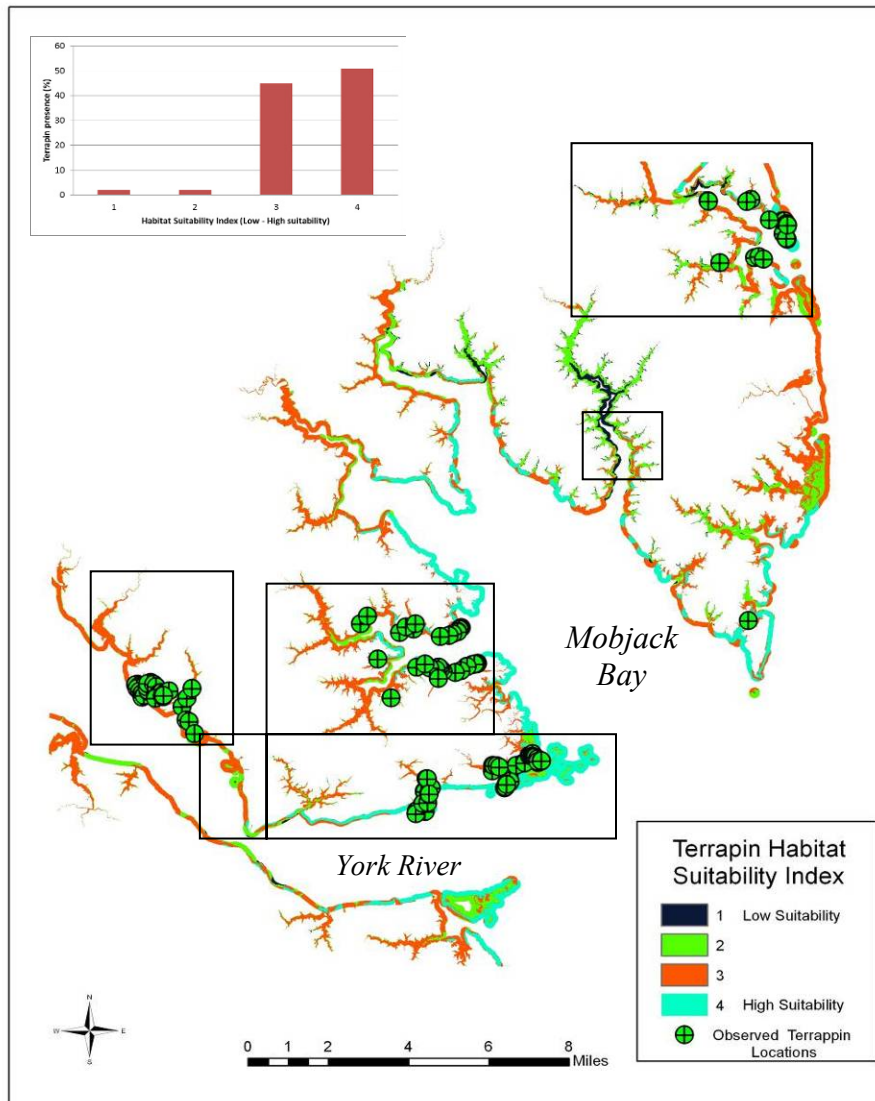


Figure 3. Terrapin field survey locations are enclosed with boxes. Terrapin absence is implied for reaches without terrapin observation symbols. Suitable terrapin habitat was represented by HSI scores of 3–4.

Vulnerability to Commercial and Recreational crabbing

- **The scope of the derelict crab pot issue**

- Within the pilot study area during a two year retrieval program, 2872 derelict pots were removed. Of these, 22% were within shallow waters (≤ 2 m) where terrapins typically reside (**Fig. 4**).
- While the amount of derelict pots generally corresponded to the number of active pots in a given area (**Fig. 5**), limitations of the derelict pot dataset include the lack of comprehensive retrieval within nearshore, shallow waters. Therefore, the absence of derelict pots in a given area does not necessarily signify a lack of fishing pressure. However, the presence of derelict pots indicates not only active fishing pressure in a given area, but also an inherent mortality risk as derelict pots can continue to capture and kill terrapin.

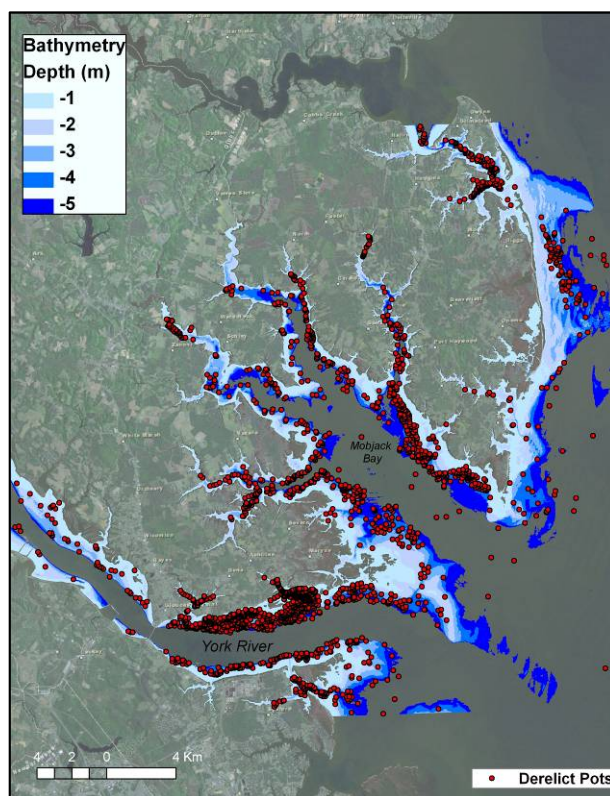


Figure 4. Distribution of derelict crab pots located and retrieved over 2 winters across the depth contours. Derelict pots are continually added to the system with estimates of $\sim 20\%$ of deployed pots lost annually.

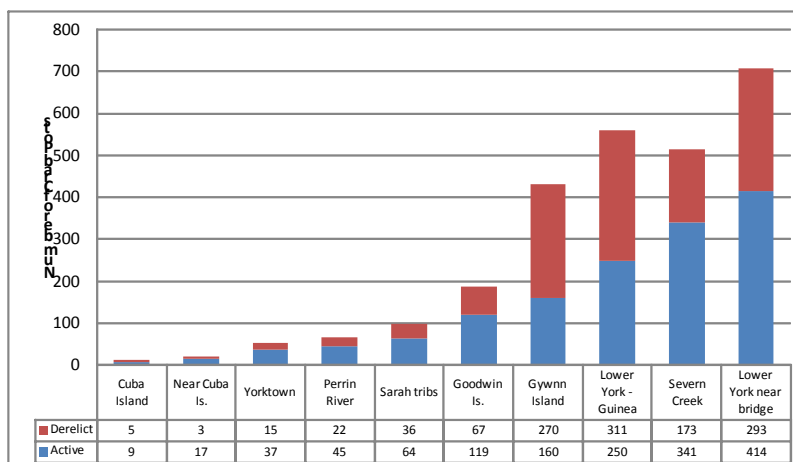


Figure 5. The number of derelict pots generally corresponded to the number of active pots observed at a single point in time. This suggests that derelict pots can be used as a metric for fishing pressure.

- **The total area of coastal shallow water habitat where commercial/recreational crabbing and potential terrapin habitat overlap**
 - 75% of the total survey area (94 km²) was classified as suitable terrapin habitat (HSI scores of 3 or 4)
 - Of the suitable terrapin habitat (70km²), 21% (15 km²) was considered vulnerable to crab fishing pressures (10% highly and 11% moderately vulnerable) (**Table 3, Fig. 6**).

Table 3.

Habitat Vulnerability	Area (km ²)	% total area	% suitable habitat
Unsuitable habitat	23.7	25%	
Suitable habitat, no/low vulnerability (0 pots)	55.3	59%	79%
Suitable habitat, moderate vulnerability (1-2 pots)	7.9	8%	11%
Suitable habitat, high vulnerability (> 3 pots)	6.8	7%	10%
TOTAL SURVEY AREA	93.6		
TOTAL SUITABLE HABITAT WITHIN SURVEY AREA	69.9		

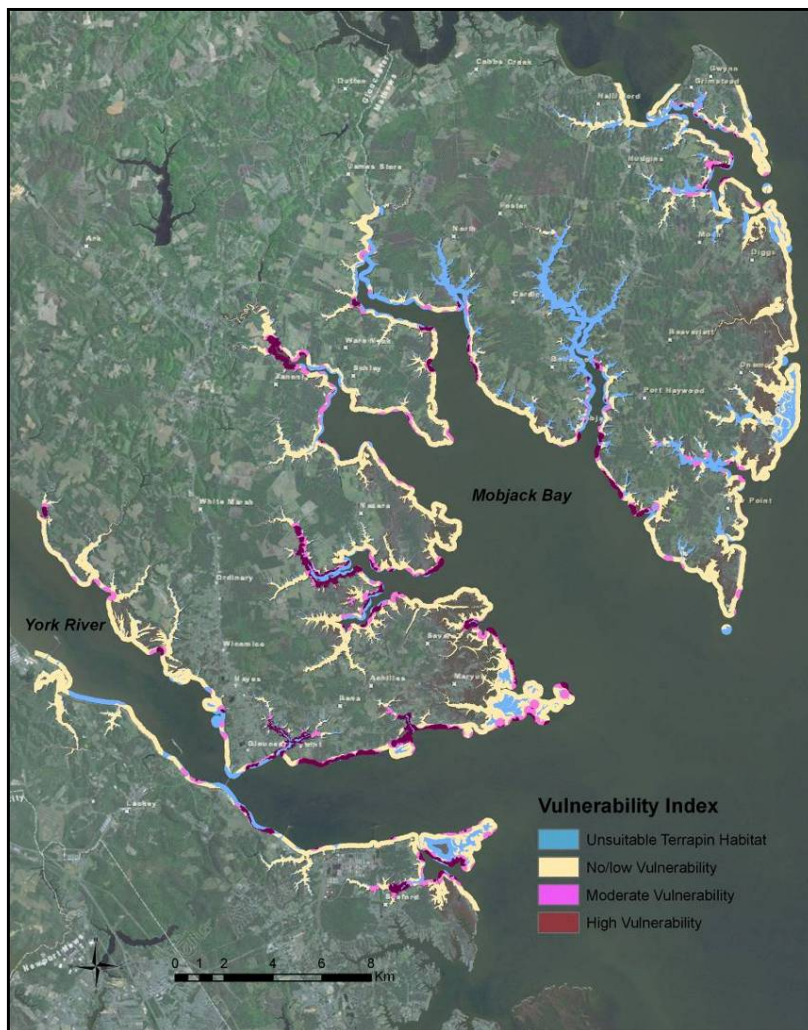


Figure 6. Areas of special concern for terrapin mortality in crab pots are depicted in shades of reds/pinks.

- **The candidate zones for the application of blue crab fishery management actions to reduce terrapin bycatch**
 - Three regions in the pilot survey area were considered areas of special concern due to high crab fishing pressure within essential terrapin habitat: Lower York River (Perrin Creek, Cuba Island, Guinea Marshes), Severn River, and Gwynn Island (Figs. 7–9). Further, terrapin occupancy was verified during field surveys.

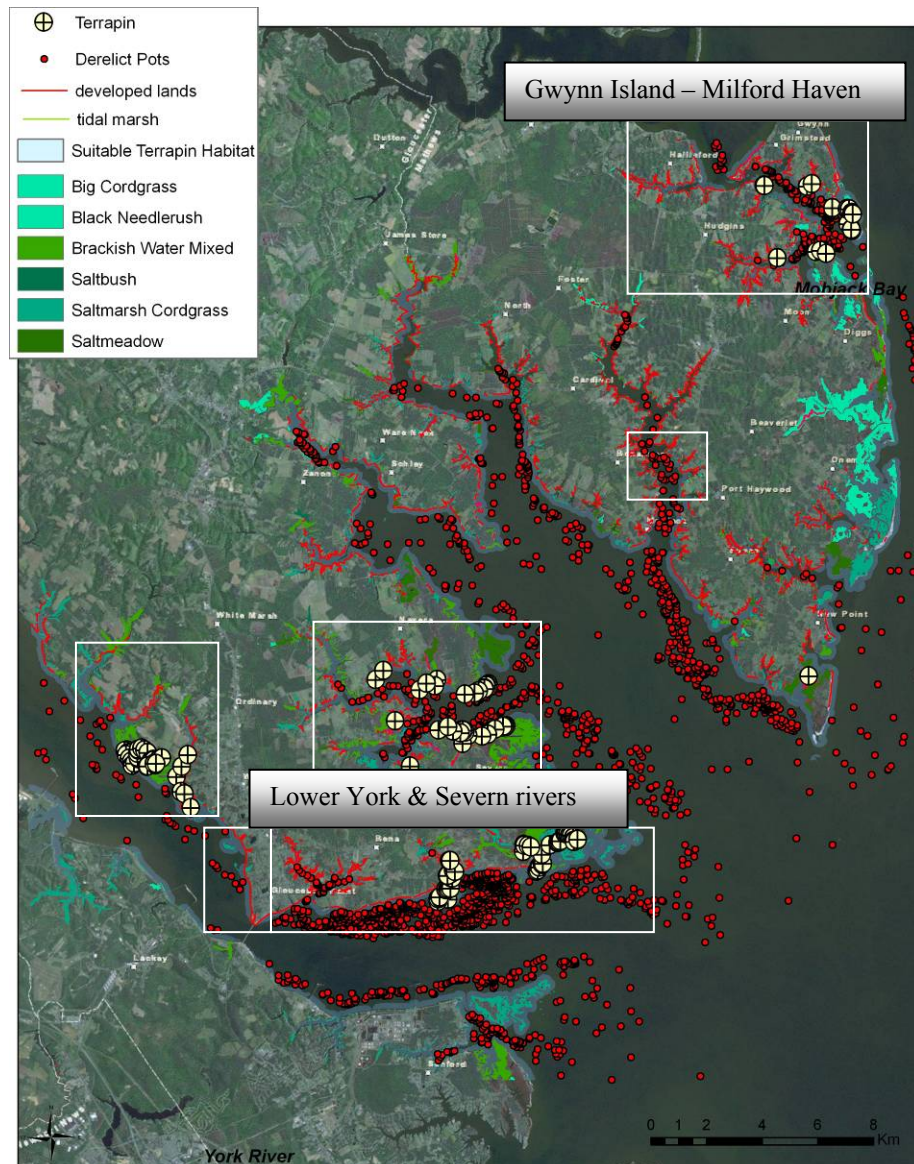


Figure 7. Results of terrapin occurrence, habitat suitability and crab pot distribution allow for the targeting of candidate zones for application of blue crab fishery management actions to reduce terrapin bycatch. Examples of these zones are shown below.

DISCUSSION

The research had dual objectives 1) ecosystem-based planning for terrapin conservation, and 2) terrapin bycatch reduction of blue crab recreational and commercial fisheries while minimizing adverse economic effects. Our approach spatially integrated biological processes and anthropogenic stressors with the goal of ultimately informing the implementation of effective and economically palatable fishery regulations that will conserve terrapin populations.

Terrapin Habitat

In this pilot study comprising ~1% of intertidal shoreline and adjacent open water and upland habitats in the Chesapeake Bay estuary, we geospatially characterized the seascape based on relatively simple environmental factors, including intertidal wetland area, adjacency to open water, adjacency to sub-tidal seagrass, and proximity to potential nesting beach. Our preliminary model defined the connectivity among terrapin habitat patches as presence-absence, and seascapes were scored for the number of links and not the quality of the patches. Suitable terrapin habitat (full connectivity among habitat metrics) accounted for over 50% of all terrapin observations, and another 45% of observations occurred in areas where only one habitat metric was absent. In contrast, full habitat connectivity was determined for only 5% of areas where terrapins were absent. Unfortunately, 50% of the areas without terrapins had just one habitat metric absent, indicating our initial model is too simplistic. While correctly predicting regions of Chesapeake Bay with terrapin population persistence, our preliminary model identified locations with apparent strong connectivity among seascape elements but without terrapins (i.e., a false positive). These Type I errors occur because superimposed upon natural variation in landscape-seascape mosaics are stressors derived primarily from human disturbance. For instance, in select regions marsh extent was not documented in the shoreline inventory and reaches with narrow fringe marsh associated with upland development were erroneously coded as suitable terrapin habitat. In future iterations, we will refine the “environmental factor” model to incorporate terrapin response based on patch quality (e.g. marsh extent), expressing that proportional response either with linear or non-linear functions, as well as develop hierarchical indices that better accommodate potential modifiers such as the presence of persistent seagrass beds.

Blue crab fishery management

Among anthropogenic stressors, the crab fishery in Virginia—via terrapin mortality in commercial and recreational pots (Rook et al. 2010; Morris et al. 2011) and via mortality in derelict pots (Havens et al. 2008)—may exert the greatest impact on terrapin populations. Prior studies of terrapins (Mitro 2003) and other long-lived turtles (Heppell et al. 1996) suggest that survival of pre-reproductive adults are most important to sustaining populations, yet it is those age and size classes that are most susceptible to drowning in crab pots—both active and derelict pots. Our analysis assessed the potential influence of the blue crab fishery on terrapin populations and identified spatially where the fishery should be managed with terrapin conservation in mind. Approximately 15% of the study area was considered to be potential resource conflict areas for terrapin and crabbing. The integration of spatial information on terrapin habitat and crabbing pressure in a single framework will allow managers to identify discrete areas where terrapins are most likely to encounter threats and target conservation efforts in those areas.

A few data limitations influenced the model outcomes. First, there is a likely underrepresentation of derelict pots in small tidal creeks or shallow waters because pot retrieval occurred to a lesser degree in those habitats. Active pots were periodically observed in tidal creeks and shallows

locations where derelict pot surveys did not occur (e.g., Timberneck Creek and Catlett Islands, York River). Therefore, fishing pressure was not comprehensively captured with derelict pot distribution data. Second, shoreline inventory protocols have been modified so that newer inventories report marsh extent (i.e. fringe, extensive, embayed), while less recent surveys did not characterize marsh extent. Gloucester County shoreline inventory was older than the one in Mathews County and does not distinguish marsh extent; therefore, some fringe marsh habitats are inaccurately coded as highly suitable terrapin habitat. For example, in a tidal creek of the Lower York River (Sarah's Creek) terrapin were not observed and designated suitable marsh habitat typically consisted of fringe marsh in front of high residential development. Future model iterations will refine predictions by the inclusion of supplemental marsh datasets and the development of thresholds of marsh extent (e.g. > 30 m width) that accommodate terrapin habitat requirements. Finally, anecdotal evidence suggests that terrapin occupy SAV habitat when available; however, additional research is needed to determine the precise nature of the association (i.e., is terrapin foraging and subsequent growth enhanced within seagrass beds?).

Special areas of concern within the pilot survey area with high crabbing pressure and abundant essential terrapin habitat included Lower York River (Perrin Creek, Cuba Island, Guinea Marshes), Severn River, and Gwynn Island. Model results were verified with terrapin and crab pot field surveys. These areas are candidates for blue crab fishery management measures that support a reduction in terrapin bycatch.

This study sought to balance the conservation of diamondback terrapins while minimizing any economic impact to the blue crab fishery. Delineation of specific resource conflict areas (i.e. terrapin habitat and blue crab fishery) can guide the targeting of discrete fishing pressure relief areas. Fishing pressure relief can be in the form of required use of bycatch reduction devices (BRDs) on recreational and/or commercial pots and fishing exclusion zones. Additional management measures may include public education programs to promote the voluntary use of BRDs, avoidance of particular habitats, proper use of gear (e.g. retrieving pots regularly to minimize terrapin mortality), as well as communicating to recreational boaters the ramifications of severing buoy lines of active crab pots.



ACKNOWLEDGEMENTS

This research was strengthened because of the commendable efforts of 70 watermen to locate and retrieve over 30,000 marine debris items from Virginia waters. Their efforts have greatly enhanced our understanding of marine debris impacts on the Chesapeake Bay, and they have assisted in finding solutions to alleviate the problems associated with derelict fishing gear. Special thanks to Nicolas Jaffe, Rosemary Hatch, Sharon Killeen, and Kory Angstadt for field support.

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APPENDIX I.

SPECIFIC OUTCOMES AND BROADER SOCIETAL BENEFITS

This research brings together information on wetland distribution, adjacent land use, and crabbing activities to generate a comprehensive index of habitat vulnerability for diamondback terrapin populations. By focusing our initial efforts on a discreet subset of Chesapeake Bay tidal wetlands, we were able to create a GIS-based, analytical scheme that was field-tested throughout the entire subset of coastal habitats in the study. Defined highly vulnerable terrapin habitat zones can be targeted for VMRC application of crab fishery regulations (e.g., use of bycatch reduction devices, fishing exclusion zones). Targeting areas for regulation will reduce the potential economic impact to the entire crab fishery.

This SEED project was designed to initiate fundamental research that is both accessible and useful to a diverse group of scientists, managers, policy makers, and the general public. Some immediate outcomes of this effort which are continuing to evolve are described below including the use of pilot study results to support the development of a NSF proposal that would extend the scope and scientific impact of the research.

- **NSF PROPOSAL SUBMITTAL** - Research conducted in this SEED grant supported the development of a NSF proposal “*Quantifying Landscape-Seascape Connectivity and Estuarine Faunal Response Patterns*” that was submitted in January 2012 to the Division of Environmental Biology (DEB) program. On the basis of the pilot study, we proposed to further examine diamondback terrapin response along disturbance gradients (such as land development and crabbing intensity) in the landscape-seascape mosaic and to forecast changes in that mosaic and associated terrapin distribution by evaluating changes in open water, wetland, and adjacent uplands associated with ongoing human development of the coastal zone and with sea level rise.
- **Newsletter** — CCRM-VIMS produces a newsletter, published twice a year and distributed to over 1500 local & state government officials, including all members of the Virginia General Assembly, planners and resource managers in all coastal localities and a variety of NGO’s. This publication is used to present emerging issues and new technical guidance to managers and policy makers. Project information was published in Rivers & Coast Newsletter (Fall 2010, Vol 5, No. 3) – [Derelict Crab Pots in the Chesapeake Bay](#) and findings will be discussed in future editions.
- **Dedicated Project Website** — CCRM has used web-based delivery for a variety of its outreach efforts for many years. Well-established protocols for delivery of both static and interactive materials have been developed, and the availability of new tools and research for managers and planners are routinely posted advertised. Project results and contributions will be highlighted at the following web address:
http://ccrm.vims.edu/research/mapping_surveying/terrapin/index.html
- **Public outreach** — CCRM presents a ‘Bay critter’ each month and discusses ongoing research and issues. Terrapin were highlighted as a Bay critter of the month with a discussion on the effects of derelict pots
http://ccrm.vims.edu/education/bay_life/September2011.html

- **Graduate education** — As part of a course in Advanced GIS for Biologists taught at the College of William & Mary by M. Leu, with guidance from project leads, a student developed terrapin distribution and habitat models with advanced spatial analysis tools. Further, a master's graduate student at College of William & Mary under the guidance of project investigators is using pilot study results as a basis for his thesis work which will be used to refine relationships among habitat predictors and anthropogenic stressors with enhanced terrapin occupancy data.
- **Professional meetings** — Project details were presented by R. Chambers at the biennial Coastal Estuarine Research Federation (CERF) meeting in Nov 2011 and by D.M. Bilkovic at the annual Virginia Sea Grant's Annual Project Participants' Symposium held in Richmond, VA in 2011 and 2012.