COMPOSITE DATASETS FACILITATE LARGE SCALE CONSERVATION

PLANNING: APPLICATION OF A REGIONAL DISTRIBUTION MODEL TO

PROTECT AN IMPERILED TURTLE

By

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ABSTRACT OF THE THESIS

Composite datasets facilitate large scale conservation planning: Application of a regional distribution model to protect an imperiled turtle

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The abundance of existing ecological data allows for many opportunities of data synthesis and derivation of novel research. In wildlife management research, the compilation of data gathered by multiple sources throughout a species' range allows for more comprehensive assessments of species distribution than if individual datasets are used. We demonstrate the utility of using an aggregate occurrence dataset compiled from disparate sources to model the regional distribution of northern diamondback terrapins (*Malaclemys terrapin terrapin*), an imperiled species facing a suite of anthropogenic threats, across their northeastern and mid-Atlantic U.S. range. The model results identified suitable habitat for nesting terrapins throughout the study area and provide a platform from which management questions can be addressed at multiple scales. We provide examples of model applications, including identifying areas for protection, assessing areas where terrapins are at high risk of road and crab pot mortality, and evaluating loss of habitat due to sea-level rise. The techniques and analyses utilized in this study can be readily applied to conservation planning for other wide-ranging species.

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Table of Contents

List of Tables

List of Figures

Introduction

The dynamic nature of ecological processes compels ecologists to collect their own site-specific data rather than rely on pre-existing datasets (Jones et al. 2006, Ellison 2010). Unlike the physical sciences, where subjects are typically contained in controlled settings, ecological phenomena often are studied in the field under fluctuating spatiotemporal contexts, necessitating data specific to target study areas and the species that inhabit them. Particularly for a wide-ranging species occurring across a regional extent, data are often collected by a multitude of interested parties throughout its range. As a result, massive quantities of organismal and environmental data exist in disparate archives throughout the globe (Reichman et al. 2011, Michener and Jones 2012) and represent an untapped resource that may contribute significantly to both theoretical and applied conservation biology.

The abundance of ecological data offers vast opportunities for data synthesis and aggregation, particularly in the context of wildlife management. Synthesis involves data-mining, aggregation and analysis of existing datasets to derive novel products and perspectives (Carpenter et al. 2009, Ellison 2010). Data aggregation is particularly advantageous in wildlife management research, where the compilation of data collected by multiple sources provides a more comprehensive spatial, temporal, and qualitative representation of our current knowledge about a species (Jarnevich et al. 2007, Williams et al. 2007, Dodds et al. 2012). These compiled datasets facilitate the preliminary action in conservation planning of delineating the distribution of a target species (Margules and Pressey 2000). Such assessments are commonly achieved through species distribution modeling (Phillips et al. 2006, Franklin 2009, Elith et al. 2011). In recent years, species distribution studies have shifted away from relying on individually-collected species occurrence data, which can bias results and hinder applicability to larger scale considerations (Diniz-Filho et al. 2010), to the incorporation of integrated datasets obtained from multiple varying sources including historic literature, museum records, government inventories, citizen science efforts, online data repositories, and otherwise unpublished data (Braunisch and Suchant 2008, Acevedo and Real 2011, Peterman et al. 2013, Dickson et al. 2014, Watson et al. 2014, Fujisaki et al. 2015). Using synthesized data broadens the extent at which we consider species and also allows for associated management questions to be considered at multiple scales (Crosier and Stohlgren 2004, Acevedo and Real 2011). This capability is especially important when targeting imperiled species that occur across large, regional scales (Corsi et al. 1999, Barbosa et al. 2003, Acevedo and Real 2011, Watson et al. 2014), where analyses of local populations are not adequate to address the needs of a species across its entire range (Gibson et al. 2004, Boyd et al. 2008, Diniz-Filho et al. 2010).

Synthesis of existing datasets is facilitated by effective data sharing and accessibility, and recent advancements in the development of infrastructure have strengthened these initiatives. The importance of open access and data reuse are exemplified by ongoing funding incentives for developing data archiving processes and synthesis-based ecological research (National Science Foundation, Office of Cyberinfrastructure; National Center for Ecological Analysis and Synthesis, NCEAS *available online*). Technological advancements in computer processors and memory have exponentially improved the ease at which data are stored and distributed, and the creation of online repositories (e.g., DataBasin [www.databasin.org]; DataOne [http://www.dataone.org]; Global Biodiversity Information Facility [http://www.gbif.org]) have made accessing data easier than ever. However, remnants of classic impediments to data sharing and accessibility in ecology persist. Compared to data in other scientific fields, such as DNA sequences in genetics (GenBank, Benson et al. 2005), there has historically been little incentive for ecological data to be archived for public dissemination. The overall lack of journal requirements and monetary incentives also perpetuates a general disinterest in the time-consuming extra step of data archiving and sharing (Zimmerman 2003, Ellison 2010, Reichman et al. 2011). Existing ecological data are thus often underutilized for their potential use in novel research (Crall et al. 2006, Heidorn 2008, Reichman et al. 2011, Hampton et al. 2013). Therefore, it is crucial to exemplify useful applications of synthesized datasets and avoid neglecting these valuable resources.

Here we demonstrate the utility of using an aggregate dataset of species occurrence, compiled from multiple disparate sources, to generate a regional scale distribution model for the imperiled northern diamondback terrapin (*Malaclemys terrapin terrapin*). Northern diamondback terrapins occur across several states along the northeast and mid-Atlantic U.S. coast and face similar threats throughout its range. Conservation efforts of multiple state agencies, non-profit groups, academia and other stakeholders have resulted in the collection of a vast quantity of occurrence data for the species at the local scale. We synthesize these data, examine landscape-scale habitat characteristics influencing nest site selection, and delineate probable nesting distribution using a maximum likelihood species distribution modeling approach. Further, we highlight applications of the model for both local and regional conservation planning and intervention.

Methodology

Model species

The diamondback terrapin (*Malaclemys terrapin*) is an estuarine Emydid turtle occurring along the U.S. Atlantic coastline from Cape Cod, Massachusetts south to the Gulf of Mexico (Roosenburg 1994, Hart and Lee 2006). The only species of turtle in the U.S. to exclusively inhabit brackish water, diamondback terrapins inhabit open bays and tidal creeks where they breed and forage on a variety of mollusks, crustaceans, and submerged aquatic vegetation (Ernst et al. 1994, Tucker et al. 1995). Females emerge from the water for a brief period of time in search of nesting grounds on dry upland beaches. Seven subspecies of diamondback terrapin are currently described; however, recent genetic analyses suggest only four subspecies exist (Hart et al. 2014). The northernmost ranging subspecies, the northern diamondback terrapin (*Malaclemys terrapin terrapin*), occurs along the northeast and mid-Atlantic coast of the U.S. from Cape Cod, Massachusetts south to Cape Hatteras, North Carolina (Ernst et al. 1994). The typical nesting season for this subspecies occurs in June and July (Roosenburg 1991, Feinberg and Burke 2003).

While diamondback terrapins are not federally listed, significant observed mortality combined with limited information on population dynamics have prompted conservation attention and proposals for protective regulations (see Appendix B). Diamondback terrapin populations are threatened by anthropogenic factors across their range. Automobile collisions, drowning in crab pots, nest predation by human-subsidized predators, collisions with recreational watercraft, and loss of nesting habitat due to coastal development are among the prevailing issues (Butler et al. 2006). Vehicle strikes are a significant cause of mortality for gravid females, which frequently encounter roads while accessing nesting habitats that are increasingly fragmented by coastal development (Roosenburg 1994). The selective loss of mature females can have significant population-level impacts on this long-lived species, which experience delayed sexual maturity and high hatchling mortality rate (Aresco 2005, Avissar 2006, Steen et al. 2006). Abandoned commercial crab traps entrap and drown vast numbers of terrapins, which enter the traps and cannot escape, until they are removed from the water (Roosenburg et al. 1997, Wood 1997). Whereas mature females are disproportionately at risk from vehicle strikes, crab pots predominantly threaten smaller males and juvenile females that can more easily enter the traps (Bishop 1983, Wood 1997, Harden and Williard 2012). Predation, predominantly by raccoons (*Procyon lotor*), has been cited for up to 70% of nest mortality in the Patuxent River, Maryland (Roosenburg and Place 1994), and 92% in Jamaica Bay, New York (Feinberg 2004). Predation rate increases with nest density (Roosenburg and Place 1994), which is driven by the diminishing presence of available sites as existing habitat is destroyed, negatively impacting the nest survivorship of these populations. Diamondback terrapins are also affected by the rapid urbanization of estuaries, which has reduced marsh habitat availability and quality (Ner and Burke 2008). Coastal development, particularly the installation of hard structures for shoreline stabilization, prevents terrapins from accessing nesting habitat (Wnek 2010, Roosenburg et al. 2014) and causes individuals to travel farther distances in search of suitable locations from which to access land, potentially reducing fitness due to greater energy expenditure (Winters et al. 2015).

Occurrence data and study area

We obtained diamondback terrapin occurrence data spanning a 75-yr period from the Conserve Wildlife Foundation of New Jersey (CWFNJ), which were gathered from approximately 50 sources including federal and state agencies, non-governmental conservation groups, museums, academic institutions, and private organizations across the Northeast and Mid-Atlantic U.S (see Appendix A). An occurrence is defined as the confirmed sighting of a terrapin found on land or in water. Data span the coasts of Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Maryland, and Virginia, and are consistent with the known range of northern diamondback terrapins. To model the probability of nesting diamondback terrapin occurrence across the landscape, we eliminated points that fell in aquatic land cover types (i.e. bays, tidal creeks) when overlaid with geospatial land use data. Because terrapins only leave the water to nest, we assumed all remaining occurrence points to represent gravid females approaching, utilizing, or leaving nesting areas. We extracted occurrence points collected between 2000-2012 to maximize the accurate reflection of current distribution patterns. We also excluded points collected after 2012 to avoid inconsistencies with environmental data resulting from landscape changes (e.g., flattened dunes, marshland inundation, altered tidal creeks) caused by Superstorm Sandy (Oct 29 - Nov 2, 2012). Environmental data portraying landscapes prior to Superstorm Sandy likely would not accurately reflect habitat conditions selected by diamondback terrapins after the event. To mitigate bias from spatial autocorrelation and prevent double-counting, we spatially rarefied the data (Brown, 2014), removing duplicate points and points that occurred within 30 m of one another. The final dataset consisted of 1,611 occurrence points (Figure 1, see Appendix C).

The spatial extent of this study encompasses all states from which the occurrence data originated, including all but one state (North Carolina) in the known range of northern diamondback terrapins. Specifically, we delineated the study area as all land and water within 15 km of the coastline from Cape Cod, Massachusetts to the Virginia-North Carolina border (approximately 72,910 km^2) (Figure 1). This approach allowed us to include all marshlands accessible to diamondback terrapins via coastal waterways.

Species distribution model

We used maximum entropy modeling (Maxent version 3.3.3k) (Phillips et al. 2006) to predict the probability of occurrence for nesting diamondback terrapins across the study area. Given geographic occurrence points and a set of geospatial environmental descriptors, Maxent builds a predictive model using machine-learning maximum likelihood algorithms to compare environmental conditions at known occurrence locations to areas with unknown occurrence (Elith et al. 2011). Maxent has been applied to an assortment of conservation issues at varying geographic scales (e.g., assessing risk of habitat loss for imperiled species, mapping the potential spread of invasive species, projecting effects of climate change on species distributions, Elith et al., 2011) and is advantageous for its relative ease of use and ability to generate robust results for presence-only input data. Since absence data were not included in the original dataset, nor could true absences be confirmed, we considered occurrence data as presence-only. No bias was assumed in the sampling of occurrence data; therefore, equal probability of occurrence was assumed across the study area (Merow et al. 2013). We applied the Maxent default parameters and settings for the model, which have been shown to perform well for most models (Phillips and Dudík 2008).

We tested the model using 10-fold cross-validation and evaluated the model using average area under the curve (AUC) scores from the averaged model runs. The AUC value is the sum of the area under the receiver operating curve (ROC) for each model iteration and ranges between 0 and 1; it is interpreted as an indicator of model fit, representing the probability that a presence location is ranked higher than a random background point of unknown presence. Models with an AUC score ≥ 0.7 are considered to have good fit (Phillips and Dudík 2008).

To examine the influence of individual predictors on the model and to ascertain the range of habitat conditions that nesting diamondback terrapins select for, we analyzed the permutation importance and response curve for each predictor. The permutation importance indicates the predictor's explanatory power and is calculated as the drop in AUC resulting from the random permutation of each predictor's values against the model's training points (Phillips 2006). The response curves plot the probability of species presence against all possible values of a predictor without the influence of the other variables. For each response curve, probabilities of presence > 0.5 represent a range of preferred values for that predictor. We applied the 10^{th} percentile training presence threshold to define probabilities of occurrence as either preferred or not preferred habitat (Phillips and Dudík 2008, Rödder et al. 2009, Maslo et al. 2015). This threshold designates that 90% of the data used in fitting the model will be included in determining preferred habitat, accounting for some error inherent in the data (Young et al. 2011).

Environmental data

We generated 7 landscape-scale environmental predictors that likely influence probability of occurrence of nesting diamondback terrapins, using temporally relevant, publicly available spatial datasets (see Appendix D). We obtained land cover data from the National Land Cover Database (Homer et al., 2015) and collapsed them into 23 classifications (Appendix E). Importantly, we separated the original category “open water”, which included all aquatic land use types such as bays and tidal creeks, into two categories, “Atlantic Ocean” and “non-ocean open water”, to distinguish general characteristics such as salinity, tidal movements, and depth. To examine the importance of estuarine emergent wetlands on diamondback terrapin distribution, we calculated the area of estuarine emergent wetland within a 100-m radius using Fragstats (McGarigal et al. 2012). The 100-m neighborhood reflects the areal land coverage that diamondback terrapins would likely encounter after emerging from the water in search of nest sites (Burger and Montevecchi 1975, Roosenburg 1994, Roosenburg and Place 1994). We also calculated the Euclidean distance to the nearest estuarine emergent wetland using ArcMap (ESRI 2014).

We obtained digital elevation models for each state in our study area from the U.S. Geological Survey (USGS) National Elevation Dataset and calculated the slope in percent rise from these elevation data. Elevation and slope have been cited as determinants of suitable diamondback terrapin nesting habitat (Burger and Montevecchi 1975, Palmer and Cordes 1988). Nests must be made at elevations sufficiently above the mean tide line to prevent inundation at high tides (Roosenburg and Place 1994, Butler et al. 2004). Shallow slopes facilitate the digging of nests and mitigates nest erosion and exposure (Burger and Montevecchi 1975).

We obtained shoreline data from the National Oceanic and Atmospheric Administration's Environmental Sensitivity Index maps (NOAA ESI 2014), which classify shorelines based on shoreline composition (e.g., salt- and brackish-water marshes; exposed, solid man-made structures; coarse-grained sand beaches). Shoreline composition represents the accessibility of upland nesting sites to terrapins from the water. Natural shorelines facilitate upland movement across the land-aquatic interface, while hard structures such as bulkheads prevent terrapins from accessing land (Wnek 2010, Roosenburg et al. 2014). We condensed the original NOAA classifications into 8 categories, grouping them based on broader composition categories and likelihood of terrapins successfully crossing them (see Appendix F). For shoreline segments consisting of more than one shoreline type (e.g., a shoreline composed of sand on the seaward front, and rocky shores landward), we first determined whether any of the shoreline compositions were "uncrossable" by terrapins (i.e. hard man-made structures, hard natural structures, or scarps and steep slopes in sand) and if so, we reclassified the segment as a singular shoreline of its respective "uncrossable" attribute. For example, a shoreline classified as "fine-grained sand/ sheltered riprap / salt-water marsh" would be reclassified as simply "sheltered riprap". If none of the multiple shorelines were "uncrossable", we used the landward-most shoreline type because this attribute was most consistently present in the dataset. Since the original data from NOAA is in a line vector format, which has no width, we generated shoreline type zones by expanding the shoreline data perpendicularly by 300 m on either side, enough to capture the maximum distance that diamondback terrapins have been observed to travel from the water to nest sites (Palmer and Cordes 1988, Roosenburg 1994, Feinberg and Burke 2003). An occurrence point falling within a shoreline zone would be assigned the respective shoreline type in the model. Though terrapins may not always travel perpendicularly from the shoreline, we made the simplifying assumption that the nearest straight-line distance from the shoreline represents where an individual left the waterway. We also calculated the Euclidean distance to the nearest shoreline because suitable nesting habitat must be located within reachable distance from open water, but far enough up shore to avoid inundation at high tide (Burger and Montevecchi 1975).

We used ArcMap 10.2.2 (ESRI 2014) to prepare environmental data for spatial modeling at a 30-m resolution. We projected all geospatial data in Albers Equal Area Conic projection (WKID: 102003) and clipped all data layers to the study area extent. For each predictor variable included in the model, we obtained the best available data for our study area and time period.

Results

The Maxent model performed well (Phillips et al. 2006), with a mean AUC of 0.922 (±0.005; Table 1). Probabilities of diamondback terrapin occurrence within suitable habitat ranged from 0.32 to 0.77. Based upon the 10-percentile threshold, there are 332,691 ha of suitable nesting habitat within the study area (Figure 2). Suitable habitat occurred along bay shorelines across the study area, with larger, more contiguous expanses located in areas such as, but not limited to, Wellfleet Harbor and Westport River (Massachusetts); Mount Hope Bay, Point Judith Pond, Nockum Hill Wildlife Refuge, and Quonochontaug Pond (Rhode Island); Little Narragansett Bay, Fishers Island Sound (Connecticut), and much of the Connecticut coast of Long Island Sound; Smithtown Bay, Peconic Bay, Shinnecock Bay, and Jamaica Bay (New York); Arthur Kill, Navesink River, Shark River, Barnegat Bay, Great Egg Harbor Bay (New Jersey), much of the coastal marshland in southern New Jersey and the New Jersey shore of the Delaware Bay; several tributaries on the eastern side of Chesapeake Bay, Smith Island, and Martin National Wildlife Refuge (Maryland); along the southern shore of Potomac River, Ingram Bay, Rappahannock River, and marshlands along the northern coast of Virginia Beach (Virginia).

Distance to estuarine emergent wetland and distance to shoreline were the most important predictors of nesting terrapin occurrence, followed by land cover, elevation, area of estuarine emergent wetland within 100-m radius, and shoreline type (Table 1).

In addition to the overall explanatory power of each predictor, the response curves impart preferred metrics for terrapin nesting habitat relative to values within each predictor (Figure 3). Suitable nesting habitat is most likely to be found within 34 m of the nearest estuarine emergent wetland and within close proximity to the nearest shoreline. Land cover classes of estuarine emergent wetland, unconsolidated shore, and bare land are most preferred as suitable habitat. The remaining land cover types were not strong predictors of diamondback terrapin occurrence. Low-lying areas with elevation between 0 – 2 m and a slope of less than 2.8% gradient rise are preferred by nesting diamondback terrapins. Nest sites are more likely to be chosen where terrapins cross shorelines composed of beaches, marshes, and exposed tidal flats. The model also denoted shorelines of scarps in sand and gravel beaches as indicators of terrapin occurrence; however, the latter is thought to be a result of the model overinflating the importance of this shoreline type due to its extreme rarity in the landscape. Shoreline types of hard man-made structures and hard natural structures were not strong predictors of nesting terrapin occurrence. Area of estuarine emergent wetland within a 100-m radius produced no preferred conditions, with suitable nesting habitat likely to occur across a wide range of 0.2 – 2.8 ha.

Discussion

The analyses presented here demonstrate the utility of synthesizing disparate datasets for the conservation planning of managed species. Using data compiled from multiple sources throughout its range, we have generated a regional scale distribution model examining probability of occurrence for nesting northern diamondback terrapins. The model results highlight insights into landscape-scale nest-site selection factors for this imperiled species. Additionally, we provide a platform from which management questions can be addressed at multiple scales, a necessary provision for effective conservation (Ricklefs 1987, Levin 1992).

The model results reflect much of what is known about diamondback terrapin nesting habitat preferences, including their habitat fidelity to estuarine marshland (Isdell et al. 2015) and usage of open, sandy areas as nest sites (Burger and Montevecchi 1975, Roosenburg 1991, Mitchell and Walls 2013). The wide range of preferred area of estuarine emergent wetland within a 100-m radius, coupled with this variable's low predictive power, suggest that diamondback terrapins are less selective about the degree of marshland coverage while searching for potential nesting areas. Rather, proximity to marsh appears to be the more critical factor, as diamondback terrapins have been found to mostly travel short distances from the water to their nest sites (Burger and Montevecchi 1975, Roosenburg 1994, Roosenburg and Place 1994). Grassland/herbaceous land and developed areas were among land cover types that were not strong predictors of suitable habitat. These areas are still utilized by nesting terrapins and represent ecological traps and sinks; in some areas, nesting terrapins are attracted to road embankments, which mimic the elevated, sandy terrain of natural nesting habitat (Szerlag and McRobert 2006), while overall coastal urbanization and habitat loss additionally pushes terrapins to nest in grassy or sandy patches within developed areas. In these areas, adult terrapins and hatchlings alike are subject to increased vehicle mortality and predation rates consequent to increased presence of human-subsidized predators such as raccoons (Roosenburg 1994, Roosenburg and Place 1994, Schlaepfer et al. 2002).

Elevation and slope reflected low predictive power in the model, consistent with the variability of these factors in nesting locations throughout the northeast and mid-Atlantic U.S. (Burger and Montevecchi 1975, Roosenburg 1994, Roosenburg and Place 1994). Roadsides, construction areas, and residential areas, where terrapins may inexplicably nest, also vary in elevation (Wood and Herlands 1997, Szerlag-Egger and McRobert 2007, Wnek 2010, Moss 2015). The preference for shallow slopes, which facilitate the digging of nests and mitigate nest erosion and exposure, is consistent with the literature; however, the model suggests that shallower slopes of < 2% rise are preferred compared to the average slope of 12% rise found in Burger & Montevecchi's (1975) study. Elevation and slope are likely to be more significant determinants at the site level scale of local populations.

Model results for shoreline type mirrored the importance of natural land-aquatic linkages that facilitate upland movement from the water (Wnek 2010, Roosenburg et al. 2014, Isdell et al. 2015), as well as the negative impacts of man-made structures, including bulkheads, riprap, and docks, which act as barriers preventing terrapins from accessing nest sites (Wnek 2010, Roosenburg et al. 2014). The shoreline type of scarps in sand was the strongest predictor of nesting terrapin occurrence; however, true scarps are not crossable by terrapins. When examined, 2% of the occurrence points fell within this shoreline type zone, and within the study area, scarps made up 1.3% of all shoreline types. Terrapins are indeed capable of nesting on the other side of fragmented sections of scarps and other "uncrossable" barriers by accessing these areas from nearby crossable shorelines, such as beach or marsh; if accessible, these areas can also exhibit traits of suitable habitat in the other nest-site selection factors. The model's designation of scarps in sand as the most preferred shoreline type relative to other types is thus appropriate. The model also denoted shorelines of gravel beaches as a relatively good predictor of occurrence; however, when examined, no occurrences fell within this shoreline zone, and gravel beaches made up only 0.5% of all shoreline types within the study area. Due to its extreme rarity in the landscape, the model's designation of gravel beaches as a predictor of suitable habitat was likely overinflated.

This model can become a useful component within the arsenal of management tools for addressing regional conservation of northern diamondback terrapins. Conservation efforts and research for diamondback terrapins are typically conducted at the local scale (Gibbons et al. 2001, Feinberg and Burke 2003, Szerlag and McRobert 2006, Crawford et al. 2013), and while these actions likely are beneficial to local populations, the large scale distribution of diamondback terrapins and their wide dispersal capabilities require consideration of population impacts at multiple scales (Poiani et al. 2000). Though diamondback terrapins typically have small home ranges within their populations (Roosenburg 1991, Spivey 1993, Gibbons et al. 2001, Butler 2002, Sheridan et al. 2010), evidence of their wide-ranging dispersal capabilities, though infrequent, have been documented (Spivey 1993, Sheridan et al. 2010). These collective traits are characteristic of metapopulations (Smith and Green 2005), which, coupled with likely population fragmentation driven by coastal development, necessitate population assessments at regional extents. Though large-scale assessments of Chelonian species distribution have been conducted before, they focus primarily on overall species richness and do not incorporate diverse geomorphological habitat factors into the analysis (Buhlmann et al. 2009, Ihlow et al. 2012). Our model serves as a foundation from which conservation questions can be asked and management actions can be developed at multiple levels of scale (e.g., county, state, regional). We provide the following example case studies of topics that can be investigated using this model: evaluation of priority areas for conservation, threat assessments of anthropogenic stressors, and the evaluation of the effects of sea level rise.

Case Study 1: Establishing areas for restoration and protection

Protection and restoration of existing habitat and the creation of new habitat for imperiled species hinge on the management practitioner's ability to identify prospective areas in the landscape. Candidate areas for diamondback terrapins must support habitat features that drive nest site selection. Diamondback terrapins have been shown to successfully detect and utilize newly-created and restored nesting habitat (Roosenburg et al. 2014), which bodes well for management plans that seek to attract terrapins from threatened populations both within and beyond local systems.

Here we identify target areas for protection in Massachusetts and Rhode Island by applying a threshold to the species distribution model, converting the continuous surface of probabilities of occurrence to a binary map delineating suitable habitat. The threshold value is user-defined and can vary based on management objectives and logistical constraints. For this case study, we first apply the 10th percentile training presence threshold (Phillips and Dudík 2008, Rödder et al. 2009, Maslo et al. 2015) of 0.32. Using this threshold, approximately 9,200 ha of suitable habitat are identified in Rhode Island, and approximately 23,000 ha are identified in Massachusetts (Figures 4a and 4b). These areal extents may be appropriate for a smaller state such as Rhode Island to consider for conservation planning, but impractical for larger territories such as Massachusetts. With a larger area of interest in question, management practitioners may only wish to protect habitats where nesting is almost certain, and thus choose a higher threshold probability to limit the expanse of candidate areas for evaluation. Thus, we apply a threshold of 0.5 to the species distribution model, and identify approximately 10,800 ha of highly-suitable habitat in Massachusetts (Figure 4c). This extent is likely more feasible for management consideration.

Case Study 2: Target areas for abandoned crab pot removal

Bycatch mortality in commercial crab pots is believed to be the cause of both population declines and reduced growth, (Hoyle and Gibbons 2000, Gibbons et al. 2001, Wolak et al. 2010), as well as female-biased populations in areas with prevalent crabbing activity (Dorcas et al. 2007). Derelict or abandoned crab pots, also known as "ghost pots", continuously attract and entrap terrapins (Bishop 1983, Roosenburg 1991, Roosenburg et al. 1997, Wood 1997). Bycatch reduction devices fitted in the openings of crab pots can be effective in reducing the number of terrapins caught (Cuevas et al. 2000, Butler and Heinrich 2007); however, juvenile females and the majority of all male terrapins are still small enough to fit through such devices (Bishop 1983, Roosenburg et al. 1997). The removal of derelict crab traps from waters occupied by diamondback terrapins is thus critical for reducing bycatch mortality.

The species distribution model we generated can be used to prioritize areas for abandoned crab pot search and retrieval, and for consideration of seasonal crabbing bans. In Figure 6, areas where terrapins are most likely to encounter crab traps are highlighted by overlaying the map of suitable habitat with bathymetry of the Chesapeake Bay. Entrapped diamondback terrapins are most frequently found in crab pots occurring in shallow waters ≤ 2 m in depth (Bilkovic et al. 2014), where abandoned traps often end up due to tidal action (Bishop 1983). Waters frequented by gravid terrapins are of particular concern.

Case Study 3: Protection against vehicle collisions

In areas closed to crabbing activity, vehicle strikes are the most detrimental anthropogenic factor affecting diamondback terrapin populations (Avissar 2006). In developed coastal areas, gravid females often must cross roads to reach nesting grounds and are subject to high rates of mortality (Wood and Herlands 1997, Szerlag and McRobert 2006, Crawford et al. 2015). In addition, the selective removal of mature females from the population by vehicle strikes is thought to skew population makeup towards a male bias and is responsible for overall population declines (Avissar 2006, Steen et al. 2006). Management actions to mitigate road mortality include installing fences to prevent terrapins from entering roads; implementing speed limit reductions using signs or speed bumps; and closing roads to vehicular traffic during the nesting season (Aresco 2005). Identifying areas where terrapins are at greatest risk of encountering roads has been recommended as an important precursor for management action (Beaudry et al. 2010, Crawford et al. 2013). Suitable nesting areas defined by the regional distribution model can be overlaid with road data to identify areas where female terrapins are likely to encounter roads (Figure 7). Roads that intersect suitable nesting habitats can be selected for management actions.

Case Study 4: Effect of sea level rise on habitat

Sea level rise is a consequence of climate change that is expected to threaten biodiversity on a global scale (Galbraith et al. 2005, Menon et al. 2010). Coastal wetlands and the species that depend on these areas are at particular risk, with the inundation of low-lying marsh habitat resulting in the loss of foraging and nesting habitats (Najjar et al. 2000, Baker et al. 2006). Intertidal zones become permanently inundated, and the natural landward shift of habitat is blocked by man-made shoreline stabilization structures (Najjar et al. 2000).

The regional distribution model can be used in conjunction with projected sea level rise maps to identify and quantify diamondback terrapin habitat at greatest risk of loss (Figure 8). For example, over half of the suitable habitat in Buzzards Bay, MA is lost under just a 0.3-m sea level increase; nearly 80% is lost under a 1.8-m sea level rise scenario. In addition to visualizing where current nesting habitat are directly impacted under sea level rise, the map can be used to identify suitable habitat to which terrapins may disperse to in response to the loss of nesting habitat. These "refuge" areas outside the projected at-risk zones can be proactively established as protection areas.

Conclusions

Ecology is a field abundant in data. Information about ecological phenomena such as species occurrence exist in disparate datasets throughout the world, representing vast opportunities for synthesis and the development of useful conservation tools. The use of compiled datasets facilitates the ability to investigate broader scale implications of familiar wildlife management issues. The demonstration of useful conservation products contributes to the promising trend in ecological research of open data sharing and development of novel research using existing datasets. This study, and others like it, exemplifies management solutions which would not be possible without the use of existing data.

For effective conservation, it is necessary to implement management actions at multiple scales (Ricklefs 1987, Levin 1992). Boyd et al. (2008) found that 18% of threatened species require a combination of site-level and large scale protection for effective conservation; these species, such as diamondback terrapins, are considered "area-demanding" and often require the protection of not only specific nesting sites (i.e. beaches) but also larger expanses of habitat (i.e. bays and tidal creeks) to support all stages in their life cycle. This goal may only be feasible with large-scale assessments of species distribution, as well as the coordination of conservation efforts across conventional administrative boundaries, which are necessary to effectively implement and regulate policies (Crall et al. 2006, Dickson et al. 2014). The regional model facilitates both these needs by providing a standardized assessment of northern diamondback terrapin nesting habitat throughout its range, which can be applied to management needs across jurisdictions.

The products derived from the synthesis of existing data enable identification of data gaps within the current knowledge base. The lack of confirmed terrapin occurrences in areas predicted suitable by the model are candidate locations for field investigations that would allow for refined delineations of preferred habitat. Additional ground-truthing efforts would serve to provide site-level explanations for these unoccupied areas. The regional model also allows for the evaluation of poorly documented areas, which may have fallen outside the jurisdictions of individual conservation efforts.

There are many complex biological and abiotic processes that cannot be definitively represented in a model space. Limitations arise from the lack of available environmental datasets required to appropriately illustrate all factors influencing habitat selection. For example, one aspect of human impact on terrapin nesting habitat was characterized in the model as a shoreline type of uncrossable man-made structures, but anthropogenic effects on any species sharing human domains are obviously farther reaching. The availability of additional proxies for human disturbance will likely improve model accuracy and applicability. Model resolution also generalizes heterogeneous landscape features within each unit of analysis, inevitably resulting in loss of detail. Model results delineating nest-site selection factors should not be interpreted as absolute descriptors of habitat quality, and are meant to complement existing and future research conducted on similar premises.

Although specific to the nest-site selection factors of northern diamondback terrapins, the analysis techniques used for this model can be applied to the habitat requirements of other imperiled species, particularly those which are wide-ranging and which may currently lack assessments that allow for evaluations at larger scales.

Tables

Table 1: Maxent model results for northern diamondback terrapins (*Malaclemys terrapin terrapin*) across the U.S. Atlantic Coast from Massachusetts to Virginia, (N = 1,611) including the area under the curve (AUC) and the permutation importance (%) of the model predictors.

N	AUC	Model predictor	Permutation importance (%)
1,611	0.922 (±0.005)		
		Distance to estuarine emergent wetland	41.4
		Distance to shoreline	37.5
		Land cover	14.7
		Elevation	2.8
		Area of estuarine emergent wetland within 100-m radius	1.6
		Shoreline type	1.0
		Slope	1.0

Figures

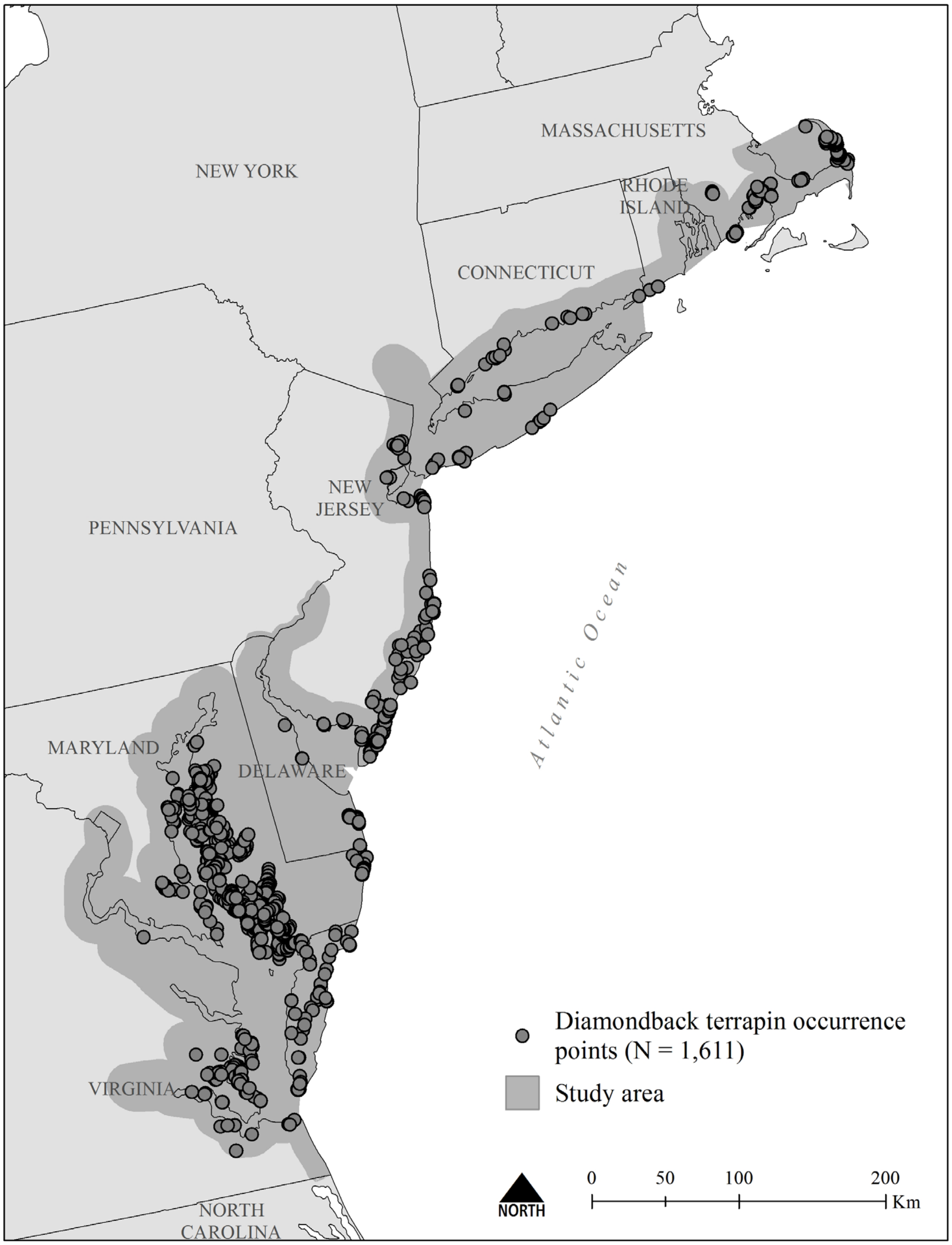


Figure 1: Northern diamondback terrapin (*Malaclemys terrapin terrapin*) occurrence points (N = 1,611) plotted on the study area.

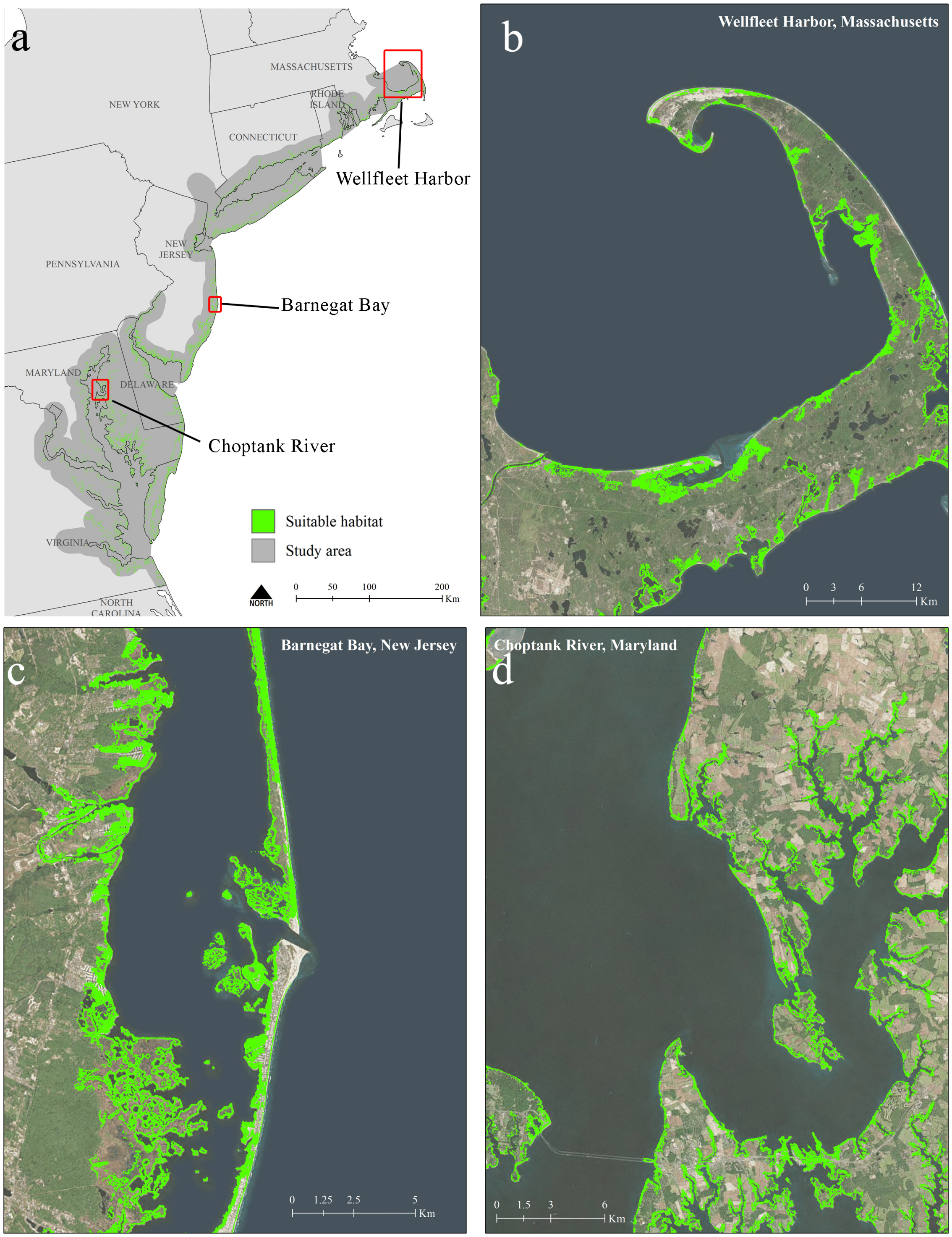


Figure 2 Suitable habitat for northern diamondback terrapins (*Malaclemys terrapin terrapin*), showing areas where probabilities of occurrence exceed the 10th percentile training presence threshold in the study area (a), and in sample detail locations of

Wellfleet Harbor, Massachusetts (b), Barnegat Bay, New Jersey (c), and Choptank River, Maryland (d).

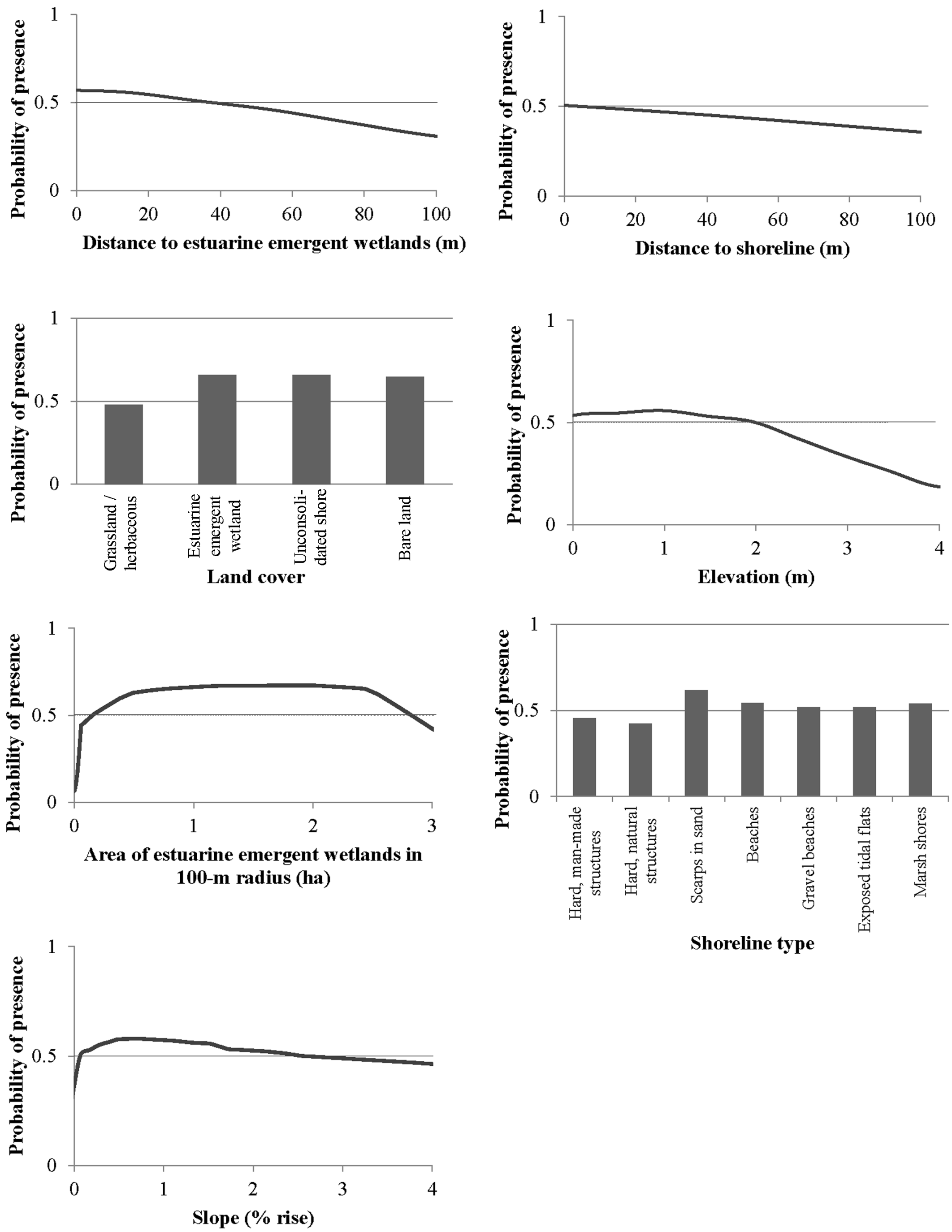


Figure 3: The response curve for each model predictor plots probability of species presence (y-axis) against predictor values. Graphs were generated as part of the Maxent output. Values reflecting probability of presence > 0.5 represent habitat

conditions that are preferred by nesting northern diamondback terrapins (*Malaclemys terrapin terrapin*).

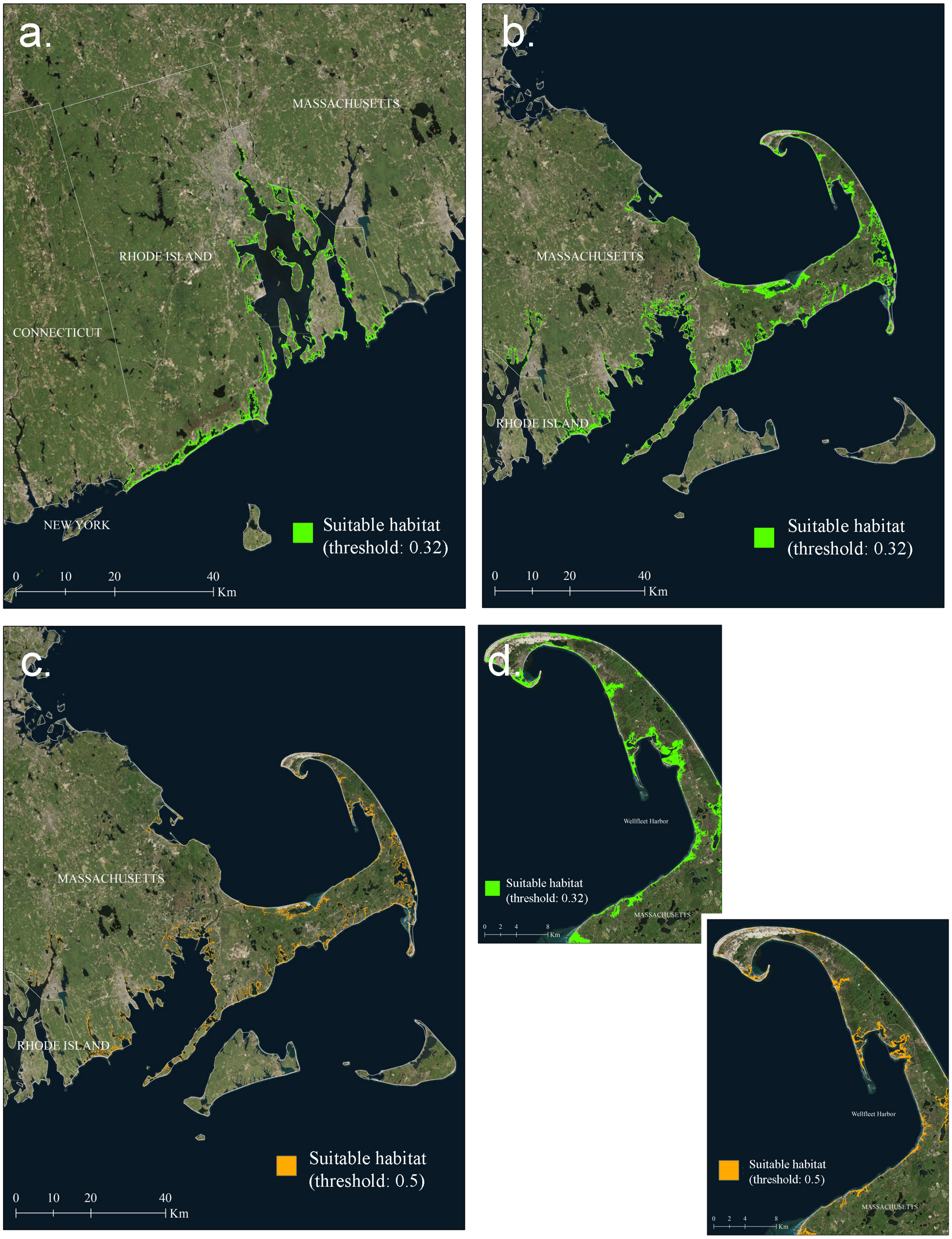


Figure 4: User-defined threshold values can be applied to the species distribution model to designate candidate areas for protection. Threshold values can vary depending on management goals and logistical constraints such as the size of the

area of interest. Using the 10th percentile training threshold (0.32), ~ 9200 ha are designated as suitable habitat in Rhode Island (a), while ~23,000 ha are designated in Massachusetts (b). These extents may be suitable for a small state such as Rhode Island, but unfeasible for larger management units. Using a threshold of 0.5, ~10,800 ha are designated as highly suitable habitat in Massachusetts (c). Detail of Wellfleet Harbor, MA shows the differences in areal coverage between the applied thresholds (d).

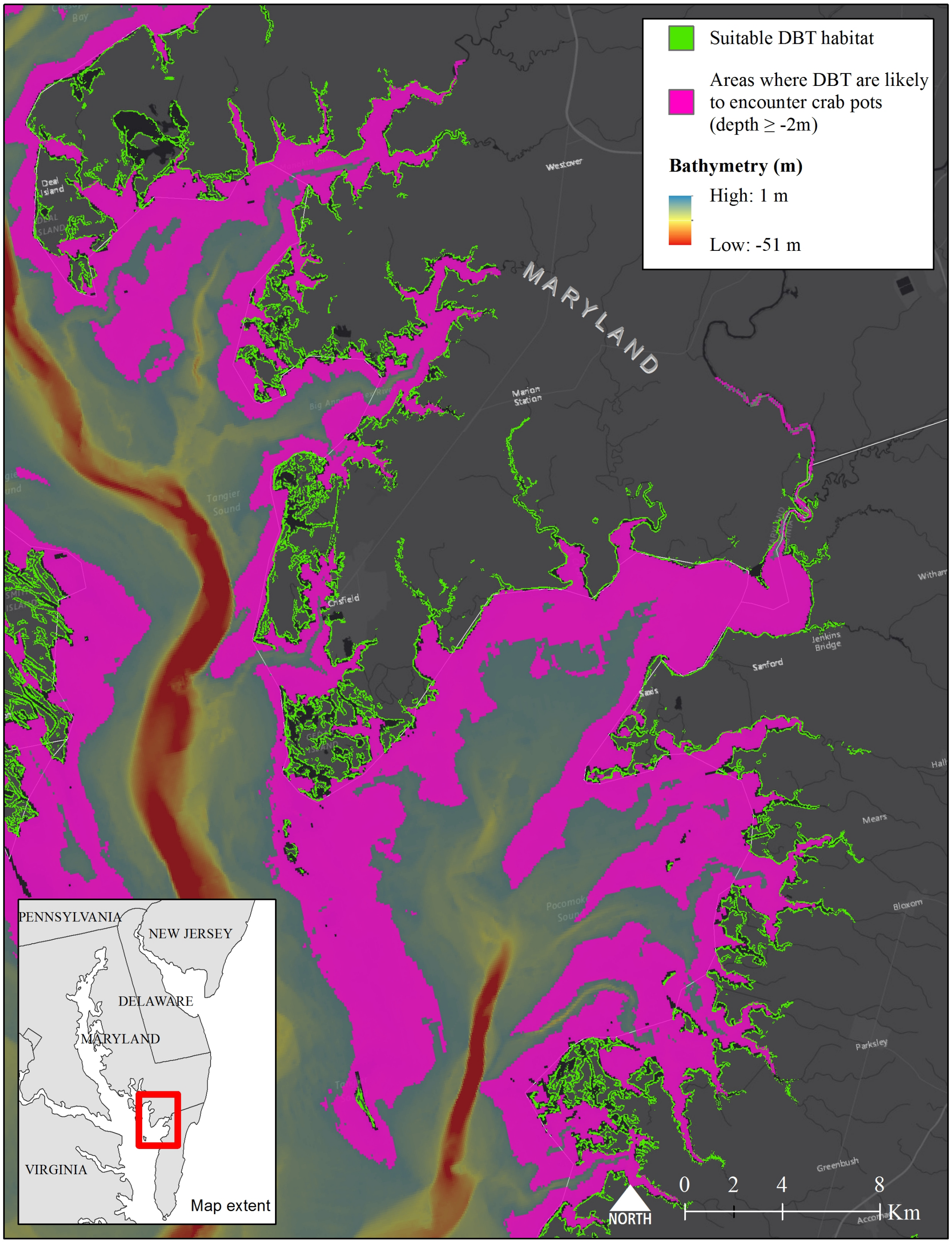
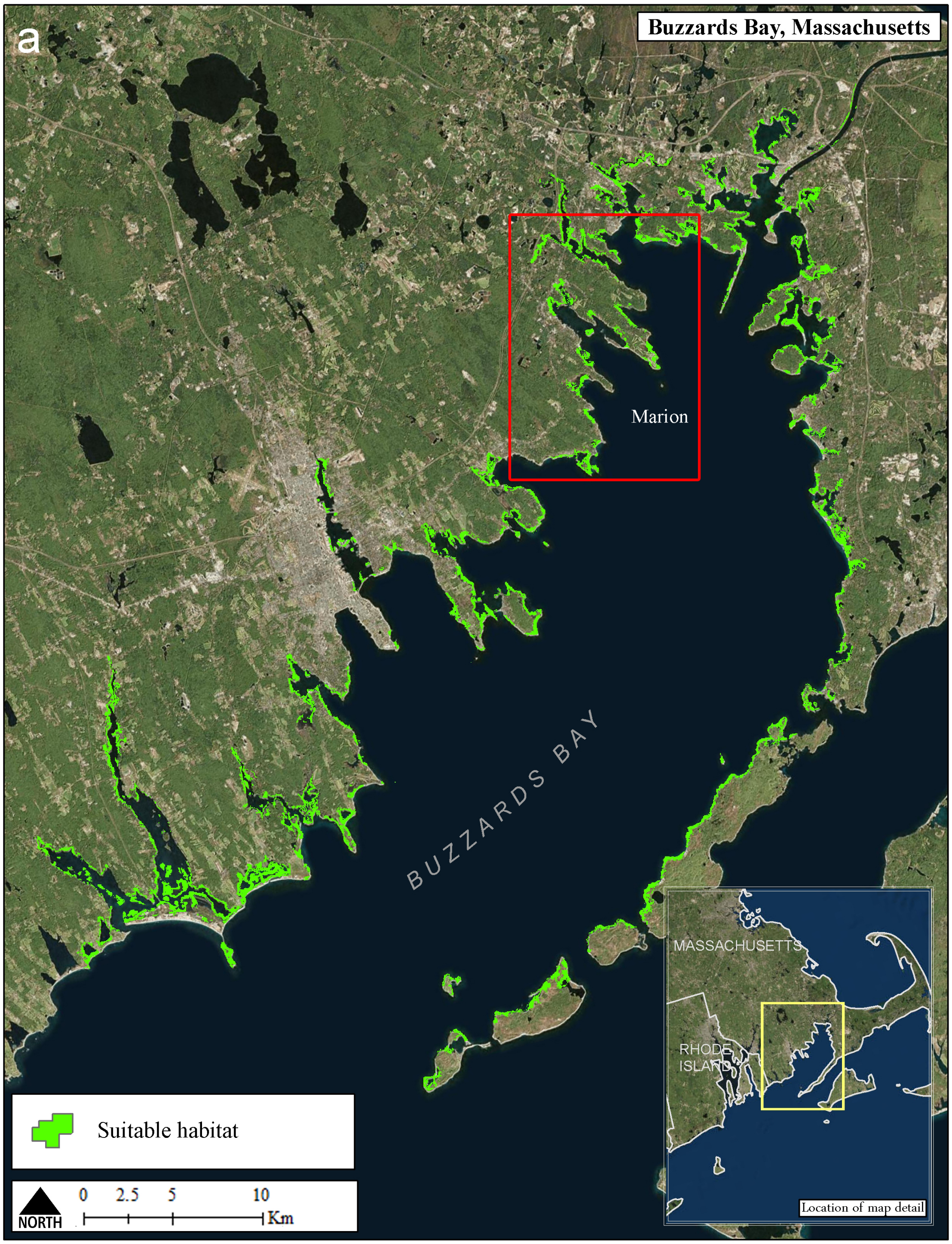


Figure 5: Preliminary overlay analysis to identify candidate areas for abandoned crab pot removal or seasonal crabbing bans in a section of the Chesapeake Bay. Northern diamondback terrapins (*Malaclemys terrapin terrapin*) are more likely to

encounter crab pots in shallow water (≤ 2 m deep, shown in magenta), particularly in waters frequented by gravid and breeding individuals.

Figure 6: Preliminary overlay analysis to identify roads where nesting northern diamondback terrapins (*Malaclemys terrapin terrapin*) are at heightened risk of road mortality. Terrapins accessing nesting areas that are intersected by roadways (roads

in red) are most vulnerable to vehicle strikes. Highly suitable diamondback terrapin habitats are shown in green.



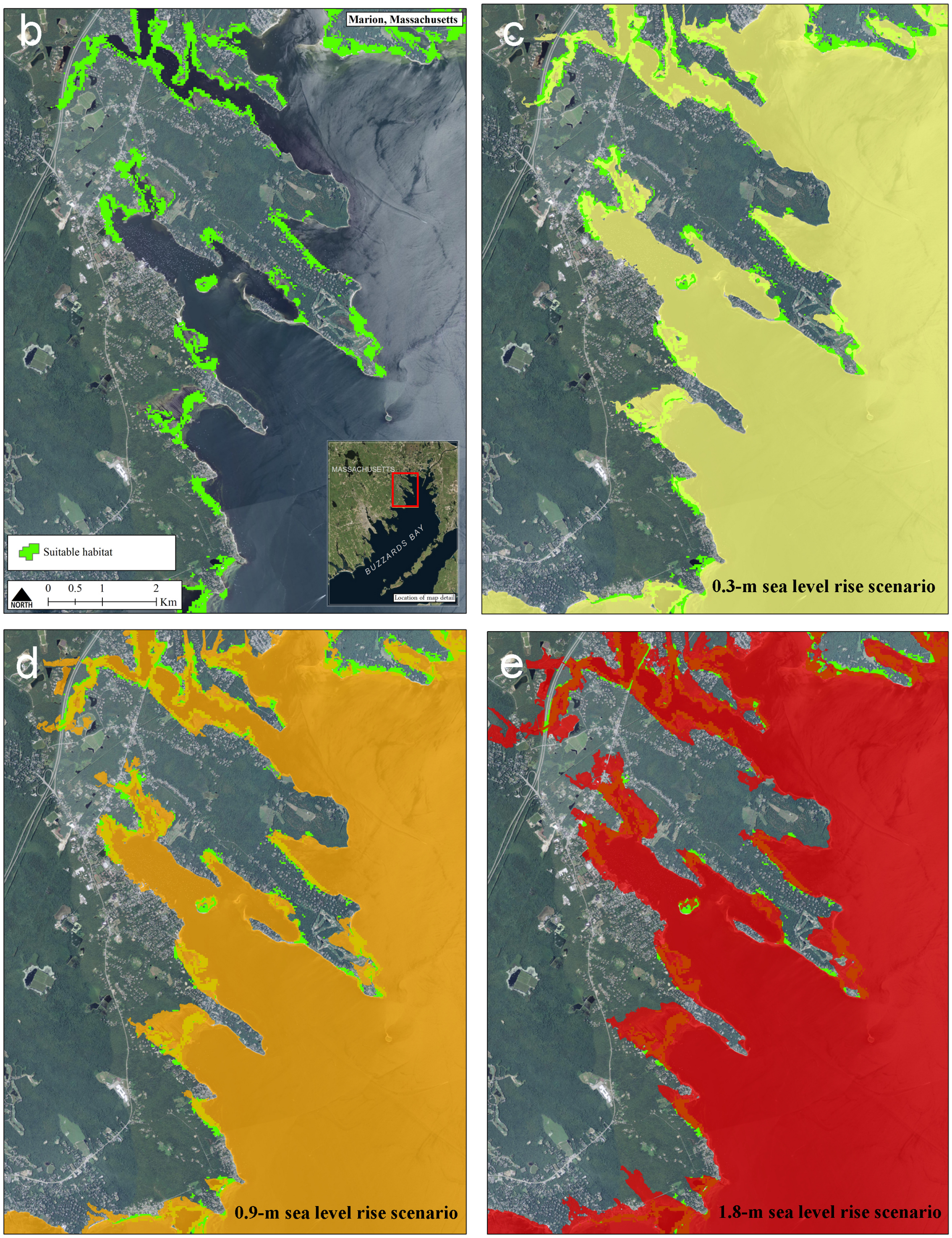


Figure 7: Highly suitable habitat for northern diamondback terrapins (*Malaclemys terrapin terrapin*) in Buzzards Bay, MA, shown in green, total approximately 3965 ha (a). The effects of sea level rise as projected by NOAA's DigitalCoast Sea Level Rise

Viewer on habitat are shown in a close-up of Marion, an estuary within Buzzards Bay (b-e). At just a 0.3-m sea level rise scenario, over half of the suitable habitat is inundated and only 1861 ha of habitat remain (c). A 0.9-m sea level rise leaves 1387 ha habitat remaining (c.), and at a 1.8-m sea level rise nearly 80% of all habitat is inundated, with 876 ha remaining (d).

Supplementary Information

Appendix A: Complete list of data contributors and sources of northern diamondback terrapin (*Malaclemys terrapin terrapin*) occurrence data obtained by Conserve Wildlife Foundation of New Jersey.

State	Data contributor / source(s)
Connecticut	Jenny Dickson, Connecticut Department of Energy and Environmental Protection
	Klemens, M. W., Gruner, H. J., Quinn, D., and Davison, E. in prep. Conservation and management of Connecticut's amphibians and reptiles.
	SoundWaters
Delaware	Holly Niederriter, Delaware Department of Natural Resources and Environmental Control
Massachusetts	Don Lewis, Cape Cod Consultants
	Mark Faherty, Massachusetts Audubon
	Nina Z. Coleman, Massachusetts Audubon
	Massachusetts Heritage Program
Maryland	Paula Henry, USGS Patuxent Wildlife Research Center
	Scott Smith, Maryland Department of Natural Resources
	Marguerite Whilden and Jeff Popp, Terrapin Institute
	William Roosenburg and Phil Allman, Ohio University
New Jersey	New Jersey Department of Environmental Protection, Division of Fish and Wildlife, Endangered & Nongame Species Program
New York	Cook, R. P., D. K. Brotherton, and J. L. Behler. 2010. Inventory of amphibians and reptiles at Fire Island National Seashore / Sagamore Hill National Historic Site / William Floyd Estate, Fire Island National Seashore. Natural Resource Technical Report. NPS/NCBN/NRTR—2010/378; 379; 380. National Park Service, Natural Resource Program Center. Fort Collins, Colorado.
	Kanonik, K. A. and R. L. Burke. 2011. Demographic analysis of the Jamaica Bay diamondback terrapin *Malaclemys terrapin* population, Hudson River, NY. Section V:1-29 pp. In D. J. Yozzo, S. H. Fernald and H.

	Andreyko (eds.), Final reports of the Tibor T. Polgar Fellowship Program, 2009. Hudson River Foundation.
	Morreale, Stephen J. 1992. The status and population ecology of the diamondback terrapin, *Malaclemys terrapin*, in New York.
	Matt Draud, Armstrong Atlantic State University
	Michael Farina, Marine Nature Study Area, Department of Conservation and Waterways, Town of Hempstead, New York
	John Ozard, New York State Department of Environmental Conservation, Division of Fish, Wildlife, and Marine Resources, New York State Amphibian and Reptile Atlas Interim Report 1990-2007
	Russ Burke, Hofstra University
	Laura Francoeur, Port Authority of New York and New Jersey
	Lorri Cramer, New York Turtle and Tortoise Society
	Friends of Flax Pond
Rhode Island	Charlotte Sornborger, Barrington Land Conservation Trust, Inc.
	Schwartz, M.L. 2013. Rhode Island South Shore Diamondback Terrapin Project Final Report 2013. Submitted to the U.S. Fish & Wildlife Service-Coastal Program, December 2013. Rhode Island Natural History Survey, Kingston, R.I.
	University of Rhode Island
Virginia	Susan Watson, Fish and Wildlife Information Services, Virginia Department of Game and Inland Fisheries
	Diane Tulipani, Virginia Institute of Marine Science
	Randy Chambers, College of William and Mary
	Matt Stone, Kutztown University
	Ruth Boettcher, Virginia Department of Game and Inland Fisheries
	Mitchell, J. C. March 2008. Inventory of amphibians and reptiles of George Washington Birthplace National Monument. National Park Service, Northeast Region. Philadelphia, PA. Natural Resources Report NPS/NER/NRTR-2008/110. http://www.nps.gov/nero/science
	Bilkovic, D.M., R. Chambers, M. Leu, T. Russell. 2012. Diamondback terrapin bycatch reduction strategies for

	commercial and recreational blue crab fisheries. Final Report to Virginia Sea Grant, National Oceanic and Atmospheric Administration. Agency Award Number: NA10OAR4170085. Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, Virginia. 21p.
	Robert E. Isdell, Center for Coastal Resources Management, Virginia Institute of Marine Science
Multiple states	Herpnet.org

Appendix B: Current legal conservation status for northern diamondback terrapins (*Malaclemys terrapin terrapin*) in states of the study area and in international conservation listings.

State / International Listing	Status
CT	Species of special concern
DE	SWAP: SGCN[1]; Game
MA	SWAP: SGCN; State Threatened
MD	SWAP: SGCN
NJ	SWAP: SGCN
NY	SWAP: SGCN; Protected Game
RI	SWAP: SGCN; State Endangered
VA	SWAP: SGCN; Protected Game
IUCN	Near threatened
CITES	Appendix II

1: State Wildlife Action Plan: Species of greatest conservation concern

Currently, diamondback terrapins are designated as endangered in Rhode Island and threatened in Massachusetts; New York and Delaware consider them a game species (Table A). They are listed under Appendix II of CITES, following a 2013 proposal to afford the species protection from illegal harvest and trade (Convention on International Trade in Endangered Species of Wild Fauna & Flora 2013). In 2011, the International Union for Conservation of Nature and Natural Resources (IUCN) recommended amending diamondback terrapin status from near threatened to vulnerable.

Appendix C: Number of northern diamondback terrapin (*Malaclemys terrapin terrapin*) occurrence points used in the regional distribution model, by each state in the study area.

State	# of occurrence points
CT	16
DE	15
MA	238
MD	843
NJ	161
NY	51
RI	3
VA	284
Total	1,611

Appendix D: Environmental predictor variables used in the species distribution model for northern diamondback terrapins (*Malaclemys terrapin terrapin*).

Predictor variable	Data source	Time period of data	Description
Land cover	MRLC[1] National Land Cover Database (Homer et al. 2015)	2009-2011	30-m resolution land cover classifica0tions
Distance to estuarine emergent wetland	Derived from land cover data	-	Euclidean distance (m) to nearest estuarine emergent wetland
Area of estuarine emergent wetland	Derived from land cover data	-	Area (ha) of estuarine emergent wetland within a 100-m radius
Elevation	USGS National Elevation Dataset, 2000-2013	2000-2013	30-m resolution digital elevation models
Slope	Derived from elevation data	-	Slope (% rise) calculated from elevation
Shoreline type	NOAA[2] Environmental Sensitivity Index (NOAA, 2014)	1999-2014	Shoreline classifications based on ESI ranking
Distance to shoreline	Derived from shoreline data	-	Euclidean distance (m) to nearest shoreline

1: Multi-Resolution Land Characteristics Consortium; 2: National Oceanic and Atmospheric Administration

Appendix E: Land cover classifications for the land cover variable used in the Maxent model for northern diamondback terrapins (*Malaclemys terrapin terrapin*).

Land cover types
Developed, high intensity
Developed, medium intensity
Developed, low intensity
Developed, open space
Cultivated crops
Pasture/hay
Grassland/herbaceous
Deciduous forest
Evergreen forest
Mixed forest
Scrub/shrub
Palustrine forested wetland
Palustrine emergent wetland
Estuarine forested wetland
Estuarine scrub/shrub wetland
Estuarine emergent wetland
Unconsolidated shore
Bare land
Estuarine aquatic bed
Palustrine aquatic bed
Non-ocean open water
Atlantic Ocean

Appendix F: Shoreline composition classifications for the shoreline type variable used in the Maxent model for northern diamondback terrapins (*Malaclemys terrapin terrapin*).

Shoreline types
Uncrossable- hard, man-made structures
Uncrossable- hard, natural structures
Uncrossable- Scarps and steep slopes in sand
Beaches
Gravel beaches
Exposed tidal flats
Vegetated/sheltered flatlands
Marsh shores

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