Ecological and Economic Effects of Derelict Fishing Gear in the Chesapeake Bay

2015/2016 Final Assessment Report

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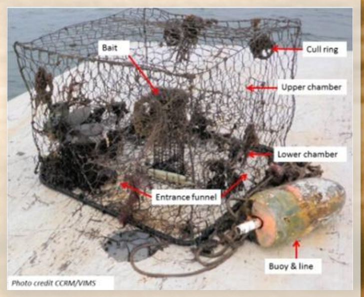

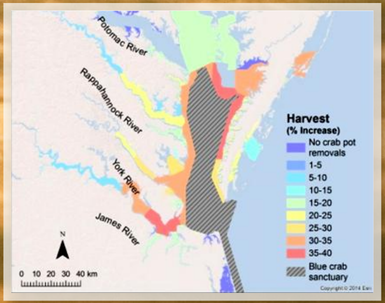

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Derelict crab pot removal in the Chesapeake Bay (Photo credit: Matt Stewart)

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Executive Summary

Derelict fishing gear represents a major challenge to marine resource management: whether through deliberate abandonment or through accidental loss, derelict traps in particular have significant negative effects both economic (*e.g.*, reduced fishery harvest from ghost fishing and gear competition that leads to the reduced efficiency of active gear) and ecological (*e.g.*, degraded habitats and marine food webs and crab and bycatch mortality). Throughout the Chesapeake Bay, commercial harvest of hard-shelled blue crabs is a major fishing activity: every year sees the deployment of several hundred thousand blue crab traps (known locally as crab "pots") across the Bay, of which an estimated 12-20% are lost each year. This report focuses on these derelict crab pots, drawing on many direct or remote observations and other data to quantify their abundance and spatial distribution across the Chesapeake Bay, and their resulting ecological and economic effects.

The study used a unified geostatistical framework to integrate disparate spatial datasets to predict the distribution and abundance of derelict crab pots in Chesapeake Bay and to evaluate their adverse effects on sensitive habitats and bay species. Predictor variables that likely affect the distribution and abundance of derelict crab pots that were evaluated included fishing effort, recreational boating activity, marine traffic patterns, and water depth. Using all of these data inputs, as well as derelict pot removal data and derelict pot field surveys, a geographically weighted regression (GWR) model successfully predicted and mapped the densities of derelict pots throughout the Chesapeake Bay, and estimated over 145,000 derelict pots Bay-wide; about 58,000 in Maryland and 87,000 in Virginia.

An inventory of data available from many different sources identified several crucial but unknown variables necessary to evaluate ecological impacts of derelict crab pots baywide, such as pot loss rates, fishing practices affecting pot loss, and escape and mortality rates for crabs and bycatch (non-crab species) caught in derelict crab pots. These "data gaps" were filled through fieldwork (inspection and removal of derelict crab pots), controlled laboratory observations of crabs in and near pots, and structured conversations with watermen. The predicted geographic distribution of these pots served to pinpoint areas with significant ecological impacts: by combining the numbers and distribution of derelict pots from this model with annual blue crab catch and mortality rates, we estimate that each year, derelict pots catch over 6 million crabs, and kill over 3.3 million — 4.5% of the 73 million crabs harvested in 2014. The effects on bycatch are also significant: for example, our model estimates that each year, derelict pots entrap over 3.5 million white perch and nearly 3.6 million Atlantic croaker across the Bay. The effects of derelict pots on marine habitats appear to be less significant: only 16% of predicted derelict pots are in areas with submerged aquatic vegetation; and only 2% are in oyster beds. However, derelict pot removal programs required the avoidance of sensitive habitats including SAV and oyster reefs; therefore the impact on habitats may be greater.

Next, a spatially explicit harvest model was used to predict the economic effect of pot removal efforts on commercial blue crab harvests, by comparing actual harvests (with the derelict pot removals that occurred from 2008-2014) against those one would have expected in a counterfactual scenario of zero derelict pot removals. Model results suggest that pot removals increased harvests by over 30 million lbs in Virginia (27.2%, valued at $22.6 million) and over 8 million lbs in Maryland (16.3%, valued at $10.9 million); for a Bay-wide total of over 38 million lbs (23.8%, valued at $33.5 million) over the 6 year period. The model also suggested that over the derelict pot removal period, pot removals increased the efficiency of active pots by 0.43 lbs/pot in Chesapeake Bay; so on average, for each pot removed, harvests increased by 868 lbs. Finally, the removal of derelict pots from high intensity potting areas (hotspots) can produce significant economic benefit beyond reducing mortality. For example, removing as little as 10% of the derelict pots from the 10 most heavily fished sites (5 sites in Virginia; 5 in Maryland) could increase blue crab harvest in the Chesapeake Bay by 22 million pounds or approximately 14%.

These findings suggest several spatially-explicit management actions likely to reduce derelict crab pot accumulations and their harmful effects in the Chesapeake Bay. Minimizing spatial conflicts between crabbing and recreational and commercial boating traffic, and educating vessel operators on pot avoidance, would greatly reduce pot loss. Targeted pot removals in heavily-fished areas would be a highly cost-effective way to increase catch efficiency and reduce bycatch mortality. The number and impact of derelict pots would also be reduced by incentives to accelerate the removal of abandoned pots and to modify crab pots with biodegradable escape panels. We can already quantify the effects of some of these mitigation measures: for example, biodegradable escape panels would likely reduce crab mortality in derelict pots from over 3.3 million per year (4.5% of the harvest) to under 440,000 (0.6%).

The report discusses the sensitivity of these findings to the various inputs; as well as the confidence and precision levels attainable with current data; and charts ways to further refine these results to inform a generalized framework for determining ecological and economic effects of derelict fishing gear that can be used in similar fisheries in the United States and elsewhere.

Appendices to the report - some of which are full research reports in their own right - provide crucial detail and context. Appendix A documents the fieldwork, analysis, and findings related to loss rates of blue crab pots. Appendix B records the laboratory (mesocosm) study of capture, escape, and mortality rates for crabs in derelict pots. Other appendices detail the data used in the study; the complex and changing regulatory context for blue crab management across the Bay; the team’s outreach activities over the course of the project; the template for conversations with watermen; and a published article detailing the economic effects analysis.

1. Introduction

1.1 Background

Marine debris, also known as marine litter, includes “any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned into the marine environment or the Great Lakes.” (Marine Debris Research, Prevention, and Reduction Act - 33 U.S.C. 1951-1958 (2006)). Marine debris comes from both land-based and ocean-based sources and is frequently comprised of synthetic materials such as plastics and metal. Synthetics, like plastics, in recent decades have become a common material for consumer waste (e.g., bags, balloons, bottles), industrial products, and derelict fishing gear. While the majority of marine debris is land-based (Sheavly and Register 2007), derelict fishing gear can make up a significant proportion of the ocean-based marine debris in coastal areas (National Research Council 2008). Derelict fishing gear includes nets, lines, traps, and other recreational or commercial fishing equipment that has been lost, abandoned, or otherwise discarded (UNEP, 2005). The availability of synthetic materials in modern times has increased the efficiency, durability, and lifespan of gear for numerous fisheries. Derelict gear is of concern because it can damage sensitive habitats, trap and kill target and non-target species, cause economic impacts from the loss of recreational and commercial harvest of valuable species, and pose a safety hazard to human navigation (e.g., Guillory, 1993; Matsuoka *et al.* 2005; Bilkovic *et al.* 2014; Scheld *et al.* 2016).

The Chesapeake Bay supports several important commercial finfish and shellfish fisheries that utilize a wide array of fishing gear, including oyster hand tong, crab pots, eel pots, ordinary clam tong, various types of gill nets, conch dredge, fyke nets, and purse seines (Kirkley, 1997). However, blue crab traps, known locally as crab “pots,” are the prevailing derelict fishing gear found in the Chesapeake Bay (**Figure 1-1**) because of the large number of pots deployed, their relatively high loss rates (~12-20%), and the long fishing season (Apr-Nov).

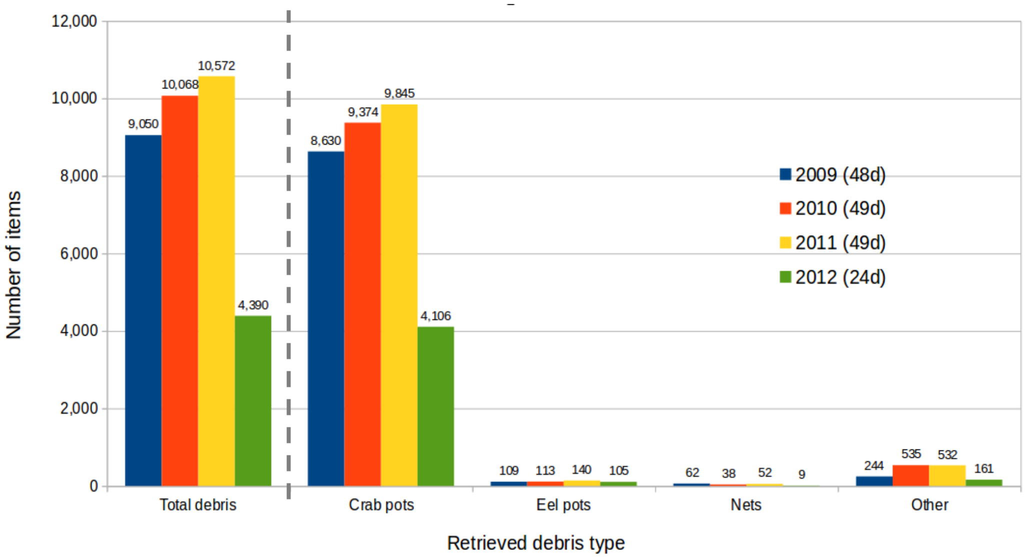


Figure 1-1. Marine Debris Items Recovered from Virginia Tidal Waters Over Four Winters.

Blue crab pots were the dominant form of marine debris retrieved in each year. Additional fishing gear retrieved were eel pots and nets (seine, gill). Other marine debris included tires, appliances, oyster aquaculture cages, buckets, chairs, and balloons. From Bilkovic et al. 2014.

Numbers fluctuate; but, in recent years, estimated summer deployment of crab pots Bay-wide has exceeded 350,000 (Slacum *et al.* 2011a; Slacum *et al.* 2012; **Figure 1-2**).

The distribution, abundance, and persistence of derelict gear are strongly related to fishery activity and management. For example, the spatial extent of areas with concentrated fishing effort or no-fishing zones will largely dictate the boundaries of expected lost gear. Characterizing the fishery is an important first step to assessing derelict fishing gear effects.

The Chesapeake Bay has always been a prominent source of blue crab, making up 50% of the national market by mid-century. However, the blue crab population has also experienced significant declines over the past few decades and only recently begun to rebound. Currently, the Chesapeake Bay blue crabs are not considered to be overfished, although large population fluctuations still occur. For the Chesapeake Bay, the target population is 215 million and the target exploitation factor for female crabs is 25% of the stock (CBSAC 2014).

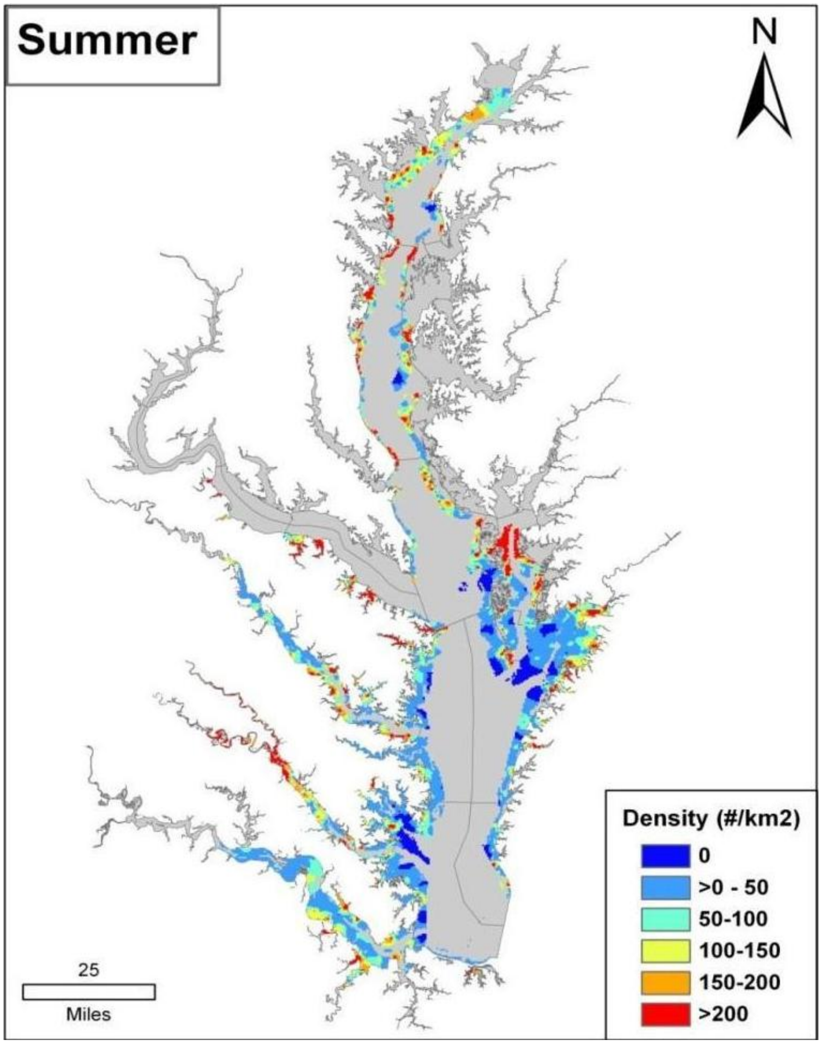


Figure 1-2. Commercial Crabbing Effort in Maryland and Virginia.

Density estimates derived from an independent survey of crabbing effort conducted in 2010. From Slacum et al. 2011a.

While blue crabs have been a noted food item in the Chesapeake Bay since before colonial times, the invention of the Chesapeake Bay crab pot and advances in crabmeat processing in the early 20th Century resulted in significant increases in hard crab harvests (Kennedy 2007). Since the mid-20th century, the primary gear used to capture blue crabs in the Chesapeake Bay is the rigid square-shaped wire pot with dimensions of approximately 2 ft. x 2 ft. x 2 ft (**Figure 1-3**).

The Chesapeake Bay blue crab fishery is managed jointly by the States of Maryland and Virginia and the Potomac River Fisheries Commission. The three jurisdictions collaborate on Bay-wide annual harvest goals, but each jurisdiction implements its own unique set of regulations to manage the harvest from their waters. Virginia and Maryland have implemented a number of blue crab management actions, including expansion of the spawning sanctuary, closure of the winter dredge fishery, establishment of daily individual and vessel harvest and possession limits, and establishment of crab and peeler pot tending requirements, as well as many other actions (Blue Crab Management in Virginia and Maryland, 2014; Maryland regulations from 2008 to 2015).

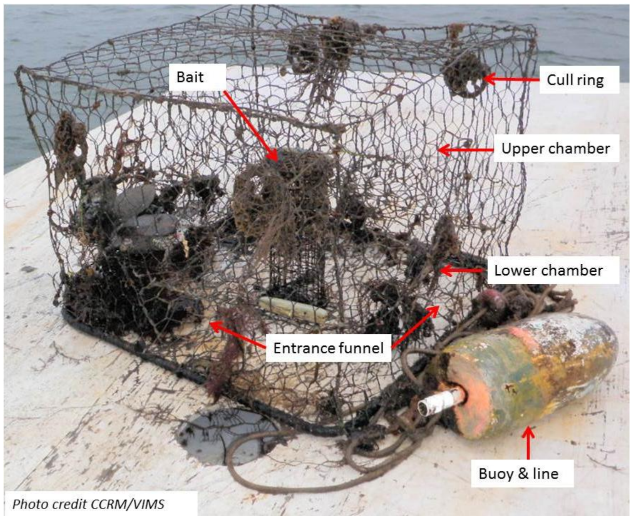


Photo credit CCRM/VIMS

Figure 1-3. Derelict Blue Crab Pot.

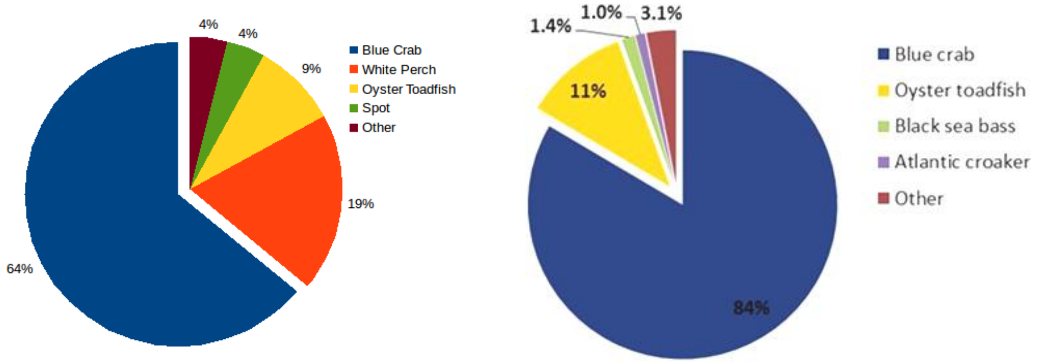
The crabbing season dedicated to potting generally runs from April through November with a closed winter season. In Virginia, the number of commercial crab pot licenses has gradually declined because of management actions and diminishing numbers of active watermen since the early 1990s (~1,800 licenses) to the present (~1,100 licenses). Similar reductions in licensed crabbers have occurred in Maryland over the past decade due to a State-initiated license buy-back program and general attrition. Though it is unclear how the number of active watermen relates to the numbers of crab pots, the number of pots has decreased over this time as well. The allowable number of crab pots fished on the basis of licenses in Virginia likewise has declined from about 440,000 to 270,000 during the same time frame (1994-2014).

Key management actions potentially influencing derelict pot distribution are 1) Maryland regulations prohibit commercial crabbing in tributaries with pots, whereas this is allowed and practiced in Virginia; 2) a no-crabbing sanctuary (928 square miles) during the crab spawning season covering the mainstem and portions of the lower Chesapeake Bay to protect the spawning females; and 3) effort restrictions.

Blue crab fishery management actions are partially linked to the complex life cycle of the blue crab, which involves multiple horizontal and vertical migrations across state boundaries and dependencies on high salinity areas in the lower Chesapeake Bay, Virginia for spawning, larval development, and overwintering. Generally, in the spring and summer blue crabs inhabit shallow low salinity waters of tributaries and creeks (Van Engel, 1958). Following insemination, females will migrate to the more saline deeper areas near the mouth of the Chesapeake Bay for egg brooding and hatching (Van Engel, 1958; Turner *et al.* 2003; Aguilar *et al.* 2005); when temperatures drop below 9°C, crabs aggregate in deeper water and bury in muddy sediments (Jensen *et al.* 2005; Jensen & Miller, 2005; Smith & Chang, 2007).

Independent surveys of crab pot efforts have documented that spatial patterns of fishing effort follow the spatial movement and migration of blue crab. The majority of crab pots are deployed in shallow waters less than 10m in the tributaries and mainstem in Virginia and only in the mainstem in Maryland (Slacum *et al.* 2011a; Slacum *et al.* 2012; **Figure 1-2**). Within Virginia, crab pots are fished singly; however, in Maryland, watermen are able to deploy pots singly or multiple pots can be attached to a single long line.

Blue crab pot loss in the Chesapeake Bay is often the result of the buoy line being separated from the pot (*e.g.*, by vessel propellers, faulty buoy lines, or vandalism). Pots are also lost due to storm events that pull the buoy below the surface. Within Virginia, pot abandonment can be as high as 41% of derelict gear (Bilkovic *et al.* 2014). Once lost, pots pose threats to the natural environment due to their ability to continue to capture marine organisms. A derelict crab pot can persist from months to several years, depending on its construction; in the Chesapeake Bay, for example, derelict crab pots were estimated to persist from 1-7 years (Arthur *et al.* 2014). Organisms caught in derelict gear often face starvation, exposure to low dissolved oxygen, cannibalism, and disease, which can lead to death (Guillory *et al.* 1993). Over forty species have been documented in derelict crab pots in the Chesapeake Bay (Bilkovic *et al.* 2014, Slacum *et al.* 2009) (**Figure 1-4**). A species known to be at high risk to mortality from active and lost crab pots is diamondback terrapin *Malaclemys terrapin*, the only entirely estuarine turtle species in Chesapeake Bay. 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). Lost crab pots represent an unknown source of mortality for terrapins- even though high numbers of terrapins, some in various stages of decay, have been reported in derelict pots suggesting that lost pots continue to capture and kill terrapin (Bishop, 1983; Roosenburg, 1991).



Maryland
Dominant species observed: blue crab, white perch, oyster toadfish, spot.
Other species: pumpkinseed, Atlantic menhaden, Atlantic croaker, American eel, sheepshead, black sea bass.
(From Slacum et al. 2009)

Virginia
Dominant species observed: blue crab, oyster toadfish, black sea bass, Atlantic croaker.
Other species: American eel, white perch, catfish, spot, flounder, tautog.
(From Bilkovic et al. 2014)

Figure 1-4. Total Derelict Pot Catch Composition for Fish and Blue Crab in the Chesapeake Bay, excluding Bait Effects.

Research addressing various aspects of derelict pots in the Chesapeake Bay has occurred for nearly a decade. The majority of this work is comprised of studies conducted independently in the waters of Maryland and Virginia. Research conducted in Maryland waters was co-led by representatives of Versar, Inc. and the NOAA Chesapeake Bay Office with support from the MD Department of Natural Resources, and commercial watermen from Maryland. Research in Virginia waters was led by representatives of the Virginia Institute of Marine Science (VIMS) with support from the Virginia Marine Resource Commission (VMRC), and commercial watermen from Virginia.

Original work conducted by Havens *et al.* 2008 and Slacum *et al.* 2009 evaluated the distributions of derelict pots and derelict pot bycatch in various Chesapeake Bay habitats. Later work included modeling the distribution of derelict pots in Maryland (Slacum *et al.* 2011b), and the implementation of several large-scale derelict pot retrieval projects in Maryland (Slacum *et al.* 2011b and 2013), and Virginia (Havens *et al.* 2011, Bilkovic *et al.* 2014). Information about derelict pot distributions, condition, and bycatch was collected from retrieval efforts providing additional insights into how pots become derelict, the lifecycle of a pot, and their effects on biota.

While Chesapeake Bay studies improved our knowledge of many characteristics of derelict pots, the ecological and socioeconomic effects across the Chesapeake Bay are still poorly understood. Fortunately, much of the derelict pot data in the Chesapeake Bay are well documented. There are many other data sources from ongoing Bay research that includes variables likely to influence derelict pot effects, and there is good information on the dynamics of the blue crab fisheries. These factors provide the NOAA Marine Debris Program with a unique opportunity to evaluate the effects of a specific type of derelict fishing gear and use this case study as a pathway to develop the framework to evaluate the effects of derelict fishing gear in other regions of the United States.

1.2 Approach

The socioeconomic and ecological effects of derelict crab pots will vary depending on structural and functional components of the Chesapeake Bay ecosystem. To approach this complex question a project team was assembled that included representatives with expertise in derelict crab pot research from Maryland and Virginia, fishery economics, spatial modeling, and data integration. The Chesapeake Bay blue crab fishery was selected as a model because of its high applicability to other fisheries in many locations. Due to the high numbers of pots set in the Chesapeake Bay and the high loss rates of pots, there is a critical need to assess the potential effects of derelict blue crab pots on both the ecology and socioeconomics of the Chesapeake Bay.

The goal of this project was to conduct a regional impact assessment of derelict fishing gear in the Chesapeake Bay, focused on derelict blue crab pots, as a basis for a more general Derelict Fishing Gear Assessment Framework.

Six objectives are being employed to accomplish the study goal:

1. Identify and evaluate characteristics of the Chesapeake Bay blue crab pot fishery that contribute to the distribution and densities of derelict crab pots.
2. Inventory available data related to variables determined in objective one with consideration to data that would likely be available in other U.S. regions.
3. Identify data gaps and design surveys and experiments to provide those data.
4. Develop a spatial model framework to evaluate factors influencing the distribution and densities of derelict crab pots.
5. Quantify the ecological and economic effects of derelict crab pots in the Chesapeake Bay.
6. Develop a framework for assessing derelict fishing gear that can be used for similar fisheries in the United States and elsewhere.

A critical first step to assess the ecological and economic effects of derelict pots is to identify and evaluate all the factors expected to contribute to pot loss and determine the amount of influence that each factor contributes to the overall effects of derelict pots. A conceptual framework was initially developed to capture both structural and functional variables. (See **Figure C-1** in **Appendix C**.) Specifically, an integrated biogeographic approach using expert opinion to determine key contributing variables was used to characterize spatial patterns in the densities and distribution of derelict crab pots as well as to infer spatial variability in the potential ecological effects within the Chesapeake Bay. A common spatial framework was used to integrate disparate datasets of derelict crab pot locations through the Maryland and Virginia portions of the Chesapeake Bay and explored the spatial inter-relationships among several variables hypothesized to affect the distribution and densities of derelict crab pots.

Furthermore, we used a geographically weighted regression model to account for spatially varying influences of the various variables and to predict and map the densities of derelict crab pots throughout the Bay. Model predictions of derelict crab pots were then used to map hotspots of derelict crab pots, identify areas of high potential ecological impacts, and recommend spatially-explicit actions that could reduce derelict crab pots.

2. Bay-wide Distribution and Densities of Derelict Crab Pots

2.1 Chesapeake Bay Biogeographic Framework

A spatial framework was created in a geographic information system (GIS) to aid in the integration and interpretation of compiled data sets. Locational data on derelict crab pots and potential independent variables that may be used to predict derelict pot distribution and abundance within the Chesapeake Bay were compiled from VIMS and Versar (see **Appendix C**) and integrated into a 1 km by 1 km polygon grid (**Figure 2-1**). The 1 km x 1 km grid was selected as the highest spatial resolution for spatial modeling based on previous analyses done by Versar and VIMS. Spatially-explicit response variables (density of derelict crab pots) and predictor variables (e.g., fishery effort, bathymetry and other derived variables) were derived through geostatistical resampling of raw data.

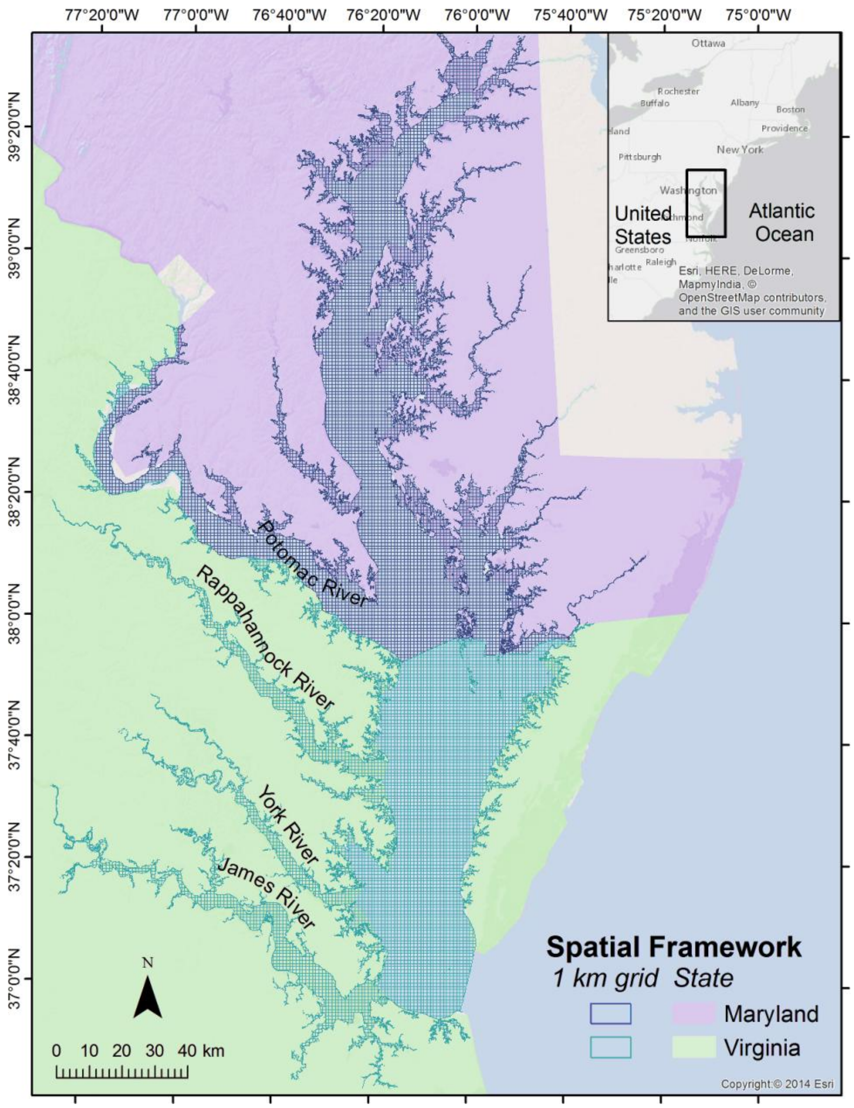


Figure 2-1. Map Showing Spatial Framework used to Characterize Chesapeake Bay Derelict Crab Pot Spatial Patterns.

The spatial grid extent covers areas in the Chesapeake Bay where crabbing occurs. Grid cells are 1km x 1km.

2.2 Key Variables/Data Acquisition and Preparation

Guided by expert local knowledge and review of historical work on derelict crab pots in the Chesapeake Bay, a list of variables expected to contribute to the distribution and effects of derelict crab pots was compiled. Variables were integrated into an ecological and economic conceptual framework to map their interactions and connectivity to one another. (See **Figure C-1** in **Appendix C**.) All variables were evaluated based on their relative contribution to the distributions, densities, and effects of derelict crab pots. Data availability for key variables was also assessed, and additional research was implemented to collect additional information when data gaps were identified. (See **Appendices A** and **B** for additional research.) A description of methods, a list of all variables and sources that were identified and evaluated is presented in **Appendix C** (Versar and VIMS supplied the derelict crab pot data used in this evaluation and are referred to as the data source owner in this report).

The compiled data sets were in different file formats ranging from excel spreadsheets to ESRI coverages that included raster grids point, line, and polygon shapefiles. Each dataset was processed in Statistical Analysis Systems (SAS, Version 9.4) to ensure that data and field names were in consistent and standardized formats. For all compiled data sets, we conducted a thorough review of their metadata to understand the purpose and intent for which the data were collected, the methods used, and any associated biases. Data were also evaluated to ensure either they met specific criteria for spatial modeling, including assumptions normality, stationarity of mean and variance, and statistically significant spatial autocorrelation or that the data could be transformed to remove non-random trends. Excel files were converted to ESRI point shapefiles and were visualized in ESRI ArcGIS to determine the spatial extent of dataset coverage and any obvious spatial patterns.

Table 2-1. Predictors of Derelict Crab Pot Distributions in the Chesapeake Bay.

Variable	Source
Blue crab fishery spatial patterns	Versar
Bathymetry	NOAA
Recreational boating hotspots	Versar, VIMS, VMRC
Vessel traffic spatial patterns	Marine Cadastre
MD derelict crab pot locations documented with SSS	Versar
VA derelict crab pot locations from retrievals	VIMS

Several predictors of derelict crab pot distribution were identified for integration into the biogeographic modeling framework (**Table 2-1**). These predictors were integrated and used to model the spatial distribution and densities of derelict crab pots, and were used along with additional variables to determine the spatial distribution of ecological effects throughout the Chesapeake Bay. These data were integrated with the 1 km x 1 km polygon grid through spatial overlays.

Below we provide detailed descriptions of the predictors along with maps showing their distributions throughout the Chesapeake Bay.

2.2.1 Blue crab fishery spatial patterns

Day to day commercial fishing operations can influence the amount of fishing gear that becomes derelict. Therefore, it is important to understand the spatial patterns of the fishery and to attain as much information about when, where, and how intense a fishery operates. Versar conducted several fisheries independent surveys across Maryland and Virginia. The surveys were stratified based on known fishing efforts and consisted of transects where number of crab pot floats were counted as a measure of fishing effort. Inverse distance weighting was used to interpolate transects to estimate fishing effort (# pots/km^2)

across the Chesapeake Bay (**Figure 2-2**). Areas where crabbing does not occur, such as the Maryland tributaries and the deep channel or “deep trough” of the Chesapeake Bay, were removed from the interpolation. Data used in this project included data from surveys conducted in Maryland during the 2007 to 2011 crabbing seasons, and from Virginia during the 2010 crabbing season. (See **Appendix C** for survey metadata.)

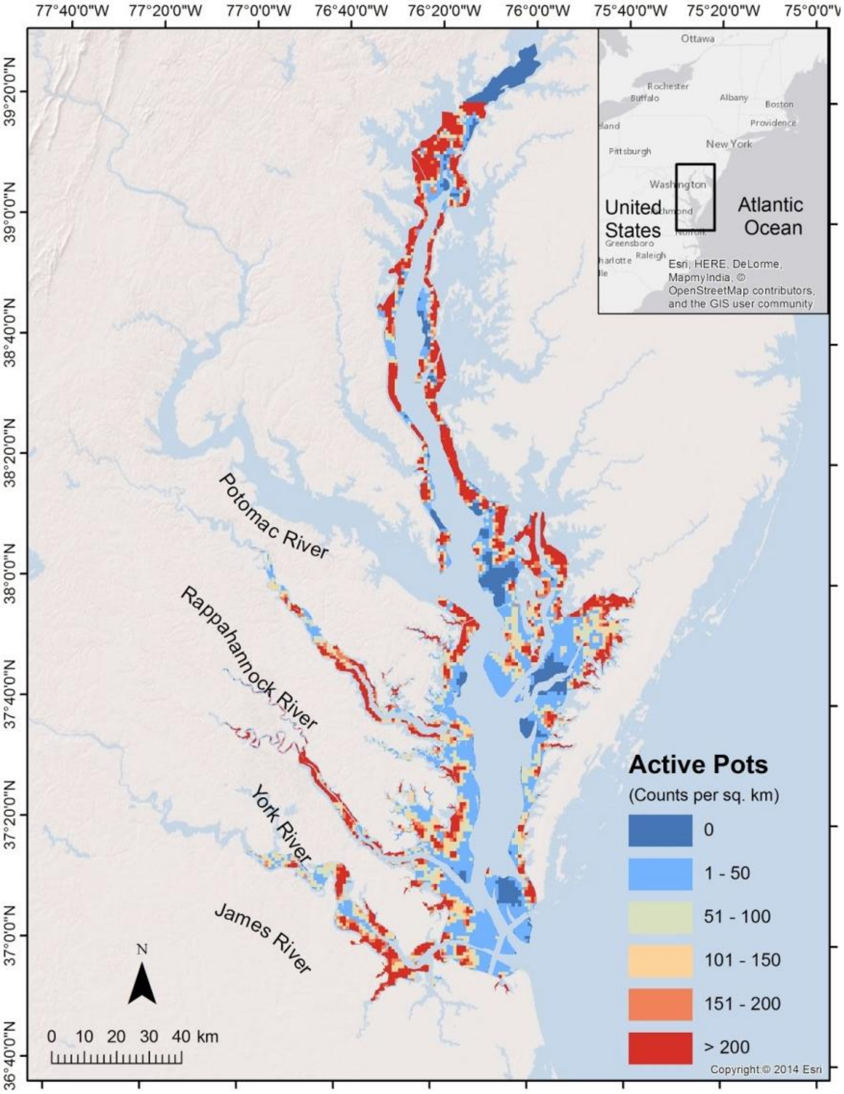


Figure 2-2. Spatial Patterns of Blue Crab Fishery Effort in the Chesapeake Bay.

2.2.2 Bathymetry

Derelict crab pots have been documented in all depths where the commercial fishery is active, but the distribution and densities of derelict pots within certain depth intervals can vary with depth (Slacum *et al.* 2009). Bathymetry data were obtained from NOAA National Centers for Environmental Information (Bathymetry for Chesapeake Bay was derived from two hundred ninety-seven surveys containing 3,178,509 depth soundings collected between 1859 to 1993 (source: http://estuarinebathymetry.noaa.gov/bathy_htmls/M130.html). The hydrographic data were used to develop a rasterized (30-meter) digital elevation model for the Chesapeake Bay, from which depth were extracted with the 1 km x 1 km grid (**Figure 2-3**).

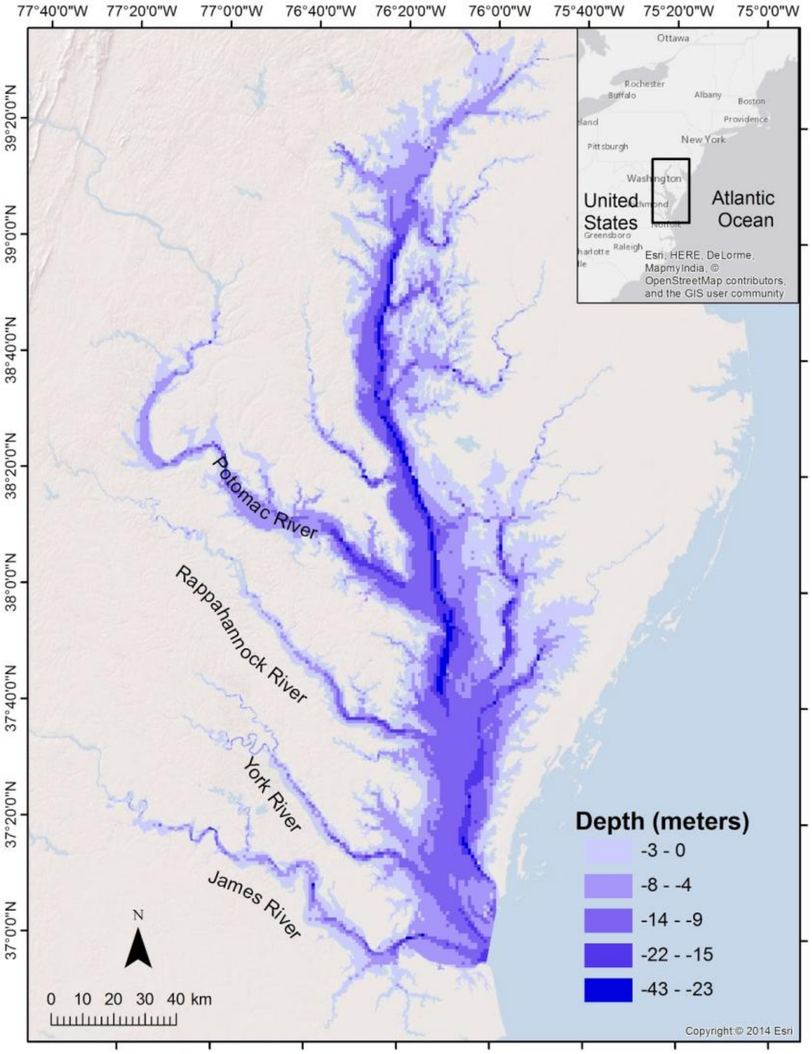


Figure 2-3. Chesapeake Bay bathymetry.

2.2.3 Recreational boat traffic activity

The intensity of recreational boating activity in the Chesapeake Bay represents a contributing factor to occurrence of derelict fishing gear in that area. Typically, watermen set their pots with a line attached to a marker buoy or 'float'. The float identifies ownership and facilitates retrieval of the pots. High intensity of recreational boat use increases the likelihood that marker buoy and pot float lines will inadvertently interact with boat propellers. Crab pots can then become 'derelict' after their float line is severed by vessel propellers, chafed through due to wave action, or tangled up on the pot itself as it is rolled by strong currents and waves. Without floats, watermen are unable to find their pots to retrieve them and harvest the contents. Areas with relatively high recreational fishing activity were mapped in Maryland and Virginia using local expert knowledge. For the Maryland portion of the Chesapeake Bay, representatives participating in the fishery independent survey of commercial crabbing effort delineated areas of relatively high recreational boating activity. For the Virginia portion of the Bay, high intensity recreational boating areas were determined using local knowledge of VIMS experts, Virginia Marine Resources Commission officers, and watermen, in combination with the locations of artificial reefs (which typically are heavily visited by recreational fishers). This participatory mapping exercise provided local expert knowledge on the locations of heavily used recreational boating areas and filled gaps in in the spatial coverage of that data. For this study, areas denoted by these local experts as high boat use areas were used as a proxy for increased derelict crab pots and were assumed to have higher likelihood of derelict gear occurrence (**Figure 2-4**).

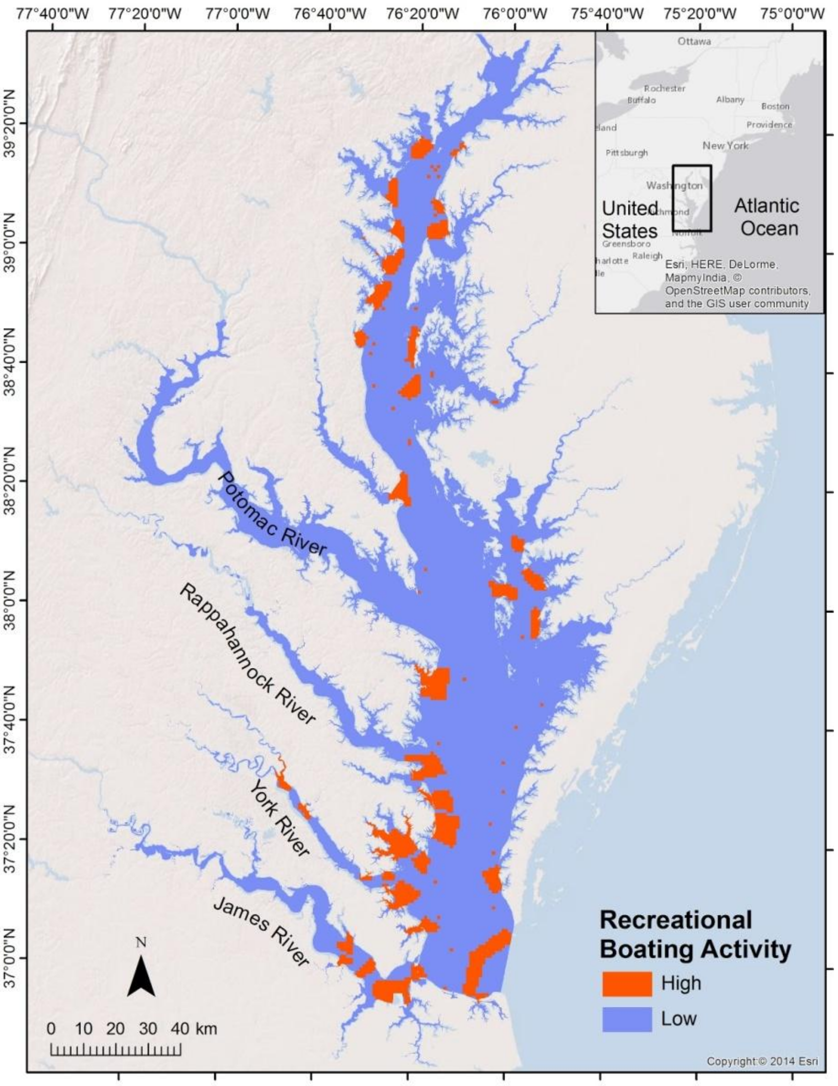


Figure 2-4. Chesapeake Bay Recreational Boating Activity.

2.2.4 Status of derelict crab pots from removal efforts

Derelict Fishing Gear Status refers to whether a crab pot was abandoned or accidentally lost. VIMS and Versar conducted derelict crab pot retrieval studies throughout the Chesapeake Bay and it is estimated that 12% to 20% of deployed pots are lost annually (**Appendix A**). In Virginia, as part of these studies, whether a pot had a buoy or line attached was noted. For this study, each pot was assigned a status of ‘abandoned’ only if the pot had a buoy attached or ‘lost’ otherwise. The assumption is that the presence of a buoy suggested that watermen deliberately abandoned rather than retrieved the crab pot, whereas the absence of a buoy suggested that the pot was accidentally lost. The Maryland studies did not distinguish between ‘abandoned’ and ‘lost’. Based on these data, we mapped the spatial occurrence of abandoned and lost pots in Virginia and lost pots only in Maryland (**Figure 2-5**). In addition, while not displayed here, 4,146 derelict pots were also removed from Virginia’s seaside eastern shore, of which 81% were considered abandoned (Bilkovic *et al*. 2014). Abandoned pots in the Virginia portion of the Chesapeake Bay accounted for 8,392 (~28%) of 29,840 mapped derelict pots.

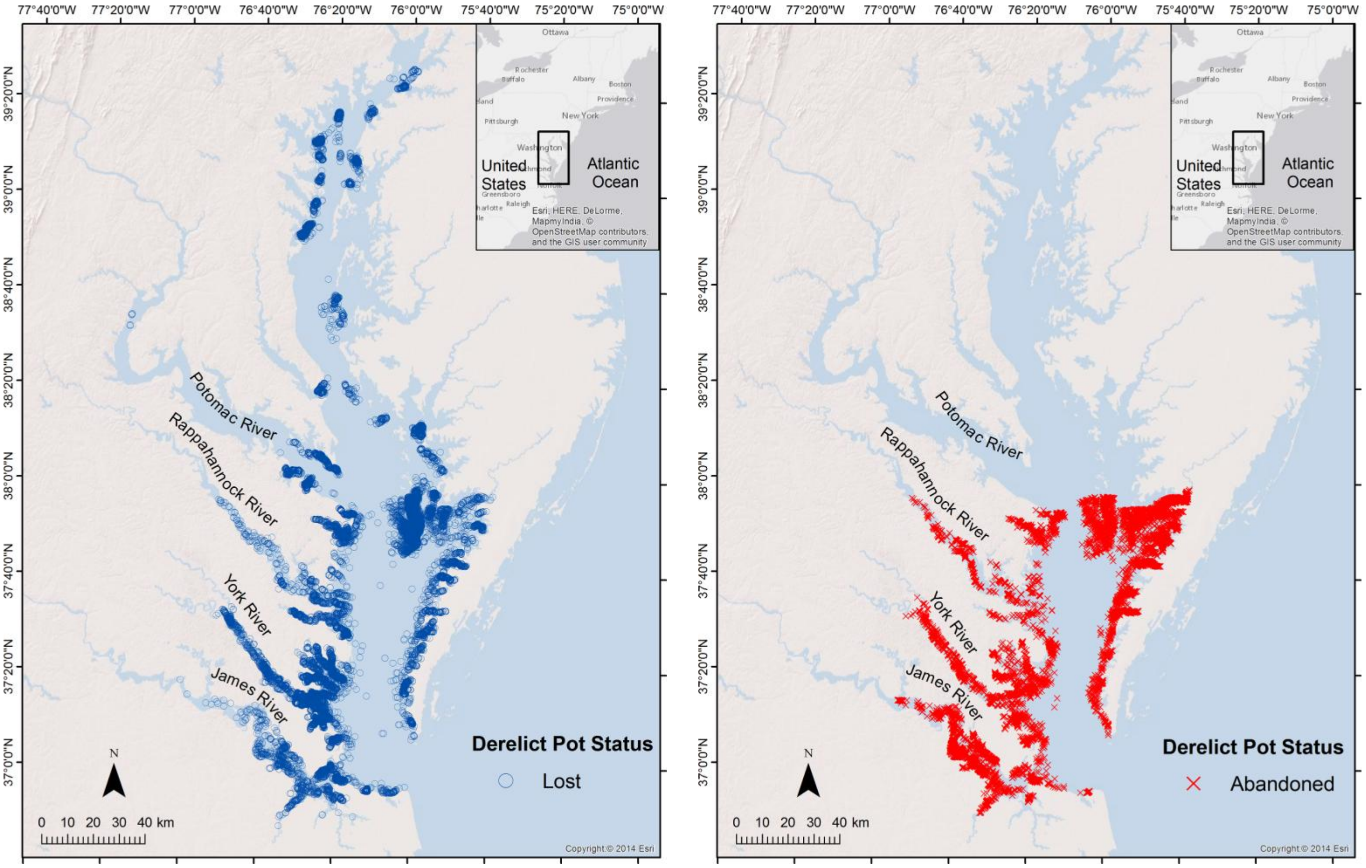


Figure 2-5. Spatial Distribution of Crab Pots identified as Lost or Abandoned during Retrieval Projects in Maryland and Virginia.

(Abandoned pots are shown only for Virginia: the Maryland studies did not distinguish ‘abandoned’ vs. *‘lost’ pots.)*

2.2.5 Vessel traffic data (AIS data)

The Chesapeake Bay is a major route for shipping, transportation, and cruise industries along the eastern seaboard. For example, Baltimore is ranked 9th for total dollar value of cargo and 13th for cargo tonnage for all U.S. ports (Maryland Manual, http://msa.maryland.gov/msa/mdmanual/01glance/html/port.html). In 2015, the total international cargo (imports and exports) moving through the Port of Baltimore was 32.4 million tons with a total cargo of around $51 billion. The Port of Baltimore serves over 50 ocean carriers that average around 1,800 visits each year.

The combination of commercial shipping and recreational boating is a constant source of vessel traffic along the mainstem, rivers, and tributaries of the Chesapeake Bay which could affect fishing activity and occurrence of derelict fishing gear in the Chesapeake Bay. Data on vessel traffic within the Chesapeake Bay were obtained from the Marine Cadastre (http://marinecadastre.gov/ais/) and used to map ship traffic patterns for calendar years 2009 through 2014. Data on Vessel traffic were collected by the U.S. Coast Guard through an Automatic Identification System (AIS). AIS is an onboard navigation safety device that transmits and monitors the location and characteristics of large vessels in U.S. and international waters in real time. The Marine Cadastre provides AIS data filtered and summarized into one-minute intervals, with each record representing a ship's location every minute. Specific AIS information obtained included vessel location, time, ship type, speed, length, beam, and draught. For this project, we calculated monthly densities of vessel traffic for each 1 km x 1 km grid cell within the Chesapeake Bay study region as the summation of the number of one-minute vessel records with instantaneous speeds greater than zero for each calendar month between January 2009 and December 2014. Monthly densities were calculated for all ships as well as only for fishing vessels (**Figure 2-6**).

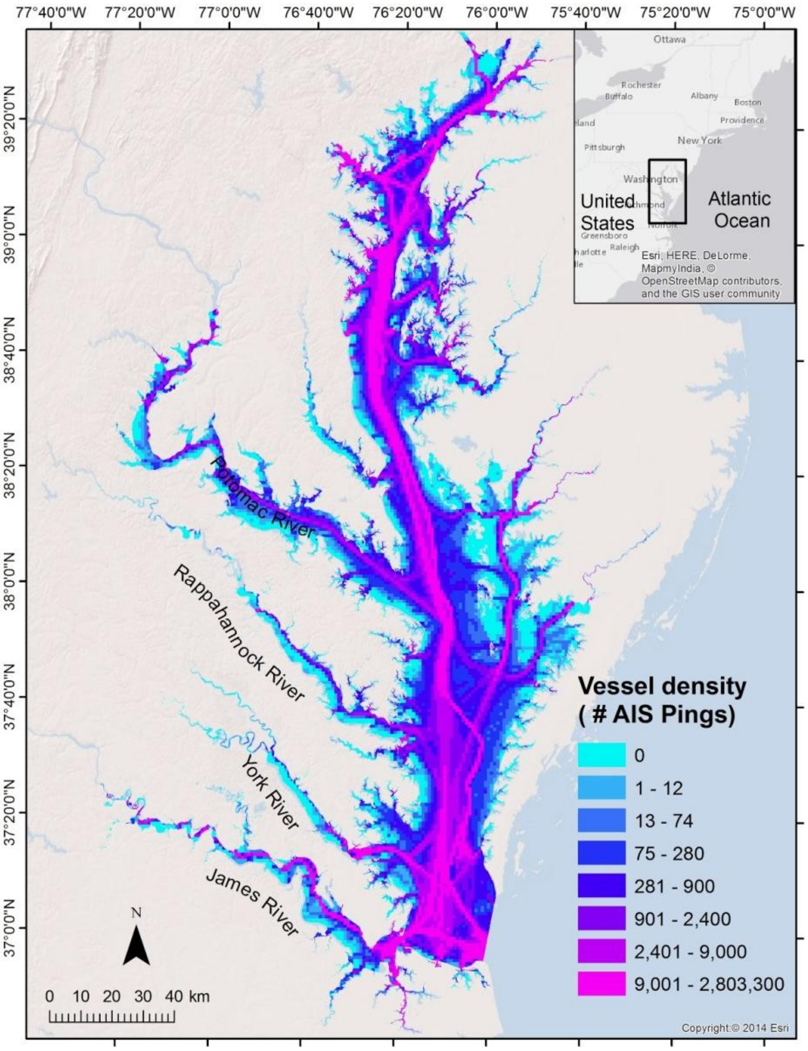


Figure 2-6. Vessel Density Aggregated from AIS Data.

2.3 Geographically Weighted Regression (GWR) Model

Previous work has shown that derelict crab pots vary spatially across the Chesapeake Bay and there are known factors that contribute to their distribution and densities. The five variables described in section 2.2 represent a portion of those factors, but were variables for which data could be attained. The influence of each factor on the presence of derelict crab pots was not known, but was expected to vary by location. A geographically weighted regression (GWR) modeling technique was chosen to estimate the distribution and densities of derelict crab pots in the Chesapeake Bay. The use of a GWR model has proved successful in estimating other marine ecological distributions (*e.g.* Windle *et al.* 2010) and a previous study of derelict crab pot hotspots in Maryland (Slacum *et al.* 2011b, 2013).

A two-step process was used to develop a predictive model of derelict crab pot distributions in the Chesapeake Bay. The overall method included a global regression to assess important parameters and then the development of a spatially explicit regression model. GWR is a local spatial statistical technique that expresses spatial variation relationships between variables.

To setup a GWR design, a global ordinary least squares (OLS) model was run in ArcGIS and identified significant variables within the variable pool for estimating known abundance of derelict pots. The general form of the OLS equation is as follows:

$$y_i = \beta_0 + \sum_j \beta_j X_{ij} + \varepsilon_i$$

where y_i is the estimated dependent variable at observation i, β_0 is the intercept, β_j is the parameter estimate for variable j, X_{ij} is the value of the j^{th} variable for i, and ε_i is the error term.

GWR modifies the global regression by including geographic coordinates for each prediction location. To do this, GWR generates a separate regression for each observation. The addition of geographic coordinates to each observation creates the following equation:

$$y_i = \beta_0(u_i, v_i) + \sum_j \beta_j(u_i, v_i) X_{ij} + \varepsilon_i$$

where β_0 is the intercept estimated at each coordinate (u_i, v_i), β_j is the parameter estimate for variable j at each coordinate (Fotheringham *et al.* 1998). This spatially explicit model then sets independent weights for parameter estimates that are dependent on geographic location (Brunsdon *et al.* 1998).

Within the GWR framework is the assumption that closely located observations have greater influence on neighbor's parameter estimations. The GWR weights observations using a distance decay function that can be tailored in a variety of ways to best suit the dataset. Various methods in modifying the decay function include manipulating the bandwidth or the distance of influence of one observation to another. Bandwidth can be set as a "fixed" value or "adaptive." Fixed bandwidth allows one to control how localized parameters are estimated across the entire spatial dataset while adaptive allows the bandwidth to expand in areas where observations are few and contract in areas with a high density of observations.

To assess the effects of these decay function manipulations, a set of candidate models were developed and evaluated using Akaike information criterion adjusted for small sample sizes (AICc). AICc values were used to rank models based on fit and performance. Smaller AICc values within the set of candidate models indicate better performance. AICc values were compared using Akaike differences (Δmodel), which determines the relative difference in AICc value for each model from the model with the lowest AICc value (Burnham and Anderson 1998). The most parsimonious model was selected using criteria for model confidence, where a Δmodel value < 2, indicates substantial support.

For model development, a calibration dataset was used with observed densities of derelict crab pots and related variables at specific locations. This dataset was used to explore variable significance and subsequently to train the GWR model. For additional independent variable review, the GWR provides local parameter coefficient estimation for each grid cell. This gives the ability to map spatial distributions of local R^2. The final output was then interpolated into a raster (power = 2, variable search radius, number of points = 4).

The training dataset of known and estimated derelict crab pot densities was compiled using a combination of survey data collected in Maryland and Virginia. The resulting data set consisted of 836 training data points. The Maryland portion of the data set included 286 locations of known derelict pots collected during a side-scan-sonar survey conducted in 2007 (see **Appendix C** for metadata). The Virginia portion of the data consisted of 550 points from the Virginia derelict crab pot cleanup efforts from 2009 to 2012 (**Figure 2-7**). The Virginia dataset was comprised of random points selected from the interpolation of Virginia pot retrieval data. The points were only selected in areas where crabbing occurs with 15% of the points selected from high densities of recovered derelict pots.

Estimates of each potential predictor variable were appended to each derelict crab pot density point and were analyzed with OLS model to indicate independent variable significance. The initial OLS global regression model indicated that independent fishing effort, depth, recreational boating traffic, and AIS data were significant variables in predicting the density of derelict crab pots.

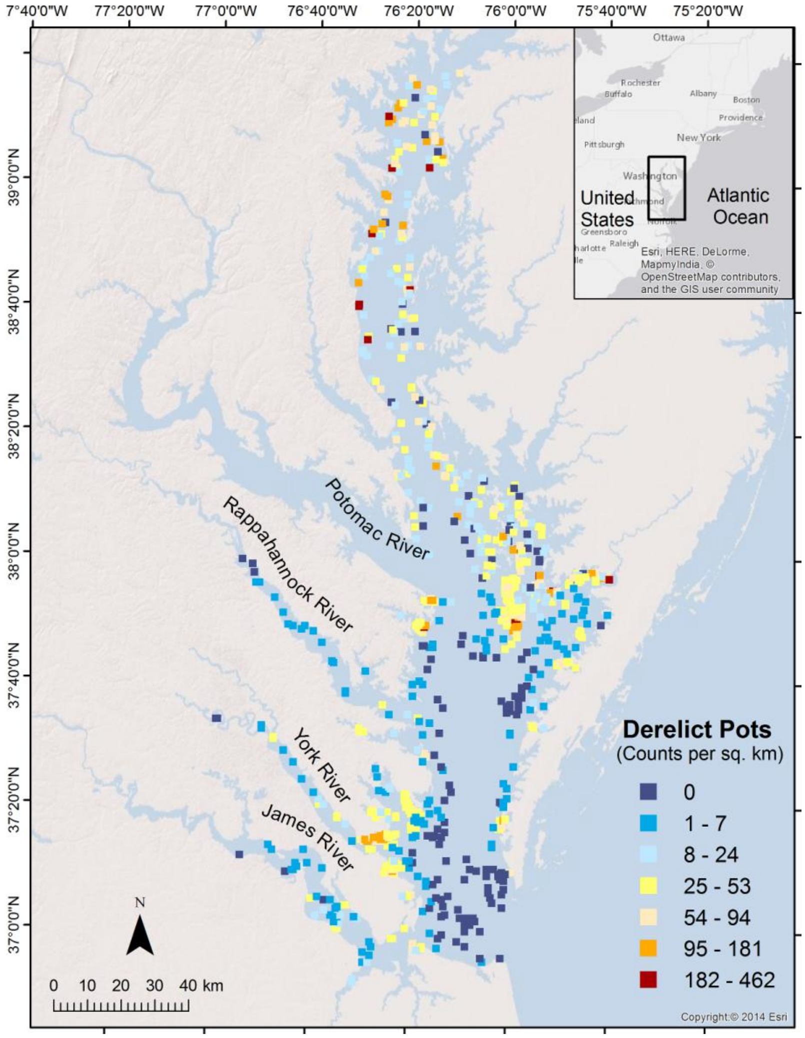


Figure 2-7. Locations of Known or Estimated Derelict Crab Pots in the Chesapeake Bay.

These data were used as a training data set to develop the geographically weighted regression model (GWR) for the Chesapeake Bay. Color scale indicates the density of derelict pots per km^2*.*

For GWR development and derelict crab pot predictions, the data were first reformatted for use in the ArcGIS modeling toolbox by converting the 1 km grid into a point grid where the centroid of the grid cell was the coordinate for the grid point. To aid in model efficiency, the "deep trough" portion of the bay where crabbing does not occur was excluded from the analysis.

The GWR model explained 34% of the variation in derelict pot density and distribution. Independent fishing effort, water depth, recreational boating traffic, and AIS vessel traffic data were significant variables in predicting the density of derelict crab pots. (**Table 2-2)**

Table 2-2. Geographic Weighted Regression (GWR) Results for Predicting Derelict Crab Pots in the Chesapeake Bay.

Parameter	Minimum	25% quartile	50% quartile	75% quartile	Maximum
Intercept	-1.59	20.44	31.49	46.42	68.32
Blue crab fishing effort	-0.06	0.03	0.06	0.09	0.33
Depth	-6.97	-4.40	-3.20	-1.58	4.23
Recreational boating	-0.12	11.39	17.34	27.22	67.02
AIS	-0.05	0.00	0.02	0.06	0.25
Condition Number	3.20	3.93	4.82	5.52	7.56
Adjusted R^2	0.34				
AICc	8,704.60				

This value attests to the difficulty in estimating derelict pot occurrence over a large spatial region that encompasses dynamic systems. The adjusted R^2 value here is similar to the previous study in Maryland (Slacum *et al*. 2013) which found the hotspots predicted by a similar model to be very consistent to estimates derived from recovery efforts. Multicollinearity was not a serious issue within the model as all condition number values were substantially less than 30.

To examine how well the GWR model predicted the local derelict pot density from the training data, a map of the locally weighted R^2 between the observed and the estimated values was created (**Figure 2-8**). Local R^2 was not homogeneously distributed across the Chesapeake Bay, with weakest fits occurring in the Maryland portion of Tangier Sound, the mainstem of the bay outside of the Choptank River, and eastern Virginia Pocomoke Sound. The poorer fit in these regions may imply the need for additional covariates to explain derelict pot distribution.

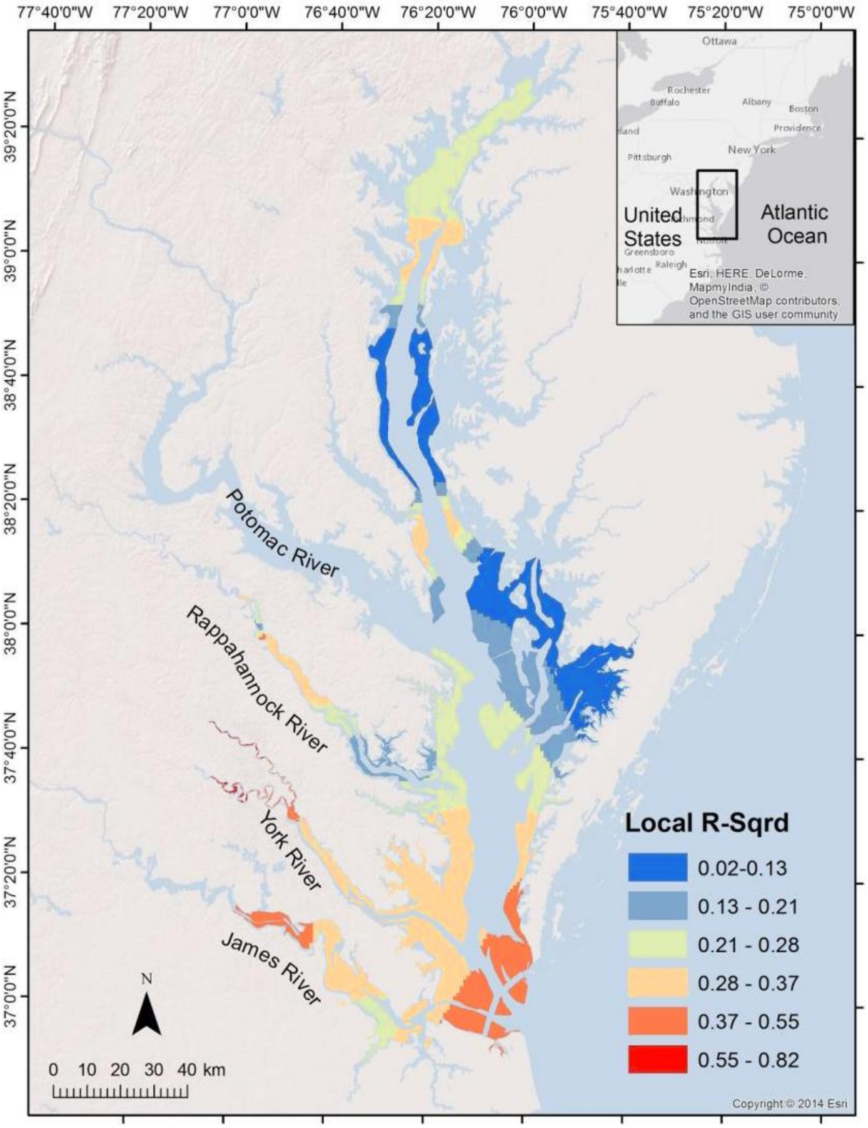


Figure 2-8. Spatial Mapping of Locally Weighted Coefficient of Determination (R^2) between GWR Observed and Fitted Values.

In addition, parameter coefficients were mapped for each independent variable where the significance was greater than 90% using the calculated pseudo *t* value (**Figure 2-9**). All parameters showed heterogeneous patterns of pseudo *t* values across the Chesapeake Bay with depth having the lowest significance of the independent parameters.

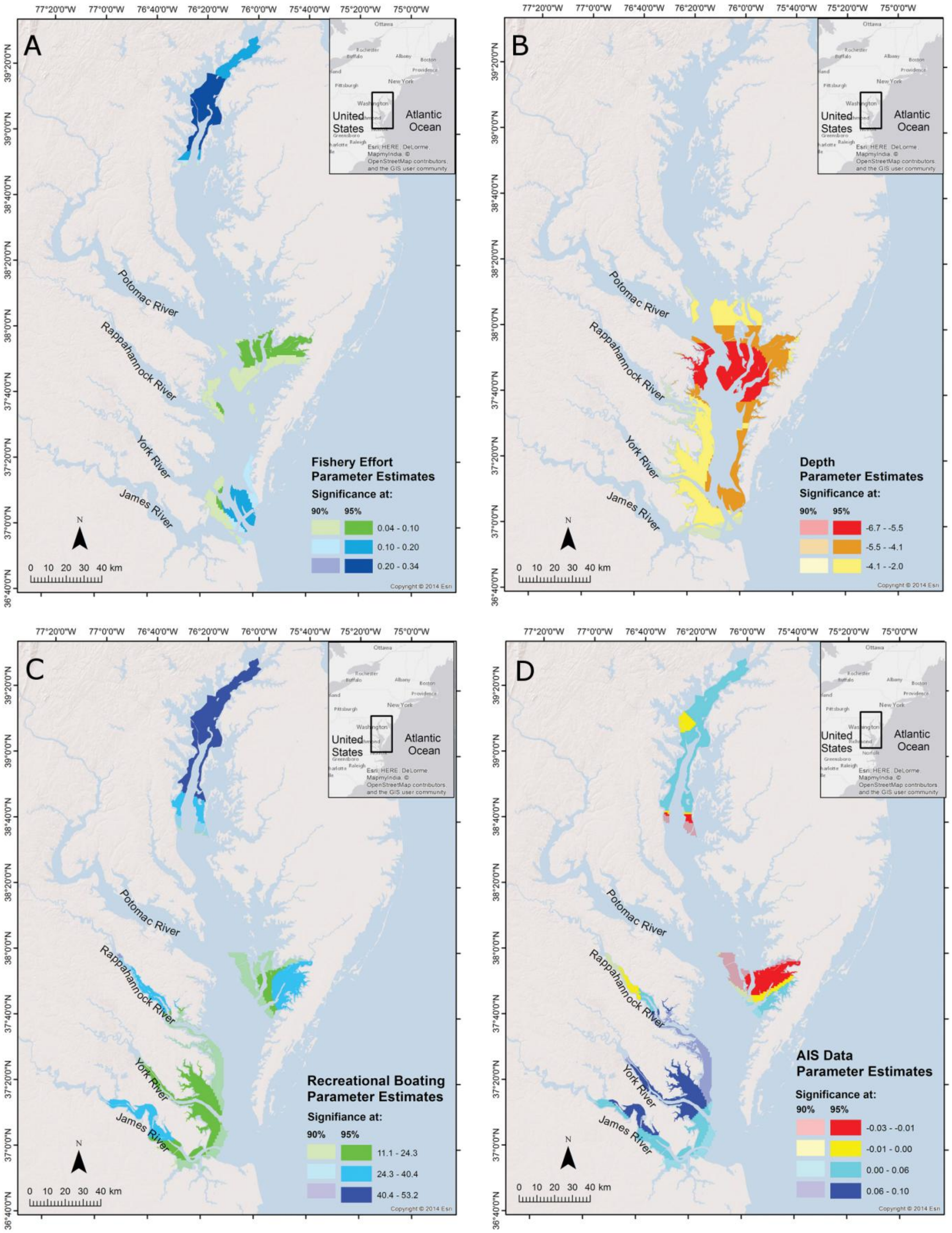


Figure 2-9. Spatial mapping of locally estimated coefficients.

Locally estimated coefficients include [A] independently measured fishing effort (Effort), [B] depth, [C] recreational boating traffic, and [D] automatic identification system vessel tracking data (AIS). Color shade denotes significance, with lighter shades for (p< 0.1) and darker shades for (p< 0.05).

Examining positive relationships between variables that can be manipulated (i.e. fishing effort and vessel traffic) indicated that higher fishing effort and greater recreational and commercial traffic occurred in most areas of higher derelict pot density (**Figure 2-10**) except in the mid-section of the Maryland portion of the Chesapeake Bay near the Choptank River.

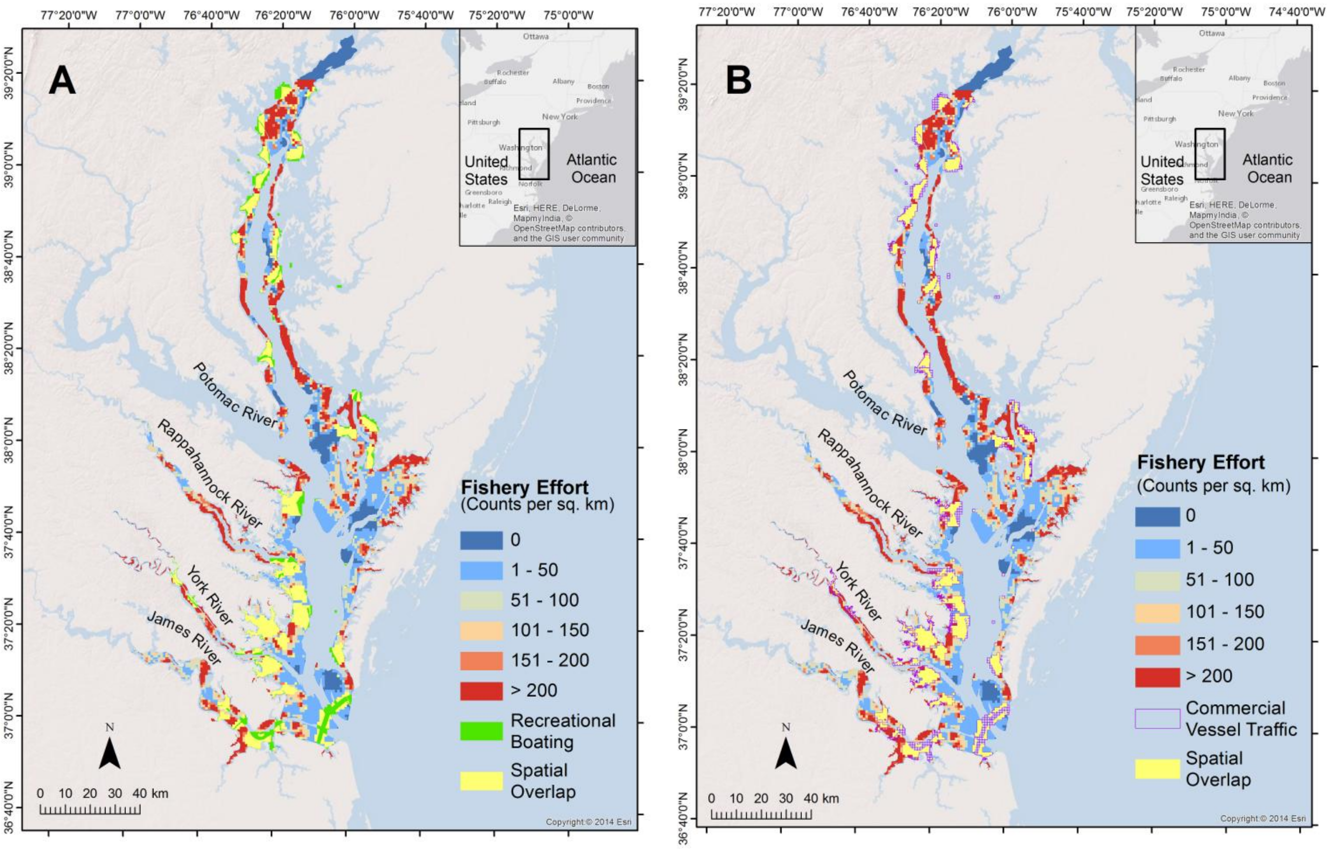


Figure 2-10. Positive impacts of Effort, Recreational Boating, and Commercial Vessel Traffic on Derelict Pot Abundance.
(A) Effort and Recreational Boating impact; (B) Effort and AIS impact. (dot = 90 derelict pots/km^2)

We used contingency analysis to test the hypothesis whether or not there was spatial overlap between predicted presence of derelict crab pots and recreational boating activity. Results indicated that only 11% (770) of grid cells had both predicted derelict crab pots and recreational boating activity whereas 80% (5,743 out of 7,216) of grid cells predicted to contain derelict crab pots did not overlap with recreational boating activity. This result indicates very low agreement and overlap occurred between derelict crab pots and recreational boating (Kappa = -0.01148782 SE= 0.003257692; p<0.063). Conversely, the absence of spatial overlap in the co-occurrence of derelict crab pots and recreational boating was significantly high (Chi-Square=5392.8, p<0.0001). Although this analysis suggested a lack of significant overlap between recreational boating and predicted presence of derelict crab pots, the result was possibly biased by the relatively small coverage of the recreational boating activity data for the Chesapeake Bay region. For example we did not have data on recreational boating activity for many grid cells where derelict pots were predicted to be present. Spatially-specific baywide data on recreational boating are needed to refine predictions of derelict pot occurrence.

2.4 Quantitative Findings from the GWR Model

Overall, the total number of derelict pots in the Chesapeake Bay was estimated at 145,233 derelict pots with 58,185 derelict pots estimated in Maryland and 87,048 in Virginia. **Figure 2-11** shows the spatial distribution of predicted derelict pots across the Bay.

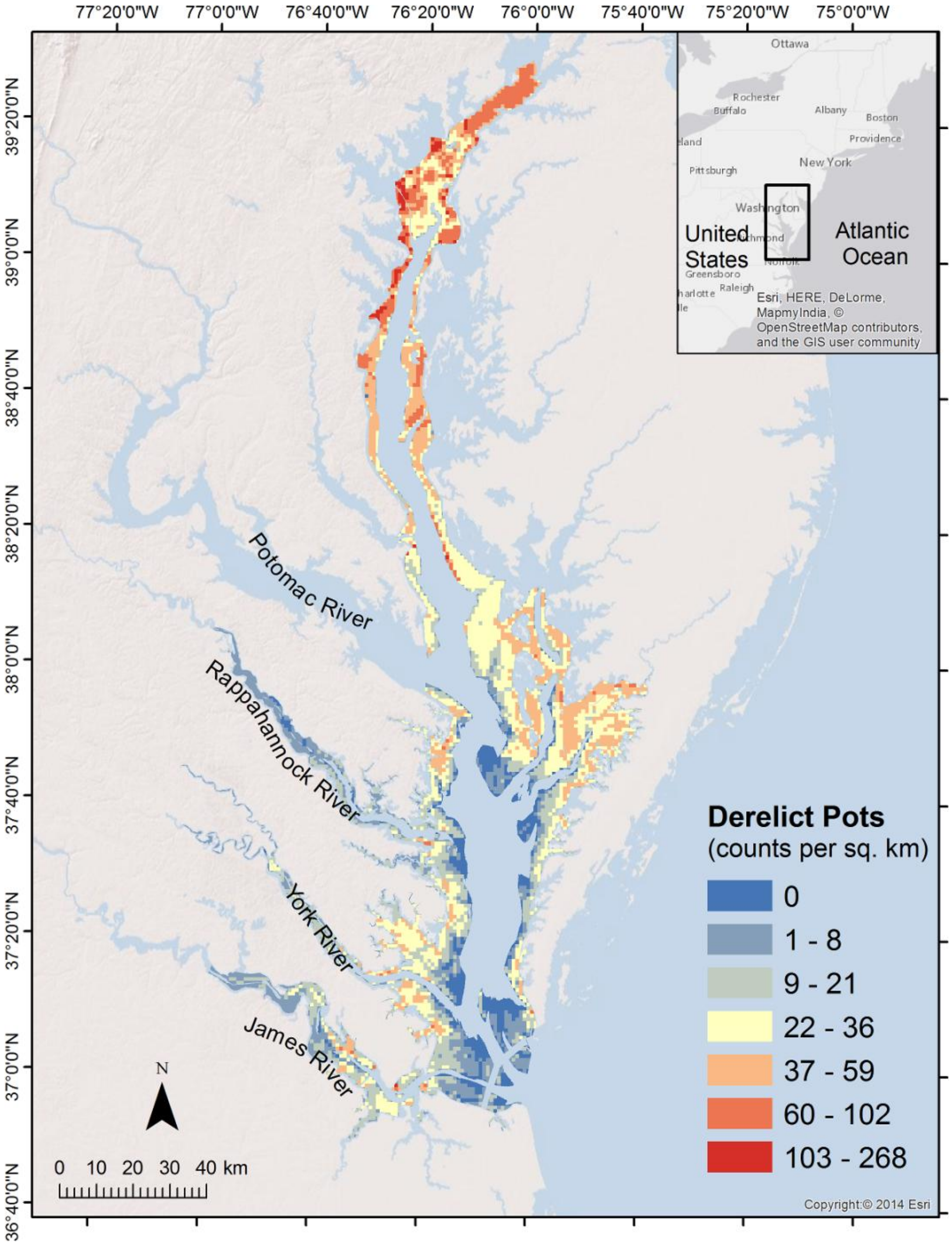


Figure 2-11. Predicted derelict crab pot densities and spatial distribution.

In addition to Bay-wide estimates, derelict pot abundance in specific regions can also be extracted from the model output: **Table 2-3** shows example numbers for several major tributaries, sounds, and mouths of tributaries.

Table 2-3. Estimated Amount of Derelict Pots in Selected Regions of the Chesapeake Bay with the Extent of the Associated Areas Where Crabbing Occurs.

Chesapeake Bay Region	Approximate Area (km^2)	Estimated Derelict Pots
Choptank Mouth	61.8	3,242
Little Choptank Mouth	60.3	2,391
Patuxent River Mouth	26.8	1,206
Eastern Bay	63.3	3,459
South River Mouth	15.8	1,438
Severn River Mouth	15.0	1,587
Magothy River Mouth	13.8	1,552
Chester River Mouth	45.8	3,059
Patapsco River Mouth	26.5	3,043
Gunpowder River Mouth	22.5	1,987
Rappahannock River	243.0	2,658
Mobjack Bay and Tribs	137.3	4,221
James River (with Elizabeth River)	414.5	7,882
Tangier Sound (MD)	192.0	7,359
Tangier Sound (VA)	99.0	3,573
Pocomoke Sound (VA)	281.0	10,209

2.5 Model Sensitivity

The goal of this predictive modeling analysis was to use known or estimated counts of derived from field surveys to predict the spatial abundance and distribution of derelict crab pots throughout the Chesapeake Bay. Through the use of co-variable datasets with extensive spatial coverage, our GWR model successfully used 856 derelict crab locations to predict the presence, absence, and mean densities and standard errors of derelict crab pots for 7,216 1 km grid cells within the Chesapeake Bay with global mean of 35.4±0.26 crab pots per grid cell. Several model performance criteria including Akaike Information Criterion (AIC), adjusted R^2, and parameter Condition number indicated that the GWR model performed adequately, although it only explained 34% of the overall variance in the estimates of the derelict crab pot density. However, locally adjusted R^2 which measures how well the model fit the available data ranged from 0.03 to as high as 0.77 for some locations. This large range in density estimate of derelict crab pots largely reflects spatial variability in the input variables. **Figure 2-12** shows a bivariate plot of predicted (from GWR) vs. observed crab pots from field surveys, with Confidence Interval ellipses. While there is an observable positive correlation between observed and predicted crab pots, this plot suggest that above a certain threshold (e.g., fishery effort of 400 crab pots per grid cell), predicted estimates of crab pots could vary widely. Nevertheless, the GWR model seems fairly robust based on the performance criteria reviewed here.

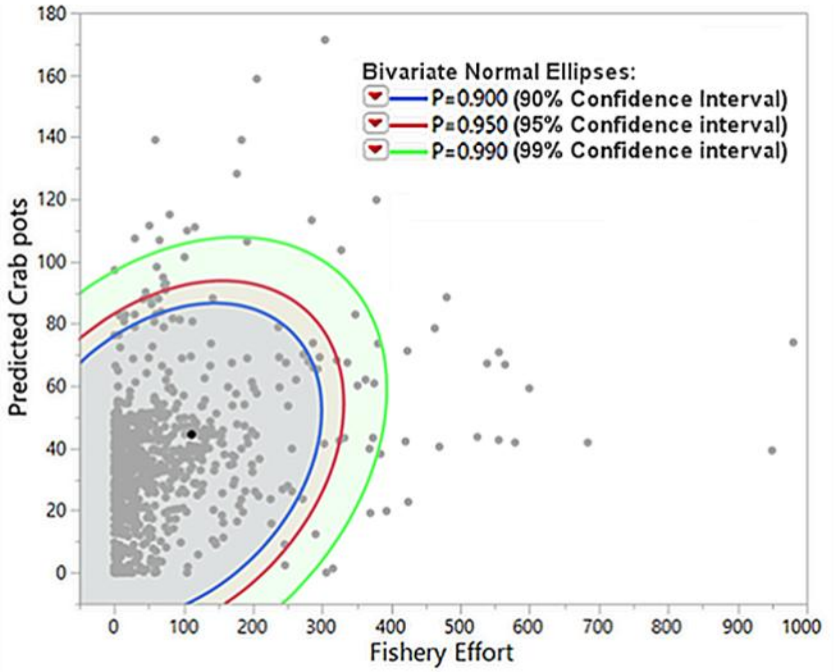


Figure 2-12. Bivariate scatterplot showing the strength of correlation and confidence interval ellipses between fishery effort and GWR predicted pot densities for the Chesapeake Bay.

2.6 Uncertainties and unknowns

Input data used for the GWR model and for quantifying potential impacts to benthic habitats were obtained from a variety of sources, were of different types (continuous and categorical), and were collected through various methods, technologies, and at a variety of spatial scales. Our spatial framework provided a useful approach for data integration, characterizing broad-scale spatial patterns in the distribution of derelict crab pots within the Chesapeake Bay, and identifying bay-wide interactions with sensitive habitats. However, it is unclear, whether these spatial patterns will hold for smaller locales. For example, because we used a grid-based approach for spatial analyses, point locations and their attributes were aggregated to 1 km^2 which could have overestimated coverages and spatial overlap between derelict crab pots and sensitive habitats. Conversely, most of the existing data on fishing effort and derelict crab pot loss are based primarily on commercial fishing, however recreational crabbing can also contribute to crab pot loss. As such our GWR predictions could underestimate abundance of blue crab pots within the Chesapeake Bay.

3. Ecological and Economic Effects Assessment

3.1 Ecological Effects

3.1.1 Ecological modeling framework and key variables

The effects of Chesapeake Bay derelict crab pots on blue crab, bycatch, sensitive habitats, and the fishery is dependent upon complex spatial and temporal interactions among these variables. Using GWR to predict the spatial patterns of Chesapeake Bay derelict crab pots was a key first step toward quantifying their ecological and economic effects. The distribution map not only provided the base for quantifying effects, but also provided useful guidance for exploratory analyses of several co-variables to evaluate their relevance. For example, direct effects of derelict crab pots could not be assumed if the modeled spatial distribution did not overlap with a particular species or habitat.

Two major ecological effects of derelict crab pots were examined: *(i)* capture and mortality of blue crab and prevalent bycatch fish species; and *(ii)* interaction with sensitive habitats. Ecological effects of derelict pots on blue crab and bycatch were quantified by applying observed blue crab and bycatch capture and mortality rates to predicted derelict pot density and distribution outputs provided by the GWR model (**Section 2.3**). To determine the potential adverse effect of derelict crab pots on Bay habitats, the spatial overlap of derelict pots with oyster reefs and submerged aquatic vegetation was quantified.

Other variables such as temperature, salinity, and dissolved oxygen vary spatially and are important environmental determinants of blue crab abundance and population demography, and indirectly affect the spatial distribution of fishing effort and derelict pot locations. The EPA Chesapeake Bay Program monitors water quality parameters throughout the Chesapeake Bay and its surrounding watershed. However, water quality variables were not included in this study because of large differences in spatial resolution and a lack of spatial overlap between water quality and derelict pot data sets within the Bay.

3.1.2 Bycatch Analysis

3.1.2.1 Estimating bycatch and mortality rates

Estimates of bycatch due to derelict crab pots were derived from field experiments conducted in Maryland and Virginia. With the Chesapeake Bay encompassing a wide range of salinity gradients, it was important to simulate derelict crab pots at field sites in both the northern low salinity and southern high salinity portions of the bay. The Maryland study was 14-month simulated study conducted by Versar and the NOAA Chesapeake Bay office between 2006 and 2008 (for additional details refer to Slacum *et al.* 2009). This Maryland study was used as a guide in developing the Virginia field experiments conducted during the 2015 crabbing season (for additional details refer to **Appendix B**).

In reviewing species that were commonly observed as bycatch in derelict crab pots, it was decided to focus on the impacts to blue crab, white perch (*Morone americana*), and Atlantic croaker (*Micropogonias undulates*). These species are common bycatch in both the Maryland and Virginia experimental derelict crab pot studies and are important commercial fisheries to the Chesapeake Bay region making their inclusion critical for a holistic bay wide assessment.

Prior to applying these estimated per pot rates to the estimated number of pots from the GWR model, several comparisons were made to review data compatibility. After comparing these baselines between the two studies, it was decided to apply the estimations derived from the field work to the Chesapeake Bay assessment for each respective state.

In addition to the catch and mortality rates, Maryland Department of Natural Resources (MDDNR) and Virginia Marine Resources Commission (VMRC) harvest data was used to guide the spatial extent of fish species distributions. By using these data as a spatial reference, we can then avoid predicting bycatch where these species do not frequently occur in the Chesapeake Bay.

3.1.2.2 Bycatch findings: blue crab

Annual blue crab catch and mortality rates from the Maryland and Virginia experimental derelict pot studies (**Table 3-1**) were applied to the estimated numbers of derelict pots from the GWR model to derive bay wide total of over 6 million crabs entrapped and over 3.3 million crabs killed annually which were mapped to review crab bycatch distribution (**Figure 3-1**). This results in an annual mortality of approximately 4.5% of the 2014 harvest (which was 35 million lbs @ 2.1 crabs/lb = 73 million crabs).

Table 3-1. Annual Measured Rates for All Blue Crabs Captured and Killed in Pots during the Simulation Studies

	Crabs per pot per year	Mean	Standard Error
Maryland	Catch	21	1.32
	Mortality	20	3.5
Virginia	Catch	65	11.5
	Mortality	25	4.4
Chesapeake Bay	Catch	43	
	Mortality	23	

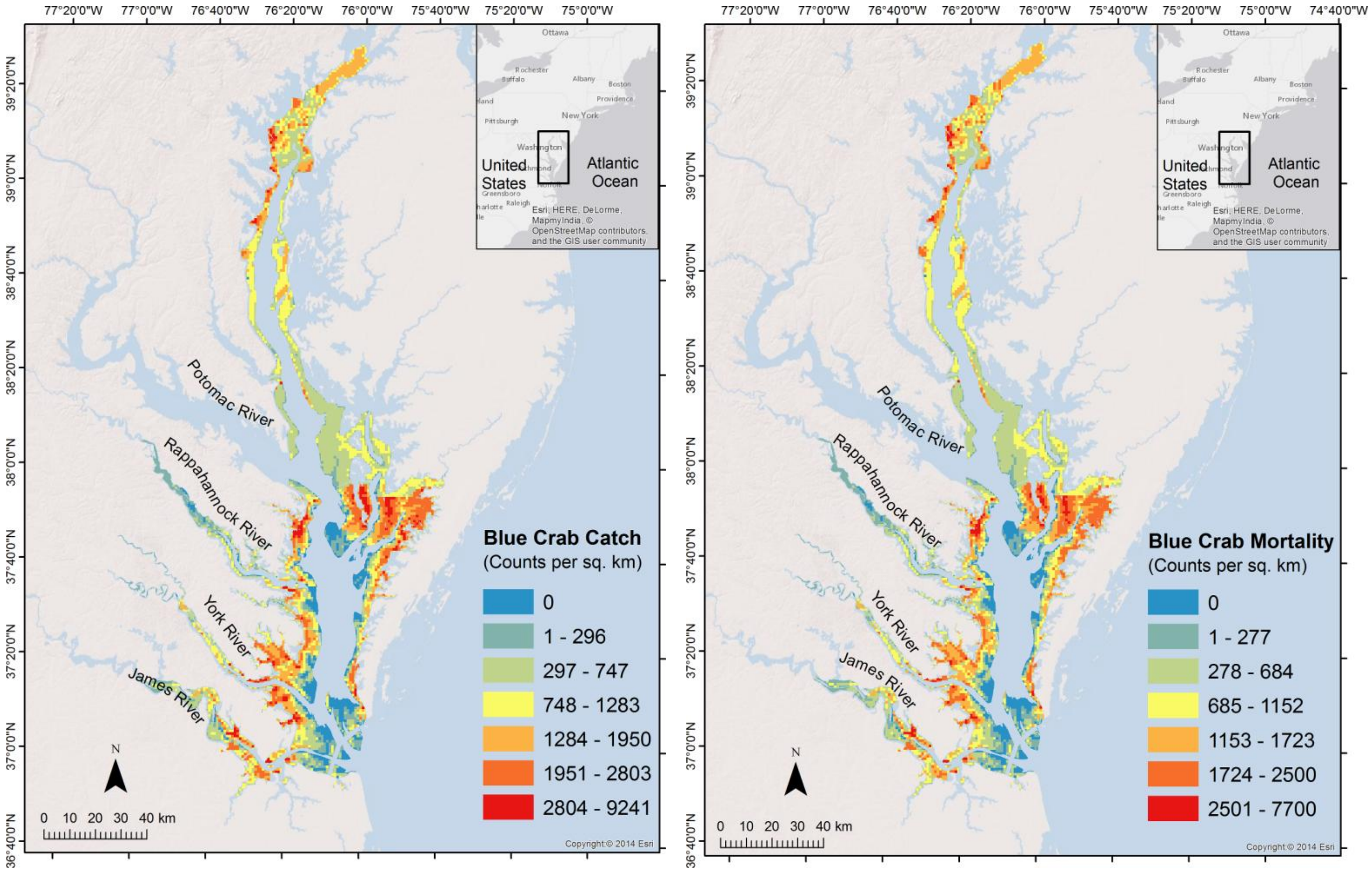


Figure 3-1. Estimated Annual Blue Crab Catch (left) and Blue Crab Mortality (right) from derelict crab pots. *Inferred from catch and mortality rates (43 & 23 crabs/pot/year) seen in simulation studies (Table 3-1).*

3.1.2.3 Bycatch findings: finfish

In addition to blue crab catch estimation, annual white perch and Atlantic croaker catch per pot were estimated from derelict pot experimental studies (**Table 3-2**, Chambers *et al.* unpublished data, Havens *et al.* 2008, Slacum *et al.* 2009). From these data and modeled numbers of derelict pots, it is estimated that derelict pots catch over 3.5 million white perch and nearly 3.6 million Atlantic croaker each year. **Figure 3-2** depicts the predicted spatial distribution of white perch and Atlantic croaker bycatch across the Bay.

Table 3-2. Annual Capture Rates for White Perch and Atlantic Croaker in Simulated Derelict Crab Pots.

State	Species	Fish per Pot per Year		Pots	Total fish per year
		Mean	Standard Error		
Maryland	White Perch	22.4	2.98	58,185	1,303,344
	Atlantic Croaker	0.89	0.45		51,785
Virginia	White Perch	25.6	3.65	87,048	2,228,429
	Atlantic Croaker	40.7	11.7		3,542,854
Chesapeake	White Perch	24.3		145,233	3,531,773
	Atlantic Croaker	24.8			3,594,638

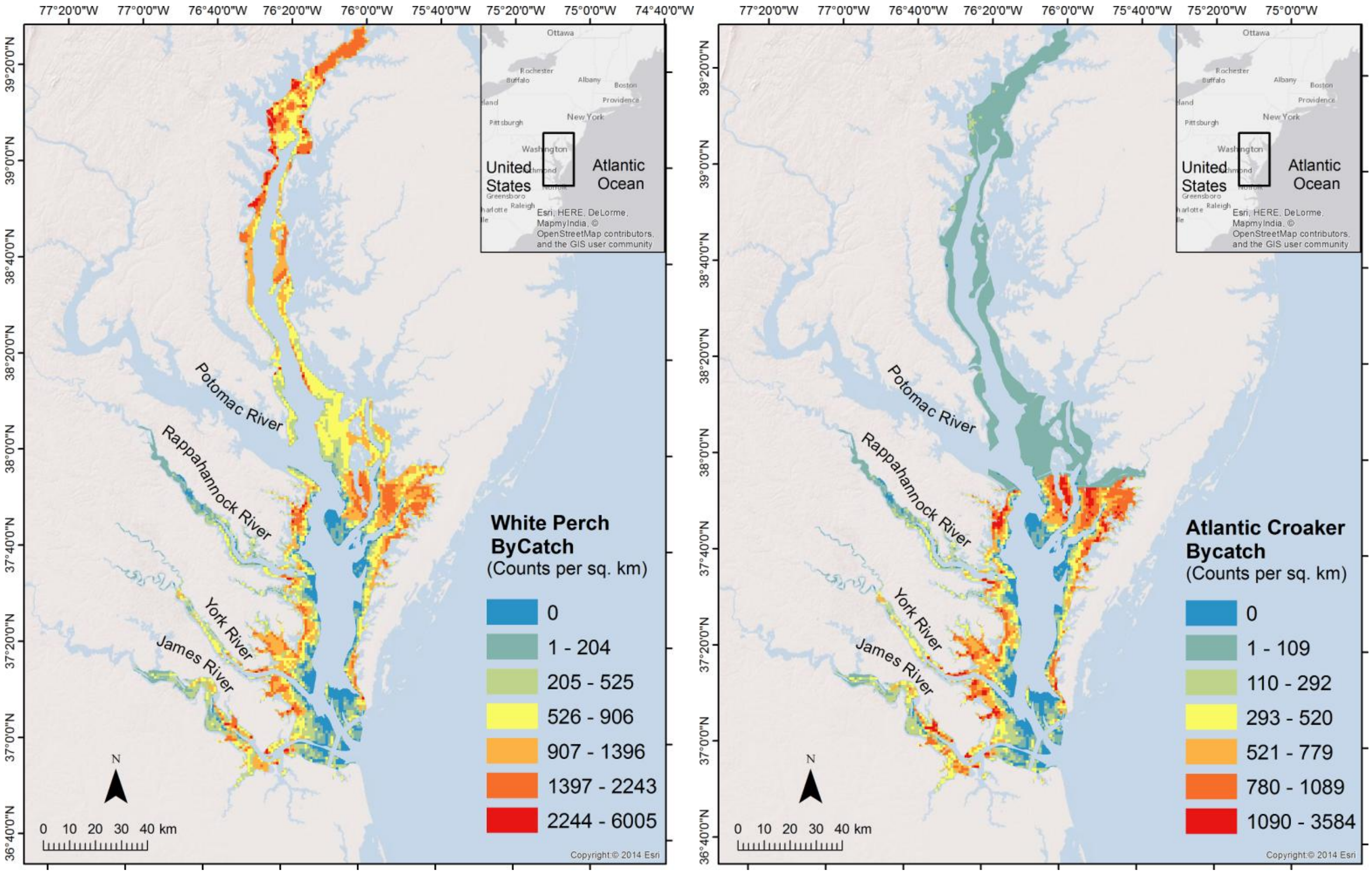


Figure 3-2. Estimated Annual Bycatch of White Perch (left) and Atlantic Croaker (right) from derelict crab pots. *Inferred from capture rates for Maryland and Virginia seen in simulation studies (Table 3-2).*

3.1.2.4 Bycatch Sensitivity Analysis; Uncertainties and Unknowns

To estimate annual bycatch for derelict pots, experiments that simulate derelict pot bycatch capture and mortality over multiple seasons and in different regions are essential. Slight differences in the experimental design of derelict pot simulation studies can influence bycatch estimates. Ideally, individuals captured would be marked and tracked over time without disturbing the pot, in an effort to most closely simulate a derelict pot. These pots will be more likely to attract additional bycatch by either acting as bait or attracting female blue crabs for mating and could help extend life expectancy within the pot as captured and killed animals may be a food source. However, this requires rigorous and time intensive field work, including divers, which may be difficult and expensive to conduct in the field for large sample sizes. Valuable information can be obtained from studies included in this assessment that periodically pull pots and do not remove animals or do not track specific individuals over time, and instead release animals with each retrieval, with an understanding that estimates derived from these approaches may be conservative.

Although there is incidental bycatch data from the pot retrieval programs, we were unable to extract fish mortality data with any confidence because data collection occurred in the winter and watermen were inconsistent with reporting of mortality. Moreover, annual catch and mortality estimates for derelict pots cannot be readily derived from incidental bycatch because of potential seasonal and spatial variability. In addition to direct mortality, delayed mortality resulting from derelict pots (injury, stress, infection, fatigue) is considered a significant issue and could result in increased mortality rates over time (Guillory 1993, Guillory 2001, Uhlmann & Broadhurst 2015). Mortality estimates presented in this report do not include any possible delayed mortality; therefore, these values may be underestimating total mortality.

3.1.3 Habitat impact analysis

3.1.3.1 Estimating interactions with sensitive benthic habitats

Research assessing the ecological impacts of marine debris suggest that derelict pots can damage the seafloor as well as sensitive shoreline and benthic habitats (Sheridan *et al.* 2005; Uhrin *et al.* 2005; Uhrin and Schellinger, 2011; Clark *et al.* 2012; Arthur *et al.* 2014). For a more comprehensive review of potential marine debris impacts on coastal and benthic habitats please refer to a recent report from the NOAA Marine Debris Program (2016; https://marinedebris.noaa.gov/reports/marine-debris-impacts-coastal-and-benthic-habitats).

Derelict crab pots can have physical damaging impacts on sensitive benthic habitats. The Chesapeake Bay comprises a variety of benthic habitats; submerged aquatic vegetation (SAV), marshes, turtle nesting beaches, and oyster reefs are considered important and sensitive habitats. Based on available data, the spatial coverages of these habitats seem relatively small (SAV~4%, Oyster reefs ~ 7% of mapped area), but they are actively protected and restored by federal state, and local agencies, along with industry, academic institutions, and nonprofit groups.

Given their widespread occurrence within the Chesapeake Bay tidal waters, it is possible that derelict crab pots can have interactions with sensitive habitats, and that their removal can aid in recovery and conservation of those habitats. June and Antonelis (2009) and Uhrin *et al.* (2005) respectively reported a 30% increase in (eelgrass) recovery in Puget Sound and full recovery of *Spartina alterniflora* (smooth cordgrass) in North Carolina tidal marsh after removal of crab pots. Benthic habitat data compiled by the NOAA Chesapeake Bay Office Benthic Habitat Integration Program indicate that SAV occupies ~512 km^2 and natural oyster reefs cover ~907 km^2 of the Chesapeake Bay. A typical crab pot has a footprint of 0.36 m^2; so assuming a summer deployment of 350,000 crab pots and an estimated 12-20% loss rate, lost crab pots could potentially physically disturb between 0.015 km^2 and 0.025 km^2 of the Chesapeake Bay seafloor annually. However, it is likely that the disturbance area is greater than this because of derelict pot movement across the seafloor.

For this study we mapped the locations of SAV and oyster reefs throughout the Chesapeake Bay for comparison with observed and predicted distributions derelict crab pots. Shapefiles showing the spatial coverage of SAV for the Chesapeake Bay region were obtained from VIMS (http://web.vims.edu/bi /sav/gis_data.html). VIMS mapped the coverage and density of SAV based on aerial photography collected at a scale of 1:24,000 for various regions of the Bay. For this analysis, composited annual SAV surveys covering the years 2003-2012 were used to be representative of potential SAV coverage in recent years. Natural oyster reef distribution was represented using the "Chesapeake_Bay_habitat" shapefile developed by the Maryland Department of Natural Resources Fisheries Division (Greenhawk 2005). This shapefile combines historic oyster reef surveys from Maryland and Virginia.

3.1.3.2 Habitat findings: submerged aquatic vegetation

To test the potential for spatial overlap between derelict crab pots and SAV occurrence within the Chesapeake Bay, derelict pots predictions from the GWR model were spatially intersected with the SAV map. Polygon grid cells with predicted derelict crab pot counts > 0 were recoded as 1 (indicating presence), whereas grid cells with predicted derelict pots counts = 0 were considered lacking derelict crab pots. Similar coding was done for the SAV map. This yielded a dataset with 7,216 grid cells each attributed with either presence or absence of predicted derelict crab pots and SAV (**Table 3-3**). A two-way contingency analysis was used to measure the degree of agreement (i.e. spatial overlap) between the occurrence of derelict crab pots predicted from the GWR model and SAV. Results indicated that only 15% (1,039) of grid cells had both predicted derelict crab pots and SAV coded 'present' whereas 76% (5,460 out of 7,216) of grid cells predicted to contain derelict crab pots were mapped as SAV absent (**Table 3-3**). Of the 1,053 grid cells with spatial overlap between derelict pots and SAV, 490 were in Maryland and 563 were in Virginia (**Figure 3-3**). This result indicates very low agreement and overlap occurred between derelict crab pots and SAV (Kappa = 0.00506 ± 0.0031; p<0.063). Conversely, the absence of spatial overlap (i.e. disagreement) in the co-occurrence of derelict crab pots and SAV was significantly high (Chi-Square=5,172, p<0.001). Given that derelict pot presence is highly correlated with fishing effort, these results suggest that blue crab operators generally may have avoided crabbing in SAV habitats. An important caveat however, is that National Environmental Policy Act requirements restricted derelict pot removal activity in sensitive habitats such as SAV and that the model for predicted derelict crab pot occurrence was based, in part, on data from retrieval programs that avoided pot removal from these habitats. To what degree these data negatively biased the amount of spatial overlap between derelict crab pots and SAV habitats is unknown and may require further investigation.

Table 3-3. Presence-absence contingency table showing counts of 1 km x 1 km grid cells containing submerged aquatic vegetation (SAV) and predicted derelict pots

Predicted Derelict Pots	SAV	Count	Expected	Percent
Present	Present	1,053	1,039	15
Present	Absent	5,460	5,474	76
Absent	Present	98	112	1
Absent	Absent	605	591	8
Total		7216	7216	100

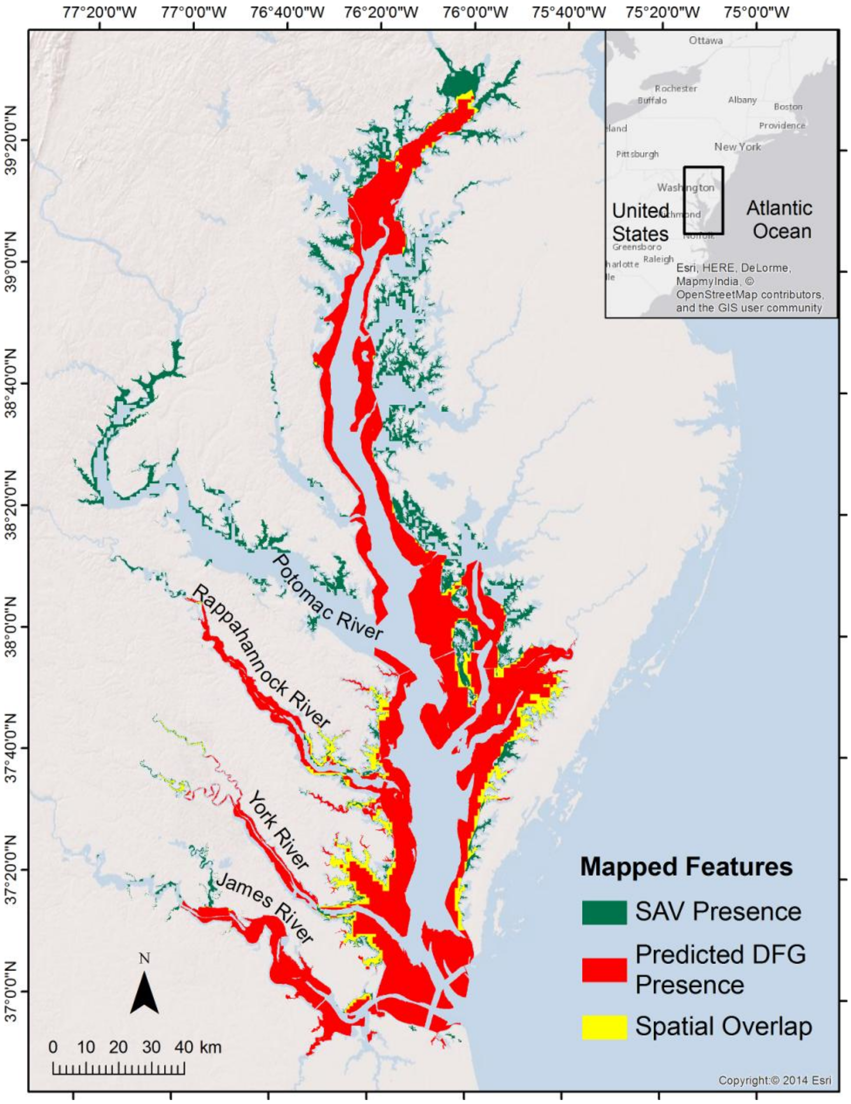


Figure 3-3. Potential spatial overlap between derelict crab pots and SAV habitats within the Chesapeake Bay.

3.1.3.3 Habitat findings: oyster reefs

The degree of spatial overlap between the occurrence of derelict crab pots and locations of oyster reefs was similarly tested with a two-way contingency analysis. Results showed that there was very little spatial overlap in the occurrence of derelict crab pots and oyster reefs within the Chesapeake Bay (Kappa = -0.0018 ± 0.0043; p<0.037). Only about 21 % (1,486 out of 7,216) of grid cells had both predicted derelict crab pots and oyster reefs whereas 70% (5,027 out of 7,216) of grid cells had predicted derelict crab pots but were not mapped as oyster reefs (**Table 3-4**). The areas of spatial overlap were well distributed throughout the Chesapeake Bay, but lower for Maryland (568 grid cells) than for Virginia which has 918 grid cells were derelict pots and oyster reefs overlap (**Figure 3-4**). Conversely, the absence of spatial overlap (i.e. disagreement) in the co-occurrence of derelict crab pots and oyster reefs was significantly high (Chi-Square=4479, p<0.001). Given that derelict pot presence is highly correlated with fishing effort, the absence of high spatial overlap between derelict pots and oyster reefs suggest that blue crab operators may be targeting non-oyster reef habitats.

Table 3-4. Presence-absence Contingency Table Showing Counts of 1 km x 1 km Grid Cells with Oyster Reefs and Predicted Derelict Pots

Predicted Derelict Pots	Oyster Reef	Count	Expected	Percent of Total
Present	Present	1,486	1,515	21
Present	Absent	5,027	4,999	70
Absent	Present	192	164	3
Absent	Absent	511	540	7
Total		7,216	7,216	100

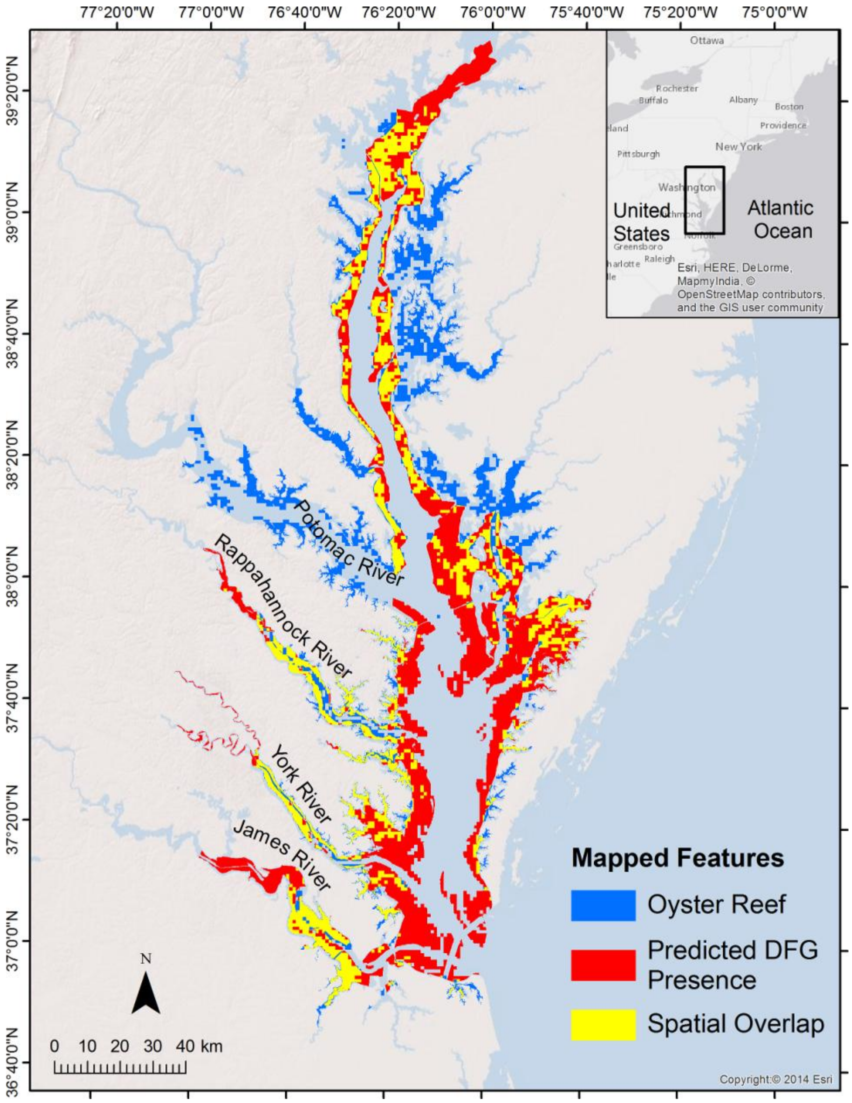


Figure 3-4. Potential spatial overlap between derelict crab pots and mapped oyster reefs within the Chesapeake Bay.

3.2 Economic Effects

There can be both direct and unexpected, indirect economic costs from derelict fishing gear, such as crab pots. Direct mortality of target and bycatch species is considered an ecological loss, though economic costs might be imposed if these animals would have contributed to commercial harvests or recreational fisheries, or hold significant non-use value. Derelict gear may also decrease harvests and recreational catch by attracting target and bycatch species, reducing the efficiency of actively fished gear and imposing a cost entirely independent of any economic losses associated with increased mortality. Other economic costs imposed by derelict fishing gear include damage to sensitive habitats, hazards to navigation, and replacement gear costs (**Figure 3-5**).

Harvest Loss from derelict crab pots – Though mortality of target and bycatch species may be significant (Slacum *et al.* 2009, Bilkovic *et al.* 2014, Section 2 of this report), due to the nature of the target species fishery, lost harvests arising from competition between active and derelict gear were also thought to be substantial. These economic costs—commercial harvests of the target species lost as a result of inefficient and underproductive gear—can be determined by assessing the effects of derelict pot removals on harvests. This modeling approach requires temporally and spatially resolved data on 1) retrieved derelict pots, 2) effort, 3) harvest, and 4) stock abundance. Annual price data are required to infer changes in revenues from predicted harvest changes. The inclusion of stock abundance is necessary to account for variations in natural factors or management actions that may contribute to shifts in stock recruitment and/or survival. Evaluating changes in harvest while controlling for abundance of the target species removes any harvest increases resulting from reduced mortality due to fewer derelict pots.

Decreased Harvests	Habitat Damage	Navigational Hazard	Replacement Gear
• Results from: stock reductions and/or reductions in efficiency of active gear	• Results from: physical damage to habitats which provide important ecosystem services	• Results from: necessary changes in navigation due to the presence of derelict gear and/or damage to vessels and equipment	• Results from: lost gear which would either need to be replaced or would require changes in behavior to reduce initial loss
• Costs from stock effects may be significant under high rates of capture and mortality by derelict gear	• Costs may be significant for sensitive and/or valuable habitats; where strong currents or storm events create substantial movement of derelict gear; and in instances of slow gear degradation	• Costs may be significant in areas with heavy vessel traffic and where waterways are used by a variety of groups with differing navigational patterns, constraints, and abilities	• Costs may be significant where gear is expensive; in instances where derelict gear physically damages active gear; or where behavioral changes to mitigate loss are not costly
• Costs from reductions in gear efficiency may be significant in fisheries with spatially concentrated effort and where derelict gear acts as an artificial habitat			

Figure 3-5. Potential Economic Costs of Derelict Fishing Gear.

Decreased harvests were modeled for the Chesapeake Bay using spatially resolved data on retrieved derelict pots, effort, harvest, and stock abundance.

3.2.1 Quantitative findings

Baywide economic benefits to subsequent blue crab harvest resulting from derelict pot removals were estimated using temporally and spatially resolved data on 1) retrieved derelict pots in Maryland (2010 and 2012) and Virginia (2008-2014), 2) effort (VMRC, MDDNR), 3) harvest (VMRC, MDDNR), and 4) stock abundance (Chesapeake Bay Stock Assessment Committee 2014; not spatially resolved). A spatially explicit harvest model was used to predict commercial blue crab harvests in the Chesapeake Bay under two scenarios: actual derelict pot removals and a counterfactual of zero derelict pot removals (i.e., what would have been harvested had no derelict pots been removed during 2008-2014 in Virginia and 2010 and 2012 in Maryland). The difference in these predictions provided a robust assessment of the removal programs' effect on harvests (**Appendix G**. Scheld *et al.* 2016).

Baywide – Model results indicate that the 43,968 removals in both VA (34,408 removals, 2008-2014) and MD (9,560 removals, 2010 and 2012) increased harvests by 38.17 million lbs (SE = 6.31), or a 23.8% increase above that which might have resulted had no removals occurred (**Table 3-5**, model RE VA-MD; **Figure 3-6**). These gains are estimated to be valued at $33.5 million in revenues (2014 dollars).

Table 3-5. Results from Different Models used to Evaluate the Economic Effects of Derelict Gear Removals.

Model:	**RE VA-MD**	**FE VA-MD**	**RE VA**	**FE VA**	**RE MD**	**FE MD**
VA-MD Δ Harvest *(millions of lbs)*	38.17 (6.31)	27.45 (5.25)	—	—	—	—
VA Δ Harvest *(millions of lbs)*	30.09 (3.78)	20.83 (2.81)	29.71 (3.74)	19.88 (2.70)	—	—
MD Δ Harvest *(millions of lbs)*	*8.08* (4.41)	*6.62* (4.09)	—	—	*2.83* (7.94)	*-0.06* (7.68)
Δ Harvest / Pot Removed (VA-MD) *(lbs)*	868 (144)	624 (119)	—	—	—	—
Δ Harvest / Pot Removed (VA, 2009-2014) *(lbs)*	875 (110)	605 (82)	864 (109)	578 (78)	—	—
Δ Harvest / Pot Removed (VA, 2013 & 2014) *(lbs)*	2,270 (461)	1,032 (366)	2,053 (450)	854 (354)	—	—
Δ Harvest / Pot Removed (MD, 2010 & 2012) *(lbs)*	*845* (462)	*693* (427)	—	—	*296* (830)	*-7* (803)
Δ Harvest / Pot Fished (VA-MD) *(lbs)*	0.43 (0.07)	0.31 (0.06)	—	—	—	—
Δ Harvest / Pot Fished (VA, 2009-2014) *(lbs)*	0.48 (0.06)	0.33 (0.04)	0.48 (0.06)	0.32 (0.04)	—	—
Δ Harvest / Pot Fished (MD, 2010 & 2012) *(lbs)*	*0.31* (0.17)	*0.25* (0.16)	—	—	*0.11* (0.30)	*-0.002* (0.29)

Notes on Table 3-5:

- All models used a translog Schaefer harvest specification allowing for area specific catchabilities.
- Random effects (RE) and fixed effects (FE) models were estimated using Virginia (VA) and Maryland (MD) data alone as well as jointly (VA-MD).
- VA-MD models allowed harvest elasticity parameters to differ by state due to differences in commercial fishery regulations, data collection, and removal programs. FE models were fit after removing group (area) means from all variables.
- Standard errors are presented in parentheses beneath average effects; they were constructed using a semi-parametric (residual) bootstrap of parameters in the harvest model.
- Estimates not significant at a 95% level of confidence are in *italics*.

Harvest improvements came from increases in the efficiency of actively fished gear, which averaged 0.43 lbs/pot (**Table 3-5**, model RE VA-MD). This amounts to nearly an additional crab every time a pot was pulled in a year following removals (1 blue crab ≈ 0.475 lbs). Harvest increases per pot removed were also substantial, averaging 868 lbs. Benefits from removals were spatially heterogeneous and tended to be concentrated in high effort areas near the main-stem of the bay (**Figure 3-7**).

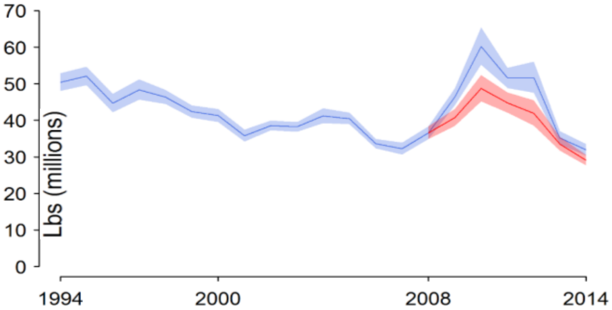


Figure 3-6. 95% Confidence Region of Chesapeake Bay Blue Crab Harvests with (Blue) and without (Red) Derelict Gear Removals.

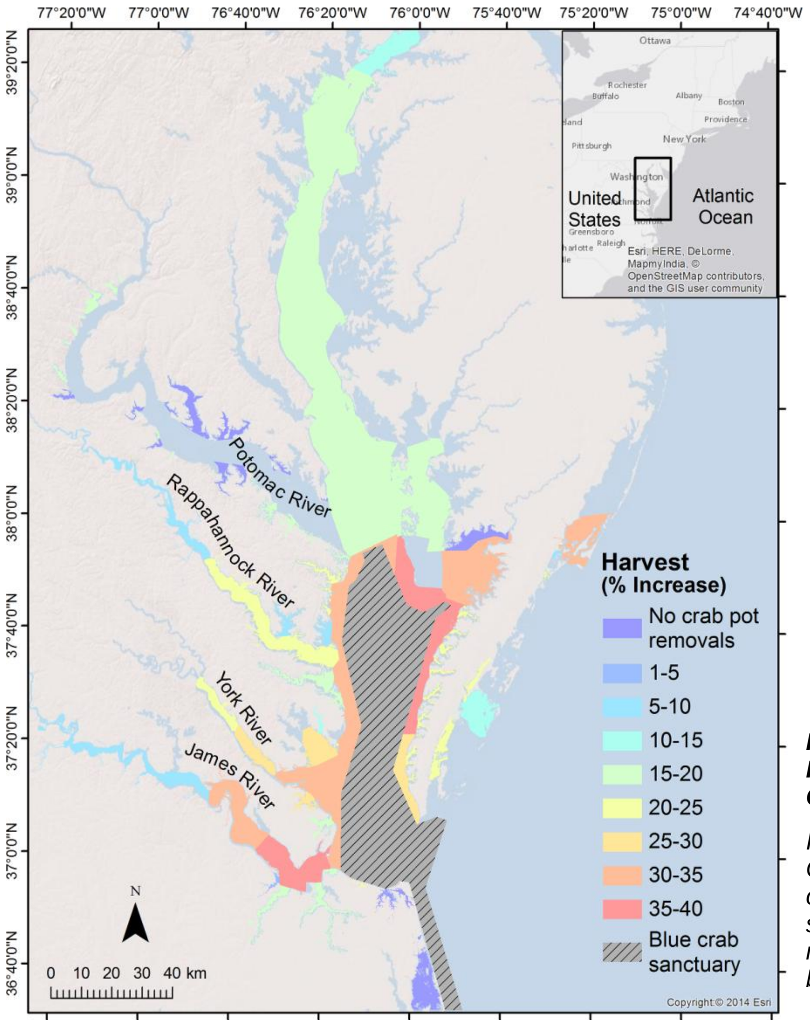


Figure 3-7. Increase in Blue Crab Harvest Resulting from Removal of Derelict Blue Crab Pots.

Increased harvests were modeled for Chesapeake Bay using spatially resolved data on retrieved derelict pots, effort, harvest, and stock abundance. The hatched area in the mainstem of the Bay represents the no-take blue crab sanctuary.

The effect of removals on commercial harvests was more difficult to assess in Maryland due to the limited spatial resolution of the data (9 management areas as opposed to 54 in Virginia) and fewer removal observations. A significant implication of these findings is that derelict gear recovery programs can yield substantial net economic benefits.

Harvests per pot were observed to be greater in areas with removals both during the removals program and when compared to harvests prior to removals (**Table 3.6**, **Table 3.7**).

Table 3.6. Average harvest/pot during years of removals in areas with and without removals

	No Removals	Removals
VA 2009 – 2014	1.45 (0.50)	2.17 (0.62)
MD 2010 & 2012	*1.88 (0.60)*	*2.18 (0.61)*

Notes on Table 3-6:

- Standard deviations are shown in parentheses.
- *Italics* indicate average harvest/pot not statistically different at a 95% level of confidence between areas with and without removals.
- Sample sizes varied depending on the size and number of management areas in each state, years of removals, and the number of areas which experienced removals in a given year (VA No Removals, n=110; VA Removals, n=190; MD No Removals, n=8; MD Removals, n=10).

Table 3.7. Average harvest/pot before and after the first year of removals in areas with and without removals.

	Before (2008)	After (VA – 2009; MD – 2010)
Removals (VA, n=38)	1.84 (0.48)	2.06 (0.68)
No Removals (VA, n=12)	*1.56 (0.70)*	*1.50 (0.52)*
Removals (MD, n=5)	1.95 (0.66)	2.58 (0.51)
No Removals (MD, n=3)	*2.15 (0.47)*	*2.22 (0.46)*

Notes on Table 3-7:

- Standard deviations are shown in parentheses.
- *Italics* indicate average harvest/pot not statistically different at a 95% level of confidence before and after the first year of removals.

Virginia model results indicate that the removal program increased harvests by 30.09 million lbs (SE =3.78), or 27.2%. These gains are valued at $22.6 million in dockside revenues (2014 dollars). Efficiency gains for active gear averaged 0.48 lbs/pot; average harvest increases per pot removed were estimated at 875 lbs (**Table 3-5**, model RE VA-MD). Targeted removals from derelict gear hotspots in 2013 and 2014 were found to be highly effective. During this time, harvest increases per pot removed grew considerably, averaging 2,270 lbs. All estimated removal effects in Virginia are significant at a 99% confidence level.

Maryland model results indicate that the removal program increased harvests by 8.08 million lbs (SE = 4.41), or 16.3%. Maryland harvest gains are valued at $10.9 million (2014 dollars; note that blue crab prices are frequently 30-50% higher in Maryland). Active gear efficiency is estimated to have increased by 0.31 lbs/pot; average harvest increases per pot removed were estimated at 845 lbs (**Table 3-5**, model RE VA-MD). Removal effects in Maryland were not statistically significant at a 95% confidence level.

3.2.2 Sensitivity analysis

Semi-parametric (residual) bootstraps were used in quantitative economic modeling to incorporate uncertainty in parameter estimates and model results. During the bootstrap procedure residuals were resampled and used to construct synthetic observations before re-estimating the statistical harvest model.

All standard errors presented, as well as those shown in **Table 3-5**, were calculated based on 10,000 bootstrap draws of the parameter vector.

Data quality concerns regarding effort reporting accuracy were handled through sensitivity analyses. A resampling procedure was used to evaluate the impact of variable effort misreporting. Three scenarios were considered: 1) half of all observations underreport actual effort by 50%; 2) three-quarters of all observations underreport actual effort by 50%; and 3) one-quarter of all observations underreport effort by 50% while one-quarter of all observations over-report effort by 50% (note that, for Maryland, the scenarios considered represented effort misreporting in addition to what had already been assumed and corrected for). After adjusting effort (number of pots) for a random sample of observations, which corresponded, to the specific misreporting scenario being evaluated, models and removal effects were re-estimated. This process was repeated 10,000 times for each misreporting scenario. (For a detailed description as applied to Virginia data, see Scheld *et al.* 2016, and Supplementary Information at http://www.nature.com/article-assets/npg/srep/2016/160121/srep19671/extref/srep19671-s1.pdf.)

The effects of variable effort misreporting were found to be fairly minimal. Estimated average harvest increases ranged from 31.5 (scenario 3) to 35.7 (scenario 2) million lbs, or roughly 82-93% of the harvest increases estimated under the null model. None of the three effort misreporting scenarios tested yielded results that were statistically different at a 95% confidence level from those estimated by the null model. This sensitivity analysis indicates that even in instances of substantial, and variable, misreporting of effort, derelict gear removal is still found to have large and positive commercial harvest effects. General results should therefore be viewed as considerably robust to misreporting of effort.

3.2.3 Uncertainties and unknowns

Commercial fisheries in each state operate differently and are managed by separate agencies (though cooperation in data collection and stock assessment does exist through the annual winter dredge survey and the Chesapeake Bay Stock Assessment Committee). As such, fishery data are collected under different processes and protocols, varying in terms of their spatial resolution, and perhaps, their degree of accuracy. Parameters were included in the statistical harvest model to capture state-by-state differences in underlying relationships, however large disparities in spatial resolutions among the two states and potential differences in data quality present challenges to a comprehensive and integrative assessment.

The modeling approach aimed to isolate effects of derelict gear removals by controlling for other factors influencing harvests. The final model controlled for both observed variables (effort, stock) and unobserved spatiotemporal effects. Still, the potential for confounding bias can never be entirely ruled out. If unobserved deterministic factors were correlated with removals (spatially and in magnitude) then the model may yield inconsistent estimates. Fortunately, there is little reason to expect this is the case.

4. Management Scenarios – Mitigation Alternatives

4.1 Introduction

Policies and management actions to reduce the loss of derelict fishing gear and its effect once lost are vital for any successful strategy to address the issue of derelict blue crab pots. Several different management and policy actions have been suggested for reducing the amount and impact of derelict pots. The loss of crab pots in the Chesapeake Bay, estimated between 12 – 20%, can be categorized as accidental or intentional (Arthur *et al.* 2014) while reduction of derelict pot effects can be divided into pot removal, pot modifications, and policy changes (Slacum *et al.* 2009, Havens *et al.* 2011).

4.2 Accidental and Intentional Loss

Accidental loss can result from improper equipment, or equipment failure, such as breakage at the line/buoy or line/pot attachment point, insufficient weighting of pot, insufficient line length, entanglement of pot trotlines, or line to dock breakage in the recreational fishery. Storm events and abnormal water currents and tides also contribute to pot loss. In 1999, over 100,000 crab pots were reported lost due to Hurricanes Dennis and Floyd (NCDMF 2013). Storms or strong currents can tumble pots wrapping the line around the pot and pulling the buoy underwater, move pots into deeper water where the buoy line no longer reaches the surface, or cause pot 'pile-up' and line entanglement. In some cases, pots are stored in advance of storms or in the closed season on estuarine islands or marshes. Such storage of pots on marshes can be problematic, affecting marsh vegetation, trapping terrestrial animals, and can become particularly troublesome when storms wash pots into adjacent waters (Lee 2009, Uhrin and Schellinger 2011, Voss *et al.* 2015).

Resource user conflicts between commercial crabbers, recreational users, and commercial shipping activities can result in pot loss due to propeller or keel entanglement (Breen *et al.* 1990). Reducing spatial conflicts between crab pots in the water and other uses may minimize pot loss. In the Chesapeake Bay a relationship between high shipping and recreational boat traffic and pot loss exists – though the modeled overlap is slightly more than 10% which may be an artifact of limited spatially explicit information on recreational boating activity. Restricting commercial vessel traffic to channels and keeping pots out of channels can reduce pot loss. Education of recreational boaters on the consequences of lost pots, how to avoid pots, and what to do should their vessel become entangled in a pot should be an ongoing program (i.e. Coast Guard auxiliary, boater safety classes). The use of reflective tape on pot buoys has been shown to reduce pot loss rates from 17% to 7% in some areas (Hassell 2007). In addition, the use of "line cutters" (cf. http://www.spursmarine.com/shaft-main.html) on propellers in areas where potting activity occurs can be problematic and lead to additional unnecessary pot loss.

4.3 Reduction of Derelict Pot Effects

4.3.1 Pot removal

In some instances, pots are intentionally discarded, vandalized, or left in the water as part of periodic pot replacement. Abandoned pots (pots that still had the line and buoy attached) have been observed in Maryland (W. Slacum per. communication) and made up 41% of the recovered pots in the four year Virginia removal program (Bilkovic *et al.* 2014). In addition to the marker buoy, identification of pot ownership with a tag on the pot itself that is replaced annually with the purchase of the commercial license has been suggested as a mechanism to reduce intentionally discarded pots (Lee 2009) and is required by the Potomac River Fisheries Commission in the Potomac River of the Chesapeake Bay. Adequate allocation of resources to state marine resource agencies to enforce the removal of illegal pots during the closed season could alleviate a large source of derelict pots.

In many states, legal restrictions prohibit the removal of derelict pots except by authorized agents. Allowing citizens to remove derelict pots during the closed season would empower local communities to police their own waterways, but could be problematic in the Chesapeake Bay where some pot fisheries remain active during the blue crab closed season and could be mistaken for abandoned pots (i.e eel pots). In addition, allowing disposal of pots in landfills at no charge would incentivize proper disposal of pots (NCDMF 2013).

In the Chesapeake Bay, direct mortality of blue crabs from derelict pots is estimated to be 4.5% of the blue crab harvest. Derelict pots removed during the winter months in the Virginia and Maryland removal programs had different percentages of entrapped mature females, 60% and 36%, respectively (Bilkovic *et al.* 2014, Slacum *et al.* 2013) which is indicative of blue crab distribution in the Chesapeake Bay. The 60% mature female catch ratio in Virginia is similar to the ratio of females versus males (67% vs. 33%) found in a study of blue crab catch during the regular season in Virginia (Bilkovic *et al.* 2012) and this study (56%) which suggests a potential impact of derelict pots on the blue crab breeding population (Havens *et al.* 2011) similar to the derelict pot effect reported for red king crab (Long *et al.* 2014) . The removal of derelict pots from high intensity potting areas (hotspots) can produce significant economic benefit beyond reducing mortality (Scheld *et al.* 2016). For example, removing just 10% of derelict pots (approximately 4,400) from the five most heavily fished sites in each of Virginia and Maryland could increase blue crab harvest in the Chesapeake Bay by 22 million pounds or approximately 14%.

4.3.2 Pot modifications

Blue crab pots capture numerous species of animals besides blue crabs including diamondback terrapin and even Atlantic sturgeon, *Acipenser oxyrinchus oxyrinchus,* (Mangold *et al.* 2007). Animals recorded captured by derelict pots in the Chesapeake Bay are listed in **Table 4-1** and the incorporation of biodegradable escape panels in crab pots has been recommended as a mechanism to reduce bycatch mortality (Guillory 1993, McKenna and Camp 1993, Guillory 2001, Lee 2009, Havens *et al.* 2011, Wagner 2013, NCDMF 2013, Arthur *et al.* 2014, Bourgeois *et al.* 2014, Voss *et al.* 2015, Perry *et al.* 2015). In Virginia, watermen tested biodegradable panels in blue crab pots and found no difference in blue crab catch (Bilkovic *et al.* 2012). Additional studies found that pots with biodegradable escape panels reduced the capture of crabs by 87% as compared to standard pots and 47% of those retained in the pots with biodegradable panels were either shedding or mating (resulting in a baywide mortality of 3 crabs/pot/yr versus 23 crabs/pot/yr, respectively). Pots with biodegradable escape panels had no captures of terrapins as compared to standard pots that captured an average of 0.18 terrapins per pot per day (Chambers *et al.* unpublished data). In a study of Dungeness crabs, Antonelis and others (2011) found that the incorporation of biodegradable components on Dungeness crab pots increased escape by 86 percent. Other work with Dungeness crab pots showed that escape mechanisms that relied on detachment and buoyancy and gravity to work rather than complete biodegradation often failed due to biofouling and the subsequent encrustation holding the device in place (Maselko *et al.* 2013). The use of bycatch reduction devices on those crab pots fished in terrapin habitat (e.g., tidal creeks, shallows near marshes or nesting beach habitat) should also minimize terrapin mortality if those pots become derelict (Upperman *et al.* 2014) .

Figure 4-1. Derelict peeler pot recovered from the Chesapeake Bay with diamondback terrapin and blue crab bycatch.

Peeler crabs are crabs preparing to shed (or "peel" off their hard shell) to become soft-shelled crabs, a highly prized cuisine product. Specialized pots are used to capture peeler crabs which are different from regular commercial-style pots in that they have a smaller mesh size and are not required to have escape or "cull" rings for smaller sized crabs or the cull ring is a smaller size than for regular hard crab pots (i.e. Potomac River Fisheries Commission). Peelers will often enter pots in an apparent search for shelter before shedding. The smaller mesh size, with no escape or cull rings, results in increased mortality of both the target species and by-catch species in derelict pots (NCDMF 2013) (**Figure 4-1**). Peeler pots made up 11.4% of recovered derelict pots in Virginia and 13.2% in Maryland (Slacum *et al.* 2013). Derelict peeler pots had proportional similar amounts of crabs as derelict hard crab pots but had a higher proportional percent fish bycatch capture of black seabass (31.2%), Atlantic croaker (10.2%), and white perch (7.5%) than hard crab pots, (5.8%; 7.3%, 3.5%; respectively) (Virginia Marine Debris Location and Removal Program 2009-2012). In Virginia, watermen tested biodegradable panels in peeler pots and found no difference in blue crab catch (NFWF 2015). Positioning the bottom of the biodegradable escape panel level with the upper chamber floor can increase the likelihood of escape by 39 times once the panel has biodegraded (Havens *et al.* 2009, NFWF 2009). However, derelict pots have been shown to provide attractive structure for oysters, *Crassostrea virginica*, and other marine animals and can have a neutral or positive impact if the pots can be 'disarmed' from continuing to capture animals (Slacum *et al.* 2009, Havens *et al.* 2008, Havens *et al.* 2011, Bilkovic *et al.* 2014, Anderson and Alford 2014, Voss *et al.* 2015).

Table 4-1. Species Recorded from Derelict Blue Crab Pots.

Species	Scientific name
Atlantic croaker	*Micropogonias undulatus*
Atlantic menhaden	*Brevoortia tyrannus*
Atlantic spadefish	*Chaetodipterus faber*
American eel	*Anguilla rostrata*
American lobster	*Homarus americanus*
Black drum	*Pogonias cromis*
Black sea bass	*Centropristis striata*
Blue crab	*Callinectes sapidus*
Bluefish	*Pomatomus saltatrix*
Bowfin	*Amia calva*
Butterfish	*Peprilus triacanthus*
Cancer crab	*Cancer spp.*
Catfish spp	Ictaluridae
Channeled whelk	*Busycotypus canaliculatus*
Cunner	*Tautogolabrus adspersus*
Mullet spp	*Mugil* spp
Muskrat	*Ondatra ziberthicus*
Oyster toadfish	*Opsanus tau*
Pigfish	*Orthopristis chrysoptera*
Pinfish	*Lagodon rhomboides*
Porgy spp	Sparidae
Pufferfish spp	Tetraodontidae
Pumpkinseed	*Lepomis gibbosus*
Red drum	*Sciaenops ocellatus*
Scup	*Stenotomus chrysops*
Shad	*Alosa or Dorosoma spp*
Sheepshead	*Archosargus probatocephalus*
Spider crab	*Libinia emarginata*
Spot	*Leiostomus xanthurus*
Stargazer	*Astroscopus guttatus*

Table 4-1. Species Recorded from Derelict Blue Crab Pots.

Diamondback terrapin	*Malaclemys terrapin*	Striped bass	*Morone saxatilis*
Duck	Duck spp.	Striped burrfish	*Chilomycterus schoepfii*
Flounder spp	Paralichthyidae	Tautog	*Tautoga onitis*
Hogchoker	*Trinectes maculatus*	Turtle	*Turtle spp.*
Horseshoe crab	*Limulus polyphemus*	Rappa whelk	*Rapana venosa*
Knobbed whelk	*Busycon carica*	White perch	*Morone americana*
Merganser (diving duck)	*Merganser spp.*		

4.4 Management Scenarios

Three main management scenarios are recommended for consideration: *(1)* avoidance of resource user conflict, *(2)* removal of derelict pots from ‘hot spots’, and *(3)* pot modification.

1. Avoidance of resource user conflict
   A. Reducing recreational boating/commercial shipping and commercial crabbing spatial overlap could reduce the input of derelict pots to the Chesapeake Bay.
2. Removal of derelict pots from hotspots.
   A. Focusing removal effort on just the most heavily fished areas (hotspots) can be a cost effective strategy to increase blue crab harvest baywide.
   B. Providing adequate resource agency support for enforcing the removal of abandoned pots (pots that still have the line and marker buoy attached) can remove thousands of derelict pots from the Chesapeake Bay annually.
3. Pot modification.
   A. Incentivize the incorporation of biodegradable escape panels in crab pots (both peeler and standard pots). Utilizing biodegradable escape panels in crab pots can reduce blue crab mortality in derelict pots from over 3.3 million marketable crabs/year (4.5% of the harvest) to under 440,000 crabs/year (< 1% of the harvest) and reduce or eliminate mortality of other animals.
   B. Cutting the wire mesh on pots where cull rings are fastened will allow proper function of the cull ring for release of sublegal crabs and smaller animals should the pot be lost.

5. Future Directions

This study represents the first Chesapeake baywide assessment of ecological and economic effects of derelict crab pots. The framework for this assessment allowed for the incorporation of new and evolving data on derelict pots in the Bay. When evaluating data on variables that may influence crab pot loss and synthesizing data into a common spatial format, several important data gaps were revealed. Filling these gaps would enable more refined predictions of derelict pot distribution, which would make management activities more effective. This would require spatially-explicit data on the following variables:

Recreational and commercial boating traffic: Recreational and boating activity likely have a greater effect on pot loss than was evident in the assessment due to the lack of spatially and temporally explicit information on boating intensity throughout the Bay.

Recreational blue crab fishery: Information on the recreational blue crab fishery in the Chesapeake Bay is lacking resulting in little information of the impact of recreational derelict crab pots. Anecdotal information suggests that recreational pots are lost though many are tied to private piers. However, in some cases recreational pots tied to piers are left unchecked in the water for extended periods acting as a *de facto* derelict pot; and because most recreational potting activity takes place near terrapin habitat, they can disproportionately impact terrapins. Spatially explicit information on the recreational blue crab fishery would be useful in completing the picture of blue crab pot loss and impact in the Chesapeake Bay.

Diamondback terrapin: Unfortunately, baywide delineations of diamondback terrapin distributions or suitable habitat do not exist which precluded the quantification of overlap between terrapin habitat and derelict pots. While state-specific data do exist, the differences in data collection and output do not make these readily comparable. In Virginia, observations of terrapin at representative sites were used to create a map of suitable terrapin habitat (Isdell *et al.* 2015). In Maryland, a beach survey during the summer 2002 nesting season covered a wide-geographic range of beaches to map terrapin observations (USGS Patuxent Wildlife Research Center 2002; http://www.pwrc.usgs.gov/terrapin/). More complete delineation of potential and/or realized terrapin habitat (including feeding and nesting habitats - marshes, beaches, shallows) are needed to fully assess potential terrapin mortality risk from derelict pots in Chesapeake Bay.

Potomac River blue crab fishery: In assessing the impacts of derelict pots on the resources of the Chesapeake Bay, commercial blue crab data were obtained primarily from Maryland and Virginia regulatory agencies. The blue crab in the Potomac River is regulated by a separate agency, the Potomac River Fisheries Commission. The Potomac River blue crab fishery represents about 5% of the total Chesapeake Bay harvest and the derelict pot removal effort in the Potomac River was limited in scope with only about 2% of the total derelict pots removed coming from the Potomac River. While a more robust removal program coupled with spatially explicit data on fishing effort and harvest would allow a specific assessment for the Potomac River, it is reasonable to assume that the impacts determined for the Chesapeake Bay and other main tributaries are similar for the Potomac River system.

Abandoned pots: In derelict pot removal activities, collecting data on pot location, bycatch, and pot condition (i.e. presence or absence of attached buoy and/or line) is extremely helpful. In this report, data on the presence of a buoy and line from each state’s derelict pot removal program was recorded for Virginia but not for Maryland. From the Virginia data, it was shown that a large percentage of pots still had their marker buoy attached and were thus considered abandoned. Similar data from Maryland would have been useful, but anecdotal information from Maryland suggests a similar pattern and specific management strategies can be targeted for abandoned pots.

Derelict pot capture efficiency over time: It is well established that blue crab pots can continue to capture and kill bycatch after they are lost for several years but information is lacking on a lost pot’s capture efficiency past a couple years. The time period for this project (two years) restricted the ability to gather data on capture rates and subsequent mortality for pots lasting more than two years. Accordingly, calculations of effects over time in this report utilized a conservative pot life span of two years.

6. Conclusions

It is estimated that between 12% to 20% of blue crab pots deployed annually in Chesapeake Bay waters are lost or abandoned and at any given time, there are on average 145,000 derelict crab pots Bay-wide, representing a non-depreciated replacement gear value between $3.6 and $5 million ($25 to $35 per pot, depending on material type and additions such as zincs, rebar, etc). These derelict pots capture and kill millions of blue crabs per year, amounting to nearly 5% of the commercial harvest as well as many other species including commercially important white perch and Atlantic croaker. Fishing effort, water depth, and recreational and commercial boating traffic were all found to be significant predictors of the density of derelict crab pots.

The lack of significant overlap of derelict pots and sensitive bay habitats suggest that commercial blue crab potting generally may avoid submerged aquatic vegetation and oyster reef habitats. An important caveat however, is that National Environmental Policy Act requirements restricted derelict pot removal activity in sensitive habitats and the model for predicted derelict crab pot occurrence was based, in part, on data from retrieval programs that avoided pot removal from these habitats.

Derelict gear may impose a variety of economic costs (see **Figure 3-5**). The costs of decreased harvests due to ghost fishing can be further separated into those which are caused by stock reductions (i.e., due to mortality and/or reduced recruitment) and those that result from increased gear competition, and thus the reduced efficiency of active gear. In fisheries with large amounts of effort and gear loss, such as blue crab fisheries in the Chesapeake Bay, the economic costs of inefficient gear may be significant. In this report it was noted that the 43,968 removals which occurred in Maryland and Virginia from 2008-2014 are thought to have resulted in an additional 38.17 million lbs of harvest valued at $33.5 million. Though measured and discussed here as harvest and revenue losses, these costs may equally be thought of in terms of additional time and effort. Increased gear competition means fishers must exert more effort and resources in procuring harvest. Chesapeake Bay blue crab fishers might therefore obtain crab at a much lower cost, were it not for derelict gear.

Several management strategies are highly likely to reduce derelict crab pot abundance and associated adverse ecological and economic effects. These include targeted derelict pot removal in high density areas, enforcement of the removal of abandoned pots, education of recreational boaters to minimize use-conflict, and pot modifications that include a biodegradable escape mechanism.

- Removing derelict pots from high intensity potting areas (hotspots) can produce significant economic benefit beyond reducing mortality. For example, removing just 10% of derelict pots (approximately 4,400) from the five most heavily fished sites in each of Virginia and Maryland could increase blue crab harvest in the Chesapeake Bay by 22 million pounds or approximately 14%.
- Recreational and commercial boating traffic are significant predictors of the distribution and abundance of derelict crab pots. Reducing the overlap between recreational and commercial boating and commercial potting activities can reduce the input of derelict pots to the Chesapeake Bay and boater education should highlight this issue in appropriate training or instruction venues.
- Biodegradable escape panels in crab pots can reduce blue crab mortality in derelict pots from over 3.3 million to under 440,000 market crabs/year and reduce or eliminate mortality of other animals.

Developing a fine scale biogeographical framework that can be matched to fishery management needs (in this case NOAA codes) enhances the utility of the information and provides a platform from which to adaptively manage impacts of derelict crab pots, as well as other similar derelict gear, in fisheries both nationally and worldwide. More generally, beyond providing a quantitative assessment of derelict fishing gear in the Chesapeake Bay, this study also validates a broader assessment framework for derelict fishing gear – a generic, structured analytical process applicable to other regions and other fisheries.

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Appendix A. Blue Crab Pot Loss Rates

Introduction

Humans have been using various trap or pot designs to capture fish and shellfish for thousands of years. In more modern times plastic, wire, and plastic coated wire for pot construction have replaced less durable material such as bamboo, reed, and wood. The substitution of more durable pot material has exacerbated the issue of lost or abandoned pots, allowing them to remain intact and continue to capture and kill marine life (Havens *et al.* 2008; Bilkovic *et al.* 2014; Uhlmann and Broadhurst 2015) and act as an attractant ultimately impacting harvests (Eggleston *et al.* 1998; Sturdivant and Clark, 2011, Scheld *et al.* 2016).

Blue crab pots are approximately 0.6m x 0.6m x 0.6m generally galvanized or vinyl-coated two-chambered wire traps designed to be deployed and recovered by a line and buoy system. Typically, pots become lost when buoy lines are severed by vessel propellers, lines break because of age, pots are abandoned or are vandalized, or storms roll the pots, pulling the buoy below the surface (Guillory, 1993) (**Table A-1**). It is estimated around 20% of deployed blue crab pots are lost annually in Virginia waters (Havens *et al.* 2008; Bilkovic *et al.* 2014) while North Carolina estimates pot loss rates of 14% – 21% (McKenna and Camp 1992; Hassell 2007; Lee 2009) though pot loss rates can vary among different pot fisheries (Morison and Murphy, 2009; Arthur *et al.* 2014). Lost or abandoned blue crab pots can continue to capture crabs, fish, and other organisms for multiple years (Guillory, 2001; Havens *et al.* 2008, Bilkovic *et al.* 2014, Arthur *et al.* 2014) and can affect blue crab harvest (Scheld *et al.* 2016).

Estimates of annual blue crab pot loss have been reported for Virginia as 10% to 30% (Havens *et al.* 2008) and later refined to 20% (Bilkovic *et al.* 2014). However, these estimates were derived from information gathered mostly from large tributaries or the mainstem of the bay. Limited information is available regarding annual pot loss from small to medium-sized tidal creeks (< 10 km^2) where potting also occurs (Havens *et al.* 2008).

Table A-1. Activities Contributing to Pot Loss with Potential Mitigation Options.

Factors Affecting Pot Loss	Accidental Loss	**Boat Traffic**
		Recreational - propeller entanglement
		Commercial – propeller entanglement, barge interception
		Equipment Failure
		Buoy & line detachment
		Line & pot detachment
		Current driven movement
		Insufficient weighting
		Biofouling causing drag and movement
		Insufficient line length and pot ‘walking’
		Entanglement of multiple pot trotlines
		Line to dock detachment (recreational)
		Storms
		Movement of pot to deeper water
		Pot ‘pile up’ and line entanglement
		Exacerbate equipment failure
	Intentional Loss	**Discarded**
		End of pot life
		Out of business

Table A-1. Activities Contributing to Pot Loss with Potential Mitigation Options.

		Periodic pot replacement
		One time pot use (i.e. peeler pots)
		Vandalism
		Theft
Mitigation Options	Reduction of Effects	**Removal**
		From high intensity fishing areas
		From high pot loss areas
		From sensitive habitats
		Pot Modifications
		Biodegradable escape mechanisms
	Policies	**Enforcement of closed seasons**
		Enforcement of shipping lanes
		Enforcement of pot prohibition in marked channels
		Incentives for proper pot disposal
		Incentives for use of biodegradable components in pots
		State funding for participants
		Extended fishing season for participants
		Enhanced product pricing for participants

Methodology

Watermen Estimated Blue Crab Pot Losses in Virginia- Five commercial fishers were employed to remove all derelict crab pots from ten tidal creeks (5 paired creeks with low and high crabbing effort in 5 regions of Virginia) during the winter of 2014 (**Figure A-2**). During the fishing season they periodically surveyed the number of active pots in these creek systems. In the winter of 2015 they returned to the creeks for and again removed all derelict pots.

Participants were provided a Humminbird 1197SI side-imaging unit and trained in its use. In addition, each participant was provided with data sheets for cataloging bycatch. Participants outfitted their own vessels with a removable transducer mount and were instructed to place the GPS directly above the side imaging transducer. Units were preprogrammed to scan using 75 ft swaths and acquire GPS points (survey tracks) with a 30 s ping rate. Participants were instructed to maintain preset functions for consistency. Proper survey procedures (i.e. scanning an area in a grid pattern with some overlap, speeds _6.0 kt) were explained and all participants were experienced surveyors having being in the Virginia Marine Debris Location and Removal Program (Havens *et al.* 2011). Participants were instructed in the proper retrieval techniques to reduce bottom disturbance using grappling devices raised slightly above the bottom surface or lines embedded with bent nails) (**Figure A-1**). These retrieval methods combined with the Global Positioning System of the side-imaging unit allowed for targeted removal of derelict crab pots. Vessel track lines were recorded to calculate the area surveyed. Mean blue crab pot loss rates per creek were calculated as number of derelict pots per active pot per month and averaged across the season.

Previous loss estimates were obtained from watermen participating in the Virginia Marine Debris Location and Removal program where they reported loss rates of 20% for three consecutive years (2009–2011) (Havens *et al.* 2011) with the bulk of the their potting activity taking place in the mainstem bay or tributaries. In addition, a five-year (2005-2009) field survey using side scan sonar to locate and remove derelict pots in one tidal creek (Sarah Creek) was conducted from 2005 – 2009 showed annual pot loss rates of 26.2% of fished pots on average over the five year period (**Table A-4**).

Watermen Estimated Blue Crab Pot Losses in Maryland – The portion of active crab pots lost annually in Maryland is unknown. In 2014 and 2015 we spoke with active Maryland watermen to gather information about annual pot losses. These conversations used a template tailored to characterize where the watermen actively fished, the percent of their crab pots lost annually, and their opinion on the cases of pot losses (See questionnaire in **Appendix F**). We sought to collect information from watermen that covered a range of fishing activity (from full time to part time), and with representative coverage throughout the extent of crabbing area in Maryland. These interactions provided background information on Maryland fishing practices by region including average loss rate of crab pots per waterman, the total number of derelict pots removed by watermen, and the total number of crab pots present. This information served in ground-truthing the modeling efforts and in comparing the Maryland and Virginia fisheries. These conversations also give insight to the potential sources of derelict pots in different geographic regions of the Chesapeake Bay; in particular they suggest that an average pot loss for watermen ranges between 1.5% and 10% of total gear in the summer and fall. 90% of the watermen we spoke with indicated that recreational boater traffic was the chief cause of pot loss, with theft as the number two cause. The template for these conversations may be found in **Appendix F**.

The information collected through interactions with watermen was unfortunately considered of limited value due to several influencing factors. The first factor was the limited sample size. The Paperwork Reduction Act which required information gathering on a one-on-one basis rather than through a broad mailing questionnaire. The second factor was the perception by watermen we spoke with that these conversations would result in new regulations. Many watermen believe they would be required to add escape panels if pot loss was determined to be high; it was assumed their responses were very conservative because of this fear. Therefore these conversations could only acknowledge that pot losses occur, but could not determine the loss rate for crab pots in Maryland.

Results & Discussion

In Virginia, the total area surveyed for derelict pots was 31.8 km^2 in 2015 and 31.6 km^2 in 2016 (**Table A-3**). Mean active blue crab potting ranged from 0 (no crabbing) in the Pagan to 498 pots in Occohannock. The number of recovered derelict pots after the 2015 fishing season ranged from 2 in Timberneck to 35 in Guilford. In Sarah Creek, the five-year study showed a mean loss rate of 26.2%. The pot loss rate ranged from 5.2 to 26.2% (not considering the Pagan but including Sarah) with a mean across all creeks of 12.7% (SE 2.6) (**Table A-2**).

A review of the number of docks, ramps (both private and public), and marinas suggests that areas with higher boating activity, near marinas and public ramps, could result in higher pot losses (**Table A-5**).

Blue crab pot loss rates measured in creeks in the Virginia portion of the Chesapeake Bay was 12.7% in the creeks sampled in this study, including a five-year study of one creek in Virginia that showed an average loss rate of 26%. Fishers in the Virginia Marine Debris Location and Removal program reported loss rates over three years, averaging 19.7% in main tributaries and the Bay. These rates are similar to those reported by Bilkovic *et al.* (2014) and Arthur *et al.* (2014).

To calculate a Virginia bay-wide estimate, the creek and tributary/mainstem loss rates were weighted based on the relative fishing pressure. The 32,000 derelict pots recovered in the first four years of the Virginia Marine Debris Location and Removal Program were used to determine the relative portion of potting activity in the creeks versus the mainstem of the bay and tributaries. Virginia bay-wide annual pot loss rate was weighted using the creek (31%) versus river/bay (69%) proportion and the loss rate weighted mean was calculated using the following equation.

$$\overline{x} = \frac{\sum_i w_i x_i}{\sum_i w_i}$$

Where $\overline{x}$ = weighted mean, w_i = proportion (weight), and x_i = loss rate.

The mean annual pot loss rate for the Virginia portion of the Chesapeake Bay is estimated at 17.5%. While no direct measurements of pot losses were made in Maryland, it's reasonable to assume that portion of active pots lost in Maryland is similar to the range of lost pots documented in Virginia. Fishing practices and effort are similar in both States and the factors affecting pot loss have also been proven to be similar. Therefore, these data suggest an annual pot loss estimate of 12% to 20% in the Chesapeake Bay depending on the location (creek or main tributary/bay), though it could be higher in areas where high potting activity is coupled with high boating activity.

Table A-2. Percent Pot loss in creek systems, main tributaries, and Chesapeake Bay.

Creek	2015 Derelict Pots	2016 Derelict Pots	Mean Number of Active Pots	Mean Percent Loss ± (SE)
Perrin	7	11	52	23.7% ± 3.8
Guilford	26	35	428	21.2% ± 13.2
Timberneck	3	2	16	13.5% ± 2.0
Queens	4	4	46	12.6% ± 3.9
Warwick	7	8	153	6.6% ± 1.9
Occohannock	1	24	498	6.5% ± 1.9
Old Plantation	1	2	87	6.3% ± 2.1
Cherrystone	23	7	232	5.2% ± 1.5
Back	0	3	59	5.2% ± 0.4
Pagan	0	0	0	NA
Sarah (mean loss rate 2005-2009)				26.2% ± 4.2
Mean across all creeks				12.7% ± 2.6
Mainstem and main tributaries* (mean loss rate 2010-2012)				19.7% ± 1.2
Chesapeake Bay wide loss rate				12 - 20%

*Bilkovic *et al.* 2014

Table A-3. Survey Areas and Number of Derelict Pots Removed.

Creek	Area Surveyed 2015 (km^2)	Derelict Pots Removed 2015	Area Surveyed 2016 (km^2)	Derelict Pots Removed 2016
Guilford (Eastern Shore)	4.7	26	6.5	35
Occohannock (Eastern Shore)	5.5	1	5.5	24
Old Plantation (Eastern Shore)	3.0	1	3.9	2
Cherrystone (Eastern Shore)	4.9	23	5.5	7
Pagan (Western Shore – James River)	2.1	NA	2.1*	NA
Warwick (Western Shore – James River)	7.9	7	4.6	8
Queens (Western Shore – York River)	0.92	4	0.98	4
Timberneck (Western Shore – York River)	1.1	3	0.83	2
Perrin (Western Shore)	0.4	7	0.4	11
Back (Western Shore)	1.3	0	1.3*	3

* Track line anomalies. 2015 track lines substituted.

Table A-4. Derelict Pot Removal and Loss Rates for Sarah Creek, VA.

Year	Active Pots	Derelict Pots	Percent Loss Rate
2005	40	8*	20.0
2006	54	12	22.2
2007	51	11	21.6
2008	53	13	24.5
2009	54	23	42.6
Mean loss rate 2005 – 2009 (± SE)			26.2 ± 4.17

*16 pots were removed but assumed a two year accumulation.

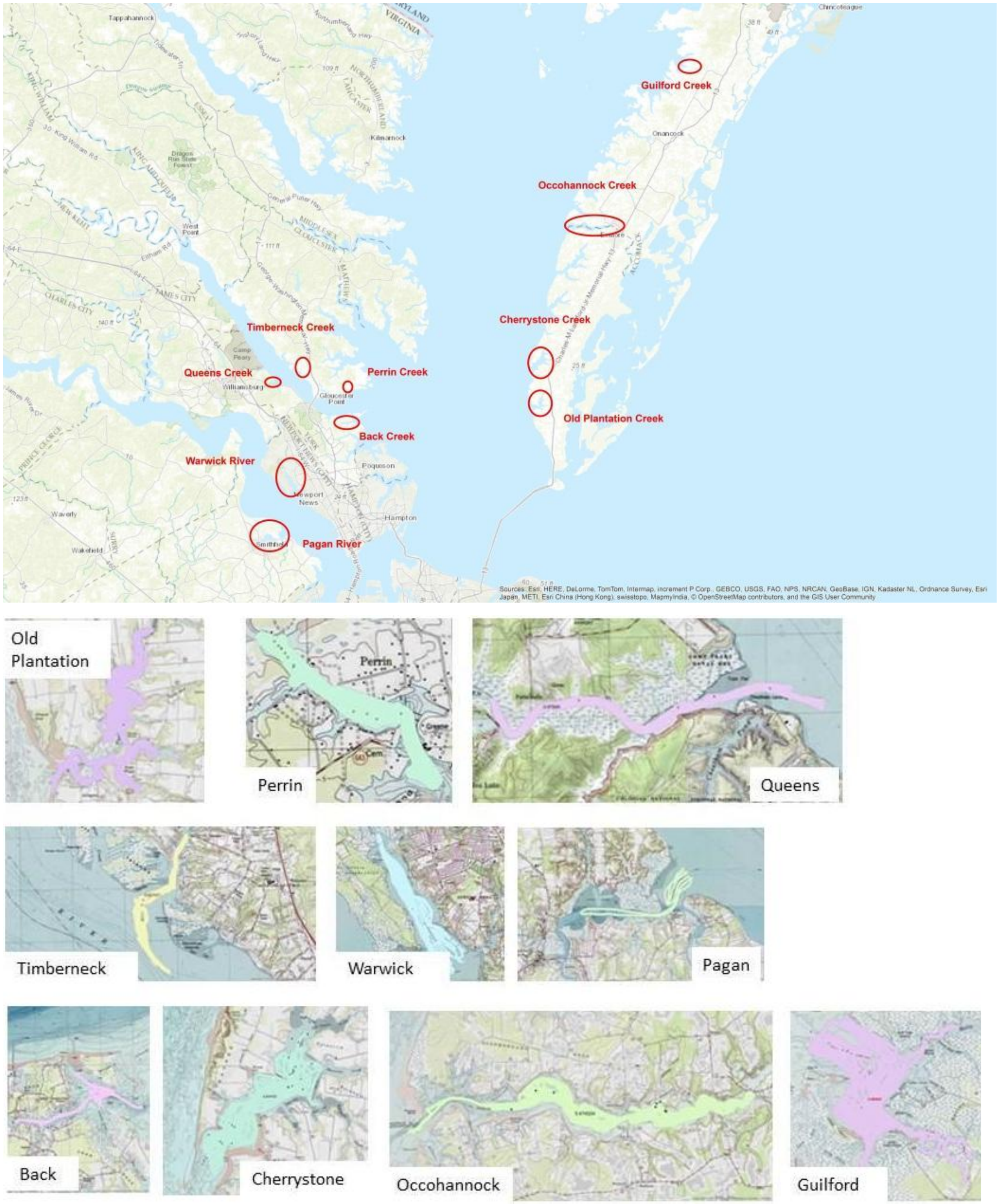
Table A-5. Docks, Ramps, and Marinas Per Creek.

Creek	Docks	Public Ramps	Private Ramps	Marina	Marina < 50 slips	Marina >50 slips	Avg % loss
[1] Sarah	92		3		3	2	26.2
Perrin	38	0	10		4		23.7
Guilford	8	2	1				21.2
Timberneck	31	0	3		1		13.5
Queens creek	21		3			1	12.6
Warwick	203	1	10				6.6
Occohannock	140	2	5	1			6.5
Old plantation	25	0	5				6.3
Back	88	2	8		2		5.2
Cherrystone	21	0	7		1		5.2
[2] Pagan	70	0	3		2	4	NA

[1] Five year average.

[2] No active pots in 2015 or 2016. It was noted that due to the boating activity in the area, watermen have recently ceased fishing the Pagan with pots (*per. comm. R. Green*).

Figure A-1. Watermen removal of derelict blue crab pots.



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure A-2. Ten Tidal Creeks in Virginia Where Derelict Pot Surveys and Removals were Conducted in 2014 and 2015.

Counts of active pots were conducted during the 2015 fishing season.

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Appendix B. Capture, Escape, and Mortality Rates in Derelict Blue Crab Pots

Introduction

Since the 1950s, one of the primary methods for capturing blue crabs is the wire-mesh crab pots (Stagg and Whilden 1997). Typical crab pots are cube-shaped and measure approximately 2ft x 2ft x 2ft. They are generally made of wire, either galvanized or vinyl-coated, and designed with a lower bait chamber and an upper trap chamber. The lower and upper chambers are separated by a v-shaped wire mesh with two opens at the top of the “v” (Kennedy *et al.* 2007). Two to four entrance funnels are located in the lower chamber and crabs enter through the funnels to access the bait that is usually held in a finer mesh wire cylinder. Circular ‘cull’ rings that permit the escape of sublegal crabs are incorporated on the side panels of the pot (**Figure B-1**).

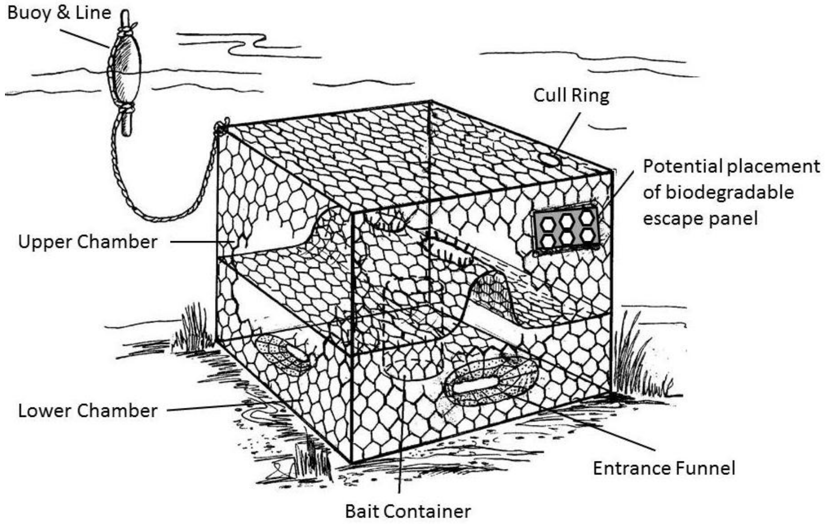

Figure B-1. Blue Crab Pot schematic (modified from Kennedy et al. 2007).

Peeler pots, which are designed to catch premolt crabs for the soft shell market, generally have smaller mesh size without cull rings resulting in a greater potential of ghost fishing mortality than hard crab pots (NCDMF 2013).

Lost or abandoned (derelict) crab pots present safety, nuisance, and environmental effects in estuarine waters. Blue crabs and fish that are entrapped and die in derelict pots can act as an attractant to crabs and other marine life, resulting in a self or auto-baiting effect (Havens *et al.* 2008; Slacum *et al.* 2009; Bilkovic *et al.* 2014). Crabs and other marine life retained in pots are subject to increased mortality due to the cannibalistic and aggressive nature of crabs (Eldridge *et al.* 1979; Savoie and Casanova 1982, Smith and Hines 1991; McKenna and Camp 1992). When a derelict pot is recovered, any bycatch present represents an instantaneous catch rate, meaning at that instance those animals were caught. However, it is well known that catch rates vary across season and multiple sampling over time is necessary to accurately estimate a seasonal or yearly catch rate.

A number of behavioral activities beyond feeding may attract crabs to derelict pots. Blue crabs have been shown to prefer structured habitat (Everette and Ruiz 1993) and may enter pots as refuge rather than to feed (Sturvidant *et al.* 2011). Sturvidant and others (2011) also suggest that, as further evidence that blue crabs may enter pots in response to their value as structure, crabs have been captured in unbaited pots

(Guillory, 1993). This is further supported by studies on unbaited pots in the Chesapeake Bay (Havens *et al.* 2008; Slacum *et al.* 2009). In addition, fishers regularly use unbaited pots (or pots baited with a large male crab) to capture pubertal-molt females (peelers) (Christian *et al.* 1987). In Virginia it has been reported that pots baited with a large male crab may catch 100 female peelers per day during the approximate two week spring period when males and females are pairing (Kennedy *et al.* 2007).

Derelict crab pots have the potential to be a significant source of unaccounted fishing mortality (Van Engel 1982, Guillory *et al.* 2001, Haddon 2005, Havens *et al.* 2008, Slacum *et al.* 2009, Sturdivant *et al.* 2011, Bilkovic *et al.* 2014). The mortality caused by derelict pots is related to the durability of the pot and its retention capability. The use of vinyl-coated wire in pot construction has increased the life of crab pots (Guillory *et al.* 2001, Lee 2009, Uhlmann and Broadhurst 2015) resulting in multiple years of blue crab and other bycatch capture and mortality. For blue crabs, estimates of annual capture rates by derelict pots have been variable across ecosystems (Gulf of Mexico, 47.7 crabs/pot/year, Guillory 1993; North Carolina Pamlico River, 32 crabs/pot/year, NCDMF 2013; North Carolina, 40 crabs/pot/year, NCDMF 2013; Lower Chesapeake Bay, 50.6 crabs/pot for April-November, Havens *et al.* 2008; Upper Chesapeake Bay 21 crabs/pot/year, Slacum *et al.* 2009) though Havens and others (2008) found that simulating self-baiting doubled the catch rate to 100 crabs/pot/season (**Table B-1**).

Table B-1. Capture Rates of Blue Crabs within Derelict Pots.

Capture		
# crabs/ pot/yr	**# of crabs/pot/day**	**Reference**
48	0.14	Guillory 1993
50.6[1] (100[2])	0.24 (0.14[3])	Havens *et al.* 2008 (simulated self-baiting)
21	0.06	Slacum *et al.* 2009
40	0.11	NCDMF 2013
40.8	0.24[4] (0.11[5])	Whitaker 1979
65	0.178	This Report Virginia
43.8	0.12	This Report[6] Chesapeake Bay-wide

[1] April – November.
[2] Simulated self-baiting.
[3] Extrapolated to one year.
[4] 168 days.
[5] Extrapolated to one year.
[6] Average of capture numbers from Slacum *et al.* 2009 (0.06) and this report (0.18).

Blue crab escapement studies, however, suggest that blue crabs may escape derelict pots at a rate of 34% (Guillory 1993) and 56% (Arcement and Guillory 1993) in the Gulf region and 14% in the upper Chesapeake Bay (Slacum *et al.* 2009). Sturdivant and others (2011) reported escape rates from blue crab pots in field and mesocosm experiments in the upper Chesapeake Bay of 41% and 85%, respectively and, while they note that crabs regularly moved in and out of the pots lower chamber, they report only a 2% escape rate of blue crabs once entrapped in the upper chamber. Underwater video has shown a consistent pattern in blue crab behavior in pots. Blue crabs rarely swim within the confines of a pot and once in the upper chamber spend most of their time crawling along the upper chamber floor (Havens *et al.* 2009). Once entrapped, crabs are believed to suffer mortality at annual rates ranging from 20-60 crabs/pot in South Carolina (Whitaker 1979), to 25.8 crabs/pot in coastal Louisiana (Guillory 1993), to 20 crabs/pot in upper Chesapeake Bay (Slacum *et al.* 2009) to 26 crabs/pot in lower Chesapeake Bay (Bilkovic *et al.* 2014), and 53.8 crabs/pot averaged across several ecosystems (Poon 2005). Mortality is usually a result of starvation, cannibalism, infection, disease, and prolonged exposure to poor water quality (i.e. low dissolved oxygen) and the longer a crab is retained within a pot, the more likely it will be injured or killed by larger conspecifics (Rudershausen and Hightower 2016).

This study investigated capture, escape, and mortality rates of blue crabs to more precisely estimate the impact of derelict blue crab pots.

Methods

To investigate derelict pot capture rates, we had five commercial watermen deploy and fish 10 “lost” pots and 10 regular pots as part of their typical fishing season. The watermen fished the “lost” pots 1 week per month for the crabbing season (March – December 2015) and recorded number and sex of crabs, other bycatch and location of animals in the pots (upper or lower chamber). The waterman conducted the work in the following locations: York River, James River, Southern Eastern Shore, Northern Eastern Shore.

To investigate escape and mortality rates, the 43,000 square foot Virginia Institute of Marine Science Seawater Research Laboratory (SRL) was used to set up a mesocosm experiment. The SLR provides 800 gallons per minute of treated seawater and a 5,700 gal tank was used to run experiments. Standard, vinyl-coated pots were deployed in the tank. Video surveillance was conducted as well as interval monitoring to record blue crab movement within the mesocosm (**Figure B-2**). For video surveillance, four (one over each crab pot) Defender™ Ultra resolution (600TVL) outdoor night vision (36 IR LEDs) security cameras (model #21006) connected to a DVR that was connected to the network to allow videos to be saved directly to backed up share drives. Crabs were numbered using a white or silver permanent paint marker (The Pumper™) (**Figure B-3**).

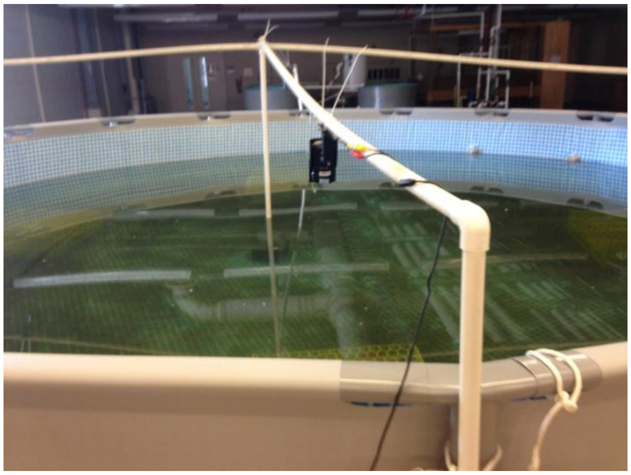

Figure B-2. Mesocosm outfitted with cameras.

Figure B-3. Blue crab marked for mesocosm experiment.

Escape Experiment

Mesocosm 1

Crabs were released into the mesocosm and allowed to acclimate for 48 hrs after which any dead crabs were removed and four standard, unbaited, vinyl-coated pots were deployed. The experiment was conducted in the summer (n=48) and fall (n=24). Crab movement was monitored continuously for 4 hrs.

Mesocosm 2

Crabs were released into the mesocosm and allowed to acclimate for 48 hrs after which any dead crabs were removed and four standard, unbaited, vinyl-coated pots were deployed. The experiment was conducted over spring (n=23), summer (n=48), and fall (n=24), though a harmful algal bloom (red tide) event in August / September required a one-month pause in the experiment. Crab movement was monitored continuously over 53 hrs.

Mesocosm 3

Twelve standard (6 less than 1 yr old, 6 2 yr old), unbaited, vinyl-coated pots were deployed with 6 randomly selected crabs (n=72) (size range: males 12.7-15.2 cm; females 12.3-15.6 cm) in the lower chamber of each pot. Six pots were less than one year old and 6 pots were 2 years old. Crabs were tagged and tracked for 7 days. Position in the pot (lower or upper chamber) was recorded daily. This experiment was replicated with a new set of crabs (size range: 11.4-15.5 cm; females 11.9-16.4 cm).

Mortality Experiment

Blue crabs from mesocosm experiment 1 were tracked for 7 days. In a second experiment, crabs were placed in the tank to acclimate for 48 hrs and any dead crabs were removed. Crabs were then tracked daily for 25 days. Mortality was estimated for each experiment.

Results

Capture Rates

Annual capture rates (crabs/pot/yr) in Virginia varied from 0.12 to 0.39 with an average annual rate of 0.178 (65 crabs) (**Table B-2** and **Figure B-4**).

Table B-2. Blue Crab Capture Rates in Virginia.

Catch of blue crabs in Virginia

Location	Average of crab catch in pot/day (SD)	Average annual crab catch pot/day	Number of crabs/pot/annual
James River [1]	0.27[1] ± (0.24)	0.13	47.5
N. Eastern Shore [2]	0.66[2] ± (0.37)	0.39	142.4
S. Eastern Shore [1]	0.37[1] ± (0.29)	0.19	69.4
York River[2]	0.28[2] ± (0.09)	0.16	58.4
Total[3]	0.41[3] ± (0.31)	0.22 ± (0.06)	80.3
Guthrie Creek (York River) [4,6]	0.26[4,6] ± (0.22)	0.15	54.8
Cedar Creek (York River) [4,6]	0.27[4,6] ± (0..22)	0.16	58.4
Sarah Creek (York River) [4,6]	0.20[4,6] ± (0.15)	0.12	43.8
York River [4,6]	0.21[4,6] ± (0.24)	0.12	43.8
Total [4,6]	0.24[4,6] ± (0.20)	0.14 ± (0.01)	51.1
Grand Total [5]	0.32[5] ± (0.15)	0.178 ± (0.03)	65

Number of days: [1] 183, [2] 214, [3] 199, [4] 211, [5] 205 in season. [6] Havens *et al.* 2008.

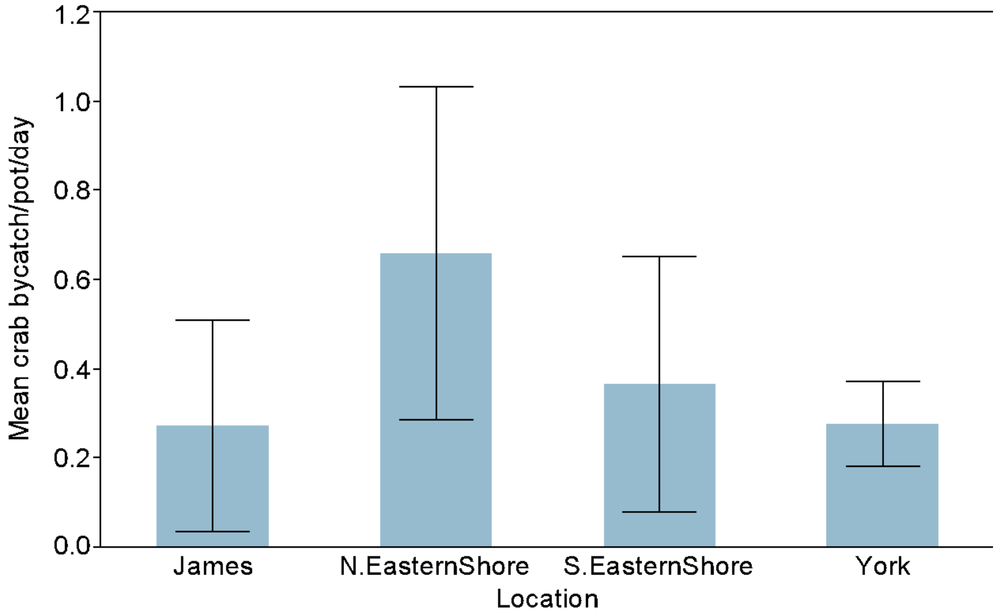

Figure B-4. Mean Crab Bycatch/Pot/Day for Four Locations.

Each error bar is constructed using 1 standard deviation from the mean.

Escape Rates

Mesocosm 1

The summer escape rate over the 4 hour continuous observation from the lower chamber was 22.5% and from the upper chamber 0% (n=12). The fall escape rate from the lower chamber was 31% and from the upper chamber 8.3% (n=15). The mean across all seasons was lower chamber 26.8% and upper chamber 4.1%.

Mesocosm 2

After 53 hours of observation, in the spring, 87% of the crabs ended up in pots with a 10% escape rate. In the summer 54% of the crabs ended up in pots with a 7.7% escape rate. In the fall 83% of crabs ended up in pots with a 15% escape rate. Mean escape rate across all seasons was 11%. All escapes were from the lower chamber.

Mesocosm 3

After 7 days, the average escape from the lower chamber of 1 year old pots was 40.3% and from the upper chamber 4.7%. Average escape from pots was 40.3%. The average escape from the lower chamber of 2 year old pots was 72.2% and from the upper chamber 8.3%. Average escape from pots was 68.05. The overall average escape from the lower chamber, upper chamber, and total pot was 56.2%, 6.1%, and 54.2%, respectively (**Table B-3**).

Table B-3. Blue Crab Escape Rates from 1 and 2 Year Old Pots.

Escape	Lower chamber	Upper chamber	Total pot
Experiment 1			
< 1 yr pots	38.9%	6.7%	36.1%
2 yr pots	75.0%	8.3%	61.1%

Table B-3. Blue Crab Escape Rates from 1 and 2 Year Old Pots.

Average	57.0%	7.2%	44.5%
Experiment 2			
< 1 yr pots	41.2%	2.3%	44.5%
2 yr pots	64.9%	16.7%	75.0%
Average	61.1%	10.0%	59.7%
Total < 1 yr pots	40.3%	4.7%	40.3%
Total 2 yr pots	72.2%	8.3%	68.0%
Grand Total	56.2%	6.1%	54.2%

Mortality

Mesocosm 4

In experiment 1 over 82% of the crabs were dead after 168 hrs (7 days) (**Table B-4**). It is important to note that the laboratory experiment crabs were obtained from a commercial crabbing operation and, while they were harvested the morning of the experiment, they had been handled prior to the start of the experiment at noon the same day.

In experiment 2, 63% of crabs were dead within 7 days (**Figure B-5**), which compares with Guillory (1993) who found approximately 40% of blue crabs died after 1 week, 70% after 2 weeks, and 90% after 4 weeks.

Table B-4. Time to Mortality of Blue Crabs in Derelict Pots in the Laboratory.

Experiment	N (alive)	Days (hrs)	N (dead)	Percent
Laboratory 1	72	7	58	80.6
Laboratory 2	72	7	61	84.8
Average				82.7

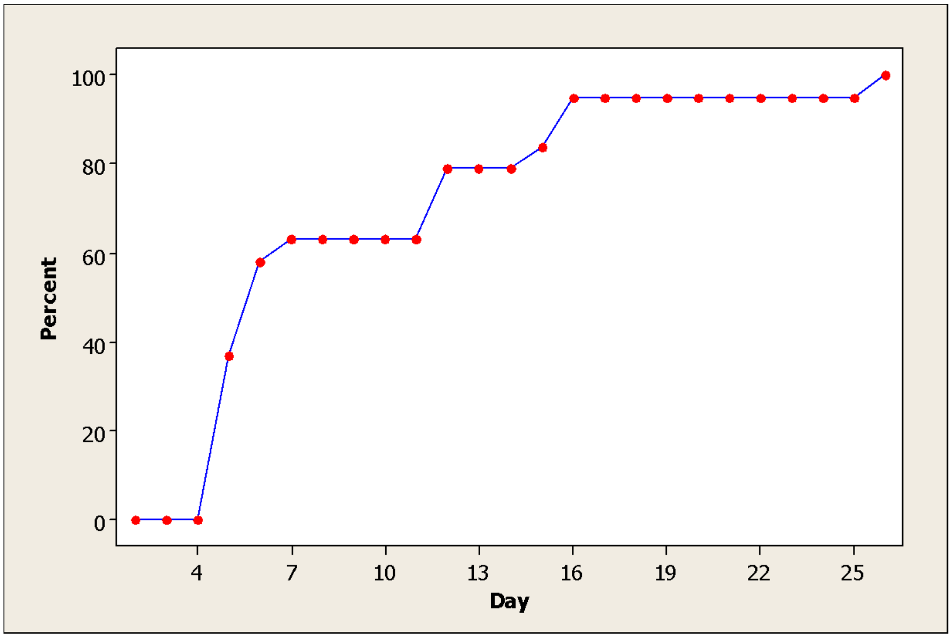

Figure B-5. Cumulative Blue Crab Mortality.

Discussion

The blue crab capture rate per derelict pot per day for Virginia was 0.18 and when averaged with the Maryland rate of 0.06 (Slacum *et al.* 2009) results in a Chesapeake Bay-wide value of 0.12.

Escape rates are variable over time and season and appear in increase over time, particularly escapement from the lower chamber (**Table B-5**). It is important to note that in our 7 day escape experiment, six crabs were placed in the lower chamber at the beginning of the experiment potentially artificially setting up an intraspecies conflict scenario, resulting in crabs more actively seeking movement out of the pots. This follows the pattern identified by Guillory (1993) who found higher escape rates in pots with more than 4 crabs (33.3%) than in pots with less than 2 crabs (16.7%). In the shorter time frame experiments, crabs were allowed to seek and independently enter pots and their movement was tracked from that point on. In these cases, the number of crabs in a pot or chamber at any one time was reduced. The laboratory escape rate of 54.2% was averaged with the Maryland field escape rate of 14% (Slacum *et al.* 2009) for an overall Chesapeake Bay-wide escape rate of 34.1%.

Table B-5. Blue Crab Escape Rates from Derelict Pots.

Escape		
Percent escape of blue crabs from pots	**Experiment Type**	**Reference**
45%	Field	Guillory 1993
56%	Field	Arcement and Guillory 1993
14%	Field	Slacum *et al.* 2009
41%	Field	Sturvidant *et al.* 2011
85%	Mesocosm	Sturvidant *et al.* 2011
2% (upper chamber only)	Mesocosm	Sturvidant *et al.* 2011
64%	Field	NCDMF 2013 (referencing NCDMF 1993)
55%	Field	NCDMF 2008
54.2%	Mesocosm	This Report
34.1%[1]	Combined field/mesocosm	Chesapeake Bay-wide

[1] Average this report and Slacum *et al.* 2009.

Table B-6. Blue Crab Mortality Rates for Derelict Pots.

Mortality		
Crabs per pot over time	**Percent**	**Reference**
20	95% (annual)	Slacum *et al.* 2009 (Maryland)
26	55% (annual)	Guillory 1993
26	37% (instantaneous)	Bilkovic *et al.* 2014
31.8[1]	NA	Poon 2005
12[2]	36% (annual)	NCDMF 2013
19	44% (annual)	NCDMF 2013
25[3]	82.7% (annual)	This Report (Virginia)
23[4]	annual	This Report Chesapeake Bay-wide

[1] Extrapolated from data from Arcement and Guillory (1993).
[2] Defined as "legal crabs."
[3] Capture rate 0.178 (65 crabs) x escape rate 54.2% (30.1 crabs retained) x mortality 82.7%.
[4] Average of MD mortality (20) and VA mortality (25).

The Virginia mortality of 25 crabs per pot per day was averaged with the Maryland mortality rate of 20 crabs per pot per day (Slacum *et al.* 2009) for a Chesapeake Bay-wide an average annual mortality of 23 crabs per derelict pot (**Table B-6**).

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Appendix C. Data Requirements, Inventory, Compilation, and Preparation

C.1 Data Requirements

The effects of derelict crab pots on blue crab, other bycatch, and habitats will vary depending on the distribution and densities of pots throughout the Chesapeake Bay. Research on derelict pots in both the Maryland and Virginia portions of the Bay suggests a number of factors contribute to derelict pot distribution and densities (Bilkovic *et al.* 2014; Slacum *et al.* 2009). The interaction between crabbing effort and boating activity are two of the factors suspected to contribute to pot loss; however other variables such as location and storm events will also modify the distribution and densities of derelict pots. A critical first step to assess the ecological and economic effects of derelict pots is to identify and evaluate all the factors expected to contribute to pot loss and determine the amount of influence that each factor contributes to the effects of derelict pots. A list of variables expected to contribute to the distribution, densities, and effects of derelict pots was developed through a review of derelict pot research in the Chesapeake Bay, other literature, and expert opinion (**Table C-1**). Variables listed in **Table C-1** were also assumed to be common factors influencing derelict pot distribution, densities, and effects in other regions outside of the Chesapeake Bay. A conceptual model depicting these variables is presented in **Figure C-1**.

Table C-1. Variables Associated with the Distribution, Densities, and Effects of derelict crab pots in the Chesapeake Bay.

Response variables are metrics describing the distribution, densities, and effects of derelict pots. Covariates are variables that influence the magnitude of the response variables.

Variable Type	Variable
Response variable	Distribution of derelict crab pots (#/km^2)
	Blue crab catch (kg/km^2)
	Other bycatch species (kg/km^2)
	Commercial blue crab harvest
Covariate	Boating activity
	Commercial crabbing effort
	Commercial harvest of finfish
	# of licensed fishers
	Geographic location
	Depth
	Time (year, month, season)
	Storm events
	Submerged Aquatic Vegetation

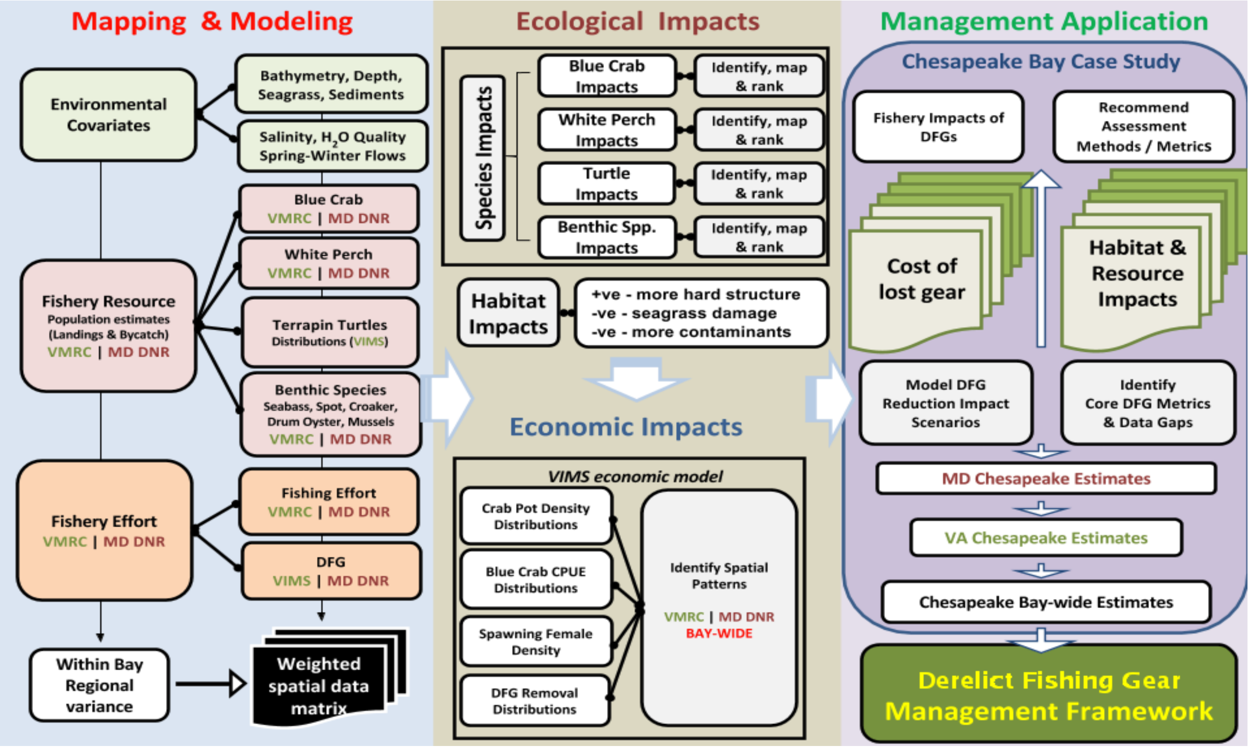


Figure C-1. Draft conceptual Framework of the distribution, densities, and effects of derelict crab pots in the Chesapeake Bay and how this framework can be used to inform a Derelict Fishing Gear Management Framework.

C.2 Data Inventory

An inventory of data was conducted to identify data sets that were readily available and to determine if data gaps existed for data considered crucial to complete the ecological and economic impact analysis. The inventory process also considered whether data were specific to the Chesapeake Bay or if the data were common to other regions and would be helpful for developing the generalized framework. Important factors considered for the data inventory were:

- Do data exist for each variable,
- What is the spatial extent of existing data,
- Where do the data reside,
- What data do exist,
- Are there data gaps and can those data be generated?

A description of each data type is listed below; while all presented inventoried data were considered for the assessment, some data had spatial limitations or other incompatibilities that precluded their synthesis into the final assessment. **Table C-2** highlights key data used in the final assessment.

Table C-2. Data types used to evaluate the ecological and economic effects of derelict crab pots in the Chesapeake Bay.

Data Type	Assessment Category	File Type	Source	Metadata Location
Crab pot distribution in MD	Derelict crab pot Distribution	GIS	Versar	GST
Crab pot distribution in VA		GIS	Versar, VIMS	GST

Table C-2. Data types used to evaluate the ecological and economic effects of derelict crab pots in the Chesapeake Bay.

Derelict crab pot distribution: MD		GIS	Versar	GST
Derelict crab pot distribution: VA		GIS	VIMS	GST
Effects of derelict crab pots to blue crab and bycatch	Target and non-target Bycatch	GIS	VIMS, Versar	GST
Effect of derelict crab pots on commercial blue crab harvest	Harvest	GIS	VIMS	GST
Bay-wide SAV distribution (nursery habitats for economically important fisheries)	Habitat	GIS	VIMS	website
Chesapeake Bay Bathymetry	Derelict crab pot Distribution	GIS	Chesapeake Bay Program	website
Recreational and commercial vessel activity	Derelict crab pot Distribution	(Various)	VIMS, VMRC, Versar; AIS from Bureau of Ocean Energy Mgmt. (BOEM), NOAA.	GST
Fisheries catch / landings data for Croaker, White Perch	Bycatch	GIS	VMRC, MDNR	GST
Dredge survey data for MD and VA (to obtain spawning female crab density estimates)	Bycatch	Database	Chesapeake Bay Pgm.	report
Oyster beds	Habitat	GIS	MDNR	GST

Note: Metadata files maintained by GST may be accessed via https://goo.gl/u6ykoA.

C.2.1 Chesapeake Bay Derelict Crab Pot Data

Distribution of Derelict Crab Pots in Maryland- The densities and distribution of derelict crab pots in Maryland were estimated based on a stratified random transect sonar survey conducted by Versar and the NOAA Chesapeake Bay office in 2007. Instantaneous derelict pot densities (pots/km^2) were calculated based on counts of derelict pots identified in side-scan sonar imagery. Derelict pot densities and distribution were evaluated for several habitat variables. Additional information on the condition, location, depth, buoy status, and bycatch was also documented through ground-truthing.

Distribution of Derelict Crab Pots in Virginia- The densities and distribution of derelict crab pots in Virginia were estimated based on temporal and spatial data provided by four years of derelict pot surveys and removal efforts which provided data on (1) mean annual survey area covered, (2) mean annual number of crab pots retrieved per km^2, and number of crab pots retrieved in shallow (≤2m) and deep (>2m) waters. NOAA bathymetric depth contours were used to quantify the number of crab pots within the different contour depths. Additional information on the condition, location, buoy status, functionality, and bycatch for every pot recovered (~34,000) was documented.

Effects of Derelict Crab Pots in Mesohaline portion of Chesapeake Bay- The effect of derelict crab pots on blue crab and other by-catch was determined through and 14-month simulated study conducted by Versar and the NOAA Chesapeake Bay office between 2006 and 2008. Study results provided data on the types and amount of species caught and killed in derelict pots. In addition, this study provided information on seasonal fluctuations in catch rates for derelict pots as well as escapement rates and pot degradation.

Effects of Derelict Crab Pots in Lower portion of the Chesapeake Bay- The effect of derelict crab pots on blue crab and other by-catch was determined from catch data obtained from the 6 year pot removal effort (2008-2014) and simulated derelict pot studies conducted from 2005 – 2007 and 2010. The results of the studies provided data on the types and amounts of species caught and killed in derelict pots as well as escapement rates and pot degradation. Because derelict pots were recovered during cold winter months in Virginia in the 6 year pot removal project, the number and abundance of species captured and reported from that project are likely underestimates of the annual loss of marine fauna to derelict pots. To provide additional information on seasonal variability of catch, five commercial watermen recorded species captured in simulated derelict pots for comparison in catch to their regular fishing activities throughout the fishing season 2015 (**Appendix B**).

Observed Blue Crab Escapement Rates in Derelict Crab Pots- When a derelict pot is recovered any bycatch present represents an instantaneous catch rate, meaning that instance those animals were caught. However, some animals may move in and out of pots while others will perish. A mesocosm study was conducted in 2015 using the VIMS state-of-the-art seawater laboratory to allow for replicate sampling and observation of crab movement within pots and likelihood of escape estimates (**Appendix B**).

Distribution of Derelict Pot Hotspots in Virginia Portion of the Chesapeake Bay – Using four years of derelict pot removal data in Virginia, high and low density areas of derelict crab pots were determined with a kernel density estimator in conjunction with ArcGIS 9.3 to spatially display the data on the basis of equal interval quantiles (excluding zeroes) to depict relatively high and low density values. The area of the highest densities (hotspots) of pots was calculated from density data in the uppermost quantile of the distribution. High density (15–311 pots/km^2) clusters of pots were identified from the kernel density analysis over 562 km^2 of Virginia waters (18% of the area surveyed). The locations within geographic regions with the strongest concentration (hotspots) of crab pots were surrounding Tangier Island, Little Wicomico River, lower York River, Mobjack Bay, Eastern Shore and Seaside tidal creeks, and Pocomoke Sound.

Distribution of Derelict Pot Hot-Spots in Maryland Portion of the Chesapeake Bay- This dataset is comprised of information collected during 48 marine debris clean up events that occurred in 2010 and 2012. Clean up events were conducted by Maryland watermen in the locations predicted to have high densities of derelict pots throughout the Maryland portion of the Chesapeake Bay. Data includes general locations of all marine debris (including derelict pots), type of debris, condition of debris, bycatch associated with derelict pots, and other variables.

Watermen Estimated Blue Crab Pot Losses in Virginia- Watermen reports (watermen participants (n = 56) for three consecutive years (2009–2011) and a 5-year (2005-2009) field survey in one tidal creek suggest that annual pot loss rates are 20% of fished pots on average. To augment these data, five watermen conducted removal efforts in ten tidal creeks (5 paired creeks with low and high crabbing effort in 5 regions of Virginia) during the winter of 2014. During the fishing season they periodically surveyed the number of active pots in these creek systems. In the winter of 2015 they returned to the creeks for an additional removal effort to help refine the pot loss rate estimates. A map of field work locations is located in **Appendix A**.

Watermen Estimated Blue Crab Pot Losses in Maryland- Conversations with Maryland watermen in the winter and spring of 2015 provided background information on Maryland fishing practices by region including average loss rate of crab pots per waterman, the total number of derelict pots removed by watermen, and the total number of crab pots present. This information served in ground-truthing the modeling efforts and in comparing the Maryland and Virginia fisheries. These conversations also give insight to the potential sources of derelict pots in different geographic regions of the Chesapeake Bay; in particular they suggest that an average pot loss for watermen ranges between 1.5% and 10% of total gear in the summer and fall. 90% of the watermen participating in these conversations indicated that recreational boater traffic was the chief cause of pot loss, with theft as the number two cause. The template for these conversations may be found in **Appendix F**.

C.2.2 Chesapeake Bay Commercial Blue Crab Fishery

Distribution of Commercial Blue Crab Effort in Maryland- A multiyear (2007-2012) stratified random transect survey of commercial crabbing effort was conducted by Versar in Maryland to provide spatially explicit counts of actively fishing blue crab pots that is used to estimate blue crab fishing effort in the Maryland portion of the Chesapeake Bay.

Distribution of Commercial Blue Crab Effort in Virginia- A one year (2010) survey of commercial crabbing effort was conducted by Versar in Virginia to provide spatially explicit counts of actively fishing blue crab pots that is used to estimate blue crab fishing effort in the Virginia portion of the Chesapeake Bay.

Reported Blue Crab Harvest Details in Virginia- Reported commercial crabbing effort and harvest for the timeframe between 1994 and 2014 were provided by the Virginia Marine Resources Commission. The Virginia Marine Resources Commission (VMRC) requires fishermen to submit weekly reports that specify total pots (and other gear) fished, their location, and pounds of blue crab harvested. From these weekly reports, aggregate annual data on area-specific harvest and potting effort from 1994-2014 for 43 unique management areas and 11 area-aggregates were obtained.

Reported Blue Crab Harvest Details in Maryland- Reported commercial crabbing effort and harvest for the timeframe between 1994 and 2014 were provided by the Maryland Department of Natural Resources (DNR) Fisheries Division. The MD DNR Fisheries Division requires fishermen to submit monthly reports that specify total pots (and other gear) fished, their location, and pounds of blue crab harvested. From these monthly reports, aggregate annual data on area-specific harvest and crab potting effort from 1994-2014 were obtained.

C.2.3 Chesapeake Bay Commercial and Recreational Vessel Traffic

Distribution of Piers and Boat Ramps in the Chesapeake Bay- Chesapeake Bay shoreline inventory data were provided by CCRM-VIMS. These data include spatially-explicit information on shoreline structures (riprap, bulkhead, piers, boat ramps, marinas), riparian land use, and bank condition for the tidal shorelines of the Chesapeake Bay. Virginia data date from June 2014 and include updated county shorelines in VA that were inventoried recently. This shoreline is always being updated and corrected when possible, but is currently the most up to date. Maryland inventories were primarily conducted in 2002-2003. These inventories are a baseline dataset used in the Environmental Sensitivity Index (ESI) used by the state.

Recreational boating hotspots - The locations of shoreline structures provided some ability to predict recreational boating density; but for a more reliable picture of recreational boating patterns we used two maps showing areas of high recreational boating activity: one for Maryland from a previous study, and the other compiled in collaboration with the VMRC Patrol Officers. Both of these are qualitative / binary maps (“high traffic” vs. “not”) based on local knowledge of Chesapeake recreational boating traffic patterns.

US Coast Guard Automated Identification System (AIS) data for commercial vessels - A year’s worth of “pings” from transponder-equipped vessels provided a detailed picture of larger commercial vessels traveling through the Bay. We filtered these to include only vehicles in motion; and aggregated them by computing their density in each 1x1km grid cell of our modeling framework.

C.2.4 Bycatch Species

Distribution and Abundance of Terrapin Turtles in Virginia-Terrapin distribution in Virginia was determined using field surveys and occupancy modeling approach. Repeat surveys were conducted at 165 sites 3 times over the course of the summers of 2012 and 2013. Key terrestrial and aquatic variables identified that explaining heterogeneity in terrapin occupancy were agriculture, low-urban development, shoreline armoring, derelict crab pot density, active crabbing pressure, and marsh area. These variables were used in a spatially applied model that predicted terrapin distribution throughout Virginia. Data outputs include the terrapin presence locations, and maps of the probability of occupancy throughout Virginia.

Distribution and Abundance of Terrapin Turtles in Maryland-This survey by USGS Patuxent Wildlife Research Center was conducted to assess the distribution of terrapins in Maryland, Chesapeake Bay, based on evidence related to nesting. They conducted a survey of the beaches during the nesting season in the summer of 2002. They walked along the shoreline of over 1,350 beach segments looking for evidence signifying the presence of terrapins based on nesting activity. These results represent a single-season snapshot of conditions during the surveys and at the locations visited during that season; it should not be assumed that this is representative of terrapin nest locations and numbers today.

Reported Commercial Finfish Harvest Details - Reported commercial fishing effort and harvest for the timeframe between 1994 and 2014 were obtained from the Maryland Department of Natural Resources Fisheries Division and the Virginia Marine Resource Commission. Data set variables included the location and pounds of species-specific harvest. We requested aggregate annual data on area-specific harvest for MD DNR management areas in Maryland, and for VMRC management areas in Virginia. Bycatch species of interest included Atlantic croaker and white perch.

C.2.5 Habitat

Chesapeake Bay Bathymetry- This dataset was created as a byproduct of the Chesapeake Bay Program's submerged aquatic vegetation (SAV) restoration goals. The bathymetric soundings were interpolated to support the development of the SAV Tier goals. The resulting interpolation was used to create the one meter low water contours for the mainstem of the Chesapeake Bay. NOAA NOS produced the dataset.

Submerged Aquatic Vegetation Distribution-Chesapeake Bay SAV data were mapped annually from aerial photography, primarily at a scale of 1:24,000 (methodology is described in each annual report - e.g. see Orth *et al*. 2013; http://web.vims.edu/bio/sav/sav13). Data were collected by the Virginia Institute of Marine Science. A ten-year composite SAV dataset covering the years 2003-2012 was created by CCRM-VIMS. These data were used to evaluate the overlap of sensitive habitats with derelict gear.

Distribution of Natural Oyster Bars- This data layer consists of compilation of several historic habitat datasets in Maryland and Virginia with some modifications. For Maryland, these historic layers include the Yates Survey, the Maryland Bay Bottom Survey, DNR repletion sites, Maryland leased bars, and sanctuaries and reserves. For Virginia, these layers included Virginia leased bars and sites identified as potential areas for oyster restoration. Details on how these layers were compiled are given by Greenhawk (2005). The cultch area data set was created for use by DNR scientists, managers, and modelers involved in work related to the preparation of an environmental impact statement entitled ‘Development of an Environmental Impact Statement for Introducing Non-Native Oyster Species into the Chesapeake Bay, Including an Evaluation of Native Oyster Restoration Alternatives.

> Greenhawk, K. 2005. *Development of a Potential Habitat Layer for Maryland Oyster Bottom, Chesapeake_Bay_habitat*. Maryland Department of Natural Resources, Fisheries Division.

C.2.6 Storm Events

Some anecdotal evidence exists, indicating pots loss due to high winds, storm surges, or increased debris (H. Ward Slacum personal communication). However, conversations with watermen (see **Appendix F**) indicated little to no pot loss by storms.

C.3 Data Compilation

A comprehensive set of metadata was developed for all data sets originating from project team members. The metadata format was standardized to include a set of common descriptors used to describe the source of each data set, methods used to derive or collect data, data creation date, data type, and file types. Additional data details were provided in abstracts included in the metadata file. Existing metadata from requested datasets and data sets without metadata were reformatted into the established project metadata format. All project data files and metadata were stored at a centralized GST ftp site for common access by project team collaborators.

Among these datasets include a variety of geospatial files that were compiled into an ESRI ArcGIS file geodatabase for assessment purposes. This includes data compiled from derelict pot research previously conducted within the Chesapeake Bay.

C.4 Data Evaluation and Standardization

Many of the variables required for the derelict crab pot ecologic and economic evaluation consisted of data collected during different time periods and in different habitats throughout the Chesapeake Bay. Previous work to evaluate derelict crab pots in Maryland and Virginia had similar goals, but often employed different survey approaches or methods, or covered different timeframes. Other source data had similar mismatches. In addition, all compiled data sets were in different file formats ranging from Excel spreadsheets to raster grids to Geographic Information System (GIS) point, line, and polygon shapefiles. Therefore, a thorough metadata review of all compiled data sets was conducted to determine the objectives of data collection, the methods that were used, and the types of variables (data) that were derived. The goal of the review was to evaluate the overall use of each data set, its connectivity to other data sets, and determine if any limitations existed for the use of each data set in future analysis.

Appendix D. Blue Crab Management in Virginia and Maryland

D.1 Virginia's 21-Point Blue Crab Management Plan

October 1994, the Commission established the following 7-point blue crab management plan:

- Expanded the spawning sanctuary (146 sq. mi.) establish in 1942 by 75 sq. mi., with no crab harvest allowed from June 1 through September 15.
- Established a 14,500-acre winter-dredge sanctuary in Hampton Roads.
- Shortened the crab pot season to April 1 through November 30.
- Required two cull (escape) rings in each commercial and recreational crab pot.
- Required four cull rings in each peeler pound that allows escapement of small peeler crabs.
- Capped the number of peeler pots per license to prevent expansion of the fishery.
- Limited the crab dredge size to 8 feet to prevent increases in effort.

The Commission reinforced the 7-point management plan in January 1996.

- Prohibited the possession of dark-colored (brown through black) sponge crabs (adult female hard crab which had extruded her eggs on her abdomen), with a 10-sponge crab per bushel tolerance.
- Limited license sales of hard crab licenses, based on previous eligibility or exemption requirements.
- Established a 300-hard crab pot limit for all Virginia tributaries of the mainstem Chesapeake Bay. Other Virginia harvest areas were limited to a 500-hard crab pot limit.
- Established a 3 1/2-inch minimum possession size limit for all soft shell crabs.

Concerns over excess effort in the fisheries and a persistent trend of low spawning stock biomass during most of the 1990s led to additional crab conservation measures in 1999 and 2000.

- Lowered the maximum limit on peeler pots from 400 to 300 pots in 1999. Harvest by this gear type increased by 90%, from 1994 through 1998, while the overall harvest remained relatively static.
- Initiated a moratorium on additional commercial licenses for all commercial crabbing gear. This moratorium became effective May 26, 1999 and continued until May 26, 2004.
- Established (in 2000) a Virginia Bay-wide Blue Crab Spawning Sanctuary, in effect June 1 through September 15. This additional sanctuary (435 sq. mil) allows for increased spawning potential.

A cooperative Bay-wide agreement (October 2000) to reduce harvest 15% by 2003 led to new measures.

- Enacted an 8-hour workday for commercial crabbers (2002) that replaced Wednesday closures of 2001.
- Established a 3-inch minimum size limit for peeler crabs (2002).
- Reduced peeler pot limits from 400 to 300 pots (for 2001).
- Reduced the winter dredge fishery limit from 20 to 17 barrels (2001).
- Augmented (2002) the Virginia Blue Crab Sanctuary by 272 sq. mi. (total sanctuary area = 928 sq. mi.).
- Reduced unlicensed recreational harvester limits to 1 bushel of hard crabs, 2 dozen peelers (2002).

- Reduced licensed recreational harvester limits to 1 bushel of hard crabs, 2 dozen peelers, with vessel limit equal to number of crabbers on board multiplied by personal limits (2001).

2008

- Larger cull ring (2-5/16") required to be open at all times in all tidal VA waters to promote additional increases in escapement.
- Peeler crab minimum size limit increased from 3" to 3 ¼" (through July 15) and to 3 ½" (as of July 16).
- Use of agents modified to prevent license "stacking" and to curtail use of agents.
- Winter dredge fishery capped at 53 licensees (from previous 225 licensees), all being active harvesters in previous two winter seasons.
- Adopted an extended closure (May 1 - September 15) of blue crab spawning sanctuary, to protect spawning females, except for the historical sanctuary (146 square miles) managed by law.
- Established a fall closure for female harvest (October 27 – November 30).
- Implemented a 15% reduction in pots per individual for 2008 crab pot fishery and a 30% reduction for 2009 crab pot and peeler pot fishery.
- Closed 2008/09 winter dredge fishery season.
- Required use of two 3/8" cull rings for all areas (except Seaside of Eastern Shore) effective July 1.
- Eliminated 5-crab pot recreational license.
- Revamped revocation procedures, to allow a hearing after just two crab violations in a 12-month period.
- In an attempt to address the latent effort, the Commission placed crab pot and peeler pot fishermen who had been inactive (no harvest) for a 4-year period (2004-07) on a waiting list until the abundance determined from the Bay-wide Winter Dredge Survey of age-1+ crabs exceeds the interim target of 200 million.

2009

- Shortened closed season for female crabs to November 21 - November 30.
- Closed 2009/10 winter dredge fishery season.
- Lowered percentage reduction of crab pots from 30% (2008) to 15% (2009).
- Reestablished 5-pot recreational crab pot license but prohibited harvest on Sunday and from Sept 16 - May 31.
- Right to hold revocation hearing for crab licensee after two crab violations by authorized agent (agents cannot be licensed for any crab fishing gear).
- Regulation tolerance of 10 per bushel (Previously March 17 – July 15).

2010

- Made it unlawful (from March 17 - June 30) to possess dark sponge crabs exceeding regulation tolerance of 10 per bushel (Previously March 17 – July 15).
- Made it lawful (indefinitely) that commercial licenses (crab/peeler pot, scrape, trap, ordinary/patent trot line, dip net) shall be sold only to commercial fishermen eligible in 2010, except those placed on the waiting list established in November 2007.
- Closed 2010/11 winter dredging fishery season.

2011

- Changed closed season on harvest from Virginia Blue Crab Sanctuaries from May 16 to May 1.
- Changed boundary line of Blue Crab Sanctuary in upper Bay near Smith Point Light.

- Closed 2011/12 winter dredging fishery season.
- Established 5-day maximum tending requirement for crab pots and peeler pots.

2012

- Closed 2012/13 winter dredge fishery season.
- Funded the Winter Dredge Gear Study using Marine Fishing Improvement Funds.
- Extended the 2012 season until December 15, 2012 for both male and female crabs and applied conservation equivalent bushel limits to the 2013 crab pot season by gear license categories as follows:
  - For up to 85 crab pots a maximum limit of 27 bushels.
  - For up to 127 crab pots a maximum limit of 32 bushels.
  - For up to 170 crab pots a maximum limit of 38 bushels.
  - For up to 255 crab pots a maximum limit of 45 bushels.
  - For up to 425 crab pots a maximum limit of 55 bushels.
  - Restricted crabbing in the Virginia portion of the Albermarle and Currituck watersheds to crab pots and peeler pots only.

2013

- Established a vessel harvest and possession limit equal to only one of the largest legal bushel limits on board any vessel.
- Limited the use of agents in the hard pot fishery to 168, with priority going to those licensees who received approval for agent use in 2012.
- Established daily individual and vessel harvest and possession limits for the 2013 season.
- Closed 2013/14 winter dredge fishery season.
- Results of the Winter Dredge Mortality Project were presented.
- Extended the 2013 season until December 15, 2013 for both male and female crabs and applied conservation equivalent bushel limits to the 2013 season extension and the 2014 crab pot season by gear license categories as follows:
  - For up to 85 crab pots a maximum limit of 16 bushels.
  - For up to 127 crab pots a maximum limit of 21 bushels.
  - For up to 170 crab pots a maximum limit of 27 bushels.
  - For up to 255 crab pots a maximum limit of 43 bushels.
  - For up to 425 crab pots a maximum limit of 55 bushels.
- Established the 2014 crab pot season as March 17 through November 30, 2014 for both male and female blue crabs.
- Established a declaration date for agent use requirements in the crab pot fishery for the 2014 season.

2014

- Closed the 2014/15 winter dredge fishery season.
- Enacted management reductions in response to the current scientific determination that the Chesapeake Bay blue crab abundance of spawning-age female crabs is depleted. The basis for this 10 percent reduction, which equals a potential savings of 1,316,726 pounds of female blue crab, is to augment spawning in summer 2014 and spring 2015 and help reverse the depleted stock condition of blue crab.
- From July 5, 2014 through November 15, 2014 and April 1, 2015 through July 4, 2015
  - 10 bushels, or 3 barrels and 1 bushel, of crabs, if licensed for up to 85 crab pots.
  - 14 bushels, or 4 barrels and 2 bushels, of crabs, if licensed for up to 127 crab pots.

  - 18 bushels, or 6 barrels, of crabs, if licensed for up to 170 crab pots.
  - 29 bushels, or 9 barrels and 2 bushels, of crabs, if licensed for up to 255 crab pots.
  - 47 bushels, or 15 barrels and 2 bushels, of crabs, if licensed for up to 425 crab pots.
- From November 16, 2014 through November 30, 2014 and March 17, 2015 through March 31, 2015.
  - 8 bushels, or 2 barrels and 2 bushels, of crabs, if licensed for up to 85 crab pots.
  - 10 bushels, or 3 barrels and 1 bushel, of crabs, if licensed for up to 127 crab pots.
  - 13 bushels, or 4 barrels and 1 bushel, of crabs, if licensed for up to 170 crab pots.
  - 21 bushels, or 7 barrels of crabs, if licensed for up to 255 crab pots.
  - 27 bushels, or 9 barrels of crabs, if licensed for up to 425 crab pots.
- The lawful season for the commercial harvest of blue crabs by all other commercial gears shall be March 17, 2014 through September 15, 2014 and May 1, 2015 through November 30, 2015. It shall be unlawful to place, set, fish or leave any lawful commercial gear used to harvest crabs, except crab pots, in any tidal waters of Virginia from September 16, 2014 through April 30, 2015.

2015

- Maintained and modified measures to conserve and allow rebuilding of the Blue Crab Resource Maintained previous crab management season and bushel limits.
- Adjusted closure dates for non-crab pot gear season, closing September 26 and reopening April 21.
- Made it unlawful for any vessel to act as both a crab harvester and a crab buyer on the same trip.
- Made it unlawful for any person to possess dark sponge crabs from March 17 through June 15.
- Redefined Virginia Blue Crab Sanctuary Area 1 as Virginia Blue Crab Sanctuary Area 1A and Blue Crab Sanctuary Area 1B and implement separate closure dates for Blue Crab Sanctuary Areas 1A, 1B and Areas 2 through 4.
- Closed the winter crab dredge fishery season from December 1, 2015 through March 31, 2016.

D.2 Significant Regulatory Changes in Maryland Blue Crab Fishery between 2008 and 2015

Table D-1 below lists the regulations imposed on the Maryland blue crab fishery in 2008-2015. This information was modified from a table included in Slacum *et al.* 2012 and information posted on the Maryland Department of Natural Resources website. Additional details are still being gathered.

Table D-1. Regulations Governing the Maryland Blue Crab Fishery in 2008-2015.

Year	Regulations Implemented to Reduce Female Harvest
2008	• Restricted participation in the fall female fishery to only those waterman with history in this portion of the fishery since 2004 • Those participants permitted to harvest females during the fall were given daily bushel limits based on their harvest history. Bushel limits ranged from 5 to 50 per day • Closed to female harvest on 10/23 (Formerly 12/15) • Banned recreational harvest of females
2009	• Replaced limited access to fall female fishery with daily bushel limits spanning the entire crabbing season.

Table D-1. Regulations Governing the Maryland Blue Crab Fishery in 2008-2015.

	• Implemented periodic closures to commercial female harvest • Closures: 6/01-6/15, 9/29-10/04, Closed to female harvest on 11/10 • Daily bushel limits ranged from 2 to 45 depending on date and license type
2010	• Implemented periodic closures to commercial female harvest • Closures: 6/01-6/15, Closed to female harvest on 11/10
2011	• Implemented periodic closures to commercial female harvest • Closures: Closed to female harvest 6/01-6/14, Closed to female harvest on 11/11 • Daily bushel limits ranged from 2 to 54 depending on date and license type
2013	• Female limits provided by public notice.
2014	• Female limits provided by public notice.
2015	• Female limits provided by public notice.

Appendix E. Derelict Fishing Gear Outreach Activities and Presentations

2014

November 7th – Crestwood Elementary School (Richmond, VA), VIMS presentation.

November 14th – VIMS briefing for Virginia Secretary of Commerce and Trade Maurice Jones.

November 17th – Smithsonian Estuarine Research Center watermen meeting (Virginia/Maryland).

2015

January 14th – Association of General Contractors, VIMS presentation.

January 16th – VIMS briefing for US Congressman Wittman.

January 28th – VIMS/W&M 75th Anniversary, VIMS presentation.

March 20th – VIMS briefing for Virginia Marine Resources Commissioner John Bull and VMRC Fisheries Chief Rob O'Reilly.

March 23rd - VIMS participation in Virginia Marine Debris Reduction Plan meeting (Richmond, VA).

March 31st- Point O' View Elementary School (Virginia Beach, VA), VIMS presentation.

April 16th – Longwood University (Farmville, VA), VIMS presentation.

April 19th - NC Coastal Federation meeting (Manteo, NC), VIMS presentation.

May 13th – Science Under Sail Event (Yorktown, VA), VIMS presentation.

May 22nd – North American Association of Fisheries Economists 8th Biennial Forum, VIMS presentation.

May 30th – Marine Science Day (Virginia Institute of Marine Science), VIMS presentation.

June 23rd – 25th – NOAA Marine Debris Reduction Plan Workshop, VIMS presentation.

July 15th – Aqua Kids™, VIMS presentation.

July 22nd- Passage Middle School (Newport News, VA), VIMS presentation.

August 5th - Middle Peninsula Governor's School (Middlesex, VA), VIMS presentation.

September 10th –Virginia House of Delegates Subcommittee on Natural Resources, Agriculture, Chesapeake Bay, VIMS presentation.

September 14th- VIMS briefing NOAA Marine Debris Chief Scientist Amy Uhrin.

September 15th- RILL Lifelong Learning, VIMS presentation.

October 8th – VIMS briefing for Preston Bryant (former Virginia Secretary of Natural Resources) and Jeff Corbin (Senior Advisor to the EPA Administrator for the Chesapeake Bay).

October 13th – A Healthy Bay for Healthy Kids: Cooking with the First Lady event. First Lady Dorothy McAuliffe, VIMS presentation.

October 18th – Historic Rosewell Event (Rosewell, VA), VIMS presentation.

November 3rd – Guest lecture in undergraduate marine science course at the College of William & Mary, VIMS presentation.

November 6th – 5th grade Crestwood Elementary, VIMS presentation

2016

January 7th – Chesapeake Bay Commission, STAC/VIMS presentation.

February 9th – Radio interview, St. John's Fisheries Broadcast, VIMS.

February 18th – Guest lecture in undergraduate remote sensing course at the College of William & Mary, VIMS presentation.

March 7th -9th – Virginia Marine Debris Summit, VIMS presentation.

March 22nd – Center for Natural Resource Economics & Policy Conference, VIMS presentation.

April 8th – Virginia Environmental Health Association, VIMS presentation.

April 11th – Abingdon Ruritan Club, VIMS presentation.

April 14th – College of William & Mary Center for Geospatial Analysis, VIMS presentation

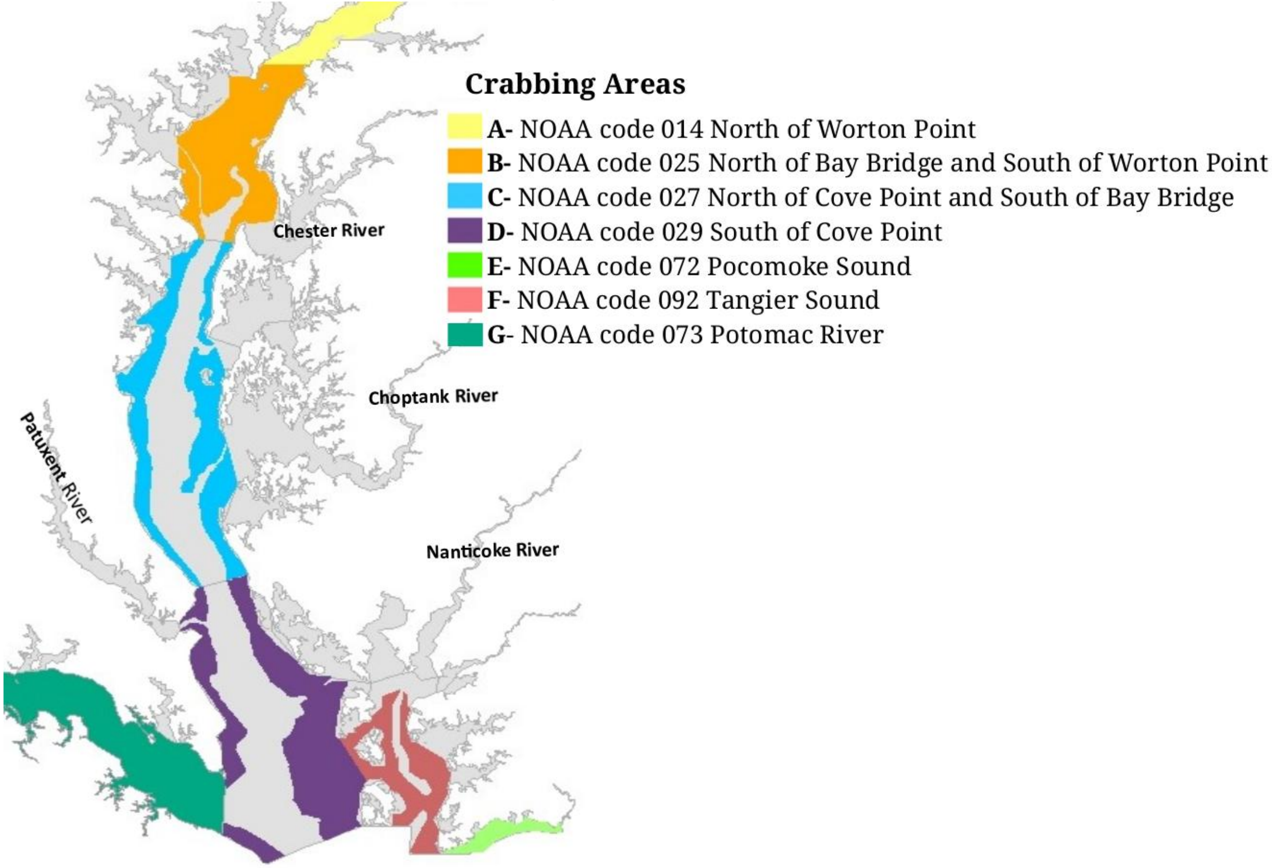
May 6th – VIMS 75th Gala Event, VIMS presentation.

May 21st – Marine Science Day, VIMS presentation.

June 13th – Indian Creek Yacht Club, VIMS presentation.

July 8th - US Department of State, Washington DC Foreign Press Center, journalists from Chile, Congo, Czech Republic, Germany, Romania, Slovakia, Ukraine, Vietnam, Europe, VIMS presentation.

Appendix F. Questions Used for Watermen Conversations in Maryland



Q1	Did you obtain a pot license last crabbing season?	A: Yes	B: No
	Did you fish crab pots last crabbing season?	A: Yes	B: No
Q2	Where did you crab in the most last crabbing season? (Please choose one area from map)	A B C D E F G	
Q3	Do you use single pot buoys or use flagged buoys (multiple crab pots attached to a line with flagged buoys on each end)?	A: Single pot buoys only B: Mix of both C: Only flagged buoys	
	If you use a mix of both, what percentage of your pots use flagged buoys? (Please choose the closest response)	A: Around 25% B: Around 50% C: Around 75%	
Q4	Do you fish with hard crab pots, peeler pots, or both?	A: Hard crab pots only B: Peeler pots only C: Both	
	If both, what is the proportion of peeler pots to total pots? (Please choose the closest response)	A: Around 25% B: Around 50% C: Around 75%	
Q5	What was the maximum number of pots you had in the water during the spring (March, April, and May)?	A: None B: 1-50 C: 51-100 D: 101-200 E: 201-300	G: 401-500 H: 501-600 I: 601-700 J: 701-800 K: 801-900

		F: 301-400	L: 901+
	What percentage of your pots was lost last? (Please write in)	%	
Q6	What was the maximum number of pots you had in the water during the summer (June, July, and August)?	A: None B: 1-50 C: 51-100 D: 101-200 E: 201-300 F: 301-400	G: 401-500 H: 501-600 I: 601-700 J: 701-800 K: 801-900 L: 901+
	What percentage of your pots was lost? (Please write in)	%	
Q7	What was the maximum number of pots you had in the water during the fall (September, October, and November)?	A: None B: 1-50 C: 51-100 D: 101-200 E: 201-300 F: 301-400	G: 401-500 H: 501-600 I: 601-700 J: 701-800 K: 801-900 L: 901+
	What percentage of your pots was lost? (Please write in)	%	
Q8	What practices do you use to reduce pot loss?		
Q9	What are your thoughts on pot loss?		
Q10	How do you prepare annually for pot loss?		
Q11	Are there any specific days or events when pot loss is greater? This might include holidays or particular weekdays.		
Q12	How do you prepare for high pot loss events such as boat traffic or storm events?		
Q13	Where do you get information about potential high pot loss events?		
Q14	In your fishing area what contributes to the greatest pot loss?	A: Recreational boat traffic B: Shipping traffic C: Storm events D: Debris E: Vandalism F: Other (please fill in)	
Q15	Do you avoid fishing in areas with lots of lost pots?		
Q16	What would you suggest to reduce pot loss? (Please write in)		
Q17	Did you retrieve any lost pots last year?	A: Yes B: No	
	If you did retrieve lost pots, approximately how many did you bring in?	A: Between 1-5 B: Between 5-10 C: Between 10-20 D: Between 20-30 E: Between 30-50 F: Over 50	
	If you did retrieve lost pots, what method did you use to retrieve lost pots?	A: Grapples B: Hooks on a line C: Modified crab dredges D: Other (please write in)	
	If you did retrieve lost pots, were there any animals in the pot?	A: Yes B: No	
	Were any alive?	A: Yes B: No	

Appendix G. The Dilemma of Derelict Gear

SCIENTIFIC REPORTS

OPEN

The Dilemma of Derelict Gear

A. M. Scheld, D. M. Bilkovic & K. J. Havens

Every year, millions of pots and traps are lost in crustacean fisheries around the world. Derelict fishing gear has been found to produce several harmful environmental and ecological effects, however socioeconomic consequences have been investigated less frequently. We analyze the economic effects of a substantial derelict pot removal program in the largest estuary of the United States, the Chesapeake Bay. By combining spatially resolved data on derelict pot removals with commercial blue crab (*Callinectes sapidus*) harvests and effort, we show that removing 34,408 derelict pots led to significant gains in gear efficiency and an additional 13,504 MT in harvest valued at US $21.3 million—a 27% increase above that which would have occurred without removals. Model results are extended to a global analysis where it is seen that US $831 million in landings could be recovered annually by removing less than 10% of the derelict pots and traps from major crustacean fisheries. An unfortunate common pool externality, the degradation of marine environments is detrimental not only to marine organisms and biota, but also to those individuals and communities whose livelihoods and culture depend on profitable and sustainable marine resource use.

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The financial ruin of commercial fisheries, thought to squander US $50 billion in economic benefits annually[1], has long been attributed to the common-pool nature of the resource[2]. Much like the 19th century dilemma of over-grazing common pasture, economically rational, self-interested fishers reap the benefit of their labors individually while sharing in the cost of a depleted stock. Unfortunately for the fisher, a common fish stock is not all that is shared. The environment in which harvest occurs is also a common resource, whose collective maintenance or degradation affects individual efficiencies and economic returns. Across many of the world's oceans and waterways, Hardin's tragedy[3] is multifaceted and complex.

Growth in global economies, together with the increasing use of long-lasting synthetic materials, has led to significant concerns surrounding marine debris[4,5]. Derelict fishing gear—the nets, lines, traps, and other recreational or commercial fishing equipment that has been lost, abandoned, or otherwise discarded[6,7]—is a major source of marine debris which has been charged with damaging sensitive habitats[8], creating navigational hazards[9], as well as reducing populations of target and non-target species[10–16]. Derelict gear may also compromise the economic vitality of fishery dependent businesses and communities as it competes with active gear and acts as a deterrent or distraction to target stocks, generating production inefficiencies which erode industry profits and inhibit commercial fishery success. These purely economic costs can be considered independent of the negative biological effects which might result from the continual capture of animals by derelict gear, termed 'ghost fishing'. That is, derelict gear may impose an economic cost, in terms of reduced gear efficiency, even in cases of little to no ghost fishing mortality.

The United States Atlantic blue crab commercial fishery lands over 77,000 metric tons (MT) worth US $150–200 million annually[17]. In the Chesapeake Bay, which accounts for nearly half of all US blue crab landings, it is thought that 20% of the approximately 800,000 fished hard crab pots become derelict each year[15]. Derelict pots may self-bait and ghost fish for several years[8] and experiments in the Chesapeake indicate structural integrity is generally maintained for two years or more[18]. Blue crabs are known to be attracted to pots as bottom structure whether or not any bait is present[18-20], and it has also commonly been observed that crustaceans enter and leave pots frequently, with retention rates varying according to pot design and intra and inter-species interactions[20-24]. In the United States' largest estuary, conservative estimates would suggest over 300,000 derelict pots are continually attracting, capturing, and possibly even killing, blue crab and other species (Fig. 1). As a result, active gear efficiency, harvests, and resource rents may be reduced considerably.

In 2008, following many years of declining harvests, the Chesapeake Bay blue crab industry was declared a commercial fishery failure by the US Department of Commerce, unleashing $30 million in disaster relief. A small portion of these funds was used to support the Virginia Marine Debris Location and Removal Program, a novel initiative in which commercial crabbers were hired during the winter closed fishing seasons to find, document, and remove derelict gear. The program proved to be a success, offering fishers an opportunity to earn

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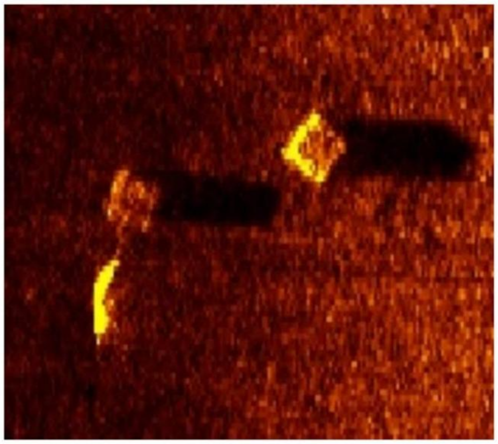

Figure 1. Side-scan sonar image of active/buoyed (left) and derelict (right) crab pots in the Chesapeake Bay (credit: CCRM/VIMS).

supplemental income while also removing considerable amounts of marine debris and generating useful scientific data[25]. From 2008 to 2014, 34,408 derelict pots were removed (Supplementary Fig. S1). Throughout the removal program, harvests and gear efficiency were observed to increase dramatically (Supplementary Fig. S2).

Results

Chesapeake Bay. A spatially explicit harvest model was used to predict harvests under two scenarios: actual removals and a counterfactual of zero removals (i.e., what *would* have been harvested had no derelict pots been removed). In the counterfactual it was assumed that the observed increases in blue crab abundance were the result of contemporaneous conservation measures or advantageous environmental conditions, allowing identification of harvest increases arising solely from reduced gear competition. Model results indicate that removing only 9% of the derelict gear in Virginia waters increased harvests by 13,504 MT ($SE = 1,660$), or 27% (Fig. 2a). Harvest increases resulting from gear efficiency improvements averaged 0.22 kg/pot ($SE = 0.03$). During the removal effort, each actively fished pot was harvesting an additional blue crab on every pull—crab which would have been captured or attracted to the now absent derelict gear.

Without the removal program, US $21.3 million in blue crab revenues would have been lost. These benefits far outweighed the program's total cost of US $4.2 million. Derelict pot removals were found to be net beneficial in every year of the program, though the difference between average benefits and costs per pot removed was greatest during the last two seasons, when limited program funds were used to target derelict gear hotspots (Fig. 2b). During targeted removals, a small group of commercial crab fishers focused removal efforts in areas which regularly experience high rates of potting activity and gear loss. Removals from these areas were more effective, and in general, areas which regularly experience high levels of effort and harvest, such as the mouths of major tributaries, saw greater program benefits (Fig. 2c). Considerable spatial and temporal heterogeneity in program effects suggests area and time prioritization of removals can be successful in producing significant economic benefit. For example, a removal effort at 10% the scale of the actual program (i.e., 3,441 removals), but focused on only the ten most heavily fished sites, would have increased harvests by 8,144 MT ($SE = 1,328$), or about 60% the improvement seen following the full removal program, *ceteris paribus*.

Global Analysis. Derelict fishing gear is a global problem[16]. High rates of gear loss plague many of the world's crustacean fisheries (Table 1) and, as a result, fishing traps and pots are thought to be one of the most common types of derelict gear worldwide[26]. Modern pots and traps are often constructed from rigid and durable materials[16] and may cause environmental, ecological, and economic damage for many years.

Total global landings from all crustacean trap fisheries grossing US $20 million or more annually (Fig. 3) average 615,560 MT and are worth US $2.5 billion (Table 1). Together, these high-value fisheries deploy tens of millions of pots and traps, millions of which become derelict each year. Extending findings from Chesapeake Bay blue crab to global crustacean fisheries suggests that removing less than 10% of the derelict pots and traps in these fisheries could increase landings by 293,929 MT, at a value of US $831 million annually. For blue crab in the United States, extensive removals from Atlantic and Gulf state fisheries might increase landings by over 40%, generating US $62 million in annual revenue benefits. In these and other pot and trap fisheries, substantial levels of gear loss likely lead to costly and inefficient outcomes. Net benefits of removal programs will ultimately depend upon removal costs however, which may vary widely.

Discussion

Increases in severe weather, boating traffic, and gear conflicts, arising from continued climate change[27] and global economic growth[28,29], could intensify gear loss over the coming decades. Preventative measures which incentivize gear conservation have been advocated in place of widespread removals on the basis of cost-effectiveness and

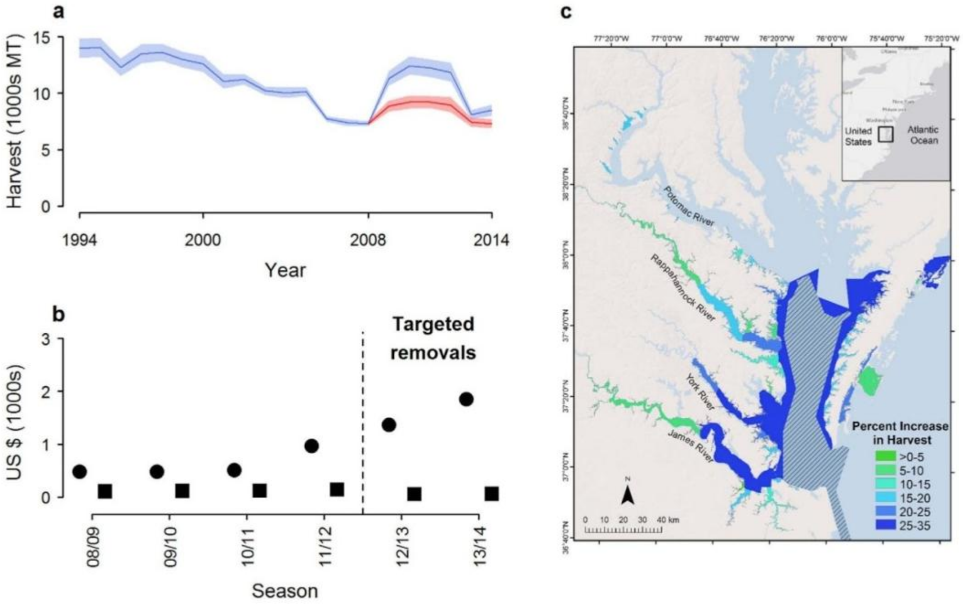

Figure 2. Economic effects of derelict pot removals. (**a**) 95% confidence region of Virginia blue crab harvest with (blue) and without (red) the Virginia Marine Debris Location and Removal Program. (**b**) Average benefits (circles) and costs (squares) per pot removed. Average benefits equal estimated total revenue increase divided by derelict pots removed. Average costs equal total compensation paid for removals divided by derelict pots removed. Vertical dashed line denotes start of removals from targeted hotspot areas. (**c**) Map of predicted harvest increases. Hatched area is a no-take crab sanctuary. Map created using Esri ArcGIS 10.0 (http://www.esri.com/software/arcgis).

sustainability[11,26]. In deep-water fisheries utilizing heavy gear, derelict gear location and removal may remain cost prohibitive[30]. Here it was seen that removal efforts can be economically viable, generating harvest and revenue benefits in excess of program costs. Simple, low-cost, and easily enforceable preventative measures should be introduced when possible, however a "one size fits all" approach has been argued to be problematic[12] and more research comparing cost-effectiveness of different measures is currently needed[26]. As all gear loss cannot be prevented, a combination of preventative and mitigating measures, such as the incorporation of effective biodegradable escape mechanisms[13,30], together with removals that target areas of high fishing pressure, is likely to yield benefits superior to any individual strategy in isolation. For small-scale removal programs, removing derelict gear from areas which regularly experience intense effort is recommended.

The harvest enhancing effects of derelict gear removals explored here were entirely the result of reduced gear competition and improved efficiency. Other studies have found derelict gear to be a source of mortality for target and non-target species[10–16], indicating the benefits of removals estimated here, though considerable, may be a lower bound. If removals led to a healthier and more abundant blue crab population, and this then led to harvest increases, total program benefits should increase. As crab and other crustaceans are generally attracted to bottom structure, and have been observed to regularly approach both active and derelict pots[19–23], it is likely that the use of biodegradable escape mechanisms would reduce, though not eliminate, the efficiency reducing effects of derelict gear.

Improvements in crustacean harvests resulting from the removal or reduction of rival derelict pots and traps can be biologically sustainable and offer clear, unfettered economic benefits. In the removal program analyzed here, it is estimated that approximately 60 million additional crab were harvested over the program's six years. This level of supplementary take averaged 2% of the estimated annual abundance, and throughout the removal program, commercial exploitation rates were found to be well within or below biological targets[31]. By 2012, blue crab abundance had increased 160% above 2008 estimates and a large number of juveniles were also observed. Following three seasons of intense removal efforts in which 80% of all removals occurred, there was no indication that the enhanced harvests afforded through derelict pot removals compromised blue crab recruitment or stock health. It is clear from our analysis however, that, absent the Virginia Marine Debris Location and Removal Program, the briefly bountiful blue crab would have yielded less harvest and economic benefit.

The economic costs of derelict gear examined here are likely not unique to pot and trap fisheries. Lost trammel-nets, gillnets, longlines, and bottom trawl gear pollute marine environments all over the world[11,26] and attract target and non-target species in much the same way as derelict pots and traps[24]. In these fisheries, it might be expected that active gear is underproductive. In addition to lost harvests arising from stock depletion by ghost fishing derelict gear, and any other detrimental biological or ecological effects, competition with active gear may generate economic inefficiencies similar to those found for Chesapeake Bay blue crab.

Species	Annual Gear Loss (% Deployed)*	Landings (MT)	Revenues (US$)	Major Producers
Blue swimmer crab *Portunus pelagicus*	70	173,647	$199M†	China, Philippines, Indonesia, Thailand, Vietnam
American lobster *Homarus americanus*	20–25	100,837	$948M	Canada, USA
Blue crab *Callinectes sapidus*	10–50	98,418	$152M	USA
Queen crab/snow crab *Chionoecetes opilio*	NA	113,709	$401M	Canada, St. Pierre and Miquelon (France), USA
Edible crab *Cancer pagurus*	NA	45,783	$49M‡	United Kingdom, Ireland, Norway, France
Dungeness crab *Metacarcinus magister*	11	35,659	$169M	USA, Canada
Spiny lobster *Panulirus argus*	10–28	34,868	$500M§	Bahamas, Brazil, Cuba, Nicaragua, Honduras, USA
King crab *Paralithodes camtschaticus*	10	10,137	$99M	USA
Stone crab *Menippe mercenaria*‖	NA	2,502	$24M	USA
TOTAL		615,560	$2.5B	

Table 1. Gear loss and global landings for major crustacean pot and trap fisheries. Average MT and US $ 2003–2012. Data from: NOAA Office of Science and Technology, National Marine Fisheries Service, Commercial fisheries statistics http://www.st.nmfs.noaa.gov/st1/commercial/index.html; Food and Agriculture Organization, United Nations, Fisheries and Aquaculture Department, http://www.fao.org/fishery/search/en, Fisheries and Oceans Canada http://www.dfo-mpo.gc.ca/stats/commercial/sea-maritimes-eng.htm. *Estimates from Bilkovic *et al.* (2012). †Based on an average price of US $1.15/kg (35). ‡Based on 2004–2012 average price of US $1.07/kg (36). §See (37). ‖Claws only.

The dilemma of derelict gear is, at its core, a common property problem. Assets which are owned by all are all too often of value to no one. The lost time, effort, and materials which result from needlessly inefficient gear represent a source of non-recoverable economic waste. These costs, though previously unacknowledged, are perhaps equally tragic to the ecological and environmental damage more commonly associated with derelict gear. Reducing or removing dominant sources of marine debris from the world's oceans, bays, and estuaries is essential not only to restoring and protecting local ecologies and environments, but also to revitalizing resource dependent communities and cultures.

Methods

Chesapeake Bay. The Virginia Marine Debris Location and Removal Program employed commercial crabbers to locate and remove derelict fishing gear from Virginia tidal waters. Participants were assigned to broad areas according to anticipated derelict pot abundance, travel time, and other logistical considerations such that excessive overlap was avoided. Individuals were provided with a side imaging unit (Humminbird™ 1197SI side imaging unit, dual frequency 455–800 kHz) preprogrammed to scan using 23 m (75 ft) swaths and acquire GPS points (survey tracks) every 30 seconds. The date, time, and location (waypoint), as well as various item descriptors, were recorded for all retrieved pots. During the first four years of the program (2008–2012), 32,421 derelict blue crab, peeler, and eel pots were recovered. The last two years of the program saw an abbreviated removal program in which 1,987 derelict pots were removed.

There are approximately 300,000 pots licensed and fished in Virginia, 20% of which, or about 60,000, are lost each year[15]. Assuming half of all derelict pots completely degrade each year—a conservative assumption as structural integrity has been shown to last for at least two years[18]—Virginia's "stock" of derelict pots can be described by the discrete time equation: $D_t = 0.5D_{t-1} + 60{,}000 - R_t$, where D_t and R_t are the stock and removals of derelict pots in year *t*, respectively. Using this formulation, intense removal efforts during the first three years of the program would have decreased the standing stock of derelict pots by 15%. Targeted hotspot removals later in the program likely led to localized decreases, however, the total stock of derelict pots would have increased during this time. Over the program's six years, removals are thought to have reduced the quantity of derelict pots by ~9% on average.

To investigate the impact of the removal program on the blue crab fishery, harvests were modeled using a modified Schaefer[32] specification which included derelict pot removals:

$$H_{it} = \begin{cases} q_{it} E_{it}^{\eta_e'} X_t^{\eta_x'} & \text{if } R_{it} = 0 \\ q_{it} E_{it}^{\eta_e} X_t^{\eta_x} R_{it}^{\eta_r} & \text{if } R_{it} > 0 \end{cases}, \tag{1}$$

where H_{it} is the harvest in area *i* at time *t*; q_{it} is an area- and time-specific catchability coefficient; E_{it} is the effort in area *i* at time *t*; X_t is the stock at time *t*; R_{it} is the amount of derelict gear removed from area *i* at time *t*; and η_e, η_x, and η_r are elasticity parameters.

Data necessary to estimate equation (1) was acquired from several different sources. Annual blue crab harvests and effort (number of pots) from 1994–2014 for 54 management delineated fishing areas were obtained from the Virginia Marine Resources Commission, the state agency responsible for managing blue crab. The 34,408 derelict pot removals were then overlaid into georeferenced management areas using the Identity operation in ArcGIS

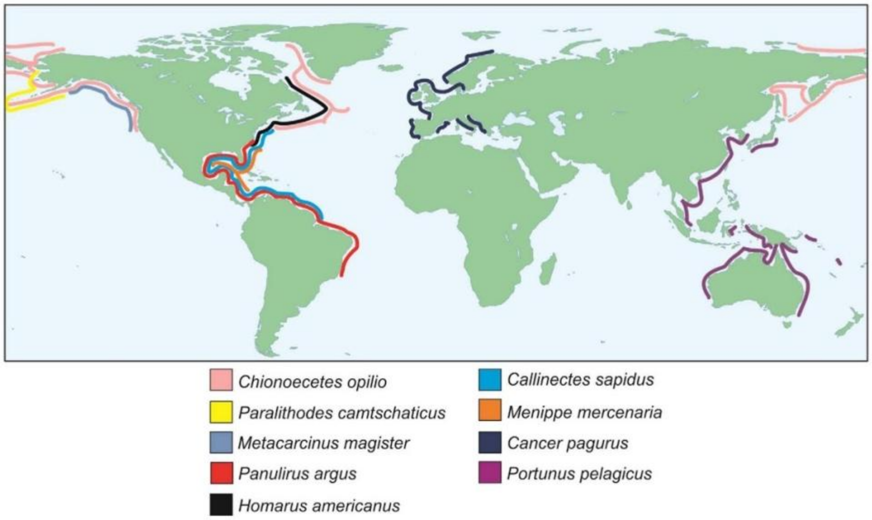

Figure 3. Global distribution of major crustacean pot and trap fisheries. Map created using Esri ArcGIS 10.0 (http://www.esri.com/software/arcgis).

10.0 and matched by year to harvests and effort. High-quality stock abundance estimates, derived from an annual winter dredge survey which samples ~1,500 sites throughout the Chesapeake Bay[31], were appended to harvest, effort, and derelict pot removal data. Equation (1) was estimated using a flexible transcendental logarithmic formulation which allowed for area random effects (see Supplementary Table S1).

Evaluating the impact of removals on harvests was accomplished through comparison of model predictions with and without derelict pot removals:

$$Effect_{it} = \hat{H}_{it}^{A} - \hat{H}_{it}^{Cf}, \tag{2}$$

where $\hat{H}_{it}^{A}$ and $\hat{H}_{it}^{Cf}$ are harvest predictions from equation (1) given actual removals and a counterfactual of zero removals. $Effect_{it}$ is the difference in predicted harvests for area i at time t attributable to the removal of derelict gear. Summation of equation (2) over i and t produced a measure of total program effects. Harvest effects were converted to revenues using average annual ex-vessel prices for Virginia hard shell blue crab in 2014 dollars.

While the potential for confounding bias in equation (2) cannot be totally eliminated, several aspects of the data and statistical model used reduce its likelihood. First, of the 54 management areas where harvest and effort were observed, 12 (22%) saw no removals during any year of the program. The number of areas experiencing removals in any given year averaged 32 (59%) and never exceeded 41 (76%). Overall, removals were found to exhibit a high degree of temporal and spatial variation ($cv(R_t) = 0.73$, $cv(R_i) = 1.52$), providing a rich set of data with which to identify marginal removal effects. Second, effort did not appear to respond to removals. That is, areas which saw more removals did not experience corresponding increases in effort. Were this not the case, a more complex counterfactual environment would be required to evaluate the removal program. Finally, the statistical harvest model included parameters to control for extraneous factors affecting harvests that were unrelated to the removal program. Area random effects enabled differences in catchability across areas to be modeled apart from any differences in area-specific removals, while a dummy indicator variable was included to control for exogenous shifts in catchability occurring contemporaneously with the removal program. Similar quasi-experimental empirical methods have been used to evaluate fisheries policies and isolate program effects in other contexts[33,34] (see Supplementary Information for additional background and description of the data and harvest model).

Global Analysis. To calculate the global impacts of wide-spread derelict gear removal or reduction, it was assumed that the following ratio would be maintained across crustacean pot and trap fisheries:

$$\frac{VA\ \ \%\ Harvest\ Increase}{VA\ \ Gear\ Loss\ Rate} = \frac{Fishery\ \ i\ \ \%\ Harvest\ Increase}{Fishery\ \ i\ \ Gear\ Loss\ Rate}. \tag{3}$$

Rather, the increase in harvests which could be expected to result after removing derelict gear from the grounds of fishery i, in an amount proportionate to that removed through the Virginia Marine Debris Location and Removal Program (i.e., ~9%), would depend on the rate of gear loss in that fishery. This relationship might be expected as most crustacean fisheries utilize pots and traps constructed from similar materials and operate in near-shore coastal environments, suggesting similar rates of gear decay. Proportionate removals from a fishery with a high rate of gear loss would imply many pots and traps were removed, and thus a large harvest increase should be expected. Additionally, as removals from areas of high potting effort were found to be more effective at enhancing harvests, removal benefits should be greater in fisheries with large stocks of derelict gear experiencing significant production inefficiencies.

To predict harvest increases using the ratio (3), our estimate of a 27% increase in blue crab harvests in Virginia, where the gear loss rate has been found to be 20%, was applied to global landings and gear loss data (Table 1). Mean loss rates were used for those fisheries where a range was reported, while a conservative 20% was applied to three fisheries without gear loss rate measurements (snow crab *Chionoecetes opilio*, edible crab *Cancer pagurus*, and stone crab *Menippe mercenaria*). Average prices were used to calculate revenues[35–37]. Large increases in landings could have offsetting price effects, however, due to data limitations, this possibility was not investigated here. Additionally, as multiple commercial fisheries exist for each of the included species, overall gear loss rates may differ from those used here. Differences in habitat and gear across fisheries may affect results, though attraction to bottom structure is a commonly observed crustacean behavior[19–23] and removal of derelict gear from global crustacean fisheries could hold similar efficiency improving effects to those observed for Chesapeake Bay blue crab if animals attracted to derelict gear might otherwise be caught by actively fished gear.

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Author Contributions

K.J.H. and D.M.B. led derelict pot removal program; A.M.S. and D.M.B. compiled data; A.M.S. performed data analyses; and all authors contributed to the writing.

Additional Information

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