2020

Investigating Economic Costs Of Derelict Blue Crab Callinectes Sapidus Pots And Preferred Mitigation Solutions In The Chesapeake Bay

James DelBene
William & Mary - Virginia Institute of Marine Science, jdelbene9@gmail.com

Recommended Citation

DelBene, James, "Investigating Economic Costs Of Derelict Blue Crab Callinectes Sapidus Pots And Preferred Mitigation Solutions In The Chesapeake Bay" (2020). *Dissertations, Theses, and Masters Projects.* Paper 1593091644.
http://dx.doi.org/10.25773/v5-3b05-hg47

Investigating economic costs of derelict blue crab *Callinectes sapidus* pots and preferred mitigation solutions in the Chesapeake Bay

A Thesis

Presented to

The Faculty of the School of Marine Science

The College of William and Mary in Virginia

In Partial Fulfillment

of the Requirements for the Degree of

Master of Science

by

James A. DelBene

January 2020

APPROVAL PAGE

This thesis is submitted in partial fulfillment of

the requirements for the degree of

Master of Science

James A. DelBene

Approved by the Committee, December 2019

Donna M. Bilkovic, Ph.D.
Committee Co-Chair / Co-Advisor

Andrew M. Scheld, Ph.D.
Committee Co-Chair / Co-Advisor

Kirk J. Havens, Ph.D.

Jeffrey D. Shields, Ph.D.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

The work presented in this thesis would not have been possible without the support and encouragement from my co-advisors, Drs. Donna Bilkovic and Andrew Scheld. Thank you for always being available to help me answer the tough questions, as well as reminding me to take a step back to see the bigger picture when I was too deep in the weeds. Donna's knowledge of the Chesapeake Bay system and interest in incorporating the human dimension was invaluable. She helped me develop and prepare for my field experiment, as well as coached me on working at the interface of science and policy. Andrew's dedication and experience working to understand the human dimension of fisheries was crucial to integrating economic theory and practice throughout my thesis. He helped with conducting focus groups with fishers and worked closely with me through survey development and data analysis. Additionally, thank you to my committee members, Drs. Kirk Havens and Jeff Shields, for providing vital insight and support through discussion and written edits. Kirk and Jeff asked me pointed questions to keep me on track and regularly shared research articles with me to expand my understanding of a topic.

The participation of watermen in all aspects of this thesis allowed my ideas to become a reality, whether helping with field work, participating in focus groups, or responding to my survey. Special thanks to Dan Knott and J.C. Hudgins for taking the time to provide me with guidance and contribute to the success of my research. For over two months, Dan allowed me to join him on the water and his patience ensured that my field experiment was a success. J.C. was my mentor throughout the development, distribution, and collection of my survey, and also facilitated me sharing survey results with other watermen. Both, Dan and J.C. played critical roles that helped me understand their perspectives as watermen and form new friendships. This work with watermen and all other research conducted for this thesis was made possible by funding support from the Virginia Institute of Marine Science, Virginia Sea Grant, and the William & Mary Committee on Sustainability Green Fee Award.

Thank you to the VIMS community and my cohort for making my time at VIMS and after hours enjoyable. Special thanks to the group at CCRM for providing support in the field, managing funds, and simply being a great group of people to work with and have a laugh. I would also like to thank the Scheld "lab" (Jen, Shelby, and Willy) for embracing our unique position as the only "lab" at VIMS focused on studying people and creating a great work environment that knew how to get work done, but also found time for casual, light-hearted conversation.

Lastly, I would like to thank my family and girlfriend, Abby Hils, for their never-ending support that helped me secure this opportunity at VIMS and ensured I would succeed. Dad, thank you for defining what an "early" morning and long work day truly are for me at a young age; it made grad school much easier! Mom, thanks for instilling your ability to pay close attention to detail in me, as it came in handy when entering all the datasheets and survey responses. Abby, thanks for putting up with me! Your energy is contagious and your expertise in public engagement helped me overcome my nerves to deliver countless practice rounds of presentations to you. Thank you for giving me that extra push when I needed it and always believing in me.

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Derelict fishing gear, particularly pots or traps, occupy waters worldwide and cause negative ecological and economic impacts. Derelict pots persist throughout Chesapeake Bay, the largest estuary in the U.S., that supports a valuable commercial fishery for the blue crab *Callinectes sapidus*. Chesapeake Bay is responsible for 30-40% of U.S. commercial blue crab harvests. Yet, few studies have quantified the impacts of derelict pots on harvest or the perceptions of commercial fishers on derelict pot mitigation activities in this predominantly pot fishery. This thesis examined the impacts of derelict pots on harvest in a field experiment and worked with commercial fishers to develop and disseminate a mail survey that was used to quantify the preferences and decision-making of commercial fishers for addressing derelict pots. The field experiment simulated the presence of derelict pots near actively fished pots and found that derelict pots can reduce harvests by up to 30% during the summer, but not during the fall. Female capture rates were consistently lower when derelict pots were present, but male capture rates were not negatively affected. To better understand the perceptions of commercial fishers and their preferences for derelict pot mitigation actions (e.g., location and removal program, installation of identification tags on pots), a stated preference survey with a discrete choice experiment was distributed to all commercial fishers licensed to deploy hard pots in Virginia. There was a 42% response rate (430 of 1,032 fishers returned the survey packet), and most mitigation activities included in the survey were too costly for commercial fishers to willingly participate in. Management incentives (e.g., bushel limit increase, pot limit increase, season extension) alone were not enough to offset costs and encourage participation in activities that were disliked by commercial fishers. However, there was strong heterogeneity observed across the population, thus some segments of the population would be far more willing to participate in mitigation efforts than others. For instance, participants that perceived derelict pots to cause only negative impacts were 37% more willing to participate in any mitigation activity on average. Results from this study can be used to better inform resource managers and policymakers responsible for addressing the issue of derelict pots and other types of derelict fishing gear plaguing fisheries around the world.

AUTHOR’S NOTE

The chapters that comprise this thesis were written in manuscript format for scientific publication. Thus, the formatting of each chapter follows the guidelines of the journal to which the manuscript was or will be submitted. At the time of writing, citations of individual chapters are as follows:

CHAPTER II:
DelBene, J.A., D.M. Bilkovic, and A.M. Scheld. 2019. Examining derelict pot impacts on harvest in a commercial blue crab *Callinectes sapidus* fishery. *Marine Pollution Bulletin* 139: 150-156. https://doi.org/10.1016/j.marpolbul.2018.12.014.

CHAPTER III:
DelBene, J.A., A.M. Scheld, and D.M. Bilkovic. Preferences for derelict gear mitigation strategies by commercial fishers. *In Prep.*

Investigating economic costs of derelict blue crab *Callinectes sapidus* pots and preferred mitigation solutions in the Chesapeake Bay

CHAPTER I

Introduction: Derelict fishing gear, management efforts, Virginia blue crab *Callinectes sapidus* fishery, and blue crab life history and ecology

The blue crab *Callinectes sapidus* is a crustacean of ecological and economic importance throughout its range in the Western Atlantic, from the East and Gulf Coasts of the United States, to the coast of Argentina. Introduction of the species to the Eastern Atlantic, in the North Sea and Mediterranean, as well as in Japan, have expanded its distribution (FAO 2018). Blue crabs support commercial and recreational fisheries that use pots and traps, as well as other methods to harvest the species (Kennedy et al. 2007). The high demand for this public resource often leads to conflict and competing interests from various stakeholders that complicate management efforts to maintain a healthy ecosystem and profitable blue crab fishery (Tobias 2009). Additionally, it is thought that 19% of all pots and traps deployed in various fisheries around the world become derelict (i.e., lost or abandoned; Richardson et al. 2019), which causes negative ecological and economic impacts (Bilkovic et al. 2016). Resource managers and decision-makers strive to reduce these impacts by implementing various mitigation actions. The most effective mitigation actions are best identified by engaging with stakeholders, including commercial fishers. It is also important to consider fishery characteristics and management practices already implemented, as well as the life history and ecology of the targeted species to fully evaluate derelict fishing gear impacts on the fishery and solutions.

Marine debris – derelict pots

Marine debris recognizes no borders. From international to local scales, it presents harmful ecological and economic impacts to coasts and waterways. In 2016, the United Nations Environment Program adopted a resolution to reduce the detrimental ecological and economic impacts of marine debris throughout oceans and coastal waterways (UNEP 2016). More recently, the United Nations General Assembly reemphasized recognition of marine debris as a global problem and called for actions to remove and prevent it, particularly derelict fishing gear

(UNGA 2018). Within the U.S., marine debris is defined by the Marine Debris Research, Prevention, and Reduction Act as "…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" (33 U.S.C. § 1951 *et seq.* 2006). Derelict fishing gear (DFG) is a type of marine debris that consists of any fishing gear that is lost, abandoned, or otherwise discarded, and includes nets, pots/traps, trawls, and longlines (Macfadyen et al. 2009, Bilkovic et al. 2016). Several factors can cause DFG, such as operational fishing factors; intentional abandonment; gear conflicts and vessel-gear interactions; vandalism and theft; faulty, degraded, or failed equipment; and losses through storms and other types of weather (Macfadyen et al. 2009, FAO 2010, Bilkovic et al. 2016, FAO 2016). A steady increase in fishing effort and improvements in gear technology have led to an increase in abundance and persistence of DFG in the marine environment (Macfadyen et al. 2009).

Negative impacts

Derelict pots are responsible for significant ecological and economic impacts through increased entanglements and bycatch mortality. Additionally, they damage marshes and seagrass beds that support marine fishes and shellfishes, harm stocks of target and non-target species, and decrease fishery profits (Guillory 1993, Arthur et al. 2014, Bilkovic et al. 2016, Scheld et al. 2016, Wilcox et al. 2016). Continued self-baiting contributes to "ghost fishing" by derelict pots that indiscriminately capture animals such as finfishes, water birds, turtles, mammals, and other invertebrate species in addition to blue crabs (Guillory 1993, Havens et al. 2011, Arthur et al. 2014). These animals could drown, become injured, or be consumed by other organisms in the pots (Guillory 1993, Matsuoka et al. 2005). Blue crab pots, rigid 0.6 x 0.6 x 0.6 m wire mesh cubes with an upper and lower chamber (Figure 1), can continue fishing for two or more years after becoming derelict (Matsuoka et al. 2005, Havens et al. 2008); and thus continue removing individuals (e.g., black seabass *Centropristis striata*, Atlantic croaker *Micropogonias undulatus*, summer flounder *Paralichthys dentatus*) that would otherwise support valuable recreational and commercial fisheries (Guillory 1993, Bilkovic et al. 2014). Moreover, studies have estimated annual blue crab mortality in derelict blue crab pots as 16 crabs/pot/yr. (Giordano et al. 2010), 23 crabs/pot/yr. (Bilkovic et al. 2016), and 26 crabs/pot/yr. (Guillory 1993).

These impacts are prevalent in Chesapeake Bay, the largest estuary in the U.S., which supports one of the country's most productive commercial and recreational blue crab fisheries. Virginia's Marine Debris Location and Removal Program (2008-2012) and a smaller targeted removal effort in the following two years (2013-2014) employed commercial fishers (locally known as watermen) to locate and remove derelict pots and other marine debris. Subsequent analyses estimated that 12-20% of all pots licensed in the region become derelict each year, with approximately 145,000 derelict pots present at any given time (Bilkovic et al. 2016). Furthermore, the removal of 10-15% of these derelict pots increased harvest by 13,504 metric tons over those six years (Scheld et al. 2016). Derelict pots may compete with nearby actively fished pots for blue crabs by attracting individuals, whether for structure (Everett and Ruiz 1993), food, or mates, away from pots that fishers actively harvest and bait. Reducing blue crab harvests creates inefficiency in the fishery that forces fishers to invest more time, money, and resources to harvest blue crabs in the presence of derelict pots (Scheld et al. 2016). Additionally, derelict pots are a navigation hazard for boaters and can cause costly damage to boat propellers and engines if the buoy line or mesh caging wraps around the propeller (Matsuoka et al. 2005). A high prevalence of derelict pots amplifies negative impacts that directly affect the well-being of commercial fishers and local communities that rely on the Chesapeake Bay for their livelihood.

Stakeholder engagement

Commercial fishers, state fishery managers, and policymakers are the key stakeholders involved with mitigating the issue of derelict pots in Virginia. Derelict pots are a negative externality imposed on commercial fishers, predominantly caused by boat propellers cutting the buoy lines of pots, abandonment, or vandalism (Bilkovic et al. 2016). The decision or action of one party (e.g., abandon pots; drive a boat over pot buoys, thus severing the buoy from the pot; leave pots in place during large storm events) imposes increased costs for commercial fishers in that area. Local communities, property owners, and recreationists are also impacted by derelict pots; however, commercial fishers are frequently the primary stakeholders affected by this externality, due to the cost of replacing the lost pots and the effects of derelict pots on their livelihoods. Because fishery managers and policymakers develop and implement regulations and actions concerning the blue crab fishery, it is important for them to engage with these stakeholders, especially commercial fishers, to better inform decision-making and efficiently allocate resources to address the complex problem of derelict pots. Information gathered from stakeholders through interviews, surveys, focus groups, and other strategies can significantly improve the quality of decisions (Reed 2008). For example, stated preference surveys that employ discrete choice experiments have been used to understand fishers' preferences for potential policy or management actions in commercial (Wattage et al. 2005, Fitzpatrick et al. 2017) and recreational (Aas et al. 2000, Goldsmith et al. 2018) fisheries. Use of such tools to understand the drivers of fishers' decision-making is essential to mitigate the impacts of derelict pots and maintain a sustainable and profitable blue crab fishery.

Mitigation activities

State resource managers and policymakers have worked with stakeholders in various voluntary and mandatory programs to mitigate ecological and economic impacts caused by derelict pots. Some of these programs include derelict pot location and removal programs (Havens et al. 2011, Bowling 2016), derelict pot buyback programs (Lebon and Kelly 2019), and development of biodegradable escape panels to reduce ghost fishing impacts (Bilkovic et al. 2012). Other mitigation activities consist of boater education to avoid pot lines and buoys, bycatch reduction devices, and installing individual pot identification tags (Guillory 1993, Bilkovic et al. 2016). Macfadyen et al. (2009) classified such activities as preventative, impact reducing, or curative measures. A combination of these measures could be implemented to reduce derelict pot abundance and impacts, but it is important to note that preventative measures (stopping pots from becoming derelict) often are the most cost-effective (Macfadyen et al. 2009).

In 2018, Virginia policymakers introduced legislation that would mandate implementation of an impact reducing measure in the commercial blue crab pot fishery. The legislation would have required commercial fishers to equip each crab pot with two biodegradable escape panels made of biopolymers or untreated cellulose-based natural products (e.g., jute, sisal, untreated wood; SB 552 2018). This proposed bill did not include incentives to encourage participation by commercial fishers, and fishers would have been responsible for any material or labor costs associated with installing the panels. Commercial fishers successfully lobbied the legislature to defeat the bill. Thus, policymakers and state resource managers were forced to develop new strategies that address derelict pots to improve the commercial blue crab fishery in Virginia waters.

Blue crab fishery and management

U.S. commercial and recreational fisheries for blue crab exist seasonally or year-round depending on the state. In 2016, the U.S. commercial fishery landed over 72 thousand metric tons of blue crab with ex-vessel revenues valued at US $219 million (NMFS 2018). The blue crab fishery in Chesapeake Bay is responsible for 30-40% of U.S. blue crab commercial harvests with ex-vessel revenues valued over US $100 million in 2016 (NMFS 2018). Information on the status and impact of the U.S. and Chesapeake Bay recreational fisheries is extremely limited (Stagg and Whilden 1997, Miller et al. 2011, McClellan 2017). The fishing gear used to harvest blue crabs includes nets, trotlines, pots or traps, scrapes, and dredges (Kennedy et al. 2007). Crab pots are the most prevalent gear used to harvest blue crabs in the Chesapeake Bay; previously estimated summer deployments exceed 350,000 annually (Bilkovic et al. 2016) but more recent estimates are lower. There is an established fishery for both hard crabs and peelers (premolt crabs for a softshell crab market) and both are predominantly captured in pot fisheries (Kennedy et al. 2007); however, peeler pots have a smaller wire mesh size and no cull rings (also known as escape rings, which allow undersized crabs to get out of a crab pot) as they target smaller juveniles for the peeler or soft-shell trade.

Blue crab management occurs at a state level, and action occurs most often when commercial fishers notice declines in harvest (Kennedy et al. 2007). Management regulations are not always supported by scientific understanding but may be influenced by political pressure from fishers or the seafood industry (Kennedy et al. 2007). Communication between scientists, commercial fishers, fishery managers, and policymakers occurs through advisory panels, stock assessments, and public meetings. Management of the Chesapeake Bay blue crab fishery is divided among the Maryland Department of Natural Resources, Virginia Marine Resources Commission (VMRC), and the Potomac River Fisheries Commission. As a result, conflicting regulations exist within the Bay; for instance, Maryland prohibits fishers from harvesting sponge crabs (egg-bearing females), whereas Virginia allows the harvest of sponge crabs (Kennedy et al. 2007). However, the three management bodies collaborate on data collection and a stock assessment model used by the Chesapeake Bay Stock Assessment Committee that incorporates data from the fishery-independent winter dredge survey. According to the most recent assessment released in 2019, the Chesapeake Bay stock is not depleted, and overfishing is not occurring (Chesapeake Bay Stock Assessment Committee 2019).

Virginia commercial fishery

The Virginia commercial fishery harvested approximately 10.4 thousand metric tons of blue crab in 2018 (Chesapeake Bay Stock Assessment Committee 2019). The VMRC is responsible for managing the blue crab fishery in Virginia. The crabbing season lasts from March through November and approximately 1,100 commercial hard pot licenses have been sold each year since 2011, compared to more than 1,800 that were sold in 2000 (VMRC 2019a). The number of hard crab pots licensed to be fished each year in Virginia is approximately 230,000, of which 70-80% are estimated to be active (VMRC 2019a). Furthermore, 479 peeler pot licenses were sold in 2017, which permitted approximately 104,000 peeler pots to be fished that year (VMRC 2019a). The VMRC recognizes 15 commercial fisher associations in Virginia and holds multiple meetings each year with the Blue Crab Management Advisory Committee to hear from fishers and other stakeholders (VMRC 2019b).

Historically a pot and dredge fishery, a collapse in the peeler fishery prompted the declaration of a federal failure for the Chesapeake Bay blue crab fishery in 2008. As a result, VMRC closed the winter dredge fishery and implemented other management actions (e.g., reduced pot limits, expanded blue crab sanctuary, shortened seasons, license buybacks; Bilkovic et al. 2016). These actions, along with Virginia’s Marine Debris Location and Removal Program (2008-2012; previously described in Marine Debris – Derelict Pots: Negative Impacts), are thought to be responsible for improvements in the health and productivity of the commercial blue crab fishery.

Virginia recreational fishery

Recreational fishery data is limited for the entire Chesapeake Bay, but is estimated at 8% of male and female commercial harvests in Virginia waters and 8% of male commercial harvests in Maryland waters (Maryland does not allow recreational harvest of female crabs; Chesapeake Bay Stock Assessment Committee 2019). VMRC does not require a recreational crab pot license for a person to use two crab pots but does require a license if an individual deploys three to five pots (VMRC 2019c). The number of recreational pots deployed each year is unknown but thought to be significant (Bilkovic et al. 2016).

Blue crab Callinectes sapidus

Biology and life history

Blue crabs are a short-lived species with a lifespan of two to three years (Van Engel 1958) that reside in shallow waters during the summer and move to deeper waters during the winter (Churchill 1919). They inhabit soft-bottom coastal environments ranging from freshwater to hypersaline water bodies (Williams 1974). Females prefer more saline waters than males, and they exhibit sexual dimorphism: males grow to be larger in size and have a narrow abdomen, whereas mature females have red tips on their claws and a rounded dome shaped abdomen, which is known colloquially as an apron. Females complete their terminal molt to maturity and mate in shallow brackish water throughout the summer in Chesapeake Bay (Turner et al. 2003). Females mate once storing the spermatophore in the seminal receptacle and may spawn two or more times throughout their lifetime, whereas males remain in brackish water year-round mating with multiple females (Van Engel 1958). Oviparous females carrying “sponges” (approximately

2,000,000 eggs each) that transition from yellow or orange to almost black coloration right before release, migrate to deeper, high salinity waters at the mouths of estuaries to spawn (Churchill 1919, Van Engel 1958). This spawning migration occurs in late summer and early fall in Chesapeake Bay (Churchill 1919, Van Engel 1958). After spawning, larvae enter the coastal waters over the continental shelf and develop as zoeae before returning to the estuary as megalopae and settling as juvenile crabs in shallow nursery habitats (Churchill 1919, Van Engel 1958, Pile et al. 1996).

Ecology and behavior

Blue crabs are voracious opportunistic feeders as juveniles and adults, mostly consuming fishes, benthic invertebrates (including cannibalism), and plant matter (Williams 1974, Seitz et al. 2011). Ecosystems, such as the Chesapeake Bay, rely on the blue crab as a species that shapes the benthic community and is predator to and prey for many species in the food web (Van Engel 1958, Virnstein 1977, Hines et al. 1990). Clark (1997) determined that blue crabs use chemosensory cues to detect patches of prey that are 10 to 15 meters away. Once prey is located, blue crabs are known to exhibit intraspecific, agonistic behavior that can interfere with foraging and lead to injury or retreat, in essence they fight each other for their prey (Clark et al. 1999a, Clark et al. 1999b, Mansour and Lipcius 1991).

This agonistic behavior occurs within pots, too. However, it does not appear to affect catch rates (Sturdivant and Clark 2011). Blue crab escape rates are high for the lower chamber of pots (escape rates of 41% and 85% in field and mesocosm experiments, respectively), but low (2%) for blue crabs in the upper chamber of pots (Sturdivant and Clark 2011). The constant movement and intraspecies interaction of crabs entering and leaving the lower chamber of pots, as well as their increased mortality rates due to cannibalism and delayed mortality due to injury, make it difficult to determine overall impacts of derelict pots and must be considered when determining appropriate mitigation activities (Guillory 1993).

Thesis objectives

This research focuses on derelict gear from the blue crab fishery in lower Chesapeake Bay and aims to inform management efforts by 1) examining the impacts of derelict pots on blue crab harvest, and 2) surveying Virginia commercial fishers to determine preferred derelict pot mitigation actions and incentives.

The first objective is to experimentally investigate the economic impacts caused by derelict pots on blue crab harvest. Results will better inform fishery management agencies on the impacts of derelict pots and quantify this production inefficiency responsible for decreasing fisher profits. It was thought that derelict pots will decrease harvest in nearby actively fished pots.

The second objective is to assess decision-making and preferences of Virginia's fishers with respect to derelict pot mitigation and management to better inform fishery management actions and reduce the impacts caused by derelict pots in Chesapeake Bay. This objective seeks to generate new information by surveying Virginia fishers and developing a framework that can be applied to other fisheries impacted by DFG. Effective and long-term solutions to DFG are more likely to occur if the preferences of fishers align with management priorities. Better understanding of commercial fishers' decision-making will help to inform future management efforts to increase participation in efforts that reduce derelict pot abundance and impacts.

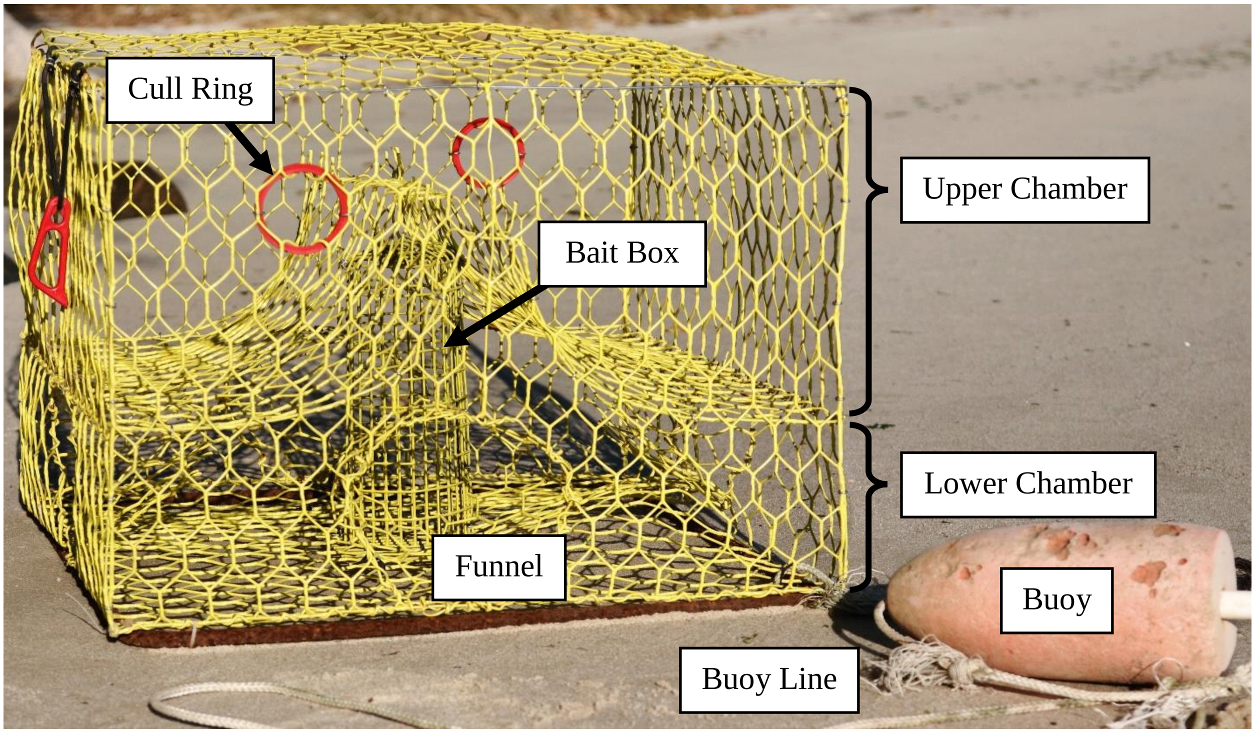


Figure 1 Diagram of a hard crab pot (photo credit: A. Hils).

References

Aas, Ø., W. Haider, and L. Hunt. 2000. Angler responses to potential harvest regulations in a Norwegian sport fishery: a conjoint-based choice modeling approach. *North American Journal of Fisheries Management* 20(4): 940-950. https://doi.org/10.1577/1548-8675(2000)020<0940:ARTPHR>2.0.CO;2.

Arthur, C., A. Sutton-Grier, P. Murphy, and H. Bamford. 2014. Out of sight but not out of mind: Harmful effects of derelict traps in selected U.S. coastal waters. *Marine Pollution Bulletin* 86: 19-28. https://doi.org/10.1016/j.marpolbul.2014.06.050.

Bilkovic, D.M., K.J. Havens, D.M. Stanhope, and K.T. Angstadt. 2012. Use of fully biodegradable panels to reduce derelict pot threats to marine fauna. *Conservation Biology* 26(6): 957-966. https://doi.org/10.1111/j.1523-1739.2012.01939.x.

Bilkovic, D.M., K. Havens, D. Stanhope, and K. Angstadt. 2014. Derelict fishing gear in Chesapeake Bay, Virginia: Spatial patterns and implications for marine fauna. *Marine Pollution Bulletin* 80: 114-123. https://doi.org/10.1016/j.marpolbul.2014.01.034.

Bilkovic, D.M., H.W. Slacum Jr, K.J. Havens, D. Zaveta, C.F. Jeffrey, A.M. Scheld, D. Stanhope, K. Angstadt, and J.D. Evans. 2016. Ecological and economic effects of derelict fishing gear in the Chesapeake Bay: 2015/2016 Final Assessment Report. Prepared for Marine Debris Program, Office of Response and Restoration, National Oceanic and Atmospheric Administration. Available: https://marinedebris.noaa.gov/reports/effects-derelict-fishing-gear-chesapeake-bay-assessment-report. (December 2019).

Bowling, T. 2016. State Derelict Fishing Gear Laws and Regulations. NSGLC-16-05-01. National Sea Grant Law Center, University, Mississippi. Available: http://nsglc.olemiss.edu/projects/dfg/index.html. (December 2019).

Chesapeake Bay Stock Assessment Committee 2019. 2019 Chesapeake Bay Blue Crab Advisory Report. (Chesapeake Bay Program, 2019). Available: https://www.chesapeakebay.net/who/group/chesapeake_bay_stock_assessment_committee. (December 2019).

Churchill Jr, E.P. 1919. Life history of the blue crab. *Bulletin of the Bureau of Fisheries* 36: 95-128.

Clark, M.E. 1997. Foraging behavior and intraspecific interactions of blue crabs (*Callinectes sapidus*) in a patchy environment: observation of individuals by ultrasonic telemetry (Doctoral dissertation). North Carolina State University, Raleigh, North Carolina, 159p.

Clark, M.E., T.G. Wolcott, D.L. Wolcott, and A.H. Hines. 1999a. Foraging and agonistic activity co-occur in free-ranging blue crabs (*Callinectes sapidus*): Observation of animals by ultrasonic telemetry. *Journal of Experimental Marine Biology and Ecology* 233: 143-160. https://doi.org/10.1016/S0022-0981(98)00129-4.

Clark, M.E., T.G. Wolcott, D.L. Wolcott, and A.H. Hines. 1999b. Intraspecific interference among foraging blue crabs *Callinectes sapidus*: Interactive effects of predator density and prey patch distribution. *Marine Ecology Progress Series* 178: 69-78. https://doi.org/10.3354/meps178069.

Dillman, D. A., J.D. Smyth, and L.M. Christian. 2014. Internet, Phone, Mail, and Mixed-mode Surveys: The Tailored Design Method. (4th ed.) Hoboken, NJ: John Wiley and Sons.

Everett, R.A. and G.M. Ruiz. 1993. Coarse woody debris as a refuge from predation in aquatic communities: An experimental test. *Oecologia* 93: 475-486. https://doi.org/10.1007/BF00328954.

Fitzpatrick, M., C.D. Maravelias, O.R. Eigaard, S. Hynes, and D. Reid. 2017. Fisher's preferences and trade-offs between management options. *Fish and fisheries* 18(5): 795-807. https://doi.org/10.1111/faf.12204.

Food and Agriculture Organization of the United Nations (FAO). 2010. The State of World Fisheries and Aquaculture 2010. Rome: Food and Agriculture Organization of the United Nations. Available: http://www.fao.org/docrep/013/i1820e/i1820e00.htm. (January 2018).

FAO. 2016. Abandoned, lost or otherwise discarded gillnets and trammel nets: methods to estimate ghost fishing mortality, and the status of regional monitoring and management by Eric Gilman, Francis Chopin, Petri Suuronen and Blaise Kuemlangan. FAO Fisheries and Aquaculture Technical Paper No. 600. Rome, Italy. Available: http://agris.fao.org/agris-search/search.do?recordID=XF2017001196. (December 2019).

FAO. 2018. Species Fact Sheets: *Callinectes sapidus* (Rathbun, 1896). FAO: Fisheries and Aquaculture Department. Available: http://www.fao.org/fishery/species/2632/en. (December 2019).

Giordano, S., J. Lazar, D. Bruce, C. Little, D. Levin, H.W. Slacum Jr., J. Dew-Baxter, L. Methratta, D. Wong, and R. Corbin. 2010. Quantifying the effects of derelict fishing gear in the Maryland portion of Chesapeake Bay. In: Final Report to the NOAA Marine Debris Program. National Oceanic and Atmospheric Administration, Silver Spring, Maryland. Available: https://marinedebris.noaa.gov/research/regional-impact-assessment-derelict-fishing-gear-chesapeake-bay. (December 2019).

Goldsmith, W.M., A.M. Scheld, and J.E. Graves. 2018. Characterizing the Preferences and Values of U.S. Recreational Atlantic Bluefin Tuna Anglers. *North American Journal of Fisheries Management* 38(3): 680-697. https://doi.org/10.1002/nafm.10064.

Guillory, V. 1993. Ghost fishing by blue crab traps. *North American Journal of Fisheries Management* 13: 459-466. https://doi.org/10.1577/1548-8675(1993)013<0459:GFBBCT>2.3.CO;2.

Havens, K.J., D.M. Bilkovic, D. Stanhope, K. Angstadt, and C. Hershner. 2008. The effects of derelict blue crab traps on marine organisms in the lower York River, Virginia. *North American Journal of Fisheries Management* 28(4): 1194–1200. https://doi.org/10.1577/M07-014.1.

Havens, K.J., D.M. Bilkovic, D. Stanhope, and K. Angstadt. 2011. Fishery failure, unemployed commercial fishers, and lost blue crab pots: An unexpected success story. *Environmental Science and Policy* 14: 445-450. https://doi.org/10.1016/j.envsci.2011.01.002.

Hines, A.H., A.M. Haddon, and L.A. Wiechert. 1990. Guild structure and foraging impact of blue crabs and epibenthic fish in a subestuary of Chesapeake Bay. *Marine Ecology Progress Series* 67: 105-126. https://doi.org/10.3354/meps067105.

Kennedy, V.S., M. Oesterling, and W.A. Van Engel. 2007. History of blue crab fisheries on the U.S. Atlantic and Gulf coasts. Pages 655–709 in V. Kennedy and L. Cronin (eds) The Blue crab: *Callinectes sapidus*. Maryland Sea Grant College, College Park.

Lebon, K.M. and R.P. Kelly. 2019. Evaluating alternatives to reduce whale entanglements in commercial Dungeness Crab fishing gear. *Global Ecology and Conservation* 18: e00608. https://doi.org/10.1016/j.gecco.2019.e00608.

Macfadyen, G., T. Huntington, and R. Cappell. 2009. Abandoned, lost or otherwise discarded fishing gear (No. 523). Food and Agriculture Organization of the United Nations (FAO). Rome, Italy. Available: http://www.fao.org/3/i0620e/i0620e00.htm. (December 2019).

Mansour, R.A. and R.N. Lipcius. 1991. Density-dependent foraging and mutual interference in blue crabs preying upon infaunal clams. *Marine Ecology Progress Series* 72: 239-246. https://doi.org/10.3354/meps072239.

Matsuoka, T., T. Nakashima, and N. Nagasawa. 2005. A review of ghost fishing: scientific approaches to evaluation and solutions. *Fisheries Science* 71: 691–702. https://doi.org/10.1111/j.1444-2906.2005.01019.x.

Miller, T.J., M.J. Wilberg, A.R. Colton, G.R. Davis, A. Sharov, R.N. Lipcius, G.M. Ralph, E.G. Johnson, and A.G. Kaufman. 2011. Stock Assessment of the Blue Crab in Chesapeake Bay 2011: Final Assessment Report. UMCES Technical Report Series No. TS- 614-11, University of Maryland Center for Environmental Science, Chesapeake Biological Laboratory, Solomons, MD, 203 p. Available: https://hjort.cbl.umces.edu/crabs/Assessment.html. (December 2019).

McClellan, K.L. 2017. Assessing the effect of climate variability on the South Carolina recreational and commercial blue crab fishery (Master's thesis). College of Charleston, Charleston, South Carolina, 129p.

National Marine Fisheries Service (NMFS). 2018. Fisheries economics of the United States,

2016. U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-F/SPO-187a, 243p. Available: https://www.fisheries.noaa.gov/content/fisheries-economics-united-states-2016. (December 2019).

Pile, A.J., R.N. Lipcius, J. Van Montfrans, and R.J. Orth. 1996. Desity-dependent settler-recruit-juvenile relationships in blue crabs. Ecological Monographs 66(3): 277-300. doi:10.2307/2963519.

Reed, M.S. 2008. Stakeholder participation for environmental management: a literature review. *Biological Conservation* 141(10): 2417-2431. https://doi.org/10.1016/j.biocon.2008.07.014.

Richardson, K., B.D. Hardesty, and C. Wilcox. 2019. Estimates of fishing gear loss rates at a global scale: A literature review and meta-analysis. *Fish and Fisheries* https://doi.org/10.1111/faf.12407.

SB 552. Crab pots and peeler pots; marine-biodegradable escape panels, penalty. 2018 Session (Virginia 2018). Available: https://lis.virginia.gov/cgi-bin/legp604.exe?181+sum+SB552. (December 2019).

Scheld, A.M., D.M. Bilkovic, and K.J. Havens. 2016. The dilemma of derelict gear. *Scientific Reports* 6: 19671. https://doi.org/10.1038/srep19671.

Seitz, R.D., K.E. Knick, and M. Westphal. 2011. Diet selectivity of juvenile blue crabs (*Callinectes sapidus*) in Chesapeake Bay. *Integrative and Comparative Biology* 51(4): 598-607. https://doi.org/10.1093/icb/icr098.

Stagg, C. and M. Whilden. 1997. The history of Chesapeake Bay's blue crab (*Callinectes sapidus*): fisheries and management. *Investigaciones Marinas* 25: 93-104. https://doi.org/10.4067/S0717-71781997002500007.

Sturdivant, K.S. and K.L. Clark. 2011. An evaluation of the effects of blue crab (*Callinectes sapidus*) behavior on the efficacy of crab pots as a tool for estimating population abundance. *Fishery Bulletin* 109: 48-55.

Tobias, C. 2009. The Tragedy of the Commons: The Case of the Blue Crab. *Southern California Interdisciplinary Law Journal* 19: 73.

Turner, H.V., D.L. Wolcott, T.G. Wolcott, and A.H. Hines. 2003. Post-mating behavior, intramolt growth, and onset of migration to Chesapeake Bay spawning grounds by adult female blue crabs, *Callinectes sapidus* Rathbun. *Journal of Experimental Marine Biology and Ecology* 295: 107-130. https://doi.org/10.1016/S0022-0981(03)00290-9.

United Nations Environment Programme (UNEP). 2016. Marine plastic debris and microplastics – Global lessons and research to inspire action and guide policy change. United Nations Environment Programme, Nairobi. Available:

https://www.unenvironment.org/resources/report/marine-plastic-debris-and-microplastics-global-lessons-and-research-inspire-action. (December 2019).

United Nations General Assembly (UNGA). 2018. A/RES/73/125. Sustainable fisheries, including through the 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, and related instruments. Available: https://undocs.org/en/A/RES/73/125. (December 2019).

Van Engel, W.A. 1958. The blue crab and its fishery in Chesapeake Bay: Part I. Reproduction, early development, growth and migration. *Commercial Fisheries Review* 20(6): 6-17.

Virginia Marine Resources Commission (VMRC). 2019a. Marine Resources Licensing and Permit Information. Available: https://mrc.virginia.gov/mrc-permits.shtm. (December 2019).

VMRC. 2019b. Watermen’s Associations. Available: https://mrc.virginia.gov/watermanassoc.shtm. (December 2019).

VMRC. 2019c. Regulation: Recreational Fishing and Crabbing in Virginia Tidal Waters. Available: https://www.mrc.virginia.gov/regulations/recfish&crabrules.shtm. (December 2019).

Virnstein, R.W. 1977. The Importance of Predation by Crabs and Fishes on Benthic Infauna in Chesapeake Bay. *Ecology* 58: 1200-1217. https://doi.org/10.2307/1935076.

Wattage, P., S. Mardle, and S. Pascoe. 2005. Evaluation of the importance of fisheries management objectives using choice-experiments. *Ecological Economics* 55(1): 85-95. https://doi.org/10.1016/j.ecolecon.2004.10.016.

Wilcox, C., N.J. Mallos, G.H. Leonard, A. Rodriguez, and B.D. Hardesty. 2016. Using expert elicitation to estimate the impacts of plastic pollution on marine wildlife. *Marine Policy* 65: 107-114. https://doi.org/10.1016/j.marpol.2015.10.014.

Williams, A.B. 1974. The swimming crabs of the genus *Callinectes* (Decapoda: Portunidae). *Fishery Bulletin* 72(3): 685-798.

CHAPTER II

Examining derelict pot impacts on harvest in a commercial blue crab *Callinectes sapidus* fishery

Published in the Marine Pollution Bulletin (2019) https://doi.org/10.1016/j.marpolbul.2018.12.014

Abstract

Keywords: blue crab, derelict fishing gear, Chesapeake Bay, commercial fishery, marine debris

Pot fisheries occur worldwide with a significant proportion of the gear becoming derelict. Derelict pots induce detrimental ecological and economic impacts, and more recently were found to reduce blue crab harvests in the Chesapeake Bay commercial fishery. We simulated the presence of derelict pots near actively fished pots in seasonal field experiments to quantify the effect derelict pots have on blue crab harvest. Derelict pots reduced harvests by 30% during the summer, but not during the fall. Female blue crab capture rates were consistently lower when derelict pots were present; while capture rates of the less abundant males were not negatively affected by derelict pots. Variable responses to derelict pots may be due to seasonal differences in female and male blue crab behavior and movements. The costly effect that derelict pots have on harvest should be investigated in other pot fisheries to recognize the magnitude and mechanisms behind these impacts.

Highlights:

- Derelict blue crab pots can reduce harvests in actively fished pots
- The effect of derelict pots on harvest differs seasonally
- Reduced harvests due to derelict pots were more evident in female blue crabs

Introduction

Derelict fishing gear (DFG) is a type of marine debris that consists of any fishing gear that is lost, abandoned, or otherwise discarded, such as nets, pots, trawls, and longlines (Macfadyen et al. 2009, Bilkovic et al. 2016). Several factors contribute to the presence of DFG, such as: operational fishing activities; intentional abandonment; gear conflicts; vessel-gear interactions; vandalism and theft; faulty, degraded, or failed equipment; and storms and weather (Macfadyen et al. 2009, FAO 2010, Bilkovic et al. 2016, Gilman et al. 2016). A steady increase in fishing effort and improvements in the lifespan of synthetic materials have led to an increase in abundance and persistence of DFG in the marine environment (Macfadyen et al. 2009).

Derelict pots are a prevalent form of DFG that occur globally and are responsible for significant ecological and economic impacts (Guillory 1993, Macfadyen et al. 2009, Arthur et al. 2014, Bilkovic et al. 2016, Scheld et al. 2016, Wilcox et al. 2016). Continued self-baiting contributes to “ghost fishing” by derelict pots that indiscriminately capture target and non-target animals including finfishes, water birds, turtles, mammals, and other invertebrate species (Guillory 1993, Havens et al. 2011, Arthur et al. 2014). These animals may become injured, drown, or be consumed by other organisms in the pots (Guillory 1993, Matsuoka et al. 2005). Bycatch mortalities by derelict pots frequently remove individuals that would otherwise contribute to valuable recreational and commercial fisheries (Guillory 1993, Bilkovic et al. 2014). Derelict pots may also degrade sensitive habitats (e.g., seagrasses, marshes) by smothering plants, abrading or removing blades of grass, and through scouring areas (Uhrin et al. 2005, Uhrin and Schellinger 2011, Arthur et al. 2014). Additionally, derelict pots can be a navigation hazard for boaters and can cause costly damage to boat propellers and engines if the buoy line wraps around the propeller (Matsuoka et al. 2005). Attraction towards derelict pots and away from actively fished pots can reduce harvests of target species in a pot fishery, whether or not the target species enter derelict pots (Fig. 1; Scheld et al. 2016).

In 2015, the US commercial blue crab *Callinectes sapidus* fishery landed over 73 thousand metric tons of blue crab valued at US $220 million (NMFS 2017). The blue crab is a shellfish of significant ecological (Van Engel 1958, Virnstein 1977, Hines et al. 1990) and economic importance on the Atlantic seaboard and Gulf Coast of the United States (Kennedy et al. 2007, NMFS 2017). Commercial and recreational blue crab fisheries primarily utilize pots, typically 0.6 x 0.6 x 0.6 m rigid wire mesh cubes with an upper and lower chamber (Kennedy et al. 2007). Blue crab pots can continue to fish for two or more years after becoming derelict (Matsuoka et al. 2005, Havens et al. 2008). Blue crab fisheries largely operate in inshore or nearshore environments, leading to a high likelihood of vessel-gear interactions that contribute to increased numbers of derelict pots. Impacts of derelict pots, such as reducing stocks of target and non-target species, decreasing fishery profits, and contributing to user group conflicts, have been well documented in US blue crab fisheries (Guillory et al. 2001, Anderson and Alford 2014, Bilkovic et al. 2016, Scheld et al. 2016).

The Chesapeake Bay is the largest estuary in the US and is responsible for 30-40% of US blue crab commercial harvests valued at over US $85 million in 2015 (NMFS 2017). Crab pots are the predominant gear used to harvest blue crabs in both the hard and soft crab fisheries. Following the 2008 US Department of Commerce's declaration of a federal fishery failure in the Chesapeake Bay blue crab fishery, the Virginia Marine Debris Location and Removal Program (2008-2012) was developed and implemented to locate and remove DFG. The program collected data on the abundance and distribution of derelict pots in the Chesapeake Bay (Bilkovic et al. 2014). Subsequent data analyses found that 12-20% of all pots licensed throughout the

Chesapeake Bay each year become derelict (approximately 145,000 derelict pots are predicted to be present at any given time; Bilkovic et al. 2016). This high prevalence of derelict pots may intensify negative impacts, affecting fishery resources and the well-being of commercial fishers and local communities who rely on the Chesapeake Bay.

Several past studies have identified the direct loss of biomass in the population of target species (e.g., blue crab, Dungeness crab *Cancer magister*) due to ghost fishing mortalities by derelict pots over time (Breen 1987, Guillory 1993, Havens et al. 2008, Giordano et al. 2010, Antonelis et al. 2011, Anderson and Alford 2014, Bilkovic et al. 2014, Voss et al. 2015). For example, bycatch mortality of blue crabs in derelict pots is estimated at 20-26 crabs per pot per year (Guillory 1993, Giordano et al. 2010, Bilkovic et al. 2016). However, limited research has focused on the instantaneous effect on harvest resulting from competition between derelict and actively fished pots. Recent analysis evaluating the Virginia Marine Debris Location and Removal Program and a smaller targeted removal effort the following two winters (2012-2013 and 2013-2014) in Virginia found removal of 34,408 derelict pots increased harvest by 30 million pounds over the course of the programs (Scheld et al. 2016). Derelict pots may compete with nearby actively fished pots by attracting blue crabs away from pots that fishers actively harvest and bait, whether for structure, shelter (Everett and Ruiz 1993), or foraging for food. Reduction in pot efficiency forces fishers to invest more time, money, and resources to harvest blue crabs in the presence of derelict pots, reducing fishery profits (Scheld et al. 2016). The large-scale analysis of Scheld et al. (2016) used established statistical methods to identify treatment effects in fishery harvests and derelict pot removal data, and suggested a novel economic impact caused by derelict pots. However, data on derelict pot removals was not collected for this purpose and further research is needed to experimentally test the effect that derelict pots have on harvest. The objectives of this study were to (1) experimentally evaluate the effect that derelict pots have on blue crab harvest in actively fished pots, which we hypothesize to be negative, and (2) investigate environmental and temporal factors influencing possible interaction between derelict and actively fished pots.

Materials and methods

Study site

The study site was in the Mobjack Bay, Virginia, in lower Chesapeake Bay (37°20’60.0” N, 76°19’57.9” W), a microtidal estuary with a tidal range of approximately 1 m. This site is polyhaline with soft sediment substrate and less than 2 m water depth. Submerged aquatic vegetation (SAV) is adjacent to the entire site and the shoreline is characterized by low-density residential development. Fishers regularly crab in this area throughout the Virginia commercial blue crab season (March - November).

Experimental design

A control group of ten actively fished crab pots without derelict pots nearby and a treatment group of ten actively fished crab pots with two derelict pots approximately 15 to 20 m away from each active pot (one on either side) were deployed with help from a commercially-licensed fisher (Fig. 2). The active pots were constructed by the commercial fisher from galvanized wire, and the derelict pots were minimally used, vinyl coated wire that we originally purchased as new. Actively fished pots were regularly baited, whereas derelict pots were unbaited. Blue crabs use chemosensory cues to detect prey up to 15 m away (Hines et al. 2009). As our study was focused on gear competition between active and derelict pots, we placed derelict pots in the treatment group outside of the active pot detection radius. This reduced the likelihood that blue crabs initially attracted to the unbaited, derelict pots would divert to the active pots for bait (see Fig. 1). The control (active pots only) and treatment (active pots and two derelict pots) groups were approximately the same distance from shore and placed in similar habitats to maintain consistency across the groups throughout the study. The groups were separated by roughly 260 m to ensure independence. Blue crabs are mobile; therefore, independence of experimental groups was determined by separating the two groups beyond the blue crab prey detection distance of 15 m (Hines et al. 2009) and further than the typical distance crabbers place between pots in the Chesapeake Bay (approx. 40 m). Within the control and treatment groups, active pots were separated by approximately 40 m, following typical pot deployment patterns used by crabbers in Chesapeake Bay. Pots in the control and treatment groups remained in the same physical location throughout the experiment to reduce confounding site and treatment effects, because site effects could change over time due to the extensive daily movements and seasonal migration of blue crabs.

A Humminbird™ Side Scan unit was used to identify and mark with a GPS point any unknown derelict pots in the sampling area before and after each sampling period (as per Havens et al. 2011). Furthermore, for the duration of the study any actively fished pots observed within 20 m of experimental pots were noted to account for additional pots that may compete with experimental pots.

Data collection and summary

Blue crab harvest and bycatch data were collected from each actively fished pot in the control and treatment groups for 11 days during each of the two sampling periods in 2017 (summer: August 9-24; fall: October 11-November 4). Actively fished pots were sampled within three days after deployment and all catch were removed and recorded. Following standard commercial crabbing practice, all legal-size crabs were harvested, and sublegal-size crabs were released. The 22 sampling days resulted in 22 replicates and 110 subsamples of data collected from the ten active pots in each experimental group (control, treatment). In addition, ancillary data were collected on each sampling day from one of the 20 derelict pots in the treatment group. The derelict pot was randomly selected using a random number generator and subsequently checked (i.e., any animals present were noted, and pots were redeployed with animals still in pot). We limited the number of times derelict pots in the treatment group were checked to more closely simulate derelict pots that would not be exposed to these disturbances. Additional derelict pots were occasionally checked for logistical reasons, such as repositioning of pots. All derelict pots in the treatment group were sampled on the final sampling day of each season. Crab carapace width (legal: ≥ 127 mm; sublegal: < 127 mm), sex (male, female), and bycatch species and abundance were recorded for each pot sampled. Sampling days were not always consecutive throughout the seasons due to foul weather, vessel maintenance, scheduling conflicts, and closure of the Virginia commercial blue crab fishery on Sundays. Between seasons, all active pots were removed from the study site while derelict pots were disarmed and remained in the water at the study site.

We noted daily water temperatures as well as the time each pot was checked to enable calculation of soak time (i.e., the duration of time each pot was in the water before being sampled). Daily salinity measurements were collected from NOAA’s York Spit Chesapeake Bay Interpretive Buoy System buoy. These measurements closely align with those at nearby Mobjack Bay. Submerged aquatic vegetation cover during 2017 near the sample site was obtained from the VIMS SAV Program that annually maps SAV distribution in Chesapeake Bay from multispectral digital imagery (http://web.vims.edu/bio/sav/). Water temperature, salinity, and

SAV cover were plotted and mapped to examine as possible environmental factors that may influence crab catch.

Data analyses

For each sampling event, capture rates (crabs/pot/day) were calculated for individual active pots in the control and treatment groups by dividing the count data (e.g., number of legal-size blue crabs) by the number of days the pot was in the water. Median and mean capture rates for legal-size, sublegal-size, and total catch were viewed across and within seasons to detect any catch differences between active pots in the control and treatment groups. Active pot capture rates were then analyzed by sex for legal-size, sublegal-size, and total catch within each experimental group after being separated by season. Shapiro-Wilk tests were used to test for normality in the capture rates and Mann-Whitney U tests were used to compare non-normal capture rates between the active pots in the control and treatment groups of each season. As a robustness check, additional Mann-Whitney U tests were used to compare legal-size capture rates between experimental groups considering: 1) individual pot as a replicate for experimental groups with sampling days as subsamples, and 2) sampling day as a replicate for each experimental group with individual pots as subsamples. In addition, bycatch was recorded during sampling events of all pots (active and derelict) in the control and treatment groups. Bycatch capture rates (individuals/pot/day) of blue crab or other species were calculated and compared across seasons (Mann-Whitney U test).

A negative binomial generalized linear mixed model (GLMM) was used to investigate the effect of derelict pot presence (control = no derelict pots present, treatment = two derelict pots present), season (summer, fall), and soak time (1, 2, or 3 days) on the number of legal-size blue crabs harvested per active pot. Variation in conditions across pot locations (e.g., position in the line of pots, nearby habitat) was accounted for by including an individual pot identifier as a random effect. The same model structure was used to evaluate effects on total (legal and sublegal-size) blue crabs captured per pot. To account for variation in sampling days (e.g., due to changes in the local environment), a second version of the GLMM was developed including sampling day as a random effect instead of individual pot. The use of individual pot and sampling day as random effects in separate GLMMs ensured results were robust to possible site effects across pot locations and changes in local environmental conditions across days (e.g., changes in water temperature and salinity), respectively. All statistical work was performed in R (R Core Team 2018) and the glmer.nb function in the lme4 package was used to estimate GLMMs (Bates et al. 2015). The function bootMer, also contained in the lme4 package, was used to perform a parametric bootstrap where the model was re-estimated 1,000 times (Bates et al. 2015). Bootstrap estimates were used to calculate means, standard errors, and the significance for GLMM parameters and predictions.

Results

No preexisting or newly introduced derelict pots were identified using side-scan sonar within the study site and no additional actively fished pots were observed within 20 m of the experimental pots. Throughout this study, the capture rate of legal-size blue crabs was similar across the two seasons (summer: mean ± SE = 4.13 ± 0.17 crabs/pot/day; fall: mean ± SE = 4.49 ± 0.18 crabs/pot/day; Fig. 3). During the summer, active pots in the control group captured significantly more legal-size and total blue crabs per pot per day than the treatment group; however, during the fall there was no significant difference between active pot capture rates in the control and treatment groups (Table 1). Results from the additional Mann-Whitney U tests were similar to Table 1 and robust in treating individual active pot samples and sampling days as independent observations. Additionally, the capture rates of total blue crabs in derelict pots were similar between the two seasons (U = 411, $p > 0.05$) and the bycatch capture rate of other species in derelict pots was relatively low (summer: mean ± SE = 0.04 ± 0.01 individuals/pot/day; fall: mean ± SE = 0.24 ± 0.07 individuals/pot/day). Bycatch species consisted predominantly of spider crab *Libinia emarginata* (n = 19), black sea bass *Centropristis striata* (n = 6), and sheepshead *Archosargus probatocephalus* (n = 5) in the derelict pots, whereas northern puffer *Sphoeroides maculatus* (n = 10), Atlantic spadefish *Chaetodipterus faber* (n = 7), and spider crab *Libinia emarginata* (n = 3) dominated the bycatch in the control and treatment group active pots. There was no significant difference in the capture rate of total bycatch between the control and treatment active pots (U = 23,537, $p > 0.05$).

Most of the blue crabs captured throughout the experiment were females (76%). During both seasons, the capture rates for total females were significantly greater in the control group than the treatment group (Table 2). Summer capture rates for legal-size females were significantly greater in the control group, but there was no significant difference in sublegal-size female capture rates. Conversely, in the fall legal-size female capture rates were similar between the active pots in the control and treatment groups, though capture rates for sublegal-size females were significantly greater in the control group. For the less abundant males, patterns of capture rates between the control and treatment varied from the females and by season. During the summer, capture rates for male blue crabs (legal-size, sublegal-size, and total) were similar between the control and treatment, while during the fall, capture rates for males (legal-size, sublegal-size, and total) in the treatment group were significantly higher than the control group. Overall, the absolute differences in average capture rates between control and treatment groups for females were always greater than those for males.

During sampling events, the highest water temperature was 27.9 °C and the lowest was 16.2 °C. The water temperature was lower during the fall (summer: mean = 26.3 °C; fall: mean = 19.3 °C). Throughout the seasons, the salinity measured at the study site ranged from 19.9 to 23.4 PSU. Mean salinity in the summer was 20.4 PSU, and in the fall was 22.3 PSU. SAV cover was adjacent to and a similar distance from the control and treatment groups in our study site (min. 105 m, max. 171 m).

Results from the negative binomial GLMM indicated that season, treatment, and an interaction between season and treatment had significant effects on the mean harvest in active pots. Model predictions of mean harvest for the summer were 5.96 (SE = 0.41) crabs per pot per day and 3.92 (SE = 0.30) crabs per pot per day for active pots in the control and treatment group, respectively. During the fall, control and treatment group model predictions of mean harvest were 4.68 (SE = 0.34) crabs per pot per day and 4.54 (SE = 0.34; mean effects derived from bootstrap resampling model output, Table 3). Soak time did not significantly affect mean harvest (Table 3), likely because there was little variation in this variable (82% of observations had a soak time of 1 day). Similar results were observed when the same model was used to estimate total catch of blue crabs and when the model was run with sampling day as the random effect.

Discussion and conclusions

The results from this study supported our hypothesis that the presence of derelict pots negatively impacts blue crab harvest. A significant harvest reduction (approx. two legal-size crabs per pot per day) was noted when derelict pots were present during summer but not fall. However, when considering capture rates by sex and focusing on females, the dominant sex observed, female capture rates were largely lower when derelict pots were present in both seasons. This suggests that derelict pots were attracting blue crabs away from the nearby actively fished pots. Thus, blue crabs did not have to enter the derelict pot but may have been simply attracted to it and away from the active pots, resulting in reduced harvest. This is supported by the consistently low capture rates of derelict pots. For instance, during the summer only 0.26 (SE = 0.07) legal-size blue crabs per pot per day were observed in the derelict pots, which did not account for the magnitude of legal-size blue crab loss in the active pots of the treatment group (Table 1).

Variability in the “derelict pot effect” may be a result of the seasonal differences in blue crab behavior and movement in Chesapeake Bay (Van Engel 1958). For instance, the frequency of blue crab molting is reduced at lower water temperatures (Churchill 1919, Van Engel 1958). During molting, blue crabs seek structured habitats for refuge from predation (Hines 2007). A potential reduction in molting frequency during colder water temperatures of the fall could have resulted in less movement to seek refuge and fewer interactions with the derelict pots. Another possibility for differences observed between seasons could have been due to increased movement of blue crabs during the mating season that occurs from early May and into October, with a peak in late August and early September (Van Engel 1958). Blue crab mating movements to find a suitable mate would be limited during the fall sampling period (October 11-November 4) and could reduce the chance of interactions with derelict pots.

The reduced harvest effect of derelict pot presence was especially noticeable in the harvest of female blue crabs, which was consistently higher in control group active pots across both seasons. We expected to capture more females than males at the study site due to female preference for higher salinities (Van Engel 1958), but the decrease in harvest observed in active pots when derelict pots were present would imply that females are more likely than males to be attracted towards derelict pots and thus not enter nearby active pots. Such behavioral difference between sexes could explain the smaller impact of derelict pot removals that Bilkovic et al. (2016) observed in Maryland, where blue crab harvests are dominated by males as opposed to Virginia, where blue crab harvests are dominated by females (Miller et al. 2011). One possible reason for this disparity between sexes in our findings is differences in overwintering migration movements. Females migrate to the mouth of the Chesapeake Bay in late summer and early fall to spawn, whereas males remain in the brackish waters year-round (Churchill 1919, Van Engel 1958). This migration of females throughout the duration of our study would increase the possibility of female interactions with derelict pots, whereas males do not participate in such large-scale movements.

The complex movement of blue crabs within dynamic estuarine environments makes it difficult to account for all variation that occurs in harvests. As a dominant species in the Chesapeake Bay ecosystem, the blue crab utilizes multiple habitats throughout its life cycle (Churchill 1919, Van Engel 1958). Adults spend most time in soft-sediment environments, but have been observed in structured habitats, such as SAV and woody debris, foraging or seeking refuge (Wolcott and Hines 1990, Everett and Ruiz 1993, Bromilow and Lipcius 2017). Additionally, the patchiness and fine scale variability in habitats (e.g., SAV, oyster reefs, soft-sediment) and environmental parameters (e.g., salinity, temperature, dissolved oxygen, pH) in the Chesapeake Bay influence the movement of blue crabs (Micheli and Peterson 1999, Stover et al. 2013, Cunningham and Darnell 2015, Glaspie et al. 2017). We attempted to control for this variation by focusing on a localized area during the late summer and mid to late fall that was positioned nearshore (< 2 m depth), outside of SAV habitat, and on soft-sediment. In addition, there were 11 replicates for each pot location during each season and a GLMM was used to control for possible site- and time-specific influences when estimating treatment effects.

Nonetheless, the effect of derelict pots was found to be variable throughout the year and by sex, possibly due to blue crab molting, mating, and migration patterns.

Derelict pots used in this study were never baited. This was a conservative representation of a derelict pot, as pots are regularly baited by commercial fishers and may become derelict afterwards. The occurrence of self-baiting in derelict pots has been shown to double their catch rate (Havens et al. 2008), which leads to an increased mortality of bycatch. Because derelict pots were not baited like the actively fished pots, blue crab detection distance and pot attractiveness would differ between derelict and active pots. Blue crabs are voracious opportunistic feeders, mostly consuming fishes, benthic invertebrates (including cannibalism), and plant matter (Williams 1974, Seitz et al. 2011). Fish such as Atlantic menhaden *Brevoortia tyrannus* are often used to bait blue crab pots due to their oily flesh. Blue crabs can use chemosensory cues to detect prey up to 15 m away (Hines et al. 2009), which would suggest a 15 m radius of attraction encircles each baited pot. The detection perimeter of a baited pot is important to consider, especially with the competition effect between derelict and active pots. Further investigation into the effect of distance on the interaction between derelict and active pots would improve our understanding of pot competition and the relationship between derelict gear and reductions in harvest.

Reductions in harvest due to the presence of derelict pots could be addressed by fishery managers to improve the efficiency of the fishery and increase profits. According to the most recent assessment in 2018, the Chesapeake Bay blue crab stock is not depleted, and overfishing is not occurring (Chesapeake Bay Stock Assessment Committee 2018). Furthermore, the exploitation fraction for female crabs was 21%, which was less than the target of 25.5% and threshold of 34% (Chesapeake Bay Stock Assessment Committee 2018). Lessening the impact of derelict pots on active fishery harvests would reduce the amount of time and money that commercial fishers spend to reach the current daily harvest limits, making fishing operations more profitable. Managers should consider the costs and benefits of mitigating harvest impacts and economic inefficiencies during comprehensive assessments of strategies addressing the issue of derelict pots.

The commercial blue crab fishery is one of many economically important pot fisheries (e.g., Dungeness crab, American lobster *Homarus americanus*, king crab *Paralithodes camtschaticus*, stone crab *Menippe mercenaria*) that support coastal communities. Our results suggest derelict pots are an uncontrolled inefficiency in the Chesapeake Bay blue crab commercial fishery; however, similar impacts in other pot fisheries have not been investigated. Efforts to mitigate impacts of derelict pots include removal programs, boater education, marine spatial planning, biodegradable escape panels, bycatch reduction devices, individual pot identification tags, and escape vents (Guillory 1993, Bilkovic et al. 2016). The potential effects of derelict pots on harvest observed in our study are primarily mitigated by removing or preventing the occurrence of derelict pots. However, derelict pot removal programs are expensive and require coordination among multiple parties to locate, remove, and then dispose of pots, whereas preventive actions (e.g., boater education to avoid pot buoys and lines, individual pot identification tags, spatial gear restrictions) can be less capital intensive though more politically challenging. Reduced harvests caused by derelict pots can be addressed through management actions and should be investigated in other pot fisheries. Globally, pot fisheries lose millions of pots each year (Macfadyen et al. 2009) that have the potential to significantly reduce harvests and increase the cost of fishing worldwide. Future studies should examine the prevalence of derelict pot impacts on harvests in other fisheries to better understand the magnitude of potential economic losses caused by derelict pots.

Acknowledgements

Funding for data collection during this project was provided by Virginia Sea Grant [grant number R71851K-PD]. These data would not have been possible without the invaluable field assistance from Dan Knott. This project benefited from the advice, support, and edits of Dr. Kirk Havens and Dr. Jeff Shields. Additionally, Maxine MacLeod provided the illustration (Fig. 1) to visualize the "derelict pot effect" and Dr. Robert Isdell helped design the study site map (Fig. 2). This paper is Contribution No. 3797 of the Virginia Institute of Marine Science, William & Mary.

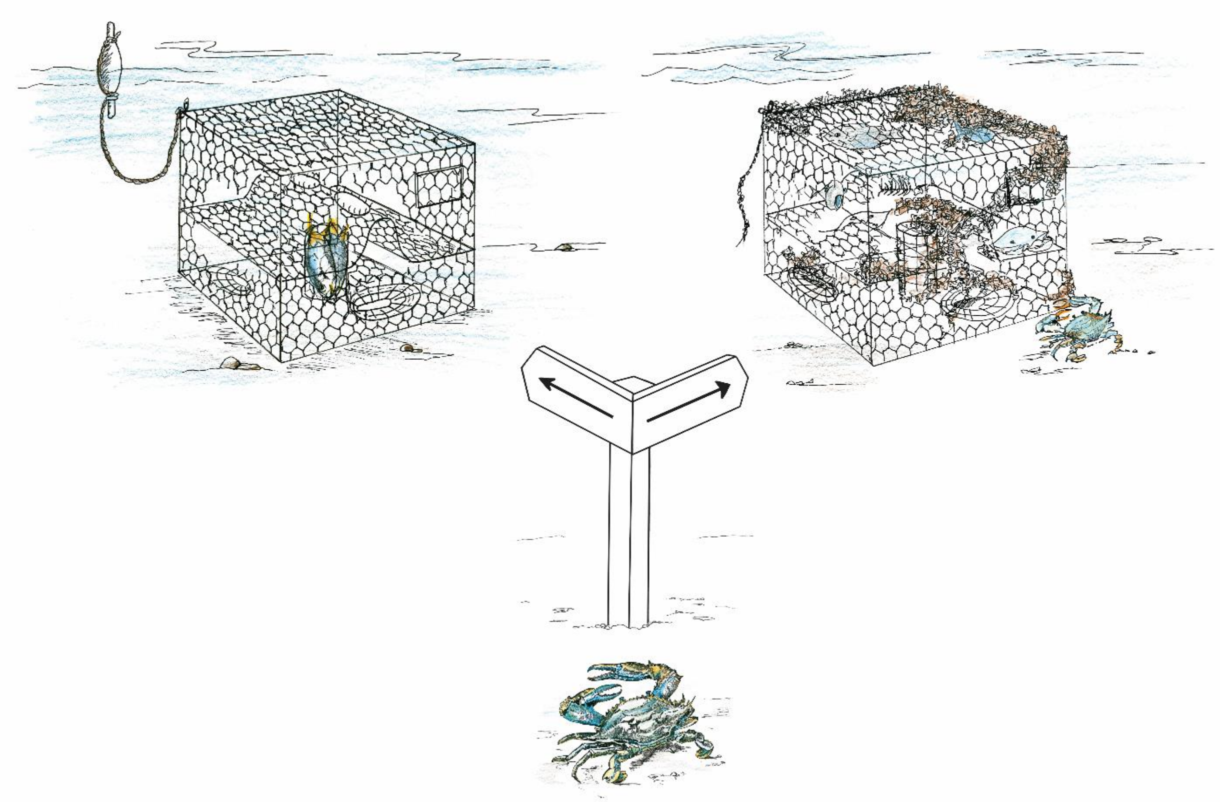


Figure 1 Illustration of the competition effect between actively fished (left) and derelict (right) pots. Commercial fishers regularly bait the active pots to attract blue crabs, but nearby derelict pots may attract crabs away from the active pots. Whether or not the blue crab enters the derelict pot, it will be removed from the commercial fisher’s harvest.

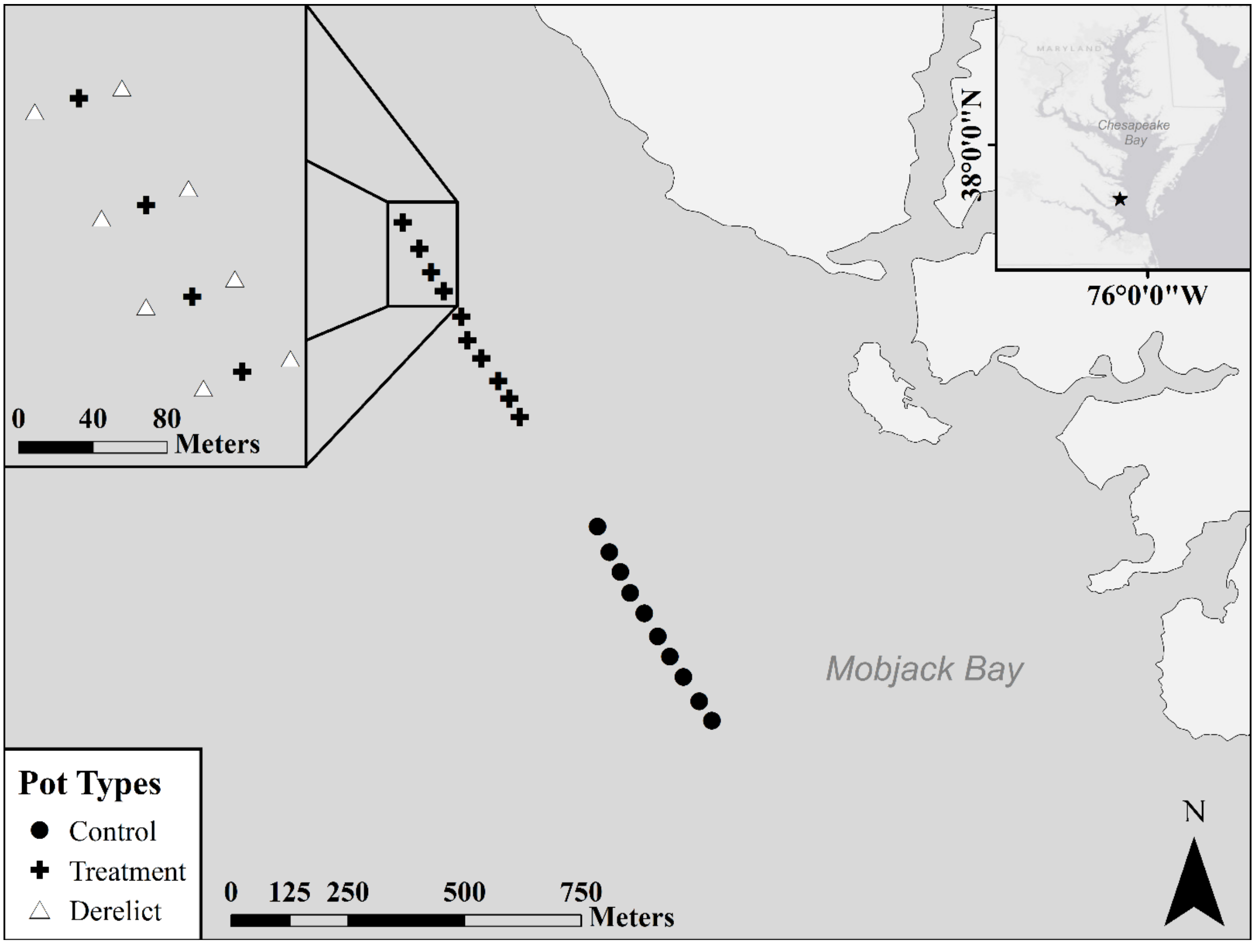


Figure 2 Diagram of the experimental design at the study site in Mobjack Bay, Virginia.

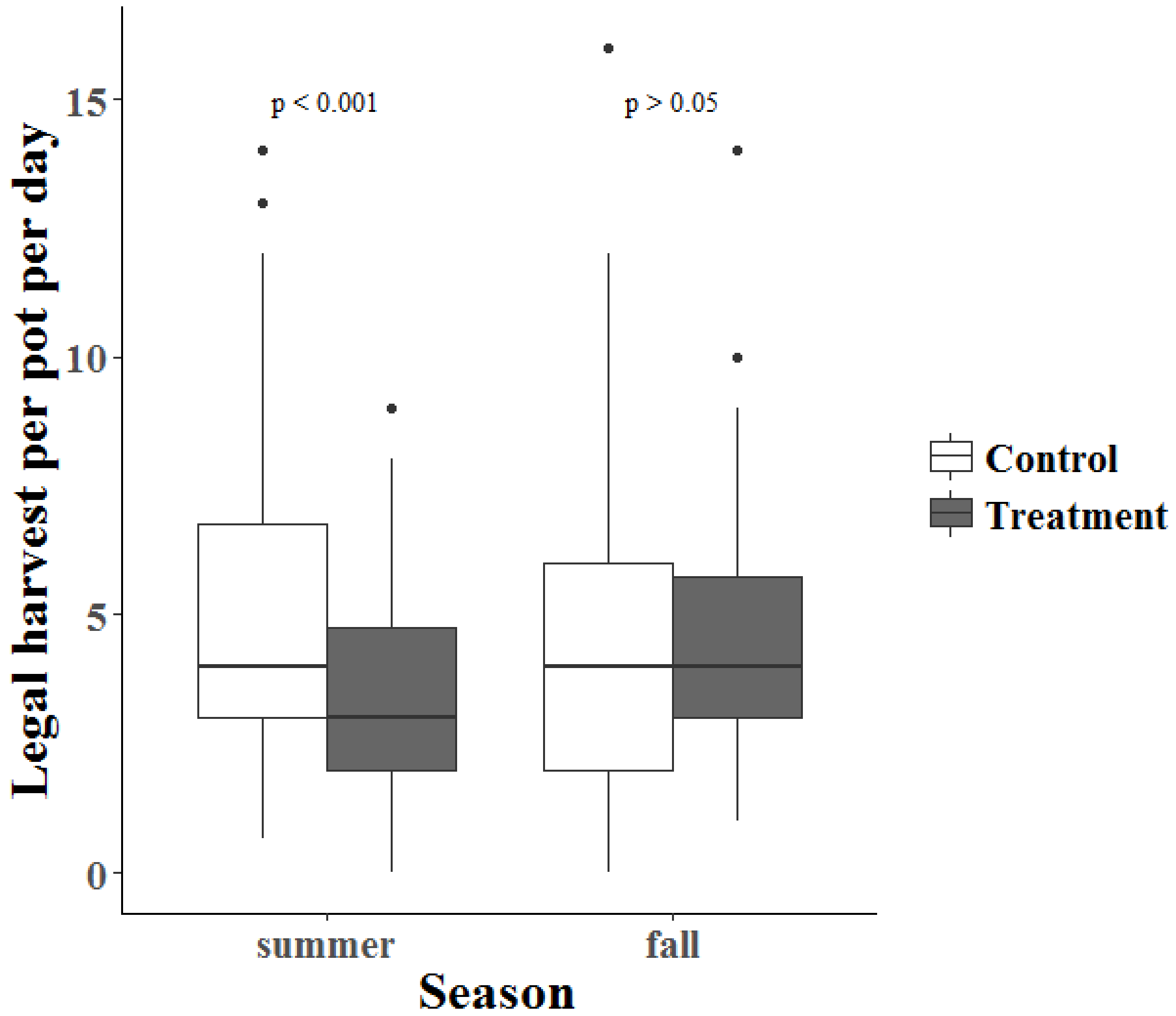


Figure 3 Boxplots of blue crab legal harvest rates (crabs/pot/day) for active pots by experimental group (Control or Treatment) during each season (summer or fall).

Table 1 Rates of blue crabs per pot per day recorded during the different seasons and within each type of active pot (Control = active pot within control group, Treatment = active pot within treatment group). Statistical results from Mann-Whitney U tests comparing corresponding control/treatment pot types within the same season are represented by the U statistic and significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Season	Pot Type	Legal Harvest Rate				Sublegal Catch Rate				Total Catch Rate			
		Mean [SE]	*Median*	*U*		*Mean [SE]*	*Median*	*U*		*Mean [SE]*	*Median*	*U*	
Summer	Control (n = 110)	4.98 [0.27]	4.00			0.89 [0.09]	0.83			5.87 [0.30]	5.00		
	Treatment (n = 110)	3.29 [0.19]	3.00	8,280.5	***	0.72 [0.08]	0.50	6,585.0		4.01 [0.21]	4.00	8,205.5	***
Fall	Control (n = 110)	4.60 [0.28]	4.00			1.35 [0.11]	1.00			5.95 [0.30]	5.50		
	Treatment (n = 110)	4.37 [0.23]	4.00	6,166.0		1.15 [0.09]	1.00	6,611.0		5.52 [0.24]	5.00	6,499.5	

Table 2 Rates of blue crabs per pot per day by sex recorded during the different seasons and within each experimental group (Control = active pot within control group, Treatment = active pot within treatment group). Statistical results from Mann-Whitney U tests comparing corresponding sex control/treatment pot types within the same season are represented by the U statistic and significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Season	Pot Type	Sex	Legal Harvest Rate				Sublegal Catch Rate				Total Catch Rate			
			Mean [SE]	*Median*	*U*		*Mean [SE]*	*Median*	*U*		*Mean [SE]*	*Median*	*U*	
Summer	Control (n = 110)	Male	1.01 [0.01]	1.00			0.37 [0.05]	0.00			1.37 [0.12]	1.00		
		Female	3.97 [0.24]	3.00			0.53 [0.08]	0.00			4.50 [0.27]	4.00		
	Treatment (n = 110)	Male	0.91 [0.09]	1.00	6,426.5		0.42 [0.07]	0.00	5,959.5		1.34 [0.11]	1.00	6,186.0	
		Female	2.38 [0.16]	2.00	8,343.0	***	0.29 [0.04]	0.00	6,696.5		2.67 [0.17]	2.50	8,456.5	***
Fall	Control (n = 110)	Male	0.48 [0.07]	0.00			0.53 [0.07]	0.00			1.01 [0.10]	1.00		
		Female	4.12 [0.26]	4.00			0.82 [0.10]	1.00			4.94 [0.28]	5.00		
	Treatment (n = 110)	Male	0.76 [0.08]	1.00	4,817.0	**	0.70 [0.07]	1.00	5,207.0	*	1.46 [0.10]	1.00	4,460.0	***
		Female	3.61 [0.23]	3.00	6,680.5		0.45 [0.07]	0.00	7,432.5	**	4.06 [0.24]	4.00	7,086.0	*

Table 3 Results of the negative binomial mixed model bootstrap estimates for legal-size blue crab harvest in active pots (number of observations = 440; residual df = 433; Significance: * p < 0.05, ** p < 0.01, *** p < 0.001).

Predictor Variables	Coefficient	SE	Sig.
Intercept	1.731	0.083	***
Season	- 0.242	0.064	***
Treatment	- 0.421	0.099	***
Soak time	+ 0.052	0.033	
Season:Treatment	+ 0.390	0.092	***

References

Anderson, J.A. and A.B. Alford. 2014. Ghost fishing activity in derelict blue crab traps in Louisiana. *Marine Pollution Bulletin* 79: 261-267. https://doi.org/10.1016/j.marpolbul.2013.12.002.

Antonelis, K., D. Huppert, D. Velasquez, and J. June. 2011. Dungeness crab mortality due to lost traps and a cost–benefit analysis of trap removal in Washington state waters of the Salish Sea. *North American Journal of Fisheries Management* 31(5): 880-893. https://doi.org/10.1080/02755947.2011.590113.

Arthur, C., A. Sutton-Grier, P. Murphy, and H. Bamford. 2014. Out of sight but not out of mind: Harmful effects of derelict traps in selected U.S. coastal waters. *Marine Pollution Bulletin* 86: 19-28. https://doi.org/10.1016/j.marpolbul.2014.06.050.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2015. Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software* 67(1): 1-48. https://doi.org/10.18637/jss.v067.i01.

Bilkovic, D.M., K. Havens, D. Stanhope, and K. Angstadt. 2014. Derelict fishing gear in Chesapeake Bay, Virginia: Spatial patterns and implications for marine fauna. *Marine Pollution Bulletin* 80: 114-123. https://doi.org/10.1016/j.marpolbul.2014.01.034.

Bilkovic, D.M., H.W. Slacum Jr, K.J. Havens, D. Zaveta, C.F. Jeffrey, A.M. Scheld, D. Stanhope, K. Angstadt, and J.D. Evans. 2016. Ecological and economic effects of derelict fishing gear in the Chesapeake Bay: 2015/2016 Final Assessment Report. Prepared for Marine Debris Program, Office of Response and Restoration, National Oceanic and Atmospheric Administration. Available: https://marinedebris.noaa.gov/reports/effects-derelict-fishing-gear-chesapeake-bay-assessment-report. (December 2019).

Breen, P.A. 1987. Mortality of Dungeness crabs caused by lost traps in the Fraser River Estuary, British Columbia. *North American Journal of Fisheries Management* 7: 429-435. https://doi.org/10.1577/1548-8659(1987)7<429:MODCCB>2.0.CO;2.

Bromilow, A.M. and R.N. Lipcius. 2017. Mechanisms governing ontogenetic habitat shifts: role of trade-offs, predation, and cannibalism for the blue crab. *Marine Ecology Progress Series* 584: 145-159. https://doi.org/10.3354/meps12405.

Chesapeake Bay Stock Assessment Committee 2019. 2019 Chesapeake Bay Blue Crab Advisory Report. (Chesapeake Bay Program, 2019). Available: https://www.chesapeakebay.net/who/group/chesapeake_bay_stock_assessment_committee. (December 2019).

Churchill Jr, E.P. 1919. Life history of the blue crab. *Bulletin of the Bureau of Fisheries* 36: 95-128.

Cunningham, S.R. and M.Z. Darnell. 2015. Temperature-dependent growth and molting in early juvenile blue crabs *Callinectes sapidus*. *Journal of Shellfish Research* 34(2): 505-510. https://doi.org/10.2983/035.034.0246.

Everett, R.A. and G.M. Ruiz. 1993. Coarse woody debris as a refuge from predation in aquatic communities: An experimental test. *Oecologia* 93: 475-486. https://doi.org/10.1007/BF00328954.

Food and Agriculture Organization of the United Nations (FAO). 2010. The State of World Fisheries and Aquaculture 2010. Rome: Food and Agriculture Organization of the United Nations. Available: http://www.fao.org/docrep/013/i1820e/i1820e00.htm. (January 2018).

Gilman, E., F. Chopin, P. Suuronen, and B. Kuemlangan. 2016. Abandoned, lost or otherwise discarded gillnets and trammel nets: methods to estimate ghost fishing mortality, and the status of regional monitoring and management. FAO Fisheries and Aquaculture Technical Paper No. 600. Rome. Available: http://agris.fao.org/agris-search/search.do?recordID=XF2017001196. (December 2019).

Giordano, S., J. Lazar, D. Bruce, C. Little, D. Levin, H.W. Slacum Jr., J. Dew-Baxter, L. Methratta, D. Wong, and R. Corbin. 2010. Quantifying the effects of derelict fishing gear in the Maryland portion of Chesapeake Bay. In: Final Report to the NOAA Marine Debris Program. National Oceanic and Atmospheric Administration, Silver Spring, Maryland. Available: https://marinedebris.noaa.gov/research/regional-impact-assessment-derelict-fishing-gear-chesapeake-bay. (December 2019).

Glaspie, C.N., K. Longmire, and R.D. Seitz. 2017. Acidification alters predator-prey interactions of blue crab *Callinectes sapidus* and soft-shell clam *Mya arenaria*. *Journal of Experimental Marine Biology and Ecology* 489: 58-65. https://doi.org/10.1016/j.jembe.2016.11.010.

Guillory, V. 1993. Ghost fishing by blue crab traps. *North American Journal of Fisheries Management* 13: 459-466. https://doi.org/10.1577/1548-8675(1993)013<0459:GFBBCT>2.3.CO;2.

Guillory, V., A. McMillen-Jackson, L. Hartman, H. Perry, T. Floyd, T. Wagner, and G. Graham. 2001. Blue crab derelict traps and trap removal programs. Gulf States Marine Fisheries Commission, Ocean Springs, Mississippi. Available: https://www.gsmfc.org/pubs.php?s=IJF&page=3. (December 2019).

Havens, K.J., D.M. Bilkovic, D. Stanhope, K. Angstadt, and C. Hershner. 2008. The effects of derelict blue crab traps on marine organisms in the Lower York River, Virginia. *North American Journal of Fisheries Management* 28(4): 1194-1200. https://doi.org/10.1577/M07-014.1.

Havens, K.J., D.M. Bilkovic, D. Stanhope, and K. Angstadt. 2011. Fishery failure, unemployed commercial fishers, and lost blue crab pots: An unexpected success story. *Environmental Science and Policy* 14: 445-450. https://doi.org/10.1016/j.envsci.2011.01.002.

Hines, A.H., A.M. Haddon, and L.A. Wiechert. 1990. Guild structure and foraging impact of blue crabs and epibenthic fish in a subestuary of Chesapeake Bay. *Marine Ecology Progress Series* 67: 105-126. https://doi.org/10.3354/meps067105.

Hines, A.H. 2007. Ecology of juvenile and adult blue crabs. Pages 565–630 in V. Kennedy and E. Cronin, editors. The blue crab: *Callinectes sapidus*. Maryland Sea Grant, College Park.

Hines, A.H., W.C. Long, J.R. Terwin, and S.F. Thrush. 2009. Facilitation, interference, and scale: the spatial distribution of prey patches affects predation rates in an estuarine benthic community. *Marine Ecology Progress Series* 385:127-135. https://doi.org/10.3354/meps08055.

Kennedy, V.S., M. Oesterling, and W.A. Van Engel. 2007. History of blue crab fisheries on the U.S. Atlantic and Gulf coasts. Pages 655–709 in V. Kennedy and L. Cronin (eds) The Blue crab: *Callinectes sapidus*. Maryland Sea Grant College, College Park.

Macfadyen, G., T. Huntington, and R. Cappell. 2009. Abandoned, lost or otherwise discarded fishing gear (No. 523). Food and Agriculture Organization of the United Nations (FAO). Rome, Italy. Available: http://www.fao.org/3/i0620e/i0620e00.htm. (December 2019).

Matsuoka, T., T. Nakashima, and N. Nagasawa. 2005. A review of ghost fishing: scientific approaches to evaluation and solutions. *Fisheries Science* 71: 691–702. https://doi.org/10.1111/j.1444-2906.2005.01019.x.

Micheli, F. and C.H. Peterson. 1999. Estuarine vegetated habitats as corridors for predator movements. *Conservation Biology* 13(4): 869-881. https://doi.org/10.1046/j.1523-1739.1999.98233.x.

Miller, T.J., M.J. Wilberg, A.R. Colton, G.R. Davis, A. Sharov, R.N. Lipcius, G.M. Ralph, E.G. Johnson, and A.G. Kaufman. 2011. Stock Assessment of the Blue Crab in Chesapeake Bay 2011: Final Assessment Report. UMCES Technical Report Series No. TS- 614-11, University of Maryland Center for Environmental Science, Chesapeake Biological Laboratory, Solomons, MD, 203 p. Available: https://hjort.cbl.umces.edu/crabs/Assessment.html. (December 2019).

National Marine Fisheries Service. 2017. Fisheries Economics of the United States, 2015. U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-F/SPO-170, 247p. Available: https://www.fisheries.noaa.gov/feature-story/fisheries-economics-united-states-2015. (December 2019).

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Scheld, A.M., D.M. Bilkovic, and K.J. Havens. 2016. The dilemma of derelict gear. *Scientific Reports* 6: 19671. https://doi.org/10.1038/srep19671.

Seitz, R.D., K.E. Knick, and M. Westphal. 2011. Diet selectivity of juvenile blue crabs (*Callinectes sapidus*) in Chesapeake Bay. *Integrative and Comparative Biology* 51(4): 598-607. https://doi.org/10.1093/icb/icr098.

Stover, K.K., K.G. Burnett, E.J. McElroy, and L.E. Burnett. 2013. Locomotory fatigue during moderate and severe hypoxia and hypercapnia in the Atlantic Blue Crab, *Callinectes sapidus*. *The Biological Bulletin* 224(2): 68-78. https://doi.org/10.1086/BBLv224n2p68.

Uhrin, A.V., M.S. Fonseca, and G.P. DiDomenico. 2005. Effect of Caribbean Spiny Lobster Traps on Seagrass Beds of the Florida Keys National Marine Sanctuary: Damage Assessment and Evaluation of Recovery. *American Fisheries Society Symposium* 41: 579-588.

Uhrin, A.V. and J. Schellinger. 2011. Marine debris impacts to a tidal fringing-marsh in North Carolina. *Marine Pollution Bulletin* 62(12): 2605-2610. https://doi.org/10.1016/j.marpolbul.2011.10.006

Van Engel, W.A. 1958. The blue crab and its fishery in Chesapeake Bay: Part I. Reproduction, early development, growth and migration. *Commercial Fisheries Review* 20(6): 6-17.

Virnstein, R.W. 1977. The importance of predation by crabs and fishes on benthic infauna in Chesapeake Bay. *Ecology* 58: 1200-1217. https://doi.org/10.2307/1935076.

Voss, C.M., J.A. Browder, A. Wood, and A. Michaelis. 2015. Factors driving the density of derelict crab pots and their associated bycatch in North Carolina waters. *Fishery Bulletin* 113(4): 378-390.

Wilcox, C., N.J. Mallos, G.H. Leonard, A. Rodriguez, and B.D. Hardesty. 2016. Using expert elicitation to estimate the impacts of plastic pollution on marine wildlife. *Marine Policy* 65: 107-114. https://doi.org/10.1016/j.marpol.2015.10.014.

Williams, A.B. 1974. The swimming crabs of the genus *Callinectes* (Decapoda: Portunidae). *Fishery Bulletin* 72(3): 685-798.

Wolcott, T.G. and A.H. Hines. 1990. Ultrasonic telemetry of small-scale movements and microhabitat selection by molting blue crabs (*Callinectes sapidus*). *Bulletin of Marine Science* 46(1): 83-94.

CHAPTER III

Preferences for derelict gear mitigation strategies by commercial fishers

Abstract

Keywords: derelict fishing gear, commercial pot fishery, random utility model, discrete choice experiment, blue crab, marine debris

Local, national, and international efforts to address the issue of derelict fishing gear are often limited by resources and costs. Managers and policymakers have implemented various preventative, impact reducing, and curative measures to decrease derelict fishing gear abundance and impacts, but stakeholder support is essential for success. To identify stakeholder preferences and the most efficient measures that could be used to address the issue of derelict blue crab pots in Chesapeake Bay, we distributed a stated preference survey with a discrete choice experiment to licensed commercial fishers in Virginia. Management incentives (e.g., bushel limit increase, pot limit increase, or season extension) were generally not found to induce participation in mitigation activities; however, we did observe heterogeneity across the preferences of commercial fishers that managers and policymakers can use to target segments of the population that would be more willing to participate. For example, individuals that perceived derelict pots to cause negative impacts only were much more willing to participate in mitigation activities. Addressing the complex problems caused by marine debris, especially derelict fishing gear, is costly, but managers and policymakers can implement more effective solutions by understanding stakeholder preferences and decision-making.

Highlights:

- Most derelict pot mitigation activities were too costly for fishers to willingly participate
- Fishers preferred monetary incentives over regulatory benefits
- Preferences of fishers for activities and incentives exhibited strong heterogeneity
- Participants with strong negative perceptions of derelict pots were much more willing to participate

Introduction

Marine debris persists around the globe, contributing to a complex problem in fisheries worldwide (Galgani et al. 2015, Richardson et al. 2019). Calls for action to combat marine debris have resounded throughout international, national, and state governing bodies (United Nations General Assembly 2004, Marine Debris Act 2006, Register 2014). Each call has explicitly identified the need to reduce derelict fishing gear, a type of marine debris that consists of any fishing gear that becomes abandoned, lost, or otherwise discarded (Macfadyen 2009). Richardson et al. (2019) estimated that 6% of all fishing nets, 19% of all traps and pots, and 29% of all fishing lines are lost around the world each year. Derelict fishing gear, in particular pots and traps, is responsible for significant ecological and economic impacts through increased entanglements and bycatch mortality, as well as damaging marshes and seagrass beds that support marine fish and shellfish, reducing stocks of target and non-target species, and decreasing fishery profits (Guillory 1993, Arthur et al. 2014, Bilkovic et al. 2016, Scheld et al. 2016, Wilcox et al. 2016, DelBene et al. 2019). Pots may become derelict when the propeller of a vessel strikes the buoy or buoy line, storms or strong currents move a pot or submerge the buoy making it difficult to locate, improper equipment is used, there is an equipment failure, or pots are intentionally abandoned or discarded in the water (Bilkovic et al. 2016).

Numerous strategies have been developed to address the issue of derelict pots, but the effectiveness of these strategies can be hindered by various obstacles and has rarely been studied. Acceptability by commercial fishers and enforcement are common barriers to effectively implement preventative, reducing impact, or curative measures (Macfadyen et al. 2009, Brodbeck 2016). Technological solutions also exist, but they are often too costly for commercial fishers to implement (e.g., using acoustic technology to mark the location of a lost pot for retrieval; He and Suuronen 2018, Lebon and Kelly 2019). A combination of these measures, as well as collaboration with commercial fishers, is likely necessary to increase acceptability by fishers and improve enforceability of efforts to address derelict pots. Various strategies to engage stakeholders (e.g., surveys, task-forces, workshops) can improve the quality of management decisions (Reed 2008). Stated preference methods can be employed in surveys to identify the preferences of stakeholders, providing valuable information for resource managers and policymakers (Hanley and Czajkowski 2019). In particular, discrete choice experiments (DCEs) have been used to evaluate fishers' preferences and decision making for policy or management options in commercial (Wattage et al. 2005, Fitzpatrick et al. 2017) and recreational (Aas et al. 2000, Lew and Larson 2015, Goldsmith et al. 2018) fisheries.

In the U.S., governments, academic institutions, non-governmental organizations, commercial fishers, and the public have worked together to combat the issue of derelict pots (Bilkovic et al. 2016, Bowling 2016, Lebon and Kelly 2019). Pot or trap fisheries in the U.S. target a variety of valuable commercial species, such as American lobster *Homarus americanus*, blue crab *Callinectes sapidus*, Caribbean spiny lobster *Panulirus argus*, and Dungeness crab *Metacarcinus magister*. Most pot fisheries operate within the territorial waters of a state, and majority of state laws only permit the pot's owner or an authorized individual to remove pots, including derelict pots. Managers and policymakers have implemented requirements that could reduce the abundance or impacts of derelict pots, for example, attachment of identification tags, installation of bycatch reduction devices and escape panels, implementation of derelict pot removal programs, as well as limits on fishing effort and temporal and spatial gear use restrictions (Bowling 2016, DelBene et al. unpublished data). Stakeholder engagement with commercial fishers has been important throughout implementation of these actions and other initiatives (Havens et al. 2011, Goodman et al. 2019, Lebon and Kelly 2019). For instance, commercial fishers have volunteered or been paid to assist in derelict pot location and removal programs, experiment with new gear modifications, recycle their old pots at facilities on land, and participate in gear buyback programs (Havens et al. 2011, Bowling 2016, Lebon and Kelly 2019).

Chesapeake Bay is the largest estuary in the U.S. and is located within Maryland and Virginia state borders. Its commercial blue crab fishery, primarily a pot fishery, supports over a thousand active fishers and is responsible for 30-40% of U.S. commercial harvests, with ex-vessel revenues valued at over US $100 million in 2016 (NMFS 2018). Derelict pots are prevalent in this system with approximately 145,000 derelict pots estimated to be present at any given time. Moreover, 12-20% of all licensed pots are estimated to become derelict each year (Bilkovic et al. 2016). These derelict pots intensify negative impacts that directly affect the well-being of commercial fishers. Analysis evaluating an extensive marine debris location and removal program in Virginia waters found that removal of 34,408 derelict pots increased harvest by 13,504 MT over six years due to reduced competition with derelict gear (Scheld et al. 2016). In Virginia, the Virginia Marine Resources Commission (VMRC) and state policymakers have engaged with fishers to address the issue of derelict pots, but historical tensions and limited resources have produced obstacles to implementing successful, long-term mitigation activities. These obstacles were evident in January 2018, when fishers organized to lobby the Virginia legislature and defeated a proposed bill that would have required crab pots to incorporate an escape panel that degraded if the pot became derelict (SB 552 2018). This bill would have increased the fishing costs for commercial fishers but lacked any direct incentives for fishers. Improved stakeholder engagement is needed to understand and incorporate commercial fishers' preferences into management decisions that address the problems produced by derelict pots in the Virginia commercial blue crab fishery.

Working collaboratively with commercial fishers, we gathered information and evaluated management preferences in an effort to develop sustainable, stakeholder-driven solutions to address the issue of derelict pots in Virginia waters. The objectives of this study were to 1) identify commercial fishers' perceptions of derelict crab pots, and 2) measure their willingness to accept and participate in activities to mitigate the negative effects of derelict crab pots.

Methods

The study surveyed commercial fishers that were licensed to operate in Virginia waters in 2017. Stated preference surveys were used and consisted of two parts: 1) attitudinal and behavioral questions on fishing activity and derelict crab pots, in addition to demographic questions, and 2) a DCE where questions presented hypothetical mitigation activities or policy measures paired with incentives to address the issue of derelict pots. The DCE was then used to quantify participants' decision-making and preferences.

Survey development

Because blue crab fisheries occur in state waters, we reviewed existing regulations and derelict pot mitigation activities in U.S. states with a commercial blue crab fishery. We solicited input from fishery managers at VMRC on hypothetical mitigation activities and incentives that were practical for the Virginia commercial blue crab fishery. For example, we considered spatial restrictions to reduce user conflicts that could cause a pot to become derelict; requirements to install owner identification tags on pots to strengthen enforcement on fishing effort limits, thus reducing the number of pots that could become derelict; or programs to locate and remove derelict pots. Possible incentives consisted of monetary payments, as well as management incentives such as increasing daily harvest or bushel limits, allowing access to set pots in areas restricted to commercial crabbing, increasing the duration of the commercial blue crab season, or reducing license fees. Draft survey materials and questions were formulated based on the information gathered from this review, input from fishery managers, questions from a previous survey that targeted fishers (Rhodes and Shabman 1994), and suggested wordings and question format from Dillman et al. (2009).

Two focus groups of commercial fishers were hosted to develop and refine survey materials. The first focus group occurred in Gloucester, Virginia, with four commercial fishers in November 2018. Each participant was allocated time to review survey materials and answer all survey questions. We then discussed the wording of questions, layout, and the purpose for including specific questions to ensure the survey was clear, concise, and well received. Survey materials were revised after the first focus group, and then shared at a second focus group of five commercial fishers in Wachapreague, Virginia, in December 2018. The second focus group was conducted following the same procedure that was used for the first focus group. Different locations were used for the two focus groups to engage fishers in unique segments of the fishery, since crabbing environments (e.g., salinity, water depth, user conflicts) vary across Virginia's tributaries, Chesapeake Bay mainstem, and coastal bays. Feedback from the focus groups was incorporated in a revised version of survey materials that was shared with state resource managers and the president of the Virginia Waterman's Association (one of the fifteen recognized commercial fisher associations in Virginia) for a final review.

Survey materials were finalized in January 2019. The final survey instrument contained 25 questions composed of multiple choice, yes-no, and fill in the blank responses in Part 1; three choice scenarios that presented hypothetical activities and incentives in Part 2 (see Table 1 for definitions) to reduce the number of derelict pots and their impacts; and a blank page for any additional thoughts or comments.

Experimental design

A DCE was employed to understand fisher decision-making and evaluate preferences for various management activities and incentives to address the issue of derelict pots. Each choice scenario asked participants to select their most preferred option from two multi-attribute options and a third alternative that represented the status quo (i.e., no mitigation activity nor incentives). Three attributes defined each hypothetical multi-attribute option: the mitigation activity, with seven levels; an incentive, with four levels; and a cash payment, also with four levels (Table 2). All levels for each attribute were defined during survey development (Table 1), and these definitions appeared beneath each choice scenario (Figure 1).

Furthermore, the effect of providing scientific information regarding derelict pot impacts on fisher decision-making was tested by creating a treatment group. Impacts caused by derelict pots have been reported in the scientific literature (Guillory 1993, Arthur et al. 2014, Bilkovic et al. 2016, Scheld et al. 2016, Wilcox et al. 2016, DelBene et al. 2019), but little is known about how these scientific results may influence fishers' decision-making. Statistics from derelict crab pot studies conducted in Chesapeake Bay (Giordano et al. 2010, Bilkovic et al. 2014, 2016, Scheld et al. 2016, DelBene et al. 2019) and other locations around the U.S. (Guillory 1993, North Carolina Division of Marine Fisheries 2013) were included in an informational sentence that was underlined in the introduction for Part 2 (DCE) of the survey for the treatment group: "Scientific studies conducted in Virginia and elsewhere have shown that each derelict crab pot may kill 16-26 blue crabs per year and that derelict crab pots can reduce fishery harvest by as much as 30% by competing with actively fished gear."

The experimental design was determined using macros in SAS software (SAS 9.4; SAS Institute, Inc., Cary, NC USA) to maximize design balance and orthogonality (Kuhfeld 2010). Restrictions were included to ensure the activities and incentives of the two multi-attribute options were never identical in a choice scenario. Additionally, we restricted the activity "Educate recreational boaters" from being paired with any incentive or cash payment (as this would not require any action from fishers), while all other activities appeared with an incentive, cash payment, or both. The final design identified 15 choice sets that were split into five blocks, resulting in three choice scenarios for each survey participant. The five blocks were duplicated to create the treatment group that included the informational sentence; thus, there were 10 unique versions (blocks) of the survey.

Survey distribution and data collection

Mailing addresses for all commercial fishers that possessed a Virginia hard crab pot license in 2017 were obtained from VMRC (N = 1,054). This included 58 Maryland, 8 North Carolina, and 988 Virginia residents. Although survey questions focused on the 2018 crabbing season, we relied on 2017 license data because license sales for 2018 were incomplete at the time of our data request. The commercial blue crab fishery in Virginia is limited entry and similar from one year to the next. The original list of mailing addresses obtained from VMRC was reduced to remove undeliverable addresses, as well as the focus group participants that helped develop the survey. We randomly assigned individuals to one of the 10 survey versions, and each version of the survey was represented approximately equally across the population. To track survey responses and maintain participant confidentiality, individuals were randomly assigned unique identification numbers that were printed on the survey cover page.

Surveys were mailed to individuals in early 2019, following the implementation procedures described by Dillman et al. (2009). This consisted of four mailings: a prenotice letter (sent on February 11), a survey packet (February 15), a postcard reminder/thank you (February 25), and a replacement survey packet sent to non-respondents (March 21). The survey packet contained a cover letter, postage-paid return envelope, and the six-page survey. Mailing dates were selected to limit overlap with the 2019 Virginia commercial blue crab season, which opened on March 17, 2019. Survey participation was incentivized by randomly selecting four participants to receive US $100 grocery gift cards. To inform fishers about the survey, we disseminated a press release to local news outlets in late January 2019. All survey responses were collected and recorded according to the protocol approved by William & Mary's Protection of Human Subjects Committee (Protocol ID: PHSC-2018-11-28-13146-amscheld).

Choice modeling

Responses to the choice scenarios were analyzed using random utility models (RUMs), which assume individuals select the choice alternative that maximizes their utility or well-being. RUMs allow for observed and unobserved factors to influence the decision to select a particular option, and thus determine utility (McFadden 1974). Observed factors, in our application, were obtained from survey responses and license information provided by VMRC, whereas unobserved factors consisted of any unknowns that could influence decision-making and were not captured by the survey. The utility, U, that individual n obtains from choice option i can be written as:

$$U_{ni} = \beta_n' x_{ni} + \varepsilon_{ni}. \tag{1}$$

The observed factors in (1) are represented by x_{ni}, which contains a vector of attributes associated with the option and individual decision-maker, whereas β_n' represents a vector of parameters capturing individual n's tastes. Unobserved factors are represented by a random scalar, ε_{ni}, that is assumed to be independently and identically Gumbel-distributed. Following utility-maximizing behavior, individuals will select the option that provides them the greatest utility. For instance, option i would be selected if and only if:

$$U_{ni} > U_{nj} \; for \; all \; j \neq i. \tag{2}$$

Utility-maximizing behavior described in (2) can be used to derive choice probabilities. The mixed logit model specifies choice probabilities as,

$$P_{ni} = \int \left(\frac{e^{\beta' x_{ni}}}{\sum_j e^{\beta' x_{nj}}} \right) f(\beta) d\beta. \tag{3}$$

In (3), the probability that individual n selects option i is dependent on the observed factors of option i for individual n, x_{ni}, as well as x_{nj}, which includes attributes of options not selected, j, and all preference parameters, β'. Additionally, the density $f(\beta)$ is a mixing distribution that allows the distribution of preferences to be defined across the population. This provides flexibility within the model to account for a variety of behavioral expectations across a heterogeneous population.

The mixed logit model was specified to accommodate survey response data where individuals were presented three choice scenarios within each survey. We allowed for differences in tastes among individuals by treating preference parameters as fixed across all three choice scenarios answered by an individual, but potentially variable across individuals. Random error terms were assumed to be independent. We estimated preference parameters by maximizing the following log-likelihood:

$$LL = \sum_{n=1}^{N} \sum_{t=1}^{T} \sum_{j=1}^{J} d_{ntj} ln(P_{ntj}), \tag{4}$$

where the natural logarithm of the choice probabilities in (4) is summed over N individuals, T choice scenarios answered by an individual, and J options within each choice scenario. A binary variable, d_{ntj}, identified when an option was selected (equal to one) or not selected (equal to zero).

The mixed logit model estimated preference parameters for alternative-specific and individual-specific attributes. Dummy variables for alternative-specific attributes were constructed for seven levels of derelict pot mitigation activities and three levels of management incentives (see Table 1 for definitions of levels). Each dummy variable was assigned a value of one when present in an option and zero when absent. Activities and incentives were included as random alternative-specific attributes with a normal distribution. Normal distributions were assumed because the population of fishers is operationally and geographically heterogeneous, thus participation in an activity will not always result in a cost (negatively affect utility) and receiving an incentive will not always benefit individuals (positively affect utility). For instance, participation in mitigation activities could positively affect the utility (or have no effect) for individuals that already performed a proposed activity (e.g., only used galvanized wire pots) or perceived derelict pots to be a problem that they wanted to help address. Whereas, receiving an incentive could negatively affect the utility of individuals that agreed with the current management practices and wanted to maintain the status quo. Cash payment was included as a continuous and non-random alternative-specific attribute to allow for straightforward calculations of willingness to accept (WTA) for mitigation activities.

Individual-specific attributes observed from answers to questions included in Part 1 (non-DCE questions) and a binary treatment effect for inclusion of the informational sentence (see Methods: Experimental design; equal to one for surveys where sentence was present and zero otherwise) were incorporated to explore different versions of the mixed logit model and improve understanding of decision-making. Interaction terms included in the model consisted of an individual-specific attribute or the binary treatment effect interacted with an alternative-specific constant for Option A or Option B (i.e., equal to one for options including mitigation activities and zero for no activity; see Figure 1). The final version of the model included all alternative-specific attributes and two interaction terms interacting the previously defined alternative-specific constant with, 1) an individual-specific attribute describing perceptions of derelict pot impacts and 2) the binary treatment effect for inclusion of the informational sentence. The interaction term for perceptions of derelict pot impacts was constructed by assigning a one to individuals that perceived derelict pots to cause only a negative impact and all other individuals a zero (i.e., individuals that did not respond to the question or perceived derelict pots to cause only positive, both positive and negative, or no impacts). A likelihood ratio test was used to compare the final model to a null model (intercept only).

Economic analysis

The marginal effect for the interaction term between an individual's perception of derelict pot impacts and participation in any mitigation activity was calculated at the means of all other covariates. The difference between the probability of willingly participating in a mitigation activity (y_{ni} is equal to one) for individual n that did (Neg_{ni} is equal to one) or did not (Neg_{ni} is equal to zero) perceive derelict pots to cause only negative impacts was calculated as:

$$\frac{\partial P_{ni}}{\partial Neg_{ni}} = P_{ni}(y_{ni} = 1 \mid Neg_{ni} = 1) - P_{ni}(y_{ni} = 1 \mid Neg_{ni} = 0). \tag{5}$$

Following the Krinsky and Robb (1986) resampling methodology, 10,000 random draws were taken from a multivariate normal distribution constructed from the mean and covariance matrix of model parameter estimates. The resampled parameter estimates were then used to calculate means, standard errors, and 95% confidence intervals for WTAs. Mean WTAs (i.e., the amount of money an individual would need to receive to participate in an activity and experience no change in utility) were calculated for activities by taking the mean of the ratio of resampled parameter estimates for activity a, β_a, divided by the negative of the resampled parameters for cash payment, β_C:

$$WTA_a = -\frac{\beta_a}{\beta_C}. \tag{6}$$

Mean WTA was not calculated for "Educate recreational boaters" because we restricted cash payments from being paired with this activity in the experimental design. Equation (6) was modified to calculate the monetary value associated with incentives, by replacing β_a with β_q. Thus, the mean monetary value for incentive q (i.e., change in WTA due to incentive q) was equal to the mean of the ratio of resampled parameter estimates for incentive q, β_q, divided by the negative of the resampled parameters for cash payment, β_C. To determine the mean WTAs and incentive values for participants that perceived derelict pots to cause only negative impacts, we added the resampled parameter for the interaction term, Any activity x Negative impact perceived, to the numerator of (6).

All statistical analyses and modeling were performed in R (R Core Team 2018). Data collected from the choice scenarios were formatted using the mlogit.data function and the mixed logit model was estimated with the mlogit function in the mlogit package (Croissant 2018). The mvrnorm function in the MASS package was used to conduct random draws from the multivariate normal distribution (Venables and Ripley 2002).

Results

Survey response rate and non-DCE questions

There was a 42% response rate for the survey with 430 out of a potential 1,032 fishers returning the survey packet (example survey packet included in Supplementary material). Survey responses were received through July 2019 and were representative of the license categories and states of residency observed in the population, as well as the various survey versions (Pearson's chi-squared tests, $p > 0.05$).

Participants reported having 34 (SE = 0.8; n = 414) years of commercial crabbing experience on average, and 56% (n = 416) of participants indicated relying on commercial crabbing for the majority of their income. The average fisher reported losing 10% (SE = 0.7%; n = 348) of all crab pots fished in 2018, and "Commercial/recreational vessel traffic" (76%) and "Storms/severe weather" (75%) were reported as the main reasons pots become derelict (n = 416). Perceptions of derelict pot impacts on Chesapeake Bay and coastal waters of Virginia were heterogeneous (n = 416): 10% positive, 29% negative, 31% both positive and negative, and 30% no impact. The primary negative impacts noted in a follow-up question were the costs required to replace the lost gear (34%) and derelict pots capture and kill fishes and crabs (30%), whereas 20% answered negligible/no impact (n = 409).

Participants were asked yes-no questions to identify their willingness to participate in specific mitigation activities and a multiple choice question concerning preferred incentives to encourage participation in a mitigation activity (see Table 3 for all responses). Participants were most willing to participate in "Drop off old/derelict pots at recycling facilities on land" (86%; n = 342) and "Locate and remove derelict pots" (80%; n = 320). "Cash payment" (38%) and "None" (26%) were the most preferred incentives (n = 399). These activities and incentives were included in the choice scenarios to better understand tradeoffs in decision-making and preference heterogeneity. A summary of additional responses pertaining to attitudinal and behavioral questions on fishing activity and derelict crab pots, in addition to demographic questions, are included in Appendix Table A.1.

Choice modeling

The mixed logit model was used to analyze 409 participant responses to 1,192 choice scenarios. Choice scenarios that were unanswered or had multiple options selected were excluded from the analysis. The status quo alternative (Option C) was selected in 35% of the choice scenarios. Multiple factors included in the model had a significant effect on fishers' decision-making (Table 4). For instance, cash payments had a significant positive effect on participation in mitigation activities ($p < 0.001$). Inclusion of an informational sentence in the DCE introduction did not have a significant effect ($p > 0.05$). However, participants that perceived derelict pots to cause only negative impacts were significantly more likely to select options with a mitigation activity ($p < 0.001$).

Unless otherwise indicated, model results presented or discussed pertain to participants that did not perceive derelict pots to cause only negative impacts (71% of DCE respondents). Decision-making for the average participant was significantly affected by all activities, except "Recycle at a facility on land." "Educate recreational boaters" was the only activity that positively affected their utility. On average, "Pot limit increase" was the only incentive that significantly affected decision-making. The standard deviation for each random factor was significant or marginally significant, identifying heterogeneity in preferences. The greatest heterogeneity was observed for "Pot tags" and "Educate recreational boaters," but the coefficients for most random factors were greater than one, suggesting substantial variability in fishers' decision-making and preferences.

Economic analysis

The mean WTAs were positive for all derelict pot mitigation activities, but the mean WTA for "Recycle at facility on land" was not significantly different from zero ($p > 0.05$). Mean WTAs ranged from US $1,449 (SE = $359) to participate in "Pot modification," to US $61 (SE = $129) to participate in "Recycle at facility on land" (Figure 2). On the other hand, if individuals were provided an incentive of a "Pot limit increase," then mean WTAs (for all mitigation activities) would decrease by an average of US $389 (SE = $149). However, this incentive was not enough to encourage participation in any activity for which WTA was significantly greater than zero. If resource managers wanted to package a US $300 cash payment with a "Pot limit increase," then willingness to participate in "Recycle at facility on land" would increase to 82% (SE = 5%) on average. The average fishers' willingness to participate in other activities would be: "Galvanized pots only" (mean ± SE; 54% ± 8%), "Three-day removal program" (49% ± 10%), "Soak time limit" (35% ± 8%), "Pot tags" (17% ± 8%), and "Pot modification" (15% ± 6%). When compared to non-DCE responses for willingness to participate in mitigation activities, the equivalent to "Recycling at facility on land" was still the most preferred and "Pot modification" and "Pot tags" were the least preferred activities (see Table 3).

On average, fishers that perceived derelict pots to cause only negative impacts were 37% (SE = 6%) more willing to participate in any activity. Mean WTAs were significantly lower and closer to zero for these fishers, ranging from US $794 (SE = $224) to participate in "Pot modification" to individuals actually willing to forgo US $594 (SE = $257) in cash payments to participate in "Recycle at facility on land." Additionally, if resource managers offered a package of US $300 cash payment and a “Pot limit increase,” then willingness to participate in mitigation activities would increase on average: “Recycle at facility on land” (mean ± SE; 95% ± 2%), “Galvanized pots only” (84% ± 6%), “Three-day removal program” (81% ± 7%), “Soak time limit” (71% ± 8%), “Pot tags” (48% ± 13%), and “Pot modification” (44% ± 10%).

Discussion

Overall, the willingness to participate in any derelict pot mitigation activity was low because it significantly reduced the utility of fishers and no single management incentive was enough to offset the perceived costs. Thus, a combination of incentives, preferably a cash payment and “Pot limit increase,” would be necessary to encourage participation. Other than a cash payment, “Pot limit increase” was the most preferred incentive, even though fishers surveyed in the past supported enforcing pot limits (Rhodes et al. 2001). Furthermore, more than 70% felt pot limits could not be adequately enforced, suggesting pot limits were a non-binding constraint. Since 2008, VMRC has enforced a 15% reduction on hard pot limits (Chapter 4 VAC 20-880-10 *et seq*. 2008). The recent history of this management decision likely influenced fishers’ preferences for a “Pot limit increase” to recover 5-10% of that 15% reduction enacted in 2008, despite the difficulties in enforcing pot limits. Unlike the previously mentioned mitigation activities, it is important to note that no incentives were required for fishers to willingly participate in “Recycle at facility on land” or support “Educate recreational boaters,” suggesting these activities would be the easiest to implement. Furthermore, there was substantial preference heterogeneity across responses from fishers, suggesting some segments of the population would be more willing to participate in mitigation activities than others and more receptive to incentives. Although most activities would be difficult to implement due to high WTAs, the model allows for calculation of participation probabilities for various combinations of activities and incentives.

Drivers of preference variability

Heterogeneity observed in fishers' preferences could be further explained by incorporating non-DCE responses in the models. Personal attitudes and values drove decision-making more than demographic variables collected in the survey. For instance, WTAs decreased by US $656 for fishers that perceived derelict pots to cause only a negative impact, indicating that implementation of any mitigation activity would be much easier within this segment of the population. Additional analysis found that the type of negative impact perceived could also influence decision-making, such that fishers were more willing to participate in an activity if they thought capturing and killing fishes and crabs was the primary negative impact (as opposed to the costs required to replace their lost gear). This agrees with past studies that have found strong connections between attitudes, values, and willingness to participate in pro-environmental behavior (Stern et al. 1995, Takahashi and Selfa 2014). On the contrary, whether an individual relied on commercial crabbing for the majority of their income did not influence decision-making. Rhodes et al. (2001) identified a strong difference in demographics between full-time and part-time fishers in their survey, yet we found no difference between the two groups when it came to their preferences for addressing derelict pots.

Lastly, fishers that previously participated in a derelict pot removal program were less willing to participate in a "Three-day removal program." This contradicted non-DCE responses where 91% (n = 35) of fishers that previously participated in a removal program were willing to "Locate and remove derelict pots." This difference between choice scenario and non-DCE responses was likely due to differences in the description of a removal program and a lack of sufficient incentives included in the DCE. A previous state-wide removal effort, Virginia's Marine Debris Location and Removal Program, occurred during the off-season months in the winter and provided monetary incentives of US $300/day and US $50/week for incidentals plus fuel costs (Havens et al. 2011) and, in subsequent years, modified to US $330/day. The maximum cash payment available in the DCE was US $500/three days, whereas the previous removal program paid over US $900/three days. The higher payments distributed to fishers during the past removal program may have instilled expectations that were not met by the attributes included in our choice scenarios. Therefore, the duration of the removal program and incentives must be carefully considered to increase fishers' willingness to participate in derelict pot removal programs.

Inability to influence decision-making

Inclusion of the informational sentence did not influence fishers' decision-making. Initially, we anticipated that inclusion of this informational sentence would increase awareness of derelict pot impacts and fishers' willingness to participate in mitigation activities. However, it is possible that fishers did not read the informational sentence because it was included on a survey page with no questions. There was also evidence that some fishers disagreed with the scientific information in the sentence. Fisher comments (n = 3) written next to the informational sentence included: "show data on this not true," "Questionable data!," "wrong," and "Fake truth," which would imply fishers read the sentence but disagreed with it. The rejection of statements that compete with an individual's own beliefs is not uncommon in fisheries, and often arises between groups that share conflicting stances on an issue (Johnson and Griffith 2010).

Application to management and policy decisions

In the U.S., state resource managers and policymakers are responsible for addressing the issue of derelict blue crab pots. Integration of local information and scientific knowledge can strengthen the decision-making process (Mackinson and Nottestad 1998). Results from our survey provide local preferences and opinions from fishers that can be integrated with existing scientific knowledge (e.g., Guillory 1993, Macfadyen et al. 2009, Arthur et al. 2014, Bilkovic et al. 2016, Scheld et al. 2016, DelBene et al. 2019) to efficiently address the issue of derelict pots. Managers and policymakers are often resource limited, so it is important that their decisions are effective and efficient. Our mixed logit model allows managers to quantify the monetary cost of achieving fisher buy-in and can be used as a management tool to estimate commercial fishers' willingness to participate in proposed mitigation activities. In practice, managers could select one of the hypothetical mitigation activities and a package of incentives and use the model to determine fisher preferences willingness to participate. For example, the strong pushback from fishers that led to the defeat of SB 552 (2018) in the Virginia legislature could have been predicted by including "Pot modification" as the hypothetical activity with no incentives in the model. Under this management scenario, the probability that an average fisher would willingly participate was just 3% (SE = 2%) and increased to 13% (SE = 6%) for individuals that perceived derelict pots to cause only negative impacts. Because only 11% (n = 419; Table A.1) of fishers reported voluntarily attending a fisheries management agency meeting in 2018, and 84% previously felt they had little impact on the regulatory process (Rhodes et al. 2001), our survey results provide managers and policymakers with local preferences to make better informed decisions to reduce impacts caused by derelict fishing gear.

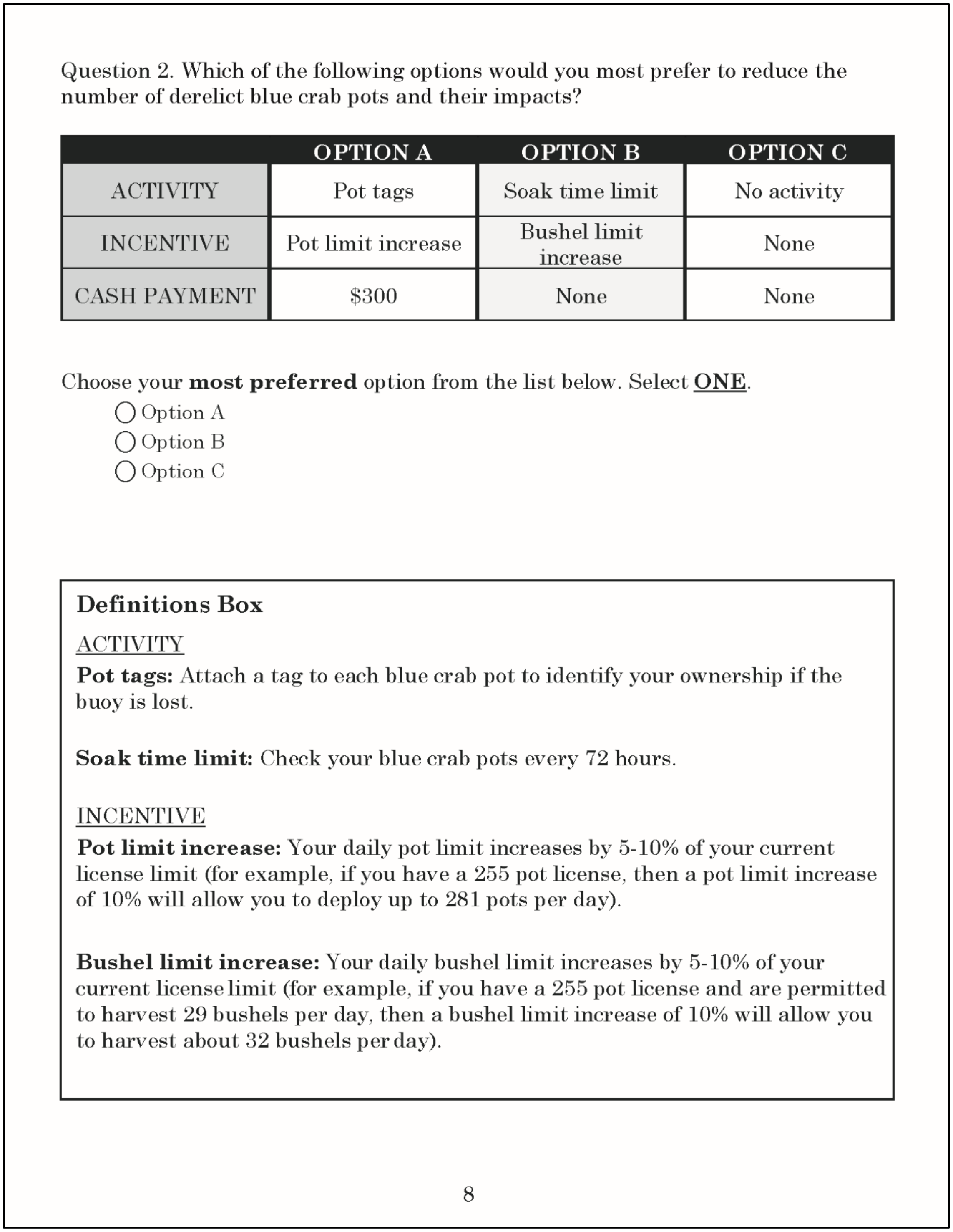
Our survey provides a framework for U.S. states and other regions to use when considering actions that address the issue of derelict fishing gear. Actions to reduce derelict gear abundance and impacts have been implemented in various fisheries around the world (Macfadyen 2009, Bowling 2016, He and Suuronen 2018, Lebon and Kelly 2019), but we are not aware of any evaluation at this scale that identified fishers' preferences for those actions. Although mitigation activities and incentives included in the survey were selected for applicability to Virginia's commercial blue crab fishery, mitigation actions implemented in other U.S. states informed development of our survey. For instance, the states of Florida, Louisiana, and Texas implement derelict pot removal programs that rely on volunteers to locate and remove derelict pots (Bowling 2016, DelBene et al. unpublished data). Members of the public, including fishers, volunteer their time and vessels to work with resource managers to recover derelict pots from designated areas. These programs are resource intensive and alternative preventative measures should be considered to help offset costs. Unfortunately, many preventative measures like gear tracking or reducing fishing effort are too costly for commercial fishers to willingly participate (Macfadyen 2009, Brodbeck 2016, He and Suuronen 2018). Research similar to that presented here could be used to inform these decisions and help better understand the magnitude of tradeoffs by incorporating commercial fisher preferences and opinions in the decision-making process.

Conclusion

Preventative measures that are of minimal cost to fishers, such as gear disposal locations provided by the Fishing for Energy partnership (Arthur et al. 2014) or fishing gear recycling offered through the Nofir project (Brodbeck 2016), seem to be the most preferred options by fishers to address the issue of derelict fishing gear. When determining the best actions to take against other types of marine debris (e.g., plastics, abandoned or derelict vessels), resource managers and policymakers need to consider the costs imposed on stakeholders. Stated preference surveys that utilize DCEs are a valuable tool to identify stakeholder preferences and decision-making to ensure actions will be effective at decreasing marine debris abundance and impacts. We worked with fishers, but other stakeholders' (e.g., recreational fishers, seafood processors, beachgoers, boaters, concerned citizens, waterfront property owners) preferences should also be included in the decision-making process to fully address the problem of marine debris. There is no universal solution for marine debris; therefore, managers and policymakers must engage with stakeholders to determine their most preferred mitigation activities and incentives to help tackle this problem.

Acknowledgements

This work was supported by the Office of Academic Studies at VIMS, the William & Mary Committee on Sustainability Green Fee Award, and Virginia Sea Grant (VASG) [grant number NA18OAR4170083]. We would like to thank J.C. Hudgins, Dan Knott, focus group participants, and the VMRC for their help with developing the survey, as well as Susan Stein (VIMS), Dr. Dave Malmquist (VIMS), Maxine MacLeod, Abigail Hils, Aileen Devlin (VASG), and Sean Fate (VIMS-ESL) for providing materials and helping to increase survey awareness among the fishers. Additionally, Dr. Kirk Havens (VIMS) and Dr. Jeff Shields (VIMS) provided edits and input for this manuscript.



Question 2. Which of the following options would you most prefer to reduce the number of derelict blue crab pots and their impacts?

	OPTION A	OPTION B	OPTION C
ACTIVITY	Pot tags	Soak time limit	No activity
INCENTIVE	Pot limit increase	Bushel limit increase	None
CASH PAYMENT	$300	None	None

Choose your **most preferred** option from the list below. Select **ONE**.

- ○ Option A
- ○ Option B
- ○ Option C

Definitions Box

ACTIVITY

Pot tags: Attach a tag to each blue crab pot to identify your ownership if the buoy is lost.

Soak time limit: Check your blue crab pots every 72 hours.

INCENTIVE

Pot limit increase: Your daily pot limit increases by 5-10% of your current license limit (for example, if you have a 255 pot license, then a pot limit increase of 10% will allow you to deploy up to 281 pots per day).

Bushel limit increase: Your daily bushel limit increases by 5-10% of your current license limit (for example, if you have a 255 pot license and are permitted to harvest 29 bushels per day, then a bushel limit increase of 10% will allow you to harvest about 32 bushels per day).

8

Figure 1 An example of a choice scenario included in the survey. Definitions for each attribute in the options were provided beneath the question.

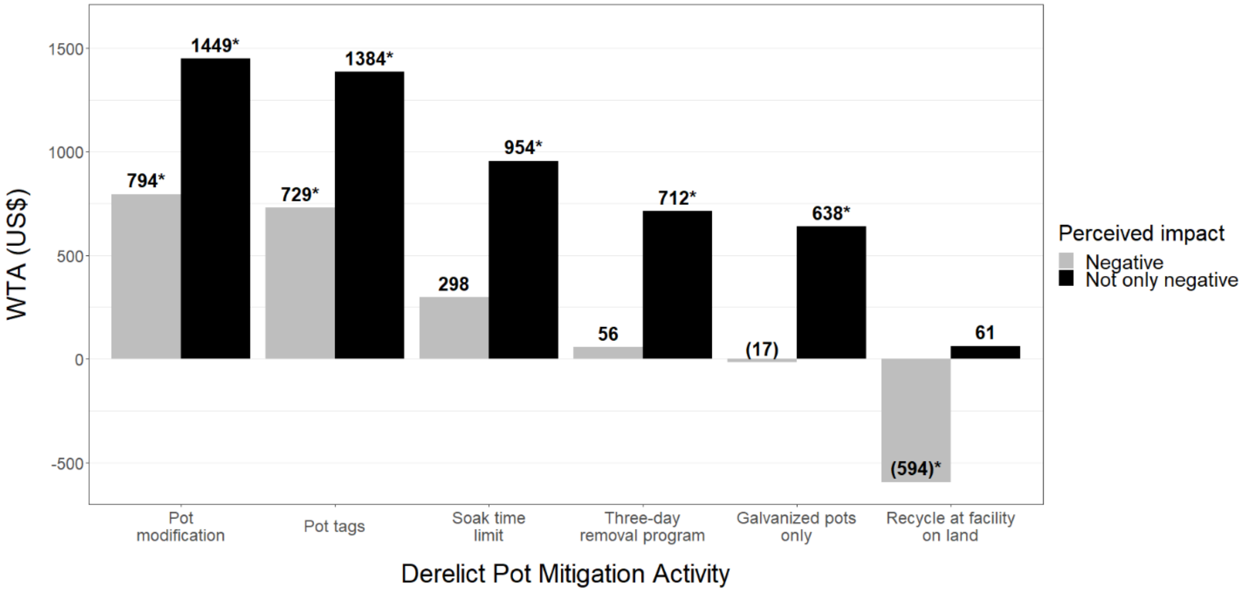


Figure 2 Mean WTA to participate in each hypothetical derelict pot mitigation activity differentiated by perceptions of derelict pot impacts. A single asterisk (*) denotes WTA significantly different from 0 at a 95% confidence level determined from 10,000 multivariate normal draws of the parameter vector.

Table 1 Definitions for hypothetical activities and incentives that were determined during survey development to be included in choice scenarios.

	Definition
Activity/Policy measure:	
Educate recreational boaters	Recreational boaters will be educated on best practices to avoid crab pot buoys and lines. This activity will not require any waterman participation.
Galvanized pots only	Only use galvanized wire crab pots (no vinyl-coated).
Pot modification	Modify each of your blue crab pots to prevent the pot from continuing to capture animals if it becomes derelict.
Pot tags	Attach a tag to each blue crab pot to identify your ownership if the buoy is lost.
Recycle at facility on land	Recycle all of your old crab pots at a facility on land.
Soak time limit	Check your blue crab pots every 72 hours.
Three-day removal program	Participate in a three-day derelict pot location and removal program.
Incentive:	
Bushel limit increase	Your daily bushel limit increases by 5-10% of your current license limit (for example, if you have a 255 pot license and are permitted to harvest 29 bushels per day, then a bushel limit increase of 10% will allow you to harvest about 32 bushels per day).
Pot limit increase	Your daily pot limit increases by 5-10% of your current license limit (for example, if you have a 255 pot license, then a pot limit increase of 10% will allow you to deploy up to 281 pots per day).
Season extension	You will be allowed to commercially crab for an additional two weeks before or after the originally permitted season.

Table 2 Alternative attributes and attribute levels included in the DCE.

Attribute	Number of levels	Values
Activity/Policy measure	7	Educate recreational boaters, Galvanized pots only, Pot modification, Pot tags, Recycle at facility on land, Soak time limit, Three-day removal program
Incentive	4	None, Bushel limit increase, Pot limit increase, Season extension
Cash payment	4	None, \$100, \$300, \$500

Table 3 Non-DCE responses to yes-no questions that asked about willingness to participate in activities and a multiple choice question on the incentive that would most encourage participation.

	% of "Yes" responses	n
Activity/Policy measure:		
Check pots every 72 hours	65	292
Drop off old/derelict pots at recycling facilities on land	86	342
Install pot identification tags on each pot	27	269
Locate and remove derelict pots	80	320
Modify each pot to reduce derelict pot bycatch	17	254
Only use galvanized wire crab pots (no vinyl-coated pots)	50	324
Incentive†:		399
Bushel limit increase	8	-
Cash payment	38	-
Pot limit increase	12	-
Season extension	7	-
None	26	-
Other (please explain)	9	-

†Incentive responses were obtained from a single multiple choice question, thus n equals 399 across all responses.

Table 4 Results for the mixed logit discrete choice model, with mean coefficients and the absolute value of standard deviation coefficients included for random variables (number of choice scenario responses = 1,192; Likelihood Ratio Test ($\chi 2$) = 359.15, p < 0.001; Significance: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$).

Variable	Coefficient (Mean)		SE	Coefficient (SD)		SE
Activity: Educate recreational boaters	1.225	*	0.560	3.780	*	1.773
Activity: Galvanized pots only	-1.570	***	0.378	2.661	***	0.667
Activity: Pot modification	-3.526	***	0.527	1.336	*	0.556
Activity: Pot tags	-3.387	***	0.642	4.082	***	0.945
Activity: Recycle at facility on land	-0.164		0.301	0.964	.	0.531
Activity: Three-day removal program	-1.762	***	0.455	2.892	***	0.837
Activity: Soak time limit	-2.342	***	0.470	1.890	**	0.645
Incentive: Bushel limit increase	0.370		0.292	2.527	***	0.573
Incentive: Pot limit increase	0.948	**	0.300	1.824	***	0.440
Incentive: Season extension	0.133		0.284	2.675	***	0.578
Cash	0.003	***	0.001			
Any activity x Informational sentence included	-0.127		0.224			
Any activity x Negative impact perceived	1.579	***	0.298			

Appendix

Table A.1 Commercial fisher responses to select non-DCE questions.

	Value	SE	n
Mean months crab potted in 2018 (max of 9)†	6.2	0.1	350
Mean number of pots fished each day in 2018†	172.5	5.7	357
Material of pots fished in 2018†:			
Mean number of galvanized pots fished	111.1	6.2	312
Mean number of vinyl pots fished	42.8	4.2	328
% that fished majority (greater than 50%) galvanized pots	66.4	-	357
% that fished majority (greater than 50%) vinyl pots	28.9	-	357
Source of pots that were fished in 2018†:			
Mean number of pots made	38.9	3.9	320
Mean number of pots bought	87.9	6.1	298
% that made majority (greater than 50%) of their pots	34.2	-	343
% that bought majority (greater than 50%) of their pots	65.8	-	343
% that regularly look for and retrieve their lost pots	91.2	-	417
% that participated in past organized derelict pot removal programs	9.9	-	420
% that were ___ generation commercial fishers:			
1st	27.6	-	416
2nd	18.2	-	416
3rd	26.8	-	416
4th	13.5	-	416
5th or more	13.9	-	416
% that selected each reason for being a commercial fisher:			
Independence, being your own boss	96.9	-	351
Lifestyle, pride of work, love of the water	98.4	-	381
To earn a living	83.5	-	340
To earn extra money	53.5	-	282

Your family history	76.9	-	329
Your friend is/was a commercial fisher	41.8	-	273
% that voluntarily attended in person or participated over the phone in a VMRC meeting in 2018	10.5	-	419

†Excludes participants that did not commercially fish for hard crabs in 2018

References

Aas, Ø., W. Haider, and L. Hunt. 2000. Angler responses to potential harvest regulations in a Norwegian sport fishery: a conjoint-based choice modeling approach. *North American Journal of Fisheries Management* 20(4): 940-950. https://doi.org/10.1577/1548-8675(2000)020<0940:ARTPHR>2.0.CO;2.

Arthur, C., A. Sutton-Grier, P. Murphy, and H. Bamford. 2014. Out of sight but not out of mind: harmful effects of derelict traps in selected U.S. coastal waters. *Marine Pollution Bulletin* 86: 19-28. https://doi.org/10.1016/j.marpolbul.2014.06.050.

Bilkovic, D.M., K. Havens, D. Stanhope, and K. Angstadt. 2014. Derelict fishing gear in Chesapeake Bay, Virginia: Spatial patterns and implications for marine fauna. *Marine Pollution Bulletin*, 80: 114-123. https://doi.org/10.1016/j.marpolbul.2014.01.034.

Bilkovic, D.M., H.W. Slacum Jr, K.J. Havens, D. Zaveta, C.F. Jeffrey, A.M. Scheld, D. Stanhope, K. Angstadt, and J.D. Evans. 2016. Ecological and Economic Effects of Derelict Fishing Gear in the Chesapeake Bay: 2015/2016 Final Assessment Report. Prepared for Marine Debris Program, Office of Response and Restoration, National Oceanic and Atmospheric Administration. Available: https://marinedebris.noaa.gov/reports/effects-derelict-fishing-gear-chesapeake-bay-assessment-report. (December 2019).

Bowling, T. 2016. State Derelict Fishing Gear Laws and Regulations. NSGLC-16-05-01. National Sea Grant Law Center, University, Mississippi. Available: http://nsglc.olemiss.edu/projects/dfg/index.html. (December 2019).

Brodbeck, L. 2016. Mechanisms to support the recycling/reuse of fishing gear and the prevention of gear becoming lost/abandoned at sea - Barrier assessment. Prepared for the Circular Ocean project. Available: http://www.circularocean.eu/research/. (December 2019).

Chapter 4 VAC 20-880-10 *et seq.* 2008. "Pertaining to Hard Crab Pot Limits." Virginia Marine Resources Commission. Available: https://mrc.virginia.gov/Notices/pn_multi0509.shtm. (December 2019).

Croissant, Y. 2018. mlogit: Multinomial Logit Models. R package version 0.3-0. https://CRAN.R-project.org/package=mlogit.

DelBene, J.A., D.M. Bilkovic, and A.M. Scheld. 2019. Examining derelict pot impacts on harvest in a commercial blue crab Callinectes sapidus fishery. *Marine Pollution Bulletin* 139: 150-156. https://doi.org/10.1016/j.marpolbul.2018.12.014.

Dillman, D.A., J.D. Smyth, and L.M. Christian. 2009. *Internet, Mail, and Mixed-mode Surveys: The Tailored Design Method. (3rd ed.)* John Wiley & Sons, Inc., Hoboken, New Jersey.

Fitzpatrick, M., C.D. Maravelias, O.R. Eigaard, S. Hynes, and D. Reid. 2017. Fisher's Preferences and trade-offs between management options. *Fish and fisheries* 18(5): 795-807. https://doi.org/10.1111/faf.12204.

Galgani, F., G. Hanke, and T. Maes. 2015. Global distribution, composition and abundance of marine litter, in: Marine anthropogenic litter (pp. 29-56). Springer, Cham. https://doi.org/10.1007/978-3-319-16510-3_2.

Giordano, S., J. Lazar, D. Bruce, C. Little, D. Levin, H.W. Slacum Jr., J. Dew-Baxter, L. Methratta, D. Wong, and R. Corbin. 2010. Quantifying the effects of derelict fishing gear in the Maryland portion of Chesapeake Bay. In: Final Report to the NOAA Marine Debris Program. National Oceanic and Atmospheric Administration, Silver Spring, Maryland. Available: https://marinedebris.noaa.gov/research/regional-impact-assessment-derelict-fishing-gear-chesapeake-bay. (December 2019).

Goldsmith, W.M., A.M. Scheld, and J.E. Graves. 2018. Characterizing the Preferences and Values of U.S. Recreational Atlantic Bluefin Tuna Anglers. *North American Journal of Fisheries Management* 38(3): 680-697. https://doi.org/10.1002/nafm.10064.

Goodman, A.J., S. Brillant, T.R. Walker, M. Bailey, and C. Callaghan. 2019. A Ghostly Issue: Managing abandoned, lost and discarded lobster fishing gear in the Bay of Fundy in Eastern Canada. *Ocean & Coastal Management* 181: 104925. https://doi.org/10.1016/j.ocecoaman.2019.104925.

Guillory, V., 1993. Ghost fishing by blue crab traps. *North American Journal of Fisheries Management* 13(3): 459–466. https://doi.org/10.1577/1548-8675(1993)013<0459:GFBBCT>2.3.CO;2.

Hanley, N. and M. Czajkowski. 2019. The role of stated preference valuation methods in understanding choices and informing policy. *Review of Environmental Economics and Policy* 13(2): 248-266. https://doi.org/10.1093/reep/rez005.

Havens, K.J., D.M. Bilkovic, D. Stanhope, and K. Angstadt. 2011. Fishery failure, unemployed commercial fishers, and lost blue crab pots: an unexpected success story. *Environmental Science & Policy* 14(4): 445–450. https://doi.org/10.1016/j.envsci.2011.01.002.

He, P. and P. Suuronen. 2018. Technologies for the marking of fishing gear to identify gear components entangled on marine animals and to reduce abandoned, lost or otherwise discarded fishing gear. *Marine Pollution Bulletin* 129(1): 253-261. https://doi.org/10.1016/j.marpolbul.2018.02.033.

Johnson, J.C. and D.C. Griffith. 2010. Finding common ground in the commons: intracultural variation in users' conceptions of coastal fisheries issues. *Society & Natural Resources* 23(9): 837-855. https://doi.org/10.1080/08941920802409585.

Krinsky, I. and A.L. Robb. 1986. On approximating the statistical properties of elasticities. *The Review of Economics and Statistics* 715-719. https://doi.org/10.2307/1924536.

Kuhfeld, W.F. 2010. Marketing research methods in SAS: experimental design, choice, conjoint, and graphical techniques. SAS Institute, Inc., Cary, North Carolina.

Lebon, K.M. and R.P. Kelly. 2019. Evaluating alternatives to reduce whale entanglements in commercial Dungeness Crab fishing gear. *Global Ecology and Conservation* 18: e00608. https://doi.org/10.1016/j.gecco.2019.e00608.

Lew, D.K. and D.M. Larson. 2015. Stated preferences for size and bag limits of Alaska charter boat anglers. *Marine Policy* 61: 66-76. https://doi.org/10.1016/j.marpol.2015.07.007.

Macfadyen, G., T. Huntington, and R. Cappell. 2009. Abandoned, lost or otherwise discarded fishing gear (No. 523). Food and Agriculture Organization of the United Nations (FAO). Rome, Italy. Available: http://www.fao.org/3/i0620e/i0620e00.htm. (December 2019).

Mackinson, S. and L. Nottestad. 1998. Points of view: combining local and scientific knowledge. *Reviews in Fish Biology and Fisheries* 8(4): 481-490. https://doi.org/10.1023/A:1008847106984.

Marine Debris Act (Marine Debris Research, Prevention, and Reduction Act), 33 U.S.C. § 1951 *et seq*. 2006. Available: https://uscode.house.gov/view.xhtml?path=/prelim@title33/chapter33A&edition=prelim. (December 2019).

McFadden, D. 1974. Conditional logit analysis of qualitative choice behavior, in: Zarembka, P. (Ed.) Frontiers in Econometrics (pp. 105-142). Academic Press, New York, New York.

National Marine Fisheries Service (NMFS). 2018. Fisheries economics of the United States, 2016. U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-F/SPO-187a, 243p. Available: https://www.fisheries.noaa.gov/content/fisheries-economics-united-states-2016. (December 2019).

North Carolina Division of Marine Fisheries. 2013. North Carolina Blue Crab (*Callinectes sapidus*) Fishery Management Plan: Amendment 2. North Carolina Department of Environmental and Natural Resources. North Carolina Division of Marine Fisheries. Morehead City, North Carolina. Available: http://portal.ncdenr.org/web/mf/fmps-under-development. (December 2019).

Reed, M.S. 2008. Stakeholder participation for environmental management: a literature review. *Biological Conservation* 141(10): 2417-2431. https://doi.org/10.1016/j.biocon.2008.07.014.

Register, K. 2014. Developing a Marine Debris Reduction Plan for Virginia. Prepared for the

Virginia Coastal Zone Management Program. Available: https://www.deq.virginia.gov/Programs/CoastalZoneManagement/CZMIssuesInitiatives/MarineDebris.aspx. (December 2019).

Rhodes, A. and L.A. Shabman. 1994. Virginia's Blue Crab Pot Fishery: The Issues and the Concerns. VSG-94-09. Virginia Sea Grant, Blacksburg, Virginia.

Rhodes, A., D.W. Lipton, and L.A. Shabman. 2001. A socio-economic profile of the Chesapeake Bay commercial blue crab fishery. Chesapeake Bay Commission. Available: http://www.chesbay.us/archives.html. (December 2019).

Richardson, K., B.D. Hardesty, and C. Wilcox. 2019. Estimates of fishing gear loss rates at a global scale: A literature review and meta-analysis. *Fish and Fisheries*. https://doi.org/10.1111/faf.12407.

SB 552, Crab pots and peeler pots; marine-biodegradable escape panels, penalty. 2018 Session (Virginia 2018). Available: https://lis.virginia.gov/cgi-bin/legp604.exe?181+sum+SB552. (December 2019).

Scheld, A.M., D.M. Bilkovic, and K.J. Havens. 2016. The dilemma of derelict gear. *Scientific Reports* 6: 19671. https://doi.org/10.1038/srep19671.

Stern, P.C., L. Kalof, T. Dietz, and G.A. Guagnano. 1995. Values, beliefs, and proenvironmental action: Attitude formation toward emergent attitude objects. *Journal of Applied Social Psychology* 25(18): 1611-1636. https://doi.org/10.1111/j.1559-1816.1995.tb02636.x.

Takahashi, B. and T. Selfa. 2015. Predictors of pro-environmental behavior in rural American communities. *Environment and Behavior* 47(8): 856-876. https://doi.org/10.1177/0013916514521208.

United Nations General Assembly (UNGA). 2004. A/RES/59/25. Resolution adopted by the General Assembly [without reference to a Main Committee (A/59/L.23 and Add.1)]. 59/25. Sustainable fisheries, including through the 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, and related instruments. Available: https://undocs.org/en/A/RES/59/25. (December 2019).

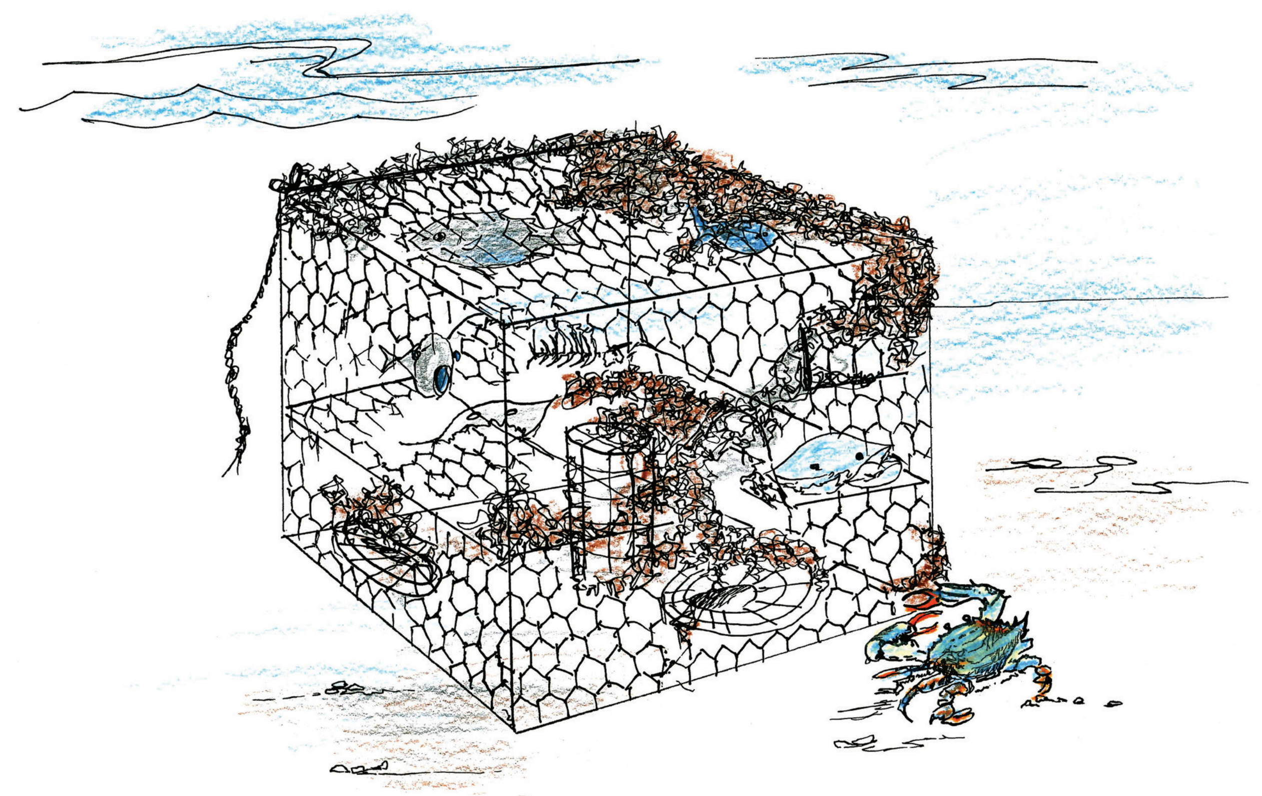
Venables, W.N. and B.D. Ripley. 2002. Modern Applied Statistics with S. Fourth Edition. Springer, New York. ISBN 0-387-95457-0.

Wattage, P., S. Mardle, and S. Pascoe. 2005. Evaluation of the importance of fisheries management objectives using choice-experiments. *Ecological Economics* 55(1): 85-95. https://doi.org/10.1016/j.ecolecon.2004.10.016.

Wilcox, C., N.J. Mallos, G.H. Leonard, A. Rodriguez, and B.D. Hardesty. 2016. Using expert elicitation to estimate the impacts of plastic pollution on marine wildlife. *Marine Policy* 65: 107-114. https://doi.org/10.1016/j.marpol.2015.10.014.

Supplementary material

Derelict Blue Crab Pot Survey



Survey Developed by:
Jim DelBene (jadelbene@vims.edu)
Graduate student at VIMS, College of William & Mary

A-

Part 1 of 2:

Derelict crab pots (also called **ghost pots**) are crab pots that have been lost, abandoned, or otherwise discarded in the water. If you have any questions or concerns regarding participation in this research, please contact Jim DelBene at the Virginia Institute of Marine Science by email (jadelbene@vims.edu) or telephone (804-684-7890). Thank you for your help with this survey.

Crabbing Activity:

1. Circle the months that you crab potted in 2018:

Mar Apr May Jun Jul Aug Sep Oct Nov None

2. When you fished for hard blue crabs in 2018, about how many pots did you normally work each day?

☐ # of pots ○ I did not commercially fish for hard crabs in 2018

3. In 2018, how many of your hard blue crab pots were galvanized and how many were vinyl-coated?

☐ # of galvanized pots

☐ # of vinyl-coated pots

○ I did not commercially fish for hard crabs in 2018

4. How many of your hard blue crab pots used in 2018 did you make and how many did you buy?

☐ # of pots made

☐ # of pots bought

○ I did not commercially fish for hard crabs in 2018

5. Approximately, how many hard blue crab pots did you replace in 2018 because they were old, damaged (unfishable), or lost?

☐ # of pots ○ I did not commercially fish for hard crabs in 2018

6. Do you dip your blue crab pots to make them last longer?

○ Yes ○ No

Derelict Crab Pots:

7. How do you think derelict (lost or abandoned) blue crab pots impact the Chesapeake Bay and coastal waters of Virginia? Select **ONE**.

○ Positively
○ Negatively
○ Both positively and negatively
○ Neither/no impact

8. Which one of the following do you think is the **primary negative impact** caused by derelict blue crab pots in Virginia waters? Select **ONE**.

○ Captures and kills fishes and crabs
○ Costs required to replace the lost gear
○ Creates navigational hazards
○ Damages habitats
○ Reduces harvests
○ Negligible/no impact
○ Other (please explain) ☐

9. Which of the following significantly adds to the number of derelict blue crab pots in Virginia waters? Please select **ALL** that apply.

☐ Abandonment/disposal of old pots
☐ Commercial/recreational vessel traffic
☐ Crabber error
☐ Storms/severe weather
☐ Vandalized or stolen pots become derelict
☐ Other (please explain) ☐

10. How many hard blue crab pots did you lose in 2018?

☐ # of pots ○ I did not commercially fish for hard crabs in 2018

11. How did the number of hard blue crab pots that you lost in 2018 compare to the number of pots that you typically lose each year? Select **ONE**.

○ Less

○ Same

○ More

○ I did not commercially fish for hard crabs in 2018

Additional comments:

12. Do you regularly look for and retrieve your lost blue crab pots?

○ Yes ○ No

13. Which of the following best describes what you do with your old or damaged (unfishable) blue crab pots? Please select **ALL** that apply.

☐ Dispose at landfill/dump on land

☐ Drop off at scrap yard/recycling facility

☐ Reuse working materials in new pots

☐ Other (please explain)

14. Have you ever participated in any organized derelict pot removal programs?

○ Yes ○ No

15. Which of the following activities would you be willing to participate in to **reduce negative impacts** from derelict blue crab pots in Virginia?

a.	Check pots every 72 hours	○ Yes	○ No
b.	Drop off old/derelict pots at recycling facilities on land	○ Yes	○ No
c.	Install pot identification tags on each pot	○ Yes	○ No
d.	Locate and remove derelict pots	○ Yes	○ No
e.	Modify each pot to reduce derelict pot bycatch	○ Yes	○ No
f.	Only use galvanized wire crab pots (no vinyl-coated pots)	○ Yes	○ No

16. Which <u>one</u> of the following incentives would most encourage watermen to participate in activities that reduce derelict blue crab pot **negative impacts** in Virginia waters? Select <u>**ONE**</u>.

○ Bushel limit increase
○ Cash payment
○ Pot limit increase
○ Season extension
○ None
○ Other (please explain) ☐

Personal Characteristics:

17. What generation waterman are you?

○ 1st ○ 2nd ○ 3rd ○ 4th ○ 5th or more

18. How many years of commercial crabbing experience do you have?

☐ # of years

19. In what city/town is your vessel docked?

☐ Name of city or town

20. Do you consider each of the following as a reason you are a waterman?

a.	Independence, being your own boss	○ Yes	○ No
b.	Lifestyle, pride of work, love of the water	○ Yes	○ No
c.	To earn a living	○ Yes	○ No
d.	To earn extra money	○ Yes	○ No
e.	Your family history	○ Yes	○ No
f.	Your friend is/was a waterman	○ Yes	○ No

21. How many different watermen do you regularly talk to about fishery-related topics?

○ None

○ 1-2 watermen

○ 3-5 watermen

○ 6-10 watermen

○ More than 10 watermen

22. How often did you communicate with other watermen about fishery-related topics in 2018?

○ Not at all

○ A few times during the year

○ About once a month

○ About once a week

○ More than once a week

23. Which one of the following types of communication did you use most frequently when communicating with other watermen about fishery-related topics in 2018? Select **ONE**.

○ E-mail

○ In person

○ Phone

○ Social media (for example, Facebook)

24. In 2018, did you voluntarily attend in person or participate over the phone in a Virginia Marine Resources Commission (VMRC) meeting?

○ Yes ○ No

25. Does the majority (greater than 50%) of your personal income come from commercial crabbing?

○ Yes ○ No

Part 2 of 2:

This part of the survey presents three questions involving hypothetical activities and incentives aimed at reducing the number of derelict blue crab pots and their impacts in the waters of Virginia. <u>Scientific studies conducted in Virginia and elsewhere have shown that each derelict crab pot may kill 16-26 blue crabs per year and that derelict crab pots can reduce fishery harvests by as much as 30% by competing with actively fished gear.</u> Each question will present two hypothetical options (Option A and Option B) and a third option of no activity and no incentive or cash payment (Option C). Activities and incentives are defined beneath each question and should be considered hypothetical; they do not correspond with current actions in Virginia. For each question, please select the option you most prefer.

<u>ACTIVITY</u>: The hypothetical activities that will be used to reduce the number of derelict blue crab pots and their impacts in the waters of Virginia. In each question, options A and B will include one hypothetical **Activity** from the following list:

- **Educate recreational boaters**
- **Galvanized pots only**
- **Pot modification**
- **Pot tags**
- **Recycle at facility on land**
- **Soak time limit**
- **Three-day removal program**

<u>INCENTIVE</u>: The hypothetical incentives that you will receive to participate in the corresponding activity. In each question, options A and B could include a hypothetical **Incentive** from the following list or None:

- **Bushel limit increase**
- **Pot limit increase**
- **Season extension**

<u>CASH PAYMENT</u>: The hypothetical amount of money that you will receive as a one-time payment for participating in the corresponding activity.

Question 1. Which of the following options would you most prefer to reduce the number of derelict blue crab pots and their impacts?

	OPTION A	OPTION B	OPTION C
ACTIVITY	Pot tags	Galvanized pots only	No activity
INCENTIVE	Season extension	None	None
CASH PAYMENT	$100	$300	None

Choose your **most preferred** option from the list below. Select **ONE**.

○ Option A
○ Option B
○ Option C

Definitions Box

ACTIVITY

Pot tags: Attach a tag to each blue crab pot to identify your ownership if the buoy is lost.

Galvanized pots only: Only use galvanized wire crab pots (no vinyl-coated).

INCENTIVE

Season extension: You will be allowed to commercially crab for an additional two weeks before or after the originally permitted season.

Question 2. Which of the following options would you most prefer to reduce the number of derelict blue crab pots and their impacts?

	OPTION A	OPTION B	OPTION C
ACTIVITY	Pot tags	Soak time limit	No activity
INCENTIVE	Pot limit increase	Bushel limit increase	None
CASH PAYMENT	$300	None	None

Choose your **most preferred** option from the list below. Select **ONE**.

○ Option A
○ Option B
○ Option C

Definitions Box

ACTIVITY

Pot tags: Attach a tag to each blue crab pot to identify your ownership if the buoy is lost.

Soak time limit: Check your blue crab pots every 72 hours.

INCENTIVE

Pot limit increase: Your daily pot limit increases by 5-10% of your current license limit (for example, if you have a 255 pot license, then a pot limit increase of 10% will allow you to deploy up to 281 pots per day).

Bushel limit increase: Your daily bushel limit increases by 5-10% of your current license limit (for example, if you have a 255 pot license and are permitted to harvest 29 bushels per day, then a bushel limit increase of 10% will allow you to harvest about 32 bushels per day).

Question 3. Which of the following options would you most prefer to reduce the number of derelict blue crab pots and their impacts?

	OPTION A	OPTION B	OPTION C
ACTIVITY	Pot modification	Recycle at facility on land	No activity
INCENTIVE	Pot limit increase	Season extension	None
CASH PAYMENT	None	$100	None

Choose your **most preferred** option from the list below. Select **ONE**.

- ○ Option A
- ○ Option B
- ○ Option C

Definitions Box

ACTIVITY

Pot modification: Modify each of your blue crab pots to prevent the pot from continuing to capture animals if it becomes derelict.

Recycle at facility on land: Recycle all of your old crab pots at a facility on land.

INCENTIVE

Pot limit increase: Your daily pot limit increases by 5-10% of your current license limit (for example, if you have a 255 pot license, then a pot limit increase of 10% will allow you to deploy up to 281 pots per day).

Season extension: You will be allowed to commercially crab for an additional two weeks before or after the originally permitted season.

Thank you for completing this survey!

If you have any additional thoughts about any of the survey topics or the survey itself, please share them here.

SUMMARY AND CONCLUSIONS

Fisheries worldwide are confronted with the issue of derelict fishing gear (DFG), and resource managers and policymakers are responsible for implementing actions that reduce DFG abundance and impacts. Pots and traps are one type of DFG that causes significant negative ecological and economic impacts (Guillory 1993, Arthur et al. 2014, Bilkovic et al. 2016, Scheld et al. 2016, Wilcox et al. 2016). Furthermore, derelict pots can continue to fish for two years or more (Matsuoka et al. 2005, Havens et al. 2008). The Chesapeake Bay commercial blue crab fishery is predominantly a pot fishery impacted by derelict pots from both Maryland and Virginia fisheries. An estimated 12-20% of fished pots in the Bay become derelict each year (approximately 145,000 predicted to be present at any given time; Bilkovic et al. 2016). In Virginia, close to 1,000 commercial fishers were licensed to deploy hard crab pots in 2018, of which approximately 100 were permitted to deploy up to 425 pots each. This research focused on contributing new information that can help resource managers and policymakers effectively address derelict pots and provides a framework for tackling other types of DFG.

This study was the first to experimentally test harvest impacts caused by derelict pots, as described by Scheld et al. 2016. Previous studies focused on the ghost fishing phenomenon of the continued capturing and killing of fishes and crabs (Guillory 1993, Giordano et al. 2010, Havens et al. 2011, Arthur et al. 2014), but this research found that derelict pots can reduce harvests by up to 30% by attracting blue crabs away from actively fished pots, regardless of whether the crabs were captured in derelict pots. Thus, impacts caused by derelict pots extend beyond the confines of a derelict pot and can be evident in actively fished pots located nearby. Findings from this study apply directly to the blue crab pot fishery in Chesapeake Bay, but further research should be conducted to investigate this economically detrimental impact in other valuable pot fisheries, for example American lobster, Dungeness crab, king crab, and stone crab.

Future work should consider the distance between derelict and actively fished pots, the number of derelict pots located nearby an active pot, how various habitat complexities may influence the observed impact on harvest, and target species behaviors that can influence the relative effect of DFG.

Resource managers and policymakers are responsible for tackling the issue of derelict pots, and stakeholder buy-in is essential for them to develop effective, long-term mitigation actions. In the U.S., states already implement various strategies that can mitigate impacts of derelict pots (see Table 1). Stakeholder buy-in can influence the effectiveness of these mitigation strategies; however, little is known about stakeholder preferences for such efforts. Furthermore, some of these strategies rely on the enforcement of existing rules and regulations, but information on the success of these enforcement efforts is limited and should be investigated to expand on the findings from this study. Results from the stated preference survey that was distributed to more than 1,000 licensed commercial fishers in Virginia can be used to identify stakeholder preferences for derelict pot mitigation activities. By understanding and considering commercial fishers' decision-making, resource managers and policymakers can form expectations for the acceptability and enforceability of potential actions. Most derelict pot mitigation actions will require incentives to increase commercial fishers' willingness to participate; however, some segments of the population were far more willing to participate than others. Commercial fishers would be most willing to participate in a recycling program for old or derelict pots and least willing to participate in a pot modification. Because of differences in fishery management and harvesting methods, future work could incorporate preferences of commercial fishers licensed in Maryland or the Potomac River to include the entire Chesapeake Bay commercial blue crab fishery. Additionally, stated preference survey work could provide crucial information in other states with valuable fisheries impacted by DFG, such as the American lobster fishery in Maine or blue crab fishery in Louisiana. For instance, a stated preference survey could help identify the preferences of Louisiana commercial fishers for expanding efforts in the state’s current derelict pot removal program or implementing complementary mitigation strategies that can prevent gear loss.

Results from this thesis can be used to assess the effectiveness of derelict pot mitigation strategies to reduce impacts of derelict pots. When determining appropriate derelict pot mitigation activities, resource managers and policymakers should consider addressing harvest reductions caused by the presence of derelict pots and commercial fishers’ willingness to participate in activities. Activities commonly implemented in states with a commercial blue crab fishery, such as channel restrictions and removal programs (Table 1), can help reduce the harvest impact caused by derelict pots by decreasing the abundance of derelict pots. Whereas, the few states that require installation of a degradable component are addressing bycatch impacts but not likely addressing the harvest impact. Disarming a derelict pot with a degradable component does not remove the pot from the environment, thus it can continue to attract crabs away from actively fished pots. Furthermore, a pot modification to install a degradable component was the least preferred mitigation activity by commercial fishers. Depending on the perceptions of local fishers, this may suggest other states like Maryland or Georgia would receive significant pushback from commercial fishers if they attempted to implement such a requirement unless it were highly incentivized. Requiring commercial fishers to attach an identification tag to each pot is another rarely implemented mitigation activity in commercial blue crab fisheries, even though it would reduce impacts of derelict pots on harvest by increasing accountability and improving controls on fishing effort. By being aware of all impacts caused by derelict pots and engaging with commercial fishers to identify their preferences, resource managers and policymakers can improve the effectiveness of their derelict pot mitigation strategies.

Commercial fishers regularly work on the water and derelict pots can cause a substantial reduction in their harvest; thus, it is important to include them in the decision-making process to address this issue. Resource managers, policymakers, and researchers can successfully engage with stakeholders, such as commercial fishers, by using tools like stated preference surveys and discrete choice experiments. The far-reaching impacts caused by derelict pots and other DFG will likely require a combination of solutions, which can be identified with insight from stakeholder groups.

Table 1 Select commercial blue crab regulations and derelict crab pot mitigation activities implemented in U.S. states with a commercial blue crab fishery (Pot Tags = require commercial fishers to attach an identification tag to each of their pots; Channel Restrictions = prohibit crab pots from being deployed in specific channels and/or waterways to reduce user conflict; Degradable Component = require installation of a degradable component to disarm the pot if it becomes derelict; Removal Program = implemented a program with stakeholders to locate and remove derelict blue crab pots within the last 10 years).

State[a]	**Regulatory Commission**	**Pot Tags**	**Channel Restrictions**	**Degradable Component**	**Removal Program**
Alabama	Department of Conservation and Natural Resources	No	Yes	No	Yes
Delaware	Division of Fish & Wildlife	No	Yes	No	Yes
Florida	Fish and Wildlife Conservation Commission	Yes	Yes	Yes	Yes
Georgia	Coastal Resources Division	No	Yes	No	No
Louisiana	Department of Wildlife and Fisheries	Yes	Yes	No	Yes
Maryland	Department of Natural Resources	No	Yes	No	Yes
Maryland/Virginia	Potomac River Fisheries Commission	No[b]	Yes	No	Yes
Mississippi	Department of Marine Resources	Yes	Yes	No	Yes
New Jersey	Division of Fish & Wildlife	No	Yes	Yes	Yes
New York	Department of Environmental Conservation	Yes	Yes	Yes	No
North Carolina	Division of Marine Fisheries	No	Yes	No	Yes
South Carolina	Marine Resources Division	No	Yes	No	Yes
Texas	Parks & Wildlife	No[b]	Yes	Yes	Yes
Virginia	Marine Resources Commission	No	Yes	No	Yes

[a] Connecticut has a commercial blue crab fishery but prohibits the taking of blue crabs with "Chesapeake-style box/cage traps."

[b] Identification tag must be attached near the buoy marking the crab pot.

References

Arthur, C., A. Sutton-Grier, P. Murphy, and H. Bamford. 2014. Out of sight but not out of mind: Harmful effects of derelict traps in selected U.S. coastal waters. *Marine Pollution Bulletin* 86: 19-28. https://doi.org/10.1016/j.marpolbul.2014.06.050.

Bilkovic, D.M., H.W. Slacum Jr, K.J. Havens, D. Zaveta, C.F. Jeffrey, A.M. Scheld, D. Stanhope, K. Angstadt, and J.D. Evans. 2016. Ecological and Economic Effects of Derelict Fishing Gear in the Chesapeake Bay: 2015/2016 Final Assessment Report. Prepared for Marine Debris Program, Office of Response and Restoration, National Oceanic and Atmospheric Administration. Available: https://marinedebris.noaa.gov/reports/effects-derelict-fishing-gear-chesapeake-bay-assessment-report. (December 2019).

Giordano, S., J. Lazar, D. Bruce, C. Little, D. Levin, H.W. Slacum Jr., J. Dew-Baxter, L. Methratta, D. Wong, and R. Corbin. 2010. Quantifying the effects of derelict fishing gear in the Maryland portion of Chesapeake Bay. In: Final Report to the NOAA Marine Debris Program. National Oceanic and Atmospheric Administration, Silver Spring, Maryland. Available: https://marinedebris.noaa.gov/research/regional-impact-assessment-derelict-fishing-gear-chesapeake-bay. (December 2019).

Guillory, V. 1993. Ghost fishing by blue crab traps. *North American Journal of Fisheries Management* 13: 459-466. https://doi.org/10.1577/1548-8675(1993)013<0459:GFBBCT>2.3.CO;2.

Havens, K.J., D.M. Bilkovic, D. Stanhope, K. Angstadt, and C. Hershner. 2008. The effects of derelict blue crab traps on marine organisms in the lower York River, Virginia. *North American Journal of Fisheries Management* 28(4): 1194–1200. https://doi.org/10.1577/M07-014.1.

Havens, K.J., D.M. Bilkovic, D. Stanhope, and K. Angstadt. 2011. Fishery failure, unemployed commercial fishers, and lost blue crab pots: An unexpected success story. *Environmental Science and Policy* 14: 445-450. https://doi.org/10.1016/j.envsci.2011.01.002.

Matsuoka, T., T. Nakashima, and N. Nagasawa. 2005. A review of ghost fishing: scientific approaches to evaluation and solutions. *Fisheries Science* 71: 691–702. https://doi.org/10.1111/j.1444-2906.2005.01019.x.

Scheld, A.M., D.M. Bilkovic, and K.J. Havens. 2016. The dilemma of derelict gear. *Scientific Reports* 6: 19671. https://doi.org/10.1038/srep19671.

Wilcox, C., N.J. Mallos, G.H. Leonard, A. Rodriguez, and B.D. Hardesty. 2016. Using expert elicitation to estimate the impacts of plastic pollution on marine wildlife. *Marine Policy* 65: 107-114. https://doi.org/10.1016/j.marpol.2015.10.014.