Title: Evaluating optimal removal of derelict blue crab pots in Virginia, US

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Abstract

Derelict fishing gear is a growing concern in many fisheries and coastal communities. Pots and traps are prevalent forms of derelict fishing gear with numerous documented harmful effects. In the Chesapeake Bay, US, a large blue crab (*Callinectes sapidus*) pot fishery produces high levels of derelict gear. From 2008 to 2014, 34,408 derelict pots were removed from blue crab fishing areas in Virginia. This research first evaluates whether observed increases in catch rates occurring contemporaneously with the removal program were the result of derelict gear removals. An econometric production model is then used to estimate marginal removal benefits and assess optimal removal levels. Fishing locations with removals during the removal program were estimated to have experienced increases in harvest per pot and harvest per trip of 22.35% and 34.68%, respectively. Optimal removal levels were found to depend on location-specific fishing effort, with high-effort areas yielding greater marginal removal benefits. Fishery productivity gains, though large, were found to last only one year following removals. Assuming a removal cost of $100/pot, the optimal level of removals was estimated to be over 7,000 pots/year and would generate productivity gains of ~17-18%, yielding over US $3M in annual net benefits to the commercial fishery. Optimizing mitigation and management strategies for derelict fishing gear and marine debris requires quantitative assessment of the benefits and costs of alternative policy measures.

Keywords: derelict fishing gear, blue crab, marine debris, translog production model, policy design

Highlights

- Removal of derelict pots in Virginia increased productivity by over 20%
- Optimal derelict gear removal policies balance marginal benefits and marginal costs
- In Virginia, optimal derelict gear removal would yield US ~$3M in annual net benefits

1. Introduction

Derelict fishing gear includes nets, lines, pots and traps, and other recreational or commercial fishing equipment that has been lost, abandoned, or otherwise discarded (UNEP 2005). It can make up a significant proportion of ocean-based marine debris in coastal areas (National Research Council 2008) and may be caused by several factors, such as human error, intentional abandonment, gear conflicts and 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; FAO 2016). The availability of synthetic materials in modern times has increased the efficiency, durability, and lifespan of gear in many fisheries, and derelict gear may persist in marine environments for several years (e.g., Havens et al. 2008; Gilman et al. 2013; Maselko et al. 2013; Arthur et al. 2014; Uhlmann and Broadhurst 2015). The accumulation and effects of derelict fishing gear (lines, nets, pots and traps) has been recognized as a global problem (e.g., Hérbert et al. 2001; UN General Assembly resolution 59/25, 2004; Matsuoka et al. 2005; Bilkovic et al. 2012; Uhlmann and Broadhurst 2015; Richardson et al. 2019), and many coastal areas are now grappling with how to most effectively assess and manage the issue (Jeffrey et al. 2016; FAO 2016; Goodman et al. 2019).

Pots and traps are passive gear typically fished in large numbers and are thought to be one of the most common types of derelict gear worldwide (Macfadyen et al. 2009; Richardson et al. 2019). Many crustacean fisheries utilize pot and trap gear and are plagued by persistently high gear loss rates (Jeffrey et al. 2016; Scheld et al. 2016), with storms and vessel-gear interactions frequently noted as primary causes of loss (Antonelis et al. 2011; Bilkovic et al. 2016; Uhrin 2016; Richardson et al. 2019). Derelict pots and traps have been found to cause a variety of detrimental ecological and economic impacts, such as bycatch mortality for target and non-target species (Antonelis et al. 2011; Maselko et al. 2013; Bilkovic et al. 2016), habitat damage (Arthur et al. 2014), and reduction of fishery harvests (Scheld et al. 2016). Additionally, many pots and traps utilize vinyl-coated metal wiring or other plastic components and thus contribute to marine plastic pollution, which may be in violation of international agreements if gear is intentionally discarded or abandoned (e.g., Annex V of MARPOL, Basel Convention).

Harvest losses due to derelict pots and traps can arise as a result of reductions in harvestable stock (Macfadyen et al. 2009; Bilkovic et al. 2012; Uhlmann and Broadhurst 2015) as well as through gear externalities (Scheld et al. 2016; DelBene et al. 2019). High rates of capture and mortality by derelict pots and traps can reduce the biomass available to commercial and recreational fisheries (Antonelis et al. 2011; Bilkovic et al. 2016), though it is often uncertain whether or not animals captured by derelict gear would have been caught through the fishery in its absence. Reductions in gear efficiency of the active fishery—rates of catch and harvest—may also occur, independently of any changes in stock abundance. It is widely accepted that fish and crustaceans are frequently attracted to structure, floating objects, and complex habitat (Orth et al. 1984; Walsh 1985; Heck and Crowder 1991; Eggleston et al. 1998; Castro et al. 2002). Derelict pots and traps may attract or capture target and bycatch species, making them unavailable to commercial and recreational fishers, even if mortality does not ultimately result (Bilkovic et al. 2016; Scheld et al. 2016; DelBene et al. 2019).

In the Chesapeake Bay, derelict blue crab (*Callinectes sapidus*) pots are thought to cause economic losses due to both reduced biomass and reductions in gear efficiency. Commercial blue crab pots are 0.6m x 0.6m x 0.6m rigid wire mesh cubes with an upper and lower chamber and have been found to fish for two years or more after becoming derelict (Havens et al. 2008). About a third of harvesters in Virginia fish with vinyl-coated pots (DelBene 2020), which may persist in the environment for longer. Bilkovic et al. (2016) estimated that derelict pots capture approximately six million harvestable blue crab annually, of which roughly three million are killed. The fishing mortality target reference point for the stock is set at 25.5% of mature females, and typically between 20% and 30% of all adults are harvested each year (CBSAC 2019). This suggests that, of the three million blue crab killed annually by derelict pots, a little under one million would have been captured in the active fishery had the derelict pots not been present. Though significant, such losses represent less than 1% of total annual fishery harvests. Losses arising due to gear externalities and competition between actively fished and derelict pots are potentially much greater. Scheld et al. (2016) evaluated the effects of a six-year derelict pot removal program on commercial blue crab harvests in Virginia by developing a production model that incorporated spatially and temporally resolved data on harvests, fishing effort, blue crab abundance, and removals. Comparing harvest model predictions under the removal program that existed and a hypothetical scenario of no removals, the authors found that removing derelict pots increased harvests by 27% (Scheld et al. 2016). A subsequent experimental study by DelBene et al. (2019) demonstrated gear competition can reduce active blue crab fishery harvests by more than 30%, suggesting economic losses arising due to derelict pots may be considerable.

Socially efficient environmental policies balance marginal social costs and marginal social benefits (Baumol and Oates 1988). Control of marine debris and derelict fishing gear can be viewed as a problem of waste management or environmental pollution control, and thus balancing the incremental costs and benefits of marine debris reduction should be considered in designing optimal policies (McIlgorm et al. 2011). Previous studies investigating the costs and benefits of derelict gear removals have analyzed total or average values, assessing net benefits and whether removals, in total or on average, are socially beneficial (e.g., Gilardi et al. 2010; Antonelis et al. 2011; Scheld et al. 2016). Optimal program design requires analysis of marginal removal benefits and costs however, such that a net benefit maximum can be identified.

This research addresses several remaining questions regarding the economic benefits of derelict pot removals and optimal program design. The analysis of Scheld et al. (2016) occurred directly following the conclusion of the removal program and the authors did not consider potential lagged effects. It is therefore not known whether the harvest benefits of removals arising from reduced gear externalities occur in only one season or across multiple years. Additionally, harvest benefits were found to be larger in areas of high fishing effort, and it was suggested future removals prioritize these "hotspots" (Bilkovic et al. 2016; Scheld et al. 2016). Marginal benefits of removals were not evaluated as a function of fishing effort however, and it is not clear what level of removals would maximize area-specific net benefits. This research aims to address existing gaps in knowledge regarding fishery benefits of derelict blue crab pot removals to facilitate design of optimal future removal programs in the Chesapeake Bay and elsewhere.

2. Materials and Methods

2.1 Data

The Chesapeake Bay commercial blue crab fishery operates in inshore and nearshore coastal environments and produces 30-40% of US commercial blue crab harvests valued at US ~\$80M-\$100M annually (NMFS 2018). In Virginia, blue crab are targeted by a fleet of several hundred small vessels, typically <10m, with pot limits ranging from 85 to 425 per license holder. In a recent survey of licensed commercial blue crab fishers, individuals actively targeting blue crab reported fishing an average of ~170 pots per day in 2018 (DelBene 2020). Each pot is required to be fished individually and have its own buoy. Recreational vessel traffic, storms, and abandonment are thought to be primary drivers of gear loss (Bilkovic et al. 2016).

Blue crab fishers in Virginia are required to submit weekly harvest reports to the Virginia Marine Resources Commission (VMRC), who manage fishery resources within state waters and restrict effort in the blue crab fishery through pot limits, seasonal and spatial closures, and limits on which days of the week and times of day fishing is allowed. Harvest reports indicate total pots or other gear fished, fishing location, and pounds of blue crab harvested. The VMRC delineates fishing locations by local hydrographic features and natural markers (e.g., bays, creeks, or sections of a river). In total there are 74 fishing locations defined throughout Virginia's tidal waters, ranging in size from 1.7 to over one thousand square kilometers (~75% of areas are < 100 km^2). Crabbing effort occurs within most of these fishing locations, though a large portion of the central Chesapeake Bay is maintained as a spawning sanctuary where blue crab harvest is prohibited during spawning season.

This analysis utilized non-confidential data on blue crab harvests and two measures of fishing effort: number of trips and number of pots fished. Harvest and effort data were aggregated across fishers by fishing location and year from 1994 to 2018. As not all locations are fished in every year, the full dataset included 1,480 observations spanning 25 years and 72 fishing locations. The two fishing locations absent from the dataset were small bays off Virginia's sparsely populated Eastern Shore. Annual data on total blue crab abundance was obtained from the Chesapeake Bay Stock Assessment Committee's 2019 Blue Crab Advisory Report (see CBSAC 2019). Abundance estimates were matched by year to commercial fishery harvest and effort data and were used in subsequent modeling to control for inter-annual fluctuations in stock size that influence harvest rates.

From 2008 through 2014, commercial crab fishers in Virginia were hired to remove derelict blue crab pots during the winter closed season (December-March). The program involved 70 participants in total, with 58-70 individuals conducting removals during the first four years and a smaller group of 4-7 individuals participating during the last two years. Program participants were restricted to working 49 days/year during the first three years, 24 days during the fourth year, and 30 days/year during the last two years. All participants were paid a flat daily rate for each day worked. Derelict pots were located by identifying buoys of abandoned gear or using side scan sonar units to find pots with detached buoys. Side-imaging technology has been shown to be effective at locating and identifying marine debris and derelict blue crab pots in the Chesapeake Bay, the latter having a shape and dimensions relatively unique in this environment (Havens et al. 2008). Program participants were instructed on proper retrieval techniques to reduce bottom disturbance. Unbuoyed pots were retrieved using grappling gear raised slightly above the bottom surface or lines embedded with bent nails. After removing a derelict pot, program participants took a photograph, recorded the date and time of removal, and documented additional data on pot condition, bycatch, and location (waypoint). Across six consecutive winters, 34,408 derelict blue crab pots were removed from Virginia waters, an amount thought to represent ~10-25% of the existing stock (protocols for debris removal, data collection, and debris disposal were coordinated with NOAA Marine Debris Program personnel; see Havens et al. 2011, Bilkovic et al. 2014, and Bilkovic et al. 2016 for an overview of the removal program as well as its ecological and economic impacts).

Derelict pot removals were matched by fishing location and year to blue crab fishery harvest and effort data using recorded waypoints. A small number of removals (3.55%) fell outside management area boundaries (e.g., due to GPS error or fisher error when logging data). These removals were matched to the nearest fishing location. Removals always occurred during the winter offseason and were matched to the following fishing season (e.g., a removal occurring in December 2011 would match to 2012 fishery data). Of the 34,408 removals, 32,475 (94.38%) were matched to fishing locations and years having observations of harvest and effort. Removal efforts were concentrated during the first three years of the program (81.99% of all removals) and were spatially heterogeneous. The number of fishing locations experiencing removals averaged 36/year (62% of areas fished annually), though varied across years from 51 in 2010 (82% of areas fished) to 11 in 2013 (19% of areas fished). In total, there were 217 observations of fishing locations with some level of removals across all six years of the removal program. Of the 72 fishing locations with reported harvest and effort, 19 had no derelict pot removals in any year. Removals ranged from one to 1,677 pots/location/year, with a median of 56 for fishing locations and years with removals.

2.2 Analyses

The derelict pot removal program in Virginia was not experimentally designed to test the effects of removals on commercial fishery harvest rates. Participating fishers were instructed to spread removal efforts throughout areas where crabbing occurred, though pots were largely removed from places individuals had fished previously, were easily accessible, or areas where abandoned gear was visible. Consequently, simple comparisons of harvest rates between areas with and without removals are confounded by selection bias (e.g., perhaps areas with removals were better fishing locations to begin with). Furthermore, pre- and post-removal comparisons among locations with removals are problematic due to annual variation in blue crab abundance and contemporaneous management measures that might impact fishing effort. A variety of robust statistical approaches exist for identification of treatment effects from non-experimental data (see, e.g., Athey and Imbens 2017). This investigation utilized regression analyses including controls for spatial and temporal factors that might influence harvest rates and thus obscure the impacts of derelict pot removals on the commercial blue crab fishery.

To assess potential changes in harvest rates in response to derelict pot removals, harvest per pot and harvest per trip were calculated for each fishing location and year. The following panel regression model was then estimated:

1. $$\theta_{it} = \alpha_t + X_{it}\beta + \varepsilon_{it},$$

where θ_{it} is the harvest rate (lb per pot pull or per trip) in fishing location *i* for year *t*; α_t is an annual fixed effect; X_{it} is a *n* x 2 matrix of covariates, where *n* is equal to the number of observations; β is a 2 x 1 vector of parameters to be estimated; and ε_{it} is a normally distributed random error term. The matrix X_{it} included two binary factors, one of which was set equal to one for all years if location *i* had removals in any year and set equal to zero otherwise (i.e., $X_{it,1} = 1 \; \forall \; t \; iff \; \sum_t R_{it} > 0 \; for \; location \; i$, where R_{it} is the number of derelict pot removals in location *i* and year *t*). The second binary variable was set equal to one only in years when location *i* experienced removals and was zero otherwise (i.e., $X_{it,2} = 1 \; iff \; R_{it} > 0 \; for \; location \; i \; and \; year \; t$). Equation 1 therefore estimated the average change in harvest rate for areas with removals during the removal program, controlling for interannual shifts in the harvest rate across all fishing locations (e.g., due changes in blue crab abundance) as well as potential selection effects among fishing locations that experienced some level of removals (e.g., if areas with removals were better fishing locations on average, independent of the removal program).

While equation (1) can be used to evaluate the average improvement in harvest rate following removal of derelict pots, optimal policy design requires estimating program benefits on the margin. A second model was used to resolve marginal benefits associated with removal of derelict pots:

$$H_{it} = q_{it} E_{it}^{\eta_e} S_t^{\eta_s}. \tag{2}$$

Equation (2) is a modified Schaefer harvest specification, where harvest in location *i* at time *t* is modeled as a function of location and time specific catchability, q_{it}, fishing effort, E_{it}, and stock abundance, S_t. Two empirical models were estimated, one for each measure of fishing effort. Empirical specifications utilized a transcendental logarithmic functional form (see Christensen et al. 1973), which allowed estimation of flexible output elasticities and has been previously used to evaluate harvest response to derelict gear removals (see Scheld et al. 2016). The harvest model was specified as:

$$\begin{aligned} ln(H_{it}) = {} & \mu_i + \nu_t + \beta_E ln(E_{it}) + \beta_S ln(S_t) + \tfrac{1}{2}\beta_{EE} ln(E_{it}) ln(E_{it}) + \\ & \tfrac{1}{2}\beta_{SS} ln(S_t) ln(S_t) + \beta_{ES} ln(E_{it}) ln(S_t) + \beta_{ER} ln(E_{it}) R_{it} + \beta_{SR} ln(S_t) R_{it} + \beta_R R_{it} + \\ & \beta_{\sqrt{R}} \sqrt{R_{it}} + \beta_{R_{lag}} R_{it-1} + \varepsilon_{it}, \end{aligned} \tag{3}$$

where μ_i is a fishing location fixed effect; ν_t is an annual fixed effect included for years during the removal program (2009-2014) to control for any unobserved contemporaneous changes in the environment or management that might affect harvest rates; E_{it} is a measure of fishing effort for location *i* and year *t*, which was either the number of pots fished or trips taken; S_t is an annual estimate of total blue crab stock abundance; R_{it} are the derelict pot removals from location *i* in year *t*; R_{it-1} are the removals from location *i* during the previous year; and ε_{it} is a normally distributed random error term. Using the empirical specification in (3), catchability and elasticity parameters from (2) can be written as:

$$q_{it} = exp\left(\mu_i + \nu_t + \beta_R R_{it} + \beta_{\sqrt{R}} \sqrt{R_{it}} + \beta_{R_{lag}} R_{it-1}\right); \tag{4}$$

$$\eta_{e_{it}} = \beta_E + \beta_{EE} ln(E_{it}) + \beta_{ES} ln(S_t) + \beta_{ER} R_{it}; \tag{5}$$

6. $$\eta_{S_{it}} = \beta_S + \beta_{SS} ln(S_t) + \beta_{ES} ln(E_{it}) + \beta_{SR} R_{it}.$$

Catchability (equation 4) was therefore modeled to be a function of location and time fixed effects, contemporaneous derelict pot removals as well as their square root, and removals from the previous year. Harvest elasticities for fishing effort and stock abundance (equations 5-6) were modeled as depending on the levels of both inputs (effort, stock) as well as derelict pot removals. Equations 2-6 thus incorporate derelict pot removals into the harvest model by allowing for removals to affect production elasticities in addition to influencing catchability directly.

The marginal benefits associated with derelict pot removals were evaluated as the change in the natural log of harvest corresponding to a change in removals:

7. $$\frac{\partial ln(H_{it})}{\partial R_{it}} = \beta_R + \tfrac{1}{2}\beta_{\sqrt{R}} (R_{it})^{-\frac{1}{2}} + \beta_{ER} ln(E_{it}) + \beta_{SR} ln(S_t).$$

Equation (7) indicates that marginal benefits were a function of parameters estimated in the harvest model (equation 3) as well as levels of fishing effort, stock, and removals. Note that this specification of marginal benefits does not include any potential lagged effects.

The models specified in equations 1 and 3 were estimated in R version 3.5.0 (R Core Team 2018) with functions contained in the plm package (Croissant and Millo 2018). Both models were fit using fixed effects (within) estimators, where fixed effects were by year or fishing location for equations 1 and 3, respectively.

3. Results

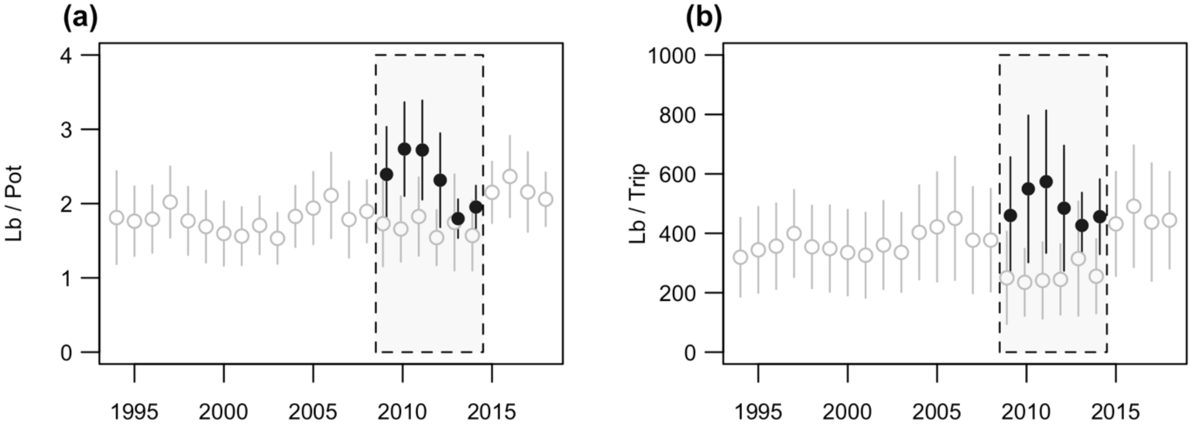

Figure 1. Annual average harvest per pot (a) and harvest per trip (b). Points are weighted averages and lines are weighted standard deviations, where weights reflect location-specific fishing effort (pots, trips). Observations during years of the derelict pot removal program (grey shaded box) are separated into averages for locations with (black filled points) or without removals (grey open points). Means and standard deviations during the removal program for locations with and without removals are slightly offset horizontally to avoid overplotting.

Areas with removals during the removal program generally experienced higher average productivities when compared to areas without removals during the removal program as well as observations prior to the removal program (Figure 1). For both measures of fishing effort, four of the top five highest productivity observations occurred in locations with removals during the removal program. Panel regression models of harvest per pot and harvest per trip (equation 1), which included annual fixed effects and dummy variables to control for potential fishing location selection bias, indicated that areas with removals during the removal program experienced average productivity increases of 0.39 lb/pot (95% CI: [0.25, 0.53]) and 99.84 lb/trip (95% CI: [56.22, 143.46]; see Appendix Table A1). These increases represent 22.35% and 34.68% of median harvest per pot and harvest per trip across all observations, respectively.

	Effort : Pots			Effort : Trips		
Variable	Coefficient		SE	Coefficient		SE
ν_{2009}	0.0309		0.0363	-0.0492		0.0428
ν_{2010}	0.0276		0.0424	0.1012	*	0.0430
ν_{2011}	0.1441	***	0.0348	0.1645	**	0.0539

ν_{2012}	-0.0936	.	0.0525	0.0524		0.0626
ν_{2013}	-0.1491	***	0.0303	-0.1691	***	0.0437
ν_{2014}	-0.0642	*	0.0257	-0.1120	**	0.0405
β_E	1.2429	***	0.2428	1.3340	***	0.2276
β_S	2.0144	*	0.9190	2.2032		1.5135
β_{EE}	-0.0263		0.0181	-0.0926	**	0.0347
β_{SS}	-0.2893	*	0.1472	-0.3939		0.2491
β_{ES}	-0.0031		0.0136	0.0394		0.0298
β_{ER}	0.0002	*	0.0001	0.0003	**	0.0001
β_{SR}	0.0001		0.0002	0.0001		0.0002
β_R	-0.0039	*	0.0016	-0.0032	*	0.0013
$\beta_{\sqrt{R}}$	0.0150	***	0.0035	0.0134	***	0.0038
$\beta_{R_{lag}}$	0.0000		0.0001	0.0000		0.0001
	$R^2 = 0.81$			$R^2 = 0.70$		
	F-statistic = 153.53***			F-statistic = 98.70***		

Table 1. Translog harvest model regression outputs. The unbalanced panel regression included 1,480 observations from 72 fishing locations and 25 years. Coefficient standard errors were calculated using a robust covariance matrix following the approach of White (1980) and Arellano (1987). Statistical significance denoted as *, **, and *** corresponding to significance at the 5, 1, and 0.1% levels, respectively.

Two specifications of the harvest model were estimated, one for each effort measure (Table 1). Outputs from the two models were similar and indicated strong increases in harvest associated with increases in effort, while relatively weak harvest responses resulted from changes in stock abundance. Using regression model parameters, output elasticities (equations 5 and 6) were estimated at covariate means. The percentage increase in harvest found to result from a 1% increase in fishing effort (i.e., $\eta_{e_{it}}$) was 0.93 (95% CI: [0.87, 0.99]) for an increase in pots and 0.99 (95% CI: [0.91, 1.07]) for an increase in trips. Conversely, the percentage increase in harvest found to result from a 1% increase in stock (i.e., $\eta_{s_{it}}$) was 0.25 (95% CI: [0.20, 0.31]) for the pots model and 0.10 (95% CI: [0.01, 0.19]) for the trips model. The effects of derelict pot removals on harvest were consistent across the two models, which found positive and highly significant square root effects, negative and less significant linear effects, and positive, though weak, interaction effects on output elasticity with respect to changes in fishing effort (i.e., derelict pot removals resulted in improvements in location-specific catchability as well as gains in the productivity of fishing effort). Interestingly, both models found no evidence for lagged effects of removals on harvests.

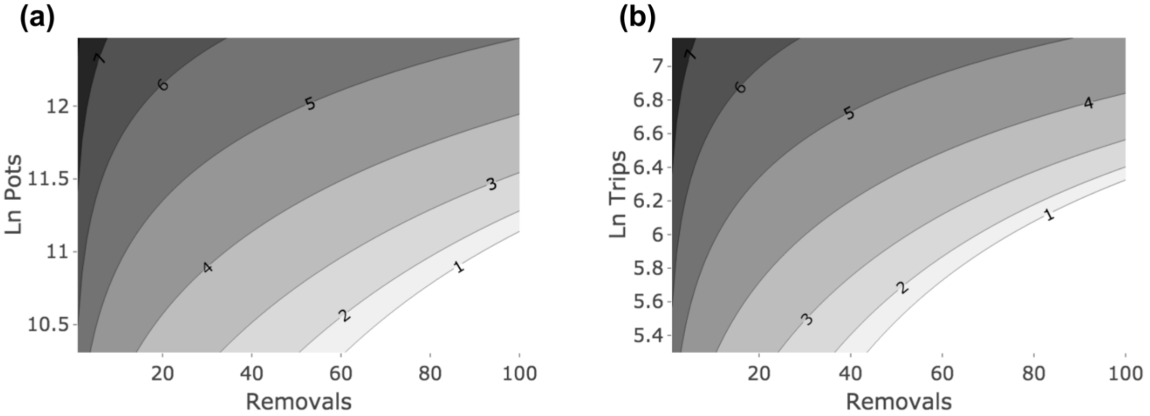

Figure 2. Contour plots depicting marginal benefits from derelict pot removals for models using pots (a) and trips (b) as measures of fishing effort. Marginal benefits correspond to the increase in the natural log of harvest from the removal of one derelict pot (i.e., $\partial ln(H_{it})/\partial R_{it}$). Marginal benefit levels are indicated on contour lines and plots display values across the interquartile range of observed location-specific fishing effort.

Marginal benefits of derelict pot removals were found to be non-linear and depend on the level of fishing effort (Figure 2). Initial derelict pot removals generated the largest increases in harvests. For example, the first pot removed from an area experiencing 2009-2018 median levels of fishing effort and harvests was predicted to yield 943.66 lb (95% CI: [500.86, 1387.88]) of additional harvest over the course of a season in the pots model and 832.09 lb (95% CI: [346.68, 1319.20]) of additional harvest in the trips model. These levels of increased harvest, though large in aggregate, corresponded to just an additional 0.01 lb per pot pull and 1.46 lb per trip for pots fished and trips taken in the location with the removal on average, respectively. The marginal benefits from additional removals declined quickly, with estimates of annual harvest gains of 137.61 lb (95% CI: [59.71, 215.55]; pots model) and 116.66 lb (95% CI: [26.76, 206.62]; trips model) for the 20th derelict pot removed from an area with 2009-2018 median effort and harvest levels. The predicted marginal benefits of removals were also found to differ considerably across fishing locations depending on fishing effort levels, with removals from high-effort areas found to be considerably more beneficial. For example, marginal benefits associated with the 10th derelict pot removed from a fishing location in the 25th percentile of effort and harvest were estimated to be 85.63 lb (95% CI: [35.40, 135.90]; pots model) and 68.53 lb (95% CI: [8.97, 128.15]; trips model). Whereas for a fishing location in the 75th percentile of effort and harvest, these benefits were estimated at 1,035.03 lb (95% CI: [559.85, 1510.64]; pots model) and 917.01 lb (95% CI: [399.10, 1435.42]; trips model).

Estimation of marginal benefit curves for derelict pot removals allows consideration of removal policies that maximize net benefits. If it is assumed that the cost to remove a derelict pot is fixed at \$100/pot, and that additional blue crab can be sold for \$1/lb, the optimal level of removals can be determined as a function of location-specific fishing effort. For fishing locations in the 25th, 50th, and 75th percentiles of effort and harvests, the optimal removal policies, where marginal benefits equal marginal costs, are estimated at 8, 28, and 145 (pots model) and 6, 23, and 133 (trips model) derelict pots removed annually. Under average levels of fishing effort and harvest experienced for each fishing location from 2009-2018, it is estimated that the removal of 7,749 (pots model) and 9,535 (trips model) derelict pots annually would maximize net benefits, i.e., this is the level of removals where marginal benefits are equal to (or slightly greater than) marginal costs for each fishing location. Removals at these levels are predicted to produce annual net benefits of $\$3.19\text{x}10^6$ (95% CI: [$2.38\text{x}10^6$, $4.16\text{x}10^6$]; pots model) and $\$3.33\text{x}10^6$ (95% CI: [$2.08\text{x}10^6$, $5.35\text{x}10^6$]; trips model). If optimal derelict pot removal programs were implemented, average productivity of fishing effort is estimated to increase by 16.83% (pots model) and 18.20% (trips model).

4. Discussion

This analysis investigated the effects of derelict pot removals on harvests in the commercial blue crab fishery of Virginia. It was found that fishing locations that experienced some level of removals during a large six-year removal program saw substantial increases in productivity during years of removals (22.35% increase in harvest per pot and 34.68% increase in harvest per trip, on average). The marginal harvest benefits associated with derelict pot removals were found to decline quickly as removals increased, were larger in high-effort fishing areas, and lasted for only a single fishing season. Assuming a removal cost of $100/pot, and that additional blue crab could be sold for $1/lb, the optimal level of removals was estimated to be over 7,000 pots/year. With aggregate fishing effort of ~230,000 pots and annual loss rates ranging from 10-20% (Bilkovic et al. 2016; DelBene 2020), this analysis suggests removing ~15-40% of the gear lost annually would produce net benefits for the commercial fishery of US ~$3M each year. While prior cost-benefit analyses of derelict gear removals have typically considered the market value of bycatch as the primary or singular benefit arising from removals (e.g., Gilardi et al. 2010; Antonelis et al. 2011), this study demonstrates that removal of derelict blue crab pots can substantially improve harvest rates and gear efficiency—benefits that may rival or exceed those arising strictly from reductions in bycatch mortality.

The findings presented here support conclusions from earlier investigations and add to a growing body of evidence documenting the harmful effects of derelict fishing gear, including economic costs related to reduced gear efficiency. Scheld et al. (2016) estimate the six-year derelict pot removal program in Virginia increased harvests by 27%, while DelBene et al. (2019), using an experimental approach, demonstrate the presence of derelict pots can reduce harvests of blue crab in actively fished pots by more than 30%. These estimates are similar to the increases in average harvest per pot and harvest per trip for areas with removals during the removal program found in this analysis. The optimal level of removals estimated here is predicted to increase productivity by ~17-18% per year, an amount somewhat lower than observed impacts of the 2009-2014 removal program. This finding suggests that some removals may have occurred at levels, or in locations, where marginal removal costs exceeded benefits, and that program net benefits could have been greater with a more targeted approach. Results of this research add to prior investigations finding that the presence of derelict pots can significantly reduce harvest rates and impose large economic costs on the blue crab fishery of Virginia. Similar analyses are lacking in other fisheries and coastal systems however, limiting the ability to more broadly characterize commercial harvest impacts resulting from derelict gear.

Determining causal responses in non-experimental data can be challenging. This analysis used statistical models that controlled for a variety of factors and exploited variation in derelict gear removals over space and time to identify program effects and estimate marginal benefits. Relatively fine-scale spatial resolution of fishery harvest and effort data paired with georeferenced derelict pot removals facilitated this investigation and suggest a similar approach may be feasible in other systems with well resolved spatial data. DelBene et al. (2019) observed the effects of derelict pots on harvest rates were not constant over time, and it was speculated that the gear competition effect may depend on the seasonal migratory or mating behavior of blue crabs. This analysis utilized annual harvest and effort data and was therefore not able to resolve seasonal differences in harvest rates resulting from derelict pot removals. Future research should explore both the mechanisms and magnitudes of interactions between derelict and actively fished gear across a variety of fixed gear fisheries to better understand this harmful and costly externality.

This investigation is the first to assess marginal removal benefits and optimal derelict pot removal policies. In determining optimal derelict pot removal levels, the marginal costs of removals were assumed to be \$100/pot. Costs associated with removals depend on pot location and condition (e.g., depth, substrate, buoyed/unbuoyed), removal method (e.g., grappling gear, diver), as well as potential disposal or recycling costs. During the six-year derelict pot removal program in Virginia, removal costs averaged \$122/pot. Total program costs included overhead and fixed costs associated program implementation (e.g., purchasing side-scan sonar units), suggesting marginal costs for removals on a continuing basis would be somewhat lower. During later years in the program, when removal efforts targeted derelict gear hotspots, average costs reduced considerably to ~\$60/pot. Additionally, cost-efficiency was not considered a central objective of the program, which was initiated to provide supplementary income to commercial fishers following a federally declared fishery failure (Havens et al. 2011). Antonelis et al. (2011) conducted a cost-benefit analysis of trap removal in Washington's Dungeness crab (*Cancer magister*) fishery, where side-scan sonar and divers were required for derelict pot location and removal. In that study, variable costs were found to be \$92.66-\$193.00 per trap removed (Antonelis et al. 2011). In Louisiana's blue crab fishery, removal of buoyed derelict pots has been documented to be under \$20/pot (Arthur et al. 2020). While there is certainly a degree of variation, a reasonable range for marginal removal costs of derelict pots and traps in coastal systems is perhaps \$50-\$150/pot, and potentially much less for easily accessible buoyed gear. For Virginia, this suggests optimal removal levels approximately between the contour lines of 4 and 5 in Figure 2.

There are a number of additional economic damages associated with derelict fishing gear that were not addressed in this research, but which could increase the benefits associated with removals. Habitat damage due to abrasion, smothering, and breakage of habitat features by derelict gear has been observed in several fisheries (Donohue et al. 2001; Macfadyen et al. 2009; Arthur et al. 2014) and may carry significant economic costs. In the Chesapeake Bay, overlap and interaction between derelict pots and sensitive habitats, such as oyster reefs and sea grass beds, is thought to be relatively minor however (Bilkovic et al. 2016). Navigational costs can arise from derelict gear if it forces route changes, causes damage to vessels and equipment, or leads to accidents, injury, or death (Johnson 2000; Cho 2004; Macfadyen et al. 2009). While substantial numbers of derelict pots may accumulate in the many small tributaries of Virginia, navigational issues related to derelict pots have not been well documented. Importantly, this analysis did not consider the benefits arising from reduced mortality of blue crab and other bycatch due to removal of derelict gear. Forty different species have been documented in derelict blue crab pots removed from Virginia waters (Bilkovic et al. 2014). Some species, such as white perch (*Morone americana*) and Atlantic croaker (*Micropogonias undulates*), are commercially and recreationally valuable, while other species, such as diamondback terrapin (*Malaclemys terrapin*), may hold non-use conservation value (e.g., existence value). To the extent that removals reduced mortality of blue crab and other valuable species, our estimates of marginal removal benefits are likely conservative.

5. Conclusions

Open access and common pool environmental resources frequently produce inefficient outcomes (Stavins 2011). The broad extent and important role of externalities in the marine environment is becoming increasingly recognized (Rickels et al. 2016), and marine debris is now generally acknowledged to be an outcome of misaligned incentives and market failure (McIlgorm et al. 2011; Newman et al. 2015; Vince and Hardesty 2018). Accordingly, economic analyses and policy instruments that consider individual incentives have been argued as critical in the reduction and control of marine litter (Oosterhuis et al. 2014).

Derelict fishing gear is a widespread form of marine debris that can be detrimental to both biological resources as well as the human ability to utilize and derive value from coastal and marine amenities. This investigation analyzed the marginal benefits of removals and found that ~7,000 – 10,000 removals/year focused on high fishing effort (“hotspot”) areas would produce over $3M in net benefits for commercial blue crab fishers in Virginia. This level of removals is thought to represent 15-40% of derelict pots lost annually. While our estimates of optimal removal levels may be conservative, as only one economic benefit of removals was considered, it is possible, or perhaps even likely, that it would never be optimal to remove all derelict pots given strong diminishing returns. Nevertheless, international agreements (e.g., Annex V of MARPOL) may obligate monitoring and mitigation of derelict gear where it is a source of plastic pollution beyond what is economically optimal. Though commonly viewed as successful (e.g., Havens et al. 2011, Antonelis et al. 2011; Arthur et al. 2020), removal efforts in coastal areas of the US often rely on inconsistent funding sources or unpaid volunteers. As some level of gear loss is likely unavoidable (e.g., due to storms or vessel traffic), establishing regular sources of funding for location and removal of derelict gear should be expected to yield environmental and economic benefits and may be needed for compliance with international agreements.

Providing monetary incentives to fishers for collection and removal of marine debris has been noted as a potentially low-cost solution supported by the fishing industry, despite failure to promote long-term preventative behavioral change (Cho 2009; Oosterhuis et al. 2014). Alternative management strategies, such as gear recycling programs, use of biodegradable escape mechanisms, or marine spatial planning, have been suggested and may be effective at reducing gear loss and its impacts (Macfadyen et al. 2009; Bilkovic et al. 2016). It is likely that a combination of targeted removals and policies that work to reduce contributing factors and incentivize or promote prevention would be most effective. Identifying long-term policy remedies that are self-sustaining and supported by fishery stakeholders remains challenging however (Goodman et al. 2019; DelBene 2020). Increased quantification of the marginal benefits and costs associated with the reduction of derelict fishing gear and other forms of marine debris can inform socially efficient future management and policy.

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

References

1. Antonelis, K., Huppert, D., Velasquez, D. 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: 880-893. https://doi.org/10.1080/02755947.2011.590113

2. Arellano, M. 1987. Computing robust standard errors for within-groups estimators. Oxford Bulletin of Economics and Statistics 49(4): 431-434. https://doi.org/10.1111/j.1468-0084.1987.mp49004006.x

3. Arthur, C., Sutton-Grier, A.E., Murphy, P. and H. Bamford. 2014. Out of sight but not out of mind: harmful effects of derelict traps in selected US coastal waters. Marine Pollution Bulletin 86 (1-2): 19-28. https://doi.org/10.1016/j.marpolbul.2014.06.050

4. Arthur, C., Friedman, S., Weaver, J., Van Nostrand, D. and J. Reinhardt. 2020. Estimating the benefits of derelict crab trap removal in the Gulf of Mexico. Estuaries and Coasts 43: 1821-1835. https://doi.org/10.1007/s12237-020-00812-2

5. Athey, S. and G.W. Imbens. 2017. The state of applied econometrics: Causality and policy evaluation. Journal of Economic Perspectives 31(2): 3-32. https://doi.org/10.1257/jep.31.2.3

6. Baumol, W.J. and W.E. Oates. 1988. *The Theory of Environmental Policy*. Cambridge University Press, New York.

7. Bilkovic, D.M., Havens, K.J., Stanhope, D.M. 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

8. Bilkovic, D.M., Havens, K.J., Stanhope, D.M. and K.T. Angstadt. 2014. Derelict fishing gear in Chesapeake Bay, Virginia: Spatial patterns and implications for marine fauna. Marine pollution bulletin 80(1-2): 114-123. https://doi.org/10.1016/j.marpolbul.2014.01.034

9. Bilkovic, D.M., Slacum Jr, H.W., Havens, K.J., Zaveta, D., Jeffrey, C.F., Scheld, A.M., Stanhope, D., Angstadt, K. 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. http://doi.org/10.21220/V54K5C

10. Castro, J.J., Santiago, J.A. and A.T. Santana-Ortega. 2002. A general theory on fish aggregation to floating objects: an alternative to the meeting point hypothesis. Reviews in Fish Biology and Fisheries 11(3): 255-277.

11. Chesapeake Bay Stock Assessment Committee (CBSAC). 2019. 2019 Chesapeake Bay Blue Crab Advisory Report. June 24, 2019. Available at: https://www.chesapeakebay.net/documents/CBSAC_2019_Blue_Crab_Advisory_Report_Final.pdf

12. Cho, D.O., 2009. The incentive program for fishermen to collect marine debris in Korea. Marine Pollution Bulletin 58(3): 415-417. https://doi.org/10.1016/j.marpolbul.2008.10.004

13. Christensen, L.R., Jorgenson, D.W. and L.J. Lau. 1973. Transcendental logarithmic production frontiers. The Review of Economics and Statistics 55(1): 28-45. https://doi.org/10.2307/1927992

14. Croissant, Y and G. Millo. 2018. Panel Data Econometrics with R: the plm package. Wiley.

15. DelBene, J.A., Bilkovic, D.M. 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

16. DelBene, J.A. 2020. 'Investigating economic costs of derelict blue crab *Callinectes sapidus* pots and preferred mitigation solutions in the Chesapeake Bay'. MS thesis, Virginia Institute of Marine Science, William & Mary, Gloucester Point, Virginia.

17. Donohue, M.J., Boland, R.C., Sramek, C.M. and G.A. Antonelis. 2001. Derelict fishing gear in the Northwestern Hawaiian Islands: diving surveys and debris removal in 1999 confirm threat to coral reef ecosystems. Marine Pollution Bulletin 42(12): 1301-1312. https://doi.org/10.1016/S0025-326X(01)00139-4

18. Eggleston, D.B., Etherington, L.L. and W.E. Elis. 1998. Organism response to habitat patchiness: species and habitat-dependent recruitment of decapod crustaceans. Journal of Experimental Marine Biology and Ecology 223(1): 111-132. https://doi.org/10.1016/S0022-0981(97)00154-8

19. Gilardi, K.V., Carlson-Bremer, D., June, J.A., Antonelis, K., Broadhurst, G. and T. Cowan. 2010. Marine species mortality in derelict fishing nets in Puget Sound, WA and the cost/benefits of derelict net removal. Marine Pollution Bulletin 60(3): 376-382. https://doi.org/10.1016/j.marpolbul.2009.10.016

20. Gilman, E., Suuronen, P., Hall, M. and S. Kennelly. 2013. Causes and methods to estimate cryptic sources of fishing mortality. Journal of Fish Biology 83(4): 766-803. https://doi.org/10.1111/jfb.12148

21. Goodman, A.J., Brillant, S., Walker, T.R., Bailey, M. 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

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

23. 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 at: http://www.fao.org/3/a-i5051e.pdf

24. Havens, K. J., Bilkovic, D.M., Stanhope, D. M., Angstadt, K. T. 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

25. Havens, K., Bilkovic, D.M., Stanhope, D. and K.T. 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

26. Heck Jr, K. and L.B. Crowder. 1991. Habitat structure and predator—prey interactions in vegetated aquatic systems. In: Bell S.S., McCoy E.D., Mushinsky H.R. (Eds.) Habitat Structure. Population and Community Biology Series, vol 8. Springer, Dordrecht. https://doi.org/10.1007/978-94-011-3076-9_14

27. Hérbert, M., Miron, G., Moriyasu, M., Vienneau, R., and P. DeGrâce. 2001. Efficiency and ghost fishing of snow crab (*Chionoecetes opilio*) traps in the Gulf of St. Lawrence. Fisheries Research 52(3): 143-153. https://doi.org/10.1016/S0165-7836(00)00259-9

28. Jeffrey, C.F.G., Havens, K.J., Slacum, Jr., H.W., Bilkovic, D.M., Zaveta, D., Scheld, A.M., Willard, S., and J.D. Evans. 2016. Assessing ecological and economic effects of derelict fishing gear: A guiding framework. Prepared for Marine Debris Program, Office of Response and Restoration, National Oceanic and Atmospheric Administration. 31p. http://doi.org/10.21220/V50W23

29. Macfadyen, G., Huntington, T. and R. Cappell. 2009. Abandoned, lost or otherwise discarded fishing gear. UNEP Regional Seas Reports and Studies No.185; FAO Fisheries and Aquaculture Technical Paper, No. 523. Rome, UNEP/FAO. 115p.

30. Maselko, J., Bishop, G. and P. Murphy. 2013. Ghost fishing in the Southeast Alaska commercial Dungeness crab fishery. North American Journal of Fisheries Management 33(2): 422-431. https://doi.org/10.1080/02755947.2013.763875

31. Matsuoka, T., Nakashima, T. and N. Nagasawa. 2005. A review of ghost fishing: scientific approaches to evaluation and solutions. Fisheries Science 71(4): 691–702.

32. McIlgorm, A., Campbell, H.F. and M.J. Rule. 2011. The economic cost and control of marine debris damage in the Asia-Pacific region. Ocean & Coastal Management 54(9): 643-651. https://doi.org/10.1016/j.ocecoaman.2011.05.007

33. 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 at: https://www.fisheries.noaa.gov/content/fisheries-economics-united-states- 2016

34. National Research Council. 2008. *Tackling Marine Debris in the 21st Century*. Washington, DC: The National Academies Press.

35. Newman, S., Watkins, E., Farmer, A., Ten Brink, P. and J.P. Schweitzer. 2015. The economics of marine litter. In Bergmann, M., Gutow, L., Klages, M. (Eds.), Marine Anthropogenic Litter. Springer, Berlin. pp. 367-394.

36. Oosterhuis, F., Papyrakis, E. and B. Boteler. 2014. Economic instruments and marine litter control. Ocean & Coastal Management 102: 47-54. https://doi.org/10.1016/j.ocecoaman.2014.08.005

37. Orth, R.J., Heck, K.L. and J. van Montfrans. 1984. Faunal communities in seagrass beds: a review of the influence of plant structure and prey characteristics on predator-prey relationships. Estuaries and Coasts 7(4): 339-350. https://doi.org/10.2307/1351618

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

39. 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 20(6): 1218-1231. https://doi.org/10.1111/faf.12407

40. Rickels, W., Dovern, J. and M. Quaas. 2016. Beyond fisheries: Common-pool resource problems in oceanic resources and services. Global Environmental Change 40: 37-49. https://doi.org/10.1016/j.gloenvcha.2016.06.013

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

42. Stavins, R.N. 2011. The problem of the commons: still unsettled after 100 years. American Economic Review 101(1): 81-108. https://doi.org/10.1257/aer.101.1.81

43. Uhlmann, S.S. and M.K. Broadhurst. 2015. Mitigating unaccounted fishing mortality from gillnets and traps. Fish and Fisheries 16(2): 183-229. https://doi.org/10.1111/faf.12049

44. Uhrin, A.V. 2016. Tropical cyclones, derelict traps, and the future of the Florida Keys commercial spiny lobster fishery. Marine Policy 69: 84-91. https://doi.org/10.1016/j.marpol.2016.04.009

45. UNEP. 2005. Marine litter: an analytical overview. United Nations Environment Programme, Kenya, p. 47.

46. UN General Assembly resolution 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*, A/RES/59/25 (17 November 2004), available from undocs.org/A/RES/59/25.

47. Vince, J. and B.D. Hardesty. 2018. Governance solutions to the tragedy of the commons that marine plastics have become. Frontiers in Marine Science 5: 214. https://doi.org/10.3389/fmars.2018.00214

48. Walsh, W.J. 1985. Reef fish community dynamics on small artificial reefs: the influence of isolation, habitat structure, and biogeography. Bulletin of Marine Science 36(2): 357-376.

49. White, H. 1980. A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. Econometrica 48(4): 817-838. https://doi.org/10.2307/1912934

Appendix

	Effort : Pots			Effort : Trips		
Variable	Coefficient		SE	Coefficient		SE
β_1	0.3258	**	0.1209	116.0835	**	38.7349
β_2	0.3933	***	0.0719	99.8421	***	22.2363
	$R^2 = 0.07$			$R^2 = 0.11$		
	F-statistic = 16.80***			F-statistic = 14.34***		

Table A1. Equation 1 regression outputs. The unbalanced panel regression included 1,480 observations from 72 fishing locations and 25 years. Coefficient standard errors were calculated using a robust covariance matrix following the approach of White (1980) and Arellano (1987). Statistical significance denoted as *, **, and *** corresponding to significance at the 5, 1, and 0.1% levels, respectively.