Estuaries and Coasts (2020) 43:1821–1835
https://doi.org/10.1007/s12237-020-00812-2

SPECIAL SECTION: RESTORATION BENEFITS IN GULF OF MEXICO

Estimating the Benefits of Derelict Crab Trap Removal in the Gulf of Mexico

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Received: 29 November 2019 / Revised: 21 July 2020 / Accepted: 29 July 2020 / Published online: 6 August 2020

Abstract

Ghost fishing in derelict blue crab traps is ubiquitous and causes incidental mortality which can be reduced by trap removal programs. In an effort to scale the benefits of such removal programs, in the context of restoring the Gulf of Mexico after the Deepwater Horizon oil spill, this paper calculates the ecological benefits of trap removal by estimating the extent of derelict blue crab traps across Gulf of Mexico waterbodies and combining these estimates with Gulf-specific crab and finfish mortality rates due to ghost fishing. The highest numbers and densities of traps are found in Louisiana, with estimates ranging up to 203,000 derelict traps across the state and up to 41 traps per square kilometer in areas such as Terrebonne Bay. Mortality rates are estimated at 26 crabs per trap per year and 8 fish per trap per year. The results of this analysis indicate a Gulf-wide removal program targeting 10% of derelict traps over the course of 5 years would lead to a combined benefit of more than 691,000 kg of crabs and fish prevented from mortality in ghost fishing traps. These results emphasize the importance of ongoing derelict trap removal programs. Future work could assess additional benefits of trap removal programs, such as fewer entanglements of marine organisms, improved esthetics, and increases in harvestable catch. Lastly, this model could be utilized by fishery managers to calculate the benefits of other management options designed to decrease the extent and impact of derelict fishing gear.

Keywords Marine debris · Crab traps · Ghost fishing · Ecological restoration

Introduction

Marine debris, defined as "any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned in the marine environment or Great Lakes" (33U.S.C. 1951 et seq., as amended), is widespread in marine and coastal environments. The effects of marine debris on wildlife have been documented for decades (CBD 2012). For example, organisms become trapped or entangled in derelict fishing gear or ingest smaller debris fragments and particles, resulting in reduced health and mortality (e.g., Chiappone et al. 2002; MacFadyen et al. 2009; Wilcox et al. 2016). Furthermore, marine debris can scar seagrass habitats and coral reefs, entangle boat engines and fishing gear, and impact beach esthetics (National Oceanic and Atmospheric Administration (NOAA) 2008). Restoration projects that remove marine debris, derelict fishing gear in particular, reduce incidental mortality in gear and restore coastal habitats.

One of the most persistent and damaging types of marine debris is derelict fishing gear because it physically impacts habitats, entangles larger organisms, and continues to catch fish and invertebrates in a process known as "ghost fishing" (Butler and Matthews 2015; MacFadyen et al. 2009; Scheld et al. 2016). Gear that is capable of ghost fishing may capture target and non-target species and be a cause of mortality to those species, because, once lost, the gear is no longer retrieved regularly by fishers. Derelict fishing gear includes gill nets, trawl nets, long lines, and traps. Trap fisheries are

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Communicated by Mark S. Peterson

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12237-020-00812-2) contains supplementary material, which is available to authorized users.

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especially susceptible to gear loss because they span large areas, require high densities of gear to remain productive, and are not continuously monitored (Breen 1990). Causes of trap loss include storms, currents, siltation, deterioration, vandalism, abandonment, and buoy lines severed by vessels in transit (Clark et al. 2012; Guillory et al. 2001b; Lewis et al. 2009; Shively 1997; Uhrin and Fonseca 2005). For example, success in blue crab (*Callinectes sapidus*) fisheries depends on fishers deploying a high number of traps over a large area and continuously replacing lost traps, creating the potential for high densities of derelict traps. Trap loss rates are difficult to estimate (personal communication, LA Sea Grant), in part because many traps are unmarked and fishers infrequently report the number of traps fished as well as trap losses. Abandoned traps are hypothesized to be a source of derelict traps due to temporary fishers leaving the fishery (Guillory et al. 2001b). Preliminary estimates of annual trap loss rates range from 20 to 100% of the total traps fished (GSMFC 2015). The high estimate of 100% is considered a result of intentional abandonment by fishers in advance of major storm systems or to avoid paying disposal fees (Guillory et al. 2001b).

In addition to being susceptible to loss, traps are designed to withstand harsh conditions for extended periods of time and thus continue to capture and kill fish and invertebrates (Arthur et al. 2014; Butler and Matthews 2015; MacFadyen et al. 2009). Blue crab traps, such as those used in the Gulf of Mexico and Chesapeake Bay, are made of galvanized metal or vinyl-coated wire, which is more effective at withstanding the corrosive nature of high salinity environments (Carr and Harris 1997; Guillory et al. 2001a). The degradation time of abandoned traps is estimated to be greater than 2 years (Giordano et al. 2010; Guillory et al. 2001b; Shively 1997; Stanhope et al. 2011). As such, derelict traps may continue to ghost fish for more than 1 year after loss or abandonment, and in Louisiana, the life expectancy has been estimated at 3 years (LDFW and LA Sea Grant, personal communication; Shively 1997; Voss et al. 2011).

The prevalence of ghost fishing and damage to benthic habitats, together with high rates of trap loss and longevity of trap function, leads to a perfect storm that makes derelict fishing traps one of the most damaging types of marine debris. Derelict traps can continue to catch and kill biota, even after the bait has disintegrated or been eaten, and may be a significant source of unaccounted blue crab and finfish mortality (Arthur et al. 2014; Guillory et al. 2001b). However, the impacts of derelict fishing traps can be prevented through robust programs to find and remove them from impacted waterbodies. Trap removal programs are a promising ecological restoration approach with a suite of benefits, such as reduction of the number of fish and invertebrates killed annually due to ghost fishing, reduction of entanglement hazards for wildlife and boaters, increased esthetics, reduction of habitat impacts such as smothering seagrasses or coral reefs, and potentially increases harvestable catch (see, e.g., Arthur et al. 2014; Scheld et al. 2016; Matthews and Uhrin 2009).

Estuarine crabs and fishes injured due to the Deepwater Horizon oil spill may benefit from restoration projects that remove derelict traps in the Gulf of Mexico, and funding for removal programs may be available as part of ongoing restoration efforts (DOJ 2016; Trustees 2016). Here, we build upon published data, state-based fishery surveys, and natural resource management approaches to quantify the benefits of removing derelict blue crab traps in the Gulf of Mexico. We utilize the concepts of resource equivalency analysis (REA), a scaling method often employed in natural resource damage assessment that uses biological metrics as the unit of measure (e.g., number of organisms or lost biomass). As Baker et al. (2020) describe, through REA natural resource injuries and the estimated restoration benefits needed to replace what was lost are easily replicated through use of transparent parameters and a stepwise replacement model. Here, the model parameters estimate the restoration benefit of a derelict trap removal project. We report restoration benefits in units of crab and finfish biomass not killed due to ghost fishing per waterbody per year, in order to allow resource managers to compare proposed removal efforts in a common currency.

Methods

The analysis presented in this paper estimates the avoided mortality expected from the removal of derelict fishing traps (i.e., the biomass of fish and invertebrates not killed in traps that are removed), based on the number of derelict traps per waterbody, the mortality rate per derelict trap, and the scale of the removal program. In addition, the analysis accounts for the gain in the number of organisms in the previous year (i.e., it is assumed that benefits accrue for 2 years, or the assumed duration over which traps may continue to ghost fish, except in Texas and Florida due to regulations for biodegradable components), the percent of traps that are ghost fishing, and the average crab and fish biomass. The derivation of each of these analytical parameters is described in the following sections.

Derelict Traps per Waterbody

The number of derelict crab traps in the fishery is a function of the number of traps deployed each year and the rate at which traps are lost. The number of traps deployed each year is dependent on the number of commercial and recreational fishers and their effort.

This analysis relied on state licensure data, estimates of inactive licenses (i.e., “latent” licenses), and state-specific regulatory limits on the number of traps allowed per license to estimate the number of commercial fishers and the corresponding number of traps in each state. The number of commercial licenses was obtained from Texas, Louisiana, Mississippi, and Alabama for years 2002–2013 and from Florida for years 2009–2013. As reported in the Louisiana blue crab fishery management plan, the number of license holders that report landings is approximately half of the total number of license holders (Bourgeois et al. 2014). To the best of our knowledge, estimates of the magnitude of underreported landings in the GoM for the blue crab fishery are not available. However, in the most recent blue crab stock assessment, VanderKooy (2013) considered the magnitude of underreporting to be small because the bulk of the fishery consists of large-scale entities that would be detected if underreporting occurred, and included a parameter estimating catch measurement error at 5%. Thus, in Louisiana, this analysis adjusted the estimate of commercial fishers to reflect active license holders plus a percentage of total license holders that may fish but do not officially report landings (5%). The assumption of 5% may underestimate the total underreporting for the region. Similar information was presented in the most recent Gulf of Mexico blue crab management plan (GSMFC 2015), and this analysis assumed 50% of license holders in Texas, Mississippi, Alabama, and Florida do not participate in the blue crab fishery each year.

Each type of commercial license is permitted to fish a certain number of blue crab traps (Table 1). In Florida, the average number of traps per license was determined by weighting the number of each license type sold within the state by the number of traps permitted by that license, and then determining a weighted average. Alabama, Mississippi, and Louisiana do not limit the number of traps used by commercial fishers. Therefore, we utilized responses to a survey of commercial fishers in Louisiana, conducted by Louisiana Sea Grant to estimate the number of traps used by Louisiana fishers (personal communication, Dr. J. Anderson Lively, LA Sea Grant). In the absence of survey data or information on the level of fishing effort in Alabama and Mississippi, we applied the average number of traps used per fisher in Louisiana to Alabama and Mississippi. We calculate the number of commercial traps in each state per year by estimating the number of license holders (reduced by 50% to account for latent licenses) then multiplying by the number of traps permitted per license.

$$\text{Commercial Traps}_{\mathrm{C,T}} = \text{License}_{\mathrm{C,T}} \times 0.50 \times \left(\frac{\text{Traps}}{\text{License}_{\mathrm{C}}}\right)$$

C = commercial blue crab fishery per state; T = year

The recreational fishing sector is also a source of derelict traps. However, the level of information that states collect on the number of recreational blue crab traps is uneven (VanderKooy 2013). Recreational licensure data for Louisiana and Mississippi were obtained from state fishery managers for years 2002–2013 and are used in this analysis. According to state regulations, each recreational license holder is permitted 10 traps in Louisiana and 6 traps in Mississippi. Recreational traps were estimated by multiplying the number of recreational blue crab fishing licenses by the number of traps permitted per license in Louisiana and Mississippi.

$$\text{Recreational Traps}_{\mathrm{R,T}}\ (\text{LA, MS}) = \left(\text{License}_{\mathrm{R,T}}\right) \times \left(\frac{\text{Traps}}{\text{License}_{\mathrm{R}}}\right)$$

R = recreational blue crab fishery per state; T = year

Recreational license data were not available from Texas, Alabama, and Florida. Based on the most recent blue crab stock assessment in the GoM, the recreational effort in Texas, Alabama, and Florida was assumed to be 5% of commercial effort (e.g., recreational traps are estimated as 5% of commercial traps in Texas, Alabama, and Florida; VanderKooy 2013).

$$\text{Recreational Traps}_{\mathrm{R,T}}\ (\text{FL, AL, TX}) = (5\%) \times \left(\text{Traps}_{\mathrm{C,T}}\right)$$

R = recreational blue crab fishery per state; T = year; C = commercial blue crab fishery per state

Commercial and recreational traps were summed per state per year. Parameters are summarized in Table 1. The spatial distribution of derelict traps is calculated as a number of derelict traps per waterbody. Juvenile and adult crabs use a wide range of estuarine habitat from freshwater to fully saline conditions and are primarily fished in large shallow and intertidal areas at depths less than 20 m (Anderson 2014). Thus, it was assumed that the majority of each estuarine waterbody, including mud and vegetated benthos, represent potential crab habitat (GSMFC 2015; VanderKooy 2013). Waterbodies were chosen by identifying locations that had reported blue crab landings for multiple years. Landings per waterbody were compared with state-wide landings to develop a proportional fishing effort for each waterbody in each year with available data. Louisiana, Alabama, and Mississippi had sufficient data to interpret landings from 2002 to 2013. Texas had landings data available from 2007 to 2013. Florida had license data available at the waterbody level from 2009 to 2013 and this analysis used those data to estimate a number of blue crab traps used in Florida waterbodies.

$$\text{Effort}_{\mathrm{W,T}} = \left(\text{Landings}_{\mathrm{W,T}}\right) \div \left(\text{Landings}_{\mathrm{S,T}}\right)$$

W = waterbody level, T = year, S = state level

The proportional fishing effort was used to apportion the total number of traps (derived at the state level) to the 28 waterbodies for each year with available data. Data were averaged across years, and the average number of traps per

Table 1 Parameters used to estimate the number of derelict traps in 28 Gulf of Mexico waterbodies

Parameter (units)	Source	Value				
		TX	LA	MS	AL	FL
Commercial licenses[a]	State Agencies	214	2240	203	201	200
Recreational licenses[b]	State Agencies	–	5115	485	–	–
Number of permitted commercial traps[c]	State Legislation	200	No limit	No limit	No limit	Varies by License
Number of permitted recreational traps[b]	State Legislation	6	10	6	5	5
Latency (%)[d]	Literature (GSMFC 2015)	50				
Commercial landings per waterbody (lbs.)	State Agencies	Varies By Waterbody See Supplementary Material				
Rate of trap loss (%)	Literature (Guillory et al. 2001b)	25				
Area of waterbody (km^2)	NODC, Census	Varies See Supplementary Material				

[a] The estimates of commercial licenses are averages using multiple years of available licensure data. In Florida, this includes only the fishing communities reporting landings north of Tampa to the state border with Alabama. In Louisiana, we use the number of licenses reporting sales and add an estimate of the number of non-reporting fishers (5%)

[b] Recreational licensure data were unavailable in Texas, Alabama, and Florida. For those states, we estimate the number of recreational licenses and the number of permitted traps by assuming recreational fishing represents 5% of the commercial fishery, the same approach taken in the recent blue crab stock assessment (Vanderkooy 2013)

[c] The number of traps permitted by a commercial license is regulated in Texas and Florida. In Florida, the limits vary by the type of commercial trap, and we determined a weighted average based type of license and its regulation ($n = 535$). In cases where the state does not impose a limit on the number of traps utilized, we determined an average number of traps reported by commercial fishers in a survey conducted by Louisiana Sea Grant ($n = 369$) and applied this average to LA, MS, and AL waterbodies

[d] Latency, as described here, refers to the number of non-reporting and non-participating fishers. We estimate that 50% commercial licenses are latent, after GSMFC (2015)

waterbody was used in subsequent analyses. In the absence of additional information, this approach inherently assumes that trap efficiency and catchability do not vary across waterbodies, and may underestimate the number of traps used in some waterbodies with smaller landings estimates.

$$\mathrm{Traps}_{\mathrm{W,T}} = \left(\mathrm{Effort}_{\mathrm{W,T}}\right) \times \left(\mathrm{Traps}_{\mathrm{C+R}}\right)$$

$$\mathrm{Annual\ Traps}_{\mathrm{W}} = \frac{\sum\left(\mathrm{Traps}_{\mathrm{W,T}}\right)}{n}$$

W = waterbody level, T = year, C = commercial traps, R = recreational traps, n = number of years

Numbers of derelict traps were estimated by multiplying a trap loss rate, informed by a literature review, by the number of traps per waterbody. Based on information in white papers and published literature, the rate at which blue crab traps are lost was assumed to be 25% of traps used in the fishery (Guillory et al. 2001b). To compare numbers of traps across waterbodies of varying sizes, trap density was calculated using the number of derelict traps per waterbody and the estimated available blue crab habitat (i.e., mud and vegetated benthos) in each waterbody. As a general rule, we assigned waterbodies that spanned multiple states to the state that reported landings for that particular waterbody. To estimate the available blue crab habitat per waterbody, we used ESRI geographical information system (GIS) software to subtract navigation channels from the available habitat (generally, the estuary bounds as delineated by Nelson and U.S. DOC 2015) to account for regulations that prohibit setting traps within navigable waterways.

$$\mathrm{Derelict\ Traps}_{\mathrm{W}} = \frac{\mathrm{Traps}_{\mathrm{W}} \times \mathrm{Loss\ Rate}}{\mathrm{Area}_{\mathrm{W}}}$$

W = waterbody level

This analysis resulted in an estimate of the density of derelict traps (in traps per square kilometer) in each of the 28 waterbodies. The data were imported into GIS to create maps that delineate the extent of each waterbody and the density of derelict traps.

Mortality in Derelict Traps

We estimated the number of organisms (crab and fish) killed per derelict trap per year by reviewing available data from in situ studies of capture and mortality rates in crab traps (e.g., Antonelis et al. 2011; Bilkovic et al. 2014; Bilkovic et al. 2016; Butler and Matthews 2015; Havens et al. 2008). While per-trap estimates of the number of crabs killed were directly available, per-trap estimates of finfish killed were not available. As such, for finfish, we estimated a number per trap killed as a function of an estimated catch rate and an assumed mortality rate.

Crab Mortality

Guillory (1993) reported the number of crabs killed per trap; thus, there is no need to utilize capture rates to estimate the number killed per trap. Our analysis assumed the crab mortality rate from Guillory (1993), 55% (equivalent to 25.8 crabs per trap per year), reflects conditions across the GoM, and used this rate in subsequent analyses for all 28 GoM waterbodies. Mortality rates were converted to biomass by multiplying the number killed by the average weight of a blue crab (VanderKooy 2013; West et al. 2016). Average crab weight was based on the average carapace width of adult crabs in the western Gulf of Mexico (146 mm) and is equivalent to 163 g (VanderKooy 2013; West et al. 2016) (Table 2).

Fish Mortality

Few studies attempt to estimate fish mortality rates in ghostfishing crab traps due to concerns that all estimates underrepresent mortality caused by predation and natural decomposition (e.g., Guillory 1993; Havens et al. 2008). Due to a lack of finfish mortality rates reported in the literature, this analysis used the results of an 18-month in situ study conducted during 2013–2014 by LDWF to estimate a finfish capture rate, then applied professional judgment to estimate a percentage of captured organisms that are killed in derelict traps. LDWF set traps in various regions and allowed them to soak for a specified amount of time (LDWF 2014). The authors returned to the traps at intervals and recorded the number of non-target organisms captured (e.g., estuarine fish), in addition to the species and length of each individual captured in the trap. Data on the number of species captured per unit time and the mean size of each species were sorted by location (e.g., five waterbodies in Louisiana). We then derived a catch per unit effort (CPUE) for each month of the survey by dividing the number of captured organisms by the number of traps utilized in the survey and by the estimated soak time. The average annual CPUE estimate was used as the annual fish capture rate for each waterbody. The mean capture rate derived across Louisiana waterbodies was applied to Texas, Alabama, Mississippi, and Florida in subsequent calculations (Table 2).

Similar to Guillory (1993) and Havens et al. (2008), Butler and Matthews (2015) recorded finfish capture rates and dead finfish but made no attempt to estimate mortality because the time between observations was considered to exceed the time required for a fish carcass to decay or otherwise disappear. Matthews and Donahue (1997) reported a daily mortality rate in spiny lobster traps (0.0009–0.0064 organisms per trap per day) for all organisms, including finfish, but note the estimate did not account for fish that might have decayed or been consumed prior to observation. Based on a literature review of relevant studies, blue crab capture and mortality rates in Timbalier Bay, Louisiana, and the Chesapeake Bay were compared, and a ratio of organisms killed to organisms captured was calculated for both studies (Guillory 1993; Havens et al. 2008). The lower ratio (30%) was applied to the average finfish capture rates in this study to estimate finfish mortality per trap per year.

For each of the five waterbodies in Louisiana, fish biomass was calculated using the number of organisms captured and the mean size of those organisms (e.g., standard length; LDWF 2014). The species-specific lengths were converted to weight through predictable length-weight relationships that were estimated using FishBase, which pulls from the underlying primary literature (Froese and Pauly 2017). For each waterbody, the mean biomass of species captured in traps was calculated as a weighted average using the species weight

Table 2 Parameters used to estimate crab and finfish mortality rates in the Gulf of Mexico

Parameter	Source	Value (units)
Crab mortality rate	Literature (Guillory 1993)	26 (crabs trap^{-1} year^{-1})
Individual crab biomass	Literature (VanderKooy 2013)	163 (g)
Mean finfish capture rate[a]	Derived in this study from data in LDWF 2014	26 (fish trap^{-1} year^{-1})
Proportion of captured finfish killed in traps[b]	Literature (Havens et al. 2008; Antonelis et al. 2011)	30 (%)
Mean finfish biomass[c]	LDWF (unpublished data)	357 (g)

[a] In Louisiana, average annual finfish capture rates (fish captured per trap per year) were estimated for Pontchartrain ($n = 7.4$), Barataria ($n = 34.0$), Terrebonne ($n = 61.6$), Vermillion-Teche ($n = 17.2$), and Sabine ($n = 9.1$) waterbodies. The average capture rate was applied to TX, MS, AL, and FL waterbodies in the absence of data from site-specific bycatch studies

[b] The proportion of captured finfish that are killed in traps has not been directly measured, either in the LDWF study or in the broader literature on this topic. Based on information related to blue crab capture and mortality rates, here we assume that 30% of captured fish are killed, which is likely an underestimate of the quick biological turnover within derelict traps (e.g., Antonelis et al. 2011; Bilkovic et al. 2012, 2016; Havens et al. 2008, 2011)

[c] In Louisiana, average captured finfish biomass was estimated for Pontchartrain (348 g), Barataria (406 g), Terrebonne (369 g), Vermillion-Teche (265 g), and Sabine (380 g). The average biomass was applied to TX, MS, and AL waterbodies. Average biomass, accounting for only species found in Florida, was estimated at 345 g

and the number of that species captured. Therefore, the estimates calculated for each waterbody in Louisiana reflect the frequency of capture of certain species at that location (Table 2). A single weighted average was derived using data from all five waterbodies and was used in benefit calculations for Texas, Alabama, and Mississippi (Table 2). Given the different species distributions expected in Florida, a separate weighted average was derived using only those species expected to naturally occur along the Florida Gulf coast (Table 2).

Benefit Calculations

The benefit calculations combine all parameters to estimate the number and weight of crabs and fish that would not be killed through a derelict crab trap removal program in 28 GoM waterbodies (i.e., the mass of organisms that would be killed in derelict traps if the program did not occur). To reflect the potential scale of a removal program, we reviewed available information and consulted with fisheries managers to determine the percentage of traps that could realistically be removed. This analysis assumed that a removal program would target 10% of the derelict traps in a given waterbody, and of the derelict traps targeted, 30% would be ghost fishing based on the findings of trap removal programs (e.g., Arthur et al. 2014; Giordano et al. 2010; Havens et al. 2008). These assumptions were based on values in the peer-reviewed literature, conversations with fishery managers, and professional judgment (e.g., Havens et al. 2011; personal communication, LA Sea Grant). Due to the number of analytical assumptions that are based on point estimates (e.g., the targeted percent of derelict traps removed per waterbody) as opposed to data collected or modeled with an underlying distribution, we report our findings as point estimates and then review the analytical parameters.

Results

Based on this analysis, a total of 223,000 derelict traps are lost annually across all waterbodies in the Gulf of Mexico (Table 3). Notably, Terrebonne Bay and Lake Pontchartrain account for 51,000 and 49,000 traps, respectively. Derelict trap density ranges across the GoM from fewer than one to 41 derelict traps per square kilometer and is highest in Louisiana's Terrebonne and Barataria Bays (Table 3).

In addition, the analysis yields a number and biomass of crabs and fish gained for each year of the removal program, in each of the 28 waterbodies (Table 4). Maps depicting the benefits of derelict trap removal programs are presented for waterbodies in Texas (Fig. 1), Louisiana (Fig. 2), Mississippi and Alabama (Fig. 3), and Florida (Fig. 4). A removal program targeting 10% of the derelict traps generated each year in the GoM would result in more than 78,000 kg of crabs and finfish not killed. On a waterbody scale, the benefits of a 1-year project targeting 10% of derelict traps ranges from 9 to 10,700 kg of crab and 6 to 17,500 kg of fish (Table 4). The minimum benefits for both crabs and fish are derived in Lower Laguna Madre, Texas, and maximum benefits are derived in Terrebonne Bay, Louisiana. The benefits of a 5-year removal program (Table 5) account for additional benefits in the second year for Alabama, Mississippi, and Louisiana (i.e., in states that do not require a degradable component), due to the assumption that ghost fishing occurs over the course of 2 years before a trap degrades, and follow the same geographical trends of a 1-year project. A 5-year program results in a benefit of 391,000 kg of crab and 300,000 kg of finfish not killed due to ghost fishing, for a combined benefit of 691,000 kg across the GoM (Table 5).

Discussion

This analysis combined site-specific fisheries data with a trap loss rate to estimate the number of derelict traps that are added annually to the Gulf of Mexico. This allowed an estimation of the likely geographic distribution of derelict crab traps and development of a resource equivalency analysis model to quantify the benefits of a removal program for blue crabs and finfish. By varying the inputs related to the scale of the program, the proposed analysis can be used by natural resource managers to quantify the avoided mortality of crabs and fish and focus restoration efforts on the most effective locations. Such a derelict blue crab trap removal program could replace crabs and fish that were injured as a result of the Deepwater Horizon oil spill as part of a suite of projects to restore fish and water column invertebrates (Trustees 2016).

Review of Analytical Parameters

The parameters that drive this analysis of the benefits of trap removal programs are the number of licenses, latency, the number of traps used, the rate of trap loss, and mortality rates in derelict traps. The trap estimates calculated in this paper are based on more than 10 years of fisheries licensure data and are robust to fluctuations over time. Fifty percent of license holders were estimated to be latent, which may underestimate the number of active blue crab fishers in the GoM but accounts for the fact that not all commercial license holders are full-time fishers.

The best available information was used to estimate the number of traps used by commercial fishers in Louisiana, Alabama, and Mississippi. These states do not limit the number of traps for commercial fishers and thus this analysis uses responses to a fisher survey conducted in Louisiana to determine an average number of traps. Personal communications

Table 3 The number of traps used in the fishery, by waterbody, compared with the estimated derelict traps

State	Waterbody	Traps in fishery	Derelict traps
AL	Bon Secour Bay/Little Lagoon, Perdido System	2152	538
	Mississippi Sound-Mobile	7846	1961
	Mobile Bay	23,815	5954
FL	Choctawhatchee Bay	3539	885
	Pensacola Bay/East Bay/Escambia Bay	5618	1404
	Perdido Bay	449	112
	St. Andrew Bay/West Bay/North Bay	5618	1404
	St. Joseph Bay	955	239
	St. Josephs Sound	3202	800
	St. Vincent Sound/Apalachicola Bay/East Bay/St George Sound	18,032	4508
	Tampa Bay	18,706	4677
LA	Atchafalaya, Vermillion, Teche Rivers	131,908	32,977
	Barataria Bay	135,279	33,820
	Calcasieu, Sabine, Mermentau Rivers	48,234	12,058
	Lake Pontchartrain	194,508	48,627
	Mississippi River	37,136	9284
	Terrebonne Bay	205,058	51,265
MS	Hancock Co.	5917	1479
	Harrison Co.	3134	784
	Jackson Co.	9585	2396
	Lake Borgne	3209	802
TX	Aransas Bay/Copano Bay	5087	1272
	Corpus Christi Bay/Nueces Bay	458	115
	Galveston Bay/Trinity Bay	9277	2319
	Lower Laguna Madre	294	73
	Matagorda Bay/Lavaca Bay	2744	686
	Sabine Lake	4450	1113
	San Antonio Bay	4833	1208
Gulf of Mexico (combined)		891,042	222,761

with fishery managers and stakeholders indicate that the number of traps used by fishers may shift over time and with personal preferences. For example, in Louisiana, some fishers may use 800 to 1000 traps, while others use 200 to 300. Further, determining location-specific estimates of fishing effort is challenging due to privacy laws, and so additional sources of data that could delineate fishing effort at a more refined spatial scale are not obtainable. Thus, the average number of traps used in this analysis may overestimate or underestimate fishing effort in some waterbodies.

The trap loss rate, set at 25%, may overestimate lost traps in recreational fisheries and underestimate traps lost in commercial fisheries. For example, it could be easier for recreational fishers to find and retrieve traps set close to shore or a pier, although it may also be more convenient to retrieve only the traps that are easily accessible and allow the others to become derelict. A wide range of commercial trap loss rates is reported in the literature, and given the many factors that may lead to gear loss, it is likely the rate used in this analysis (25% of actively fished traps) does not overestimate trap loss over time. For example, severe storms may cause up to 100% loss and some years may disproportionately contribute to the overall loss rate (Guillory et al. 2001b).

The capture and mortality rates derived in this analysis are quite similar to those calculated in similar studies. For example, research in the Chesapeake Bay has determined between 18 and 20 crabs killed per trap per year, with a total of 51 crabs captured per trap per year (Arthur et al. 2014; Havens et al. 2008). Similarly, in Puget Sound, research studies calculated mortality and capture rates of 21 and 49 Dungeness crabs per trap per year, respectively (Antonelis et al. 2011). These estimates align well with the crab mortality rate used in this analysis (26 crabs per trap per year; Guillory 1993).

In this analysis, the capture rates of finfish varied by an order of magnitude depending on the location within Louisiana. This indicates that site-specific estimates of ghost

Table 4 Benefits of a 1-year derelict trap removal project

State	Waterbody	Blue crab (kg)	Finfish (kg)	Biomass (kg)	Total biomass (kg)
AL	Bon Secour Bay/Little Lagoon, Perdido System	112	74	186	2927
	Mississippi Sound-Mobile	408	271	679	
	Mobile Bay	1239	823	2061	
FL	Choctawhatchee Bay	110	71	181	2875
	Pensacola Bay/East Bay/Escambia Bay	175	113	288	
	Perdido Bay	14	9	23	
	St. Andrew Bay/West Bay/North Bay	175	113	288	
	St. Joseph Bay	30	19	49	
	St. Josephs Sound	100	64	164	
	St. Vincent Sound/Apalachicola Bay/East Bay/St George Sound	563	361	924	
	Tampa Bay	584	375	958	
LA	Atchafalaya, Vermillion, Teche Rivers	6861	2268	9129	69,663
	Barataria Bay	7037	7003	14,039	
	Calcasieu, Sabine, Mermentau Rivers	2509	605	3114	
	Lake Pontchartrain	10,118	1904	12,021	
	Mississippi River	1932	1283	3214	
	Terrebonne Bay	10,666	17,479	28,145	
MS[a]	Hancock Co.	308	204	512	1891
	Harrison Co.	163	108	271	
	Jackson Co.	499	331	830	
	Lake Borgne	167	111	278	
TX	Aransas Bay/Copano Bay	159	105	264	1410
	Corpus Christi Bay/Nueces Bay	14	9	24	
	Galveston Bay/Trinity Bay	290	192	482	
	Lower Laguna Madre	9	6	15	
	Matagorda Bay/Lavaca Bay	86	57	142	
	Sabine Lake	139	92	231	
	San Antonio Bay	151	100	251	

[a] Although Lake Borgne is located in Louisiana waters, landings were reported only by Mississippi

fishing, conducted in each waterbody, may yield different results than the mean capture and mortality rates derived in Louisiana and transferred to the other states. Few studies have estimated the impact of ghost fishing on non-target fish species. Research in the Chesapeake Bay has shown 13.6 Atlantic croakers are caught per trap per season (Havens et al. 2008), which is comparable with the ghost fishing estimates presented in this paper. Guillory (1993) documented 8.6 fish captured per trap per year, although escapement and mortality were not assessed because of the quick degradation and predation on fish by other organisms within the traps. Thus, the fish capture rates used in this analysis are comparable with other estimates.

Ultimately, this analysis utilizes available datasets that reflect the site-specific ghost fishing impacts in Louisiana, which is the largest market for the blue crab fishery and accounts for almost 80% of blue crab fishing effort (i.e., traps used) as well as 78% of blue crab landings across the GoM (NMFS 2018). Furthermore, this study was designed to utilize conservative estimates for less certain parameters, which may therefore underestimate the ecological benefits of trap removal programs.

Impact of Removal Program

The geographic distribution of derelict traps is an important consideration when building sustainable removal programs. Trap density can be used by state and federal fishery managers as well as conservation organizations to prioritize trap removal efforts in easily accessible locations with higher densities of derelict traps. Implementing a trap removal program in areas with higher trap densities may lead to greater success in removal operations and thus a greater ecological benefit (Scheld et al. 2016). Focusing on areas with high trap densities lends a more efficient cost structure due to decreased time necessary to remove the targeted number of traps. Louisiana accounts for approximately 188,000 derelict traps or 84% of the total derelict traps across the GoM. As the Louisiana blue crab fishery accounts for approximately 78% of the Gulf of Mexico's blue

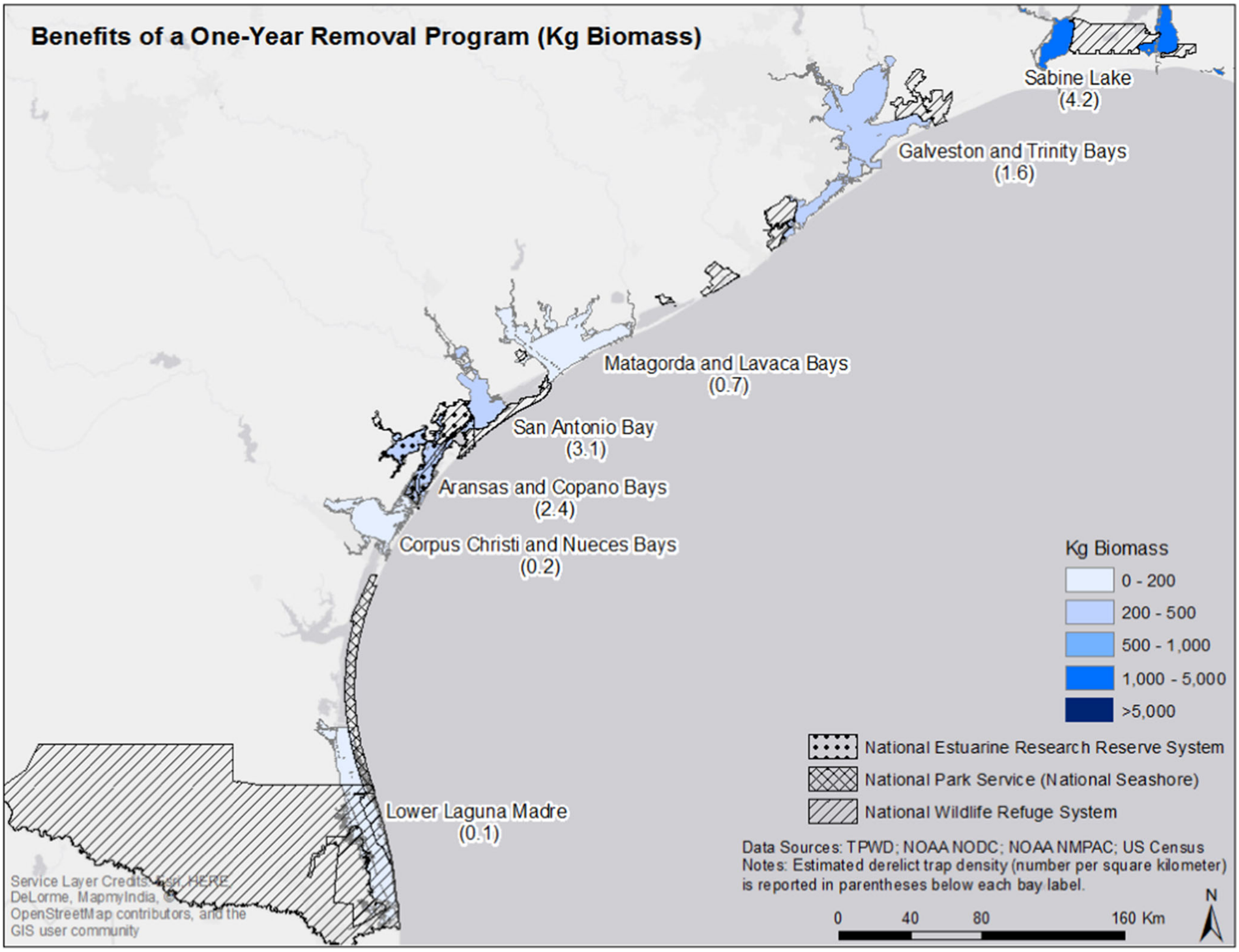

Fig. 1 Estimated benefits (kg biomass) of a trap removal program in Texas (derelict crab trap density in parentheses)

crab landings (e.g., 18.2 of 23.3 million kilograms in 2016), it is not surprising that the majority of effort in the GoM blue crab fishery is distributed across Louisiana or that derelict traps are concentrated there (NMFS 2018; NOAA 2014). Blue crab landings revenue across the Gulf of Mexico increased from approximately $46 million in 2007 to $64 million in 2016, though landings decreased during that time period from 57.9 to 51.3 million pounds (NMFS 2018). The decrease in landings may explain the increase in price per pound over time and indicate that fishers could be increasing fishing effort to meet demand, which could lead to an increase in derelict fishing traps over time.

The localized trap densities calculated in this paper indicate a need for ongoing removal programs, particularly focused in Louisiana waterbodies. Through LDWF, Louisiana runs an annual derelict crab trap removal program that utilizes volunteer support to find and retrieve gear during annual crab fishery closures. In 2018, volunteers removed 4061 traps over 68 boat days, which is a significant investment but does not approach the 10% figure used in this paper to scale the derelict trap removal program (i.e., more than 18,000 traps per year). Funding for the LDWF program is provided in part by the sale of crab fishing licenses, though further information on costs is not provided to the public. The Lake Pontchartrain Basin Foundation, a nonprofit that implements crab trap removal projects in Louisiana, estimates a cost of between $9 and $18 per trap removed, focusing on traps that are visible (i.e., traps left in the water during the closed season, with an attached float). Based on knowledge of local removal efforts, the Foundation estimates the Louisiana coastal zone may have up to 133,000 visible derelict traps and more that are not visible from the surface, which reinforces our estimate of more than 188,000 derelict traps across Louisiana (Butcher et al. 2019).

Other derelict trap removal programs have been effectively implemented at scale, such as the $4.2 million program conducted over 6 years that removed more than 34,000 traps from the Chesapeake Bay and led to an increase in harvestable catch valued at more than $20 million (Scheld et al. 2016). More site-specific information is needed to assess program

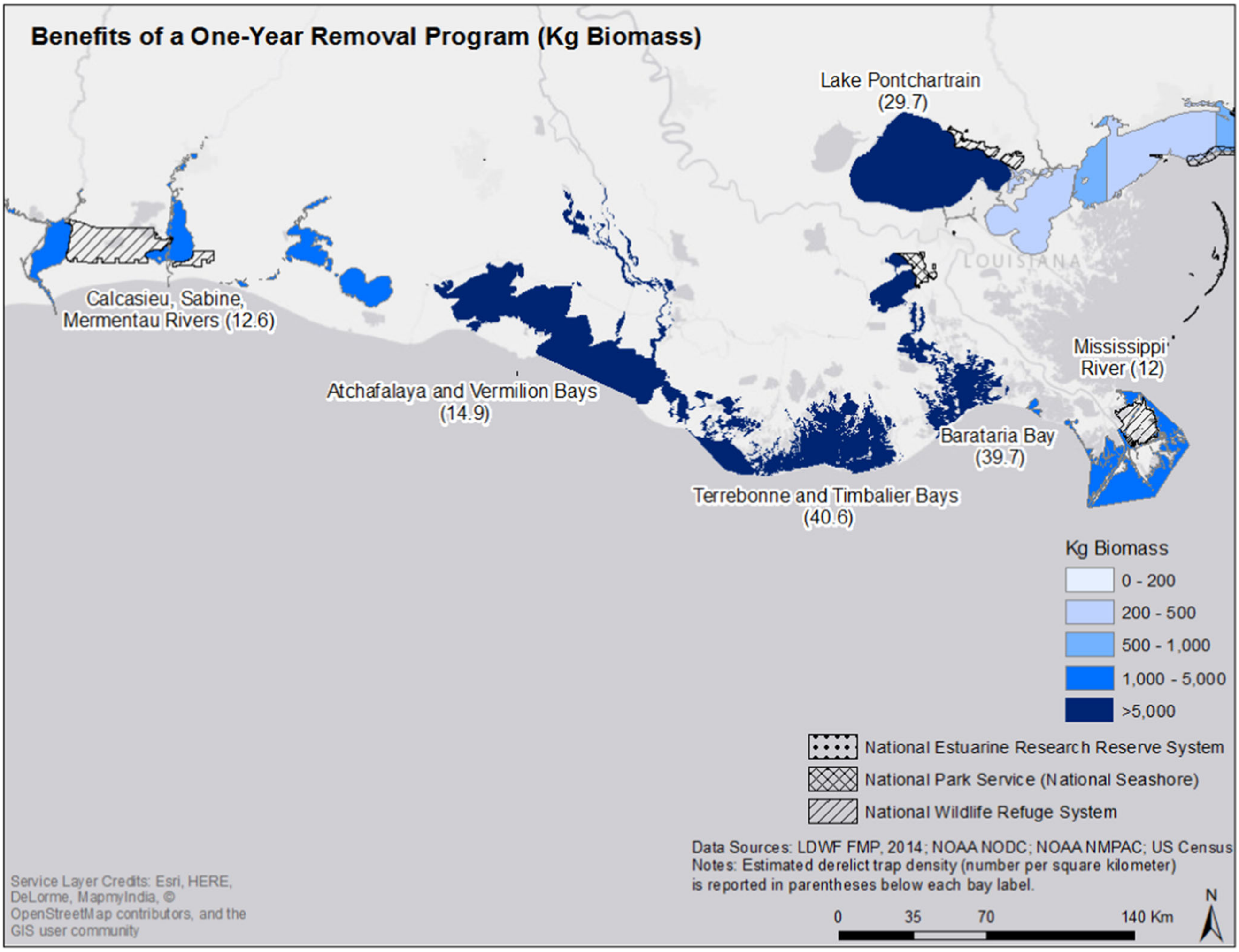

Fig. 2 Estimated benefits (kg biomass) of a trap removal program in Louisiana (derelict crab trap density in parentheses)

costs in the Gulf of Mexico, as well as the potential impact on harvestable catch. Based on this analysis, the benefit of a 5-year removal program in Louisiana translates to more than 352,000 kg of blue crab not killed in derelict traps; if all crabs were harvestable, this biomass would be valued at more than $978,000 in 2016 prices. We provide this information for context, as benefit cost analysis was not a stated goal of this study and our model does not estimate the impact on the value of harvestable catch.

Future Work to Address Derelict Fishing Traps

This analysis provides quantitative information about the value of derelict trap removal programs, and could easily act as a springboard for developing a benefit cost model that targets a specific program size and location in the Gulf of Mexico, as well as calculating the benefits of removal programs targeting other trap fisheries, the ancillary benefits of blue crab trap removal programs, and the benefits of potential management measures to reduce the number and impact of derelict traps in the Gulf of Mexico.

The blue crab fishery is ubiquitous across the GoM and touches dozens of communities that depend on fisheries as a way of life. The landings data utilized in this analysis closely match a recent evaluation of fishing communities. The NOAA Fisheries Southeast Regional Office published an online tool of key indicators of fishing communities, including demographics and dependence on fisheries (NOAA SERO 2017). Blue crab landings were common throughout all major fishing communities designated by NOAA. The blue crab fishery is especially clustered in fishing communities in Louisiana, such as Terrebonne and Barataria Bays, which have a high density of derelict traps. In addition to the blue crab fishery, traps are allowable gear for commercial and recreational fishing in smaller-scale fisheries across the GoM, including the stone crab (*Menippe mercenaria* and *M. adina*), golden crab (*Geryon fenneri*), spiny lobster (*Panulirus argus*), and octopus (e.g., *Octopus vulgaris*) fisheries (GMFMC 2010). This analysis provides a model framework that could be applied to

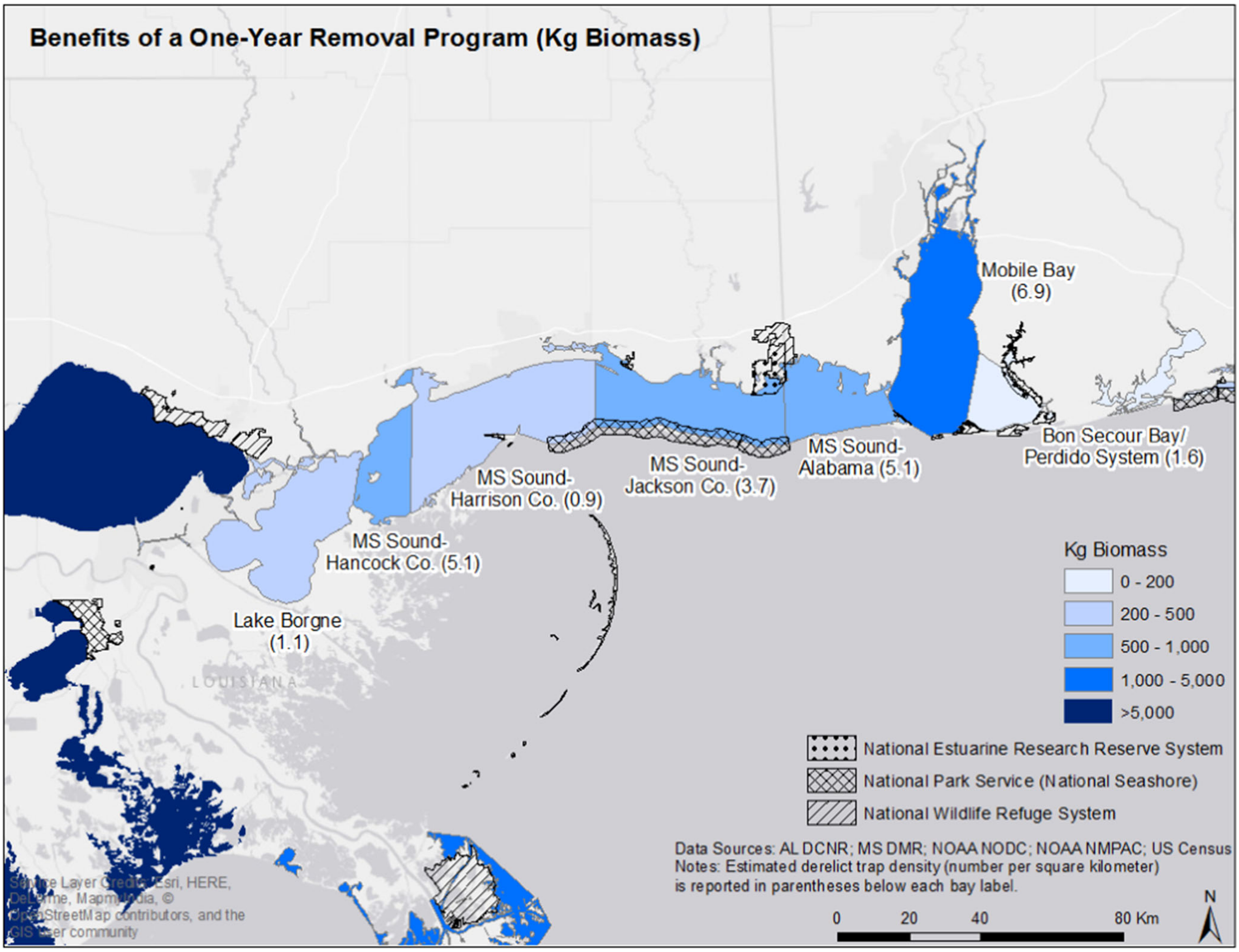

Fig. 3 Estimated benefits (kg biomass) of a trap removal program in Mississippi and Alabama (derelict crab trap density in parentheses)

other trap fisheries in the GoM to determine the benefits of additional trap removal programs.

Much of the peer-reviewed and gray literature has focused on method development for finding and retrieving traps as well as determining the density of traps in coastal areas across the USA, as opposed to quantifying the ecological benefits afforded by habitat restoration through derelict trap removal programs (e.g., Morison and Murphy 2009; Havens et al. 2008; Maselko et al. 2013; Voss et al. 2011). Studies have published the species captured in traps, usually determined as part of intermittent volunteer-based trap removal efforts. Studies of volunteer trap removal efforts (Anderson and Alford 2014; personal communication, Dr. J. Anderson Lively, LA Sea Grant) provide information on the ecological losses associated with ghost fishing in derelict traps. However, it is not possible to determine realistic catch or mortality rates solely from data collected during trap removal programs. The LDWF study is one of the most comprehensive ghost fishing assessments available, though it is important to note that the ghost fishing estimates are reflective of a single point in time when the traps were removed and the ghost fishing was assessed (LDWF 2014). Without underwater observation of the traps, accurate estimates of both capture and mortality of bycatch are elusive and a derived ghost-fishing rate will not fully represent mortality due to the quick turnover of organism remains in traps through degradation and consumption by other captured individuals (see, e.g., Guillory 1993). While this paper relies on the best available information to derive the benefits of removal programs, there is a scarcity of in situ measurements to corroborate the assumptions across the GoM. For example, restoration-focused studies could further investigate the role of location, ghost fishing duration, mortality rates for bycatch species, and how environmental factors affect trap functionality.

Traps lost or abandoned in one location may be transported across state boundaries and reach inshore and offshore habitats far from the initial point of loss. More information from field surveys is needed to create probability distributions for derelict gear aggregations across the GoM. Future in situ studies could investigate the range of physical and chemical

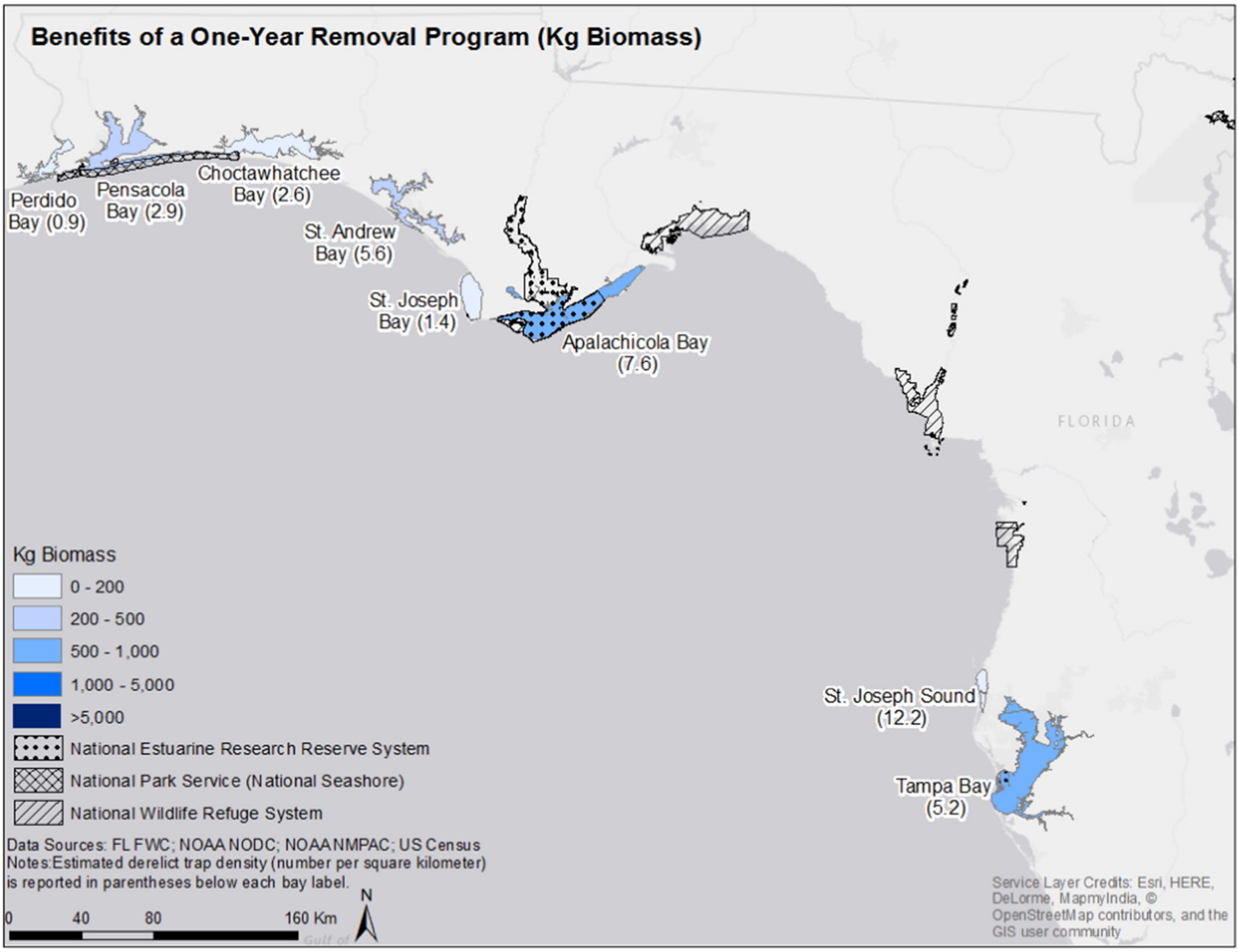

Fig. 4 Estimated benefits (kg biomass) of a trap removal program on the west coast of Florida (derelict crab trap density in parentheses)

oceanographic parameters that affect trap loss, movement, and degradation; for example, depth, water clarity, suspended solids, dissolved oxygen, microbial activity, siltation, benthic cover (i.e., softbottom versus hard bottom or reef habitat), and remaining buoy attachments likely play a role in how quickly traps degrade or are made ineffective through burial and removal (Butler and Matthews 2015; Lewis et al. 2009; Uhrin et al. 2014). Future field studies and/or restoration pilot projects in the GoM could ground-truth our benefit estimates.

The number of derelict traps targeted in a removal program has a large impact on the benefit of that program, such that doubling the number of removed traps doubles the expected benefit. Consistent with the findings and recommendations of Scheld et al. (2016), focusing removal efforts on waterbodies with the highest densities of derelict traps is the best strategy to maximize the benefits and minimize the cost of the removal program. Scheld et al. (2016) found that the difference between average benefits and costs per pot removed was highest when derelict gear hotspots were targeted. Resource managers can utilize the model developed in this analysis to determine the relative GoM hotspots where derelict crab traps are generated, and therefore the locations that possess the greatest benefits for concentrated removal programs. Side-scan sonar may be used to estimate the number and density of derelict traps in GoM waterbodies. Better-informed loss rates could be determined through fisher surveys or estimates of crab trap sales. Additional in situ restoration monitoring studies may be conducted in tandem with trap removal programs to investigate site-specific differences in the species impacted and therefore the ecological benefits derived from a removal project.

However, even with additional field studies and more efficient removal programs, a significant amount of gear is likely to be lost or abandoned. In fact, as noted in Martens and Huntington (2012), it is likely that the in situ debris supply exceeds potential removal efforts. As such, sustained and adequately funded removal programs are necessary to mitigate the continued impacts and continuous resupply of derelict traps (GSMFC 2015). In the absence of management options that limit the impact of derelict traps, such as degradable

Table 5 Benefits of a 5-year derelict trap removal project

State	Waterbody	Blue crab (kg)	Finfish (kg)	Biomass (kg)	Total biomass (kg)
AL	Bon Secour Bay/Little Lagoon, Perdido System	1008	669	1677	26,340
	Mississippi Sound-Mobile	3673	2439	6112	
	Mobile Bay	11,149	7403	18,552	
FL	Choctawhatchee Bay	552	354	907	14,377
	Pensacola Bay/East Bay/Escambia Bay	877	563	1439	
	Perdido Bay	70	45	115	
	St. Andrew Bay/West Bay/North Bay	877	563	1439	
	St. Joseph Bay	149	96	245	
	St. Josephs Sound	500	321	820	
	St. Vincent Sound/Apalachicola Bay/East Bay/St George Sound	2814	1806	4620	
	Tampa Bay	2919	1873	4792	
LA	Atchafalaya, Vermillion, Teche Rivers	61,752	20,410	82,162	626,968
	Barataria Bay	63,330	63,024	126,354	
	Calcasieu, Sabine, Mermentau Rivers	22,580	5444	28,024	
	Lake Pontchartrain	91,058	17,134	108,191	
	Mississippi River	17,385	11,544	28,929	
	Terrebonne Bay	95,997	157,311	253,307	
MS	Hancock Co.	2770	1839	4609	17,017
	Harrison Co.	1467	974	2442	
	Jackson Co.	4487	2980	7467	
	Lake Borgne	1502	997	2500	
TX	Aransas Bay/Copano Bay	794	527	1321	7048
	Corpus Christi Bay/Nueces Bay	71	47	119	
	Galveston Bay/Trinity Bay	1448	961	2409	
	Lower Laguna Madre	46	30	76	
	Matagorda Bay/Lavaca Bay	428	284	712	
	Sabine Lake	694	461	1156	
	San Antonio Bay	754	501	1255	

panels that allow trapped organisms to escape unharmed, derelict traps will continue to have the same impact over time. Some states have legislated measures such as cull rings and degradable panels, though the impact of these devices on the ghost fishing capability of a derelict trap has not been studied in the GoM. Assuming additional supporting data become available, the model developed here could be used to assess the benefits of such management measures.

Likewise, future assessments could investigate the economic impacts of derelict traps on GoM fishing communities to provide added support and/or direction to derelict trap removal programs. A reduction in the number of derelict blue crab traps would lead to increases in crab and finfish biomass, economic benefits to fishing communities, and ancillary benefits such as reduced interaction with marine mammals, sea turtles, and boating traffic. Calculating the economic impact of restoration benefits is a logical extension of this paper, and would create a more complete understanding of the benefits and costs of derelict trap removal programs.

Acknowledgments We thank Drs. Julie Anderson Lively and Joan Browder for assistance in gathering data and discussing rationale behind certain model parameters, Amy Uhrin for reviewing this manuscript and providing valuable feedback, and Meredith Amend and Ellen Plane for assistance with mapping. We also thank two anonymous reviewers for their careful review and considered feedback.

Funding Information Funding of this study and production of this publication was provided by the Federal and State Natural Resource Agencies' (Trustees') Natural Resource Damage Assessment (NRDA) for the Deepwater Horizon (DWH) oil spill through the National Oceanic and Atmospheric Administration (NOAA) Damage Assessment, Remediation and Restoration Program (DARRP) (NOAA Contract No. AB133C-11-CQ-0050).

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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