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Identification, recovery, and impact of ghost fishing gear in the Mullica River-Great Bay Estuary (New Jersey, USA): Stakeholder-driven restoration for smaller-scale systems

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ABSTRACT

The impact of ghost fishing in large coastal ecosystems has generated considerable interest. In smaller, understudied systems with fewer stakeholders, derelict fishing gear (DFGs) may have impacts similar to these larger systems at the same relative scale. Four years of side scan sonar surveys in the Mullica River-Great Bay Estuary (New Jersey, USA) supported the recovery of 1776 DFGs off-season by commercial partners. Locations with high densities of recovered DFGs (> 200 DFGs/km^2) occupied intersections of recreational vessel traffic and commercial crabbing activity. Condition and depth-in-sediment of recovered DFGs was used to evaluate true bycatch (terrapins, whelks, blue crabs) versus species utilizing degraded gear as habitat (juvenile tautog, oyster toadfish). Critically, gear recovered in-season with low cost sonars (an additional 225 DFGs) prevented the accumulation of new DFGs which likely generate the highest percentages of bycatch. Removal of DFGs in this system led to significant ecological (reduced bycatch), economic (> $61,000 in direct pay, reused gear), and anticipated future benefits (increased harvest).

1. Introduction

Over the last two decades, issues related to Essential Fish Habitat (EFH) in the United States have gained prominence in Fishery Management Plans, industry articles, and the popular press with the reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act (USDOC, 1996; Rosenberg et al., 2000). EFH focuses on the waters and substrates critical for growth, survival, and reproductive success of managed species (Benaka, 1999). More recently, attention has focused on identifying and quantifying Habitat Areas of Particular Concern (HAPC): subsets of EFH that provide critical ecosystem functions, yet may be vulnerable to degradation.

Despite the acceptance that EFH-based insight is critical to effective management, knowledge of interactions between fisheries and associated habitats remains poorly understood. This is particularly apparent in estuarine systems representing unique intersections between diverse organisms and habitats as well as commercial and recreational fishing interests (Peterson et al., 2000). Along the east coast of the United States, estuaries comprise > 30,000 km^2 of habitat which support a wide variety of fish and invertebrate species as obligate or facultative users (NOAA, 1985). Estuarine habitats and associated species are referred to as "trust resources" which are actively protected and restored by the U.S Department of Commerce on behalf of current and future stakeholders. Commercial and recreational fishing generated 1.6 million jobs (and over $208 billion in sales) for these stakeholders in 2015 (NMFS, 2016).

The direct impacts of fisheries on target species in estuaries are not difficult to quantify (i.e. the mid-Atlantic striped bass, *Morone saxatilis*, decline in the late 1980s due to overfishing; Secor, 2000). However, the indirect effects of fishing on non-target species and associated HAPCs are less straightforward. One topic of increased scientific focus over the past two decades is the impact of mobile bottom fishing gear (e.g. scallop dredges, otter trawls) on benthic environments (Watling and Norse, 1998; Auster and Langton, 1999; Sullivan et al., 2003). Mobile gear frequently leaves an indelible mark on a variety of habitats (mud, rock, hard bottom substrates) that allows researchers to quantify frequency and intensity of impact (Collie et al., 2000). Ghost fishing – static or derelict fishing gear (DFG) that continues to fish for an

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unknown time after being lost or intentionally discarded (Jennings et al., 2001; Matsuoka et al., 2005) – represents an indirect effect that is more difficult to assess. Due to vessel traffic, coastal storm events, and vandalism – gear can be lost and displaced into new habitats not originally targeted by fishers (Brown and Macfadyen, 2007). Because the circumstances of DFG loss are varied and system-dependent, it is difficult to make general statements about the longevity of ghost fishing and suites of species impacted.

The frequency and impact of ghost fishing has generated considerable interest in larger U.S. estuarine and coastal ecosystems (Anderson and Alford, 2014; Arthur et al., 2014). Although estimates vary by region, technique, and habitat - commercial fishers may lose 25–30% of traps annually (Guillory et al., 2001; Havens et al., 2008; Arthur et al., 2014). Recent studies centered around the profitable blue crab (*Callinectes sapidus*) trap fishery in the Chesapeake Bay (Havens et al., 2008; Havens et al., 2011; Bilkovic et al., 2014) have made impressive strides identifying the scale of the problem and impacts on bycatch species while initiating removal efforts to restore trust resources. Havens et al., 2011 offer a compelling cooperative research model for engaging stakeholders directly in the debris identification and removal process. Further, the application of removal study results has shown the potential for significant gains in gear efficiency as well as realized harvest for impacted fisheries (Scheld et al., 2016). As larger systems tend to receive a majority of the attention from an economic standpoint, commercial and recreational fishers may feel that ghost fishing is negligible in smaller systems that distribute fewer licenses and generate lower overall profits.

One such system is the Mullica River–Great Bay Estuary (MRGB) in southern New Jersey (USA) (Figs. 1 & 2). Located within the Jacques Cousteau National Estuarine Research Reserve (JCNERR), MRGB is relatively undisturbed and considered one of the more pristine estuaries in the northeastern U.S. (Psuty et al., 1993; Able et al., 1994; Kennish, 2004). The system is comprised of a drowned river valley (Mullica River), embayment (Great Bay) and barrier beach estuary (Little Egg Harbor). The Mullica River is 34 km long along its tidal main stem and drains an ~915 km^2 area of the central southern New Jersey Pinelands. For its overall size (surface area = 41.6 km^2; Kennish et al., 2004), the estuary is heavily fished both commercially and recreationally. On average, 2460 commercial crab traps (primarily blue crab) are fished each year in the low-to-mid salinity areas. These traps are divided between 8 and 10 individual licenses while the maximum number of traps is capped at 400 per individual for all New Jersey waters outside of Delaware Bay (L. Barry, New Jersey Department of Fish and Wildlife, pers comm). Assuming a trap loss rate of 20% (commercial partners, pers comm), > 400 traps may be lost per year. Although more difficult to track, recreational fishing accounts for a smaller, but not insignificant fraction of the total effort. On a New Jersey state-wide scale, more effort is expended by recreational fishers on blue crabs than any other single fish or shellfish species, with an estimated 1.24 million trips taken per year (Muffley et al., 2007).

A large percentage of the commercial effort in MRGB is focused on highly productive areas at the intersection of Mullica River and Great Bay - the Fitney Bit and Reef oyster beds (Fig. 2). Species associated with these oyster beds are frequently found as crab trap bycatch in the Chesapeake Bay (black drum, *Pogonias cromis*, white perch, *Morone americana*, oyster toadfish, *Opsanus tau*, juvenile blue crab; Havens et al., 2011). In the winter of 2011, a preliminary survey identified 118 DFGs in an 0.4 km^2 subsection of this reef area (Fig. 3). Extrapolating this survey out, > 2500 DFGs at densities upwards of 295 DFGs/km^2 may be present in this relatively small-scale system. Although MRGB has been studied exhaustively from a fish and invertebrate standpoint (Kennish et al., 2004; Able and Fahay, 2011) virtually no data exists on species impacted by ghost fishing. This species-level information is critical around oyster beds, in particular, as organisms benefitting from EFH may be compromised as bycatch.

To date, no comprehensive efforts had attempted to quantify the frequency and extent of ghost fishing, catalog bycatch, and remove DFGs from MRGB to restore EFH and HAPCs. Thus, the objectives of this study were as follows: (1) Identify and remove DFGs over an ~18 km^2 area at the mouth of the Mullica River and heavily fished portions of Great Bay, NJ. (2) Identify bycatch species and quantify physical characteristics of recovered gear related to bycatch production (DFG condition, depth in sediment, etc.). (3) Establish a best practices, cooperative research framework (NRC, 2004) to prevent future loss by

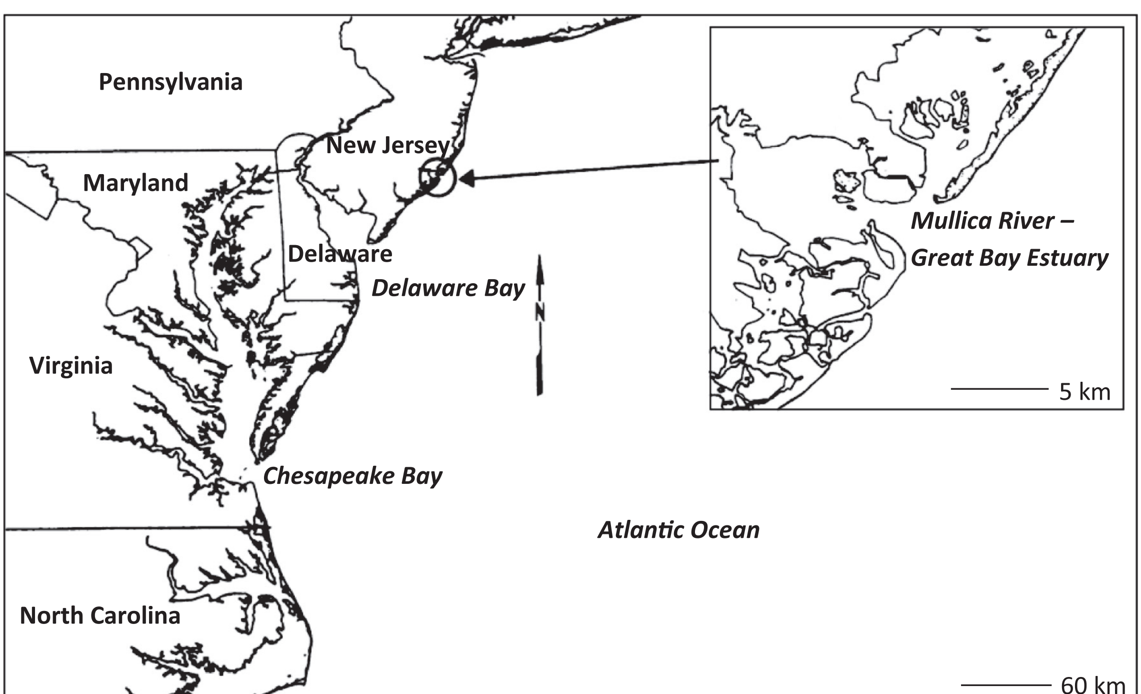

Fig. 1. Location and size of the Mullica River – Great Bay Estuary (MRGB) on the United States east coast relative to Chesapeake and Delaware Bays.

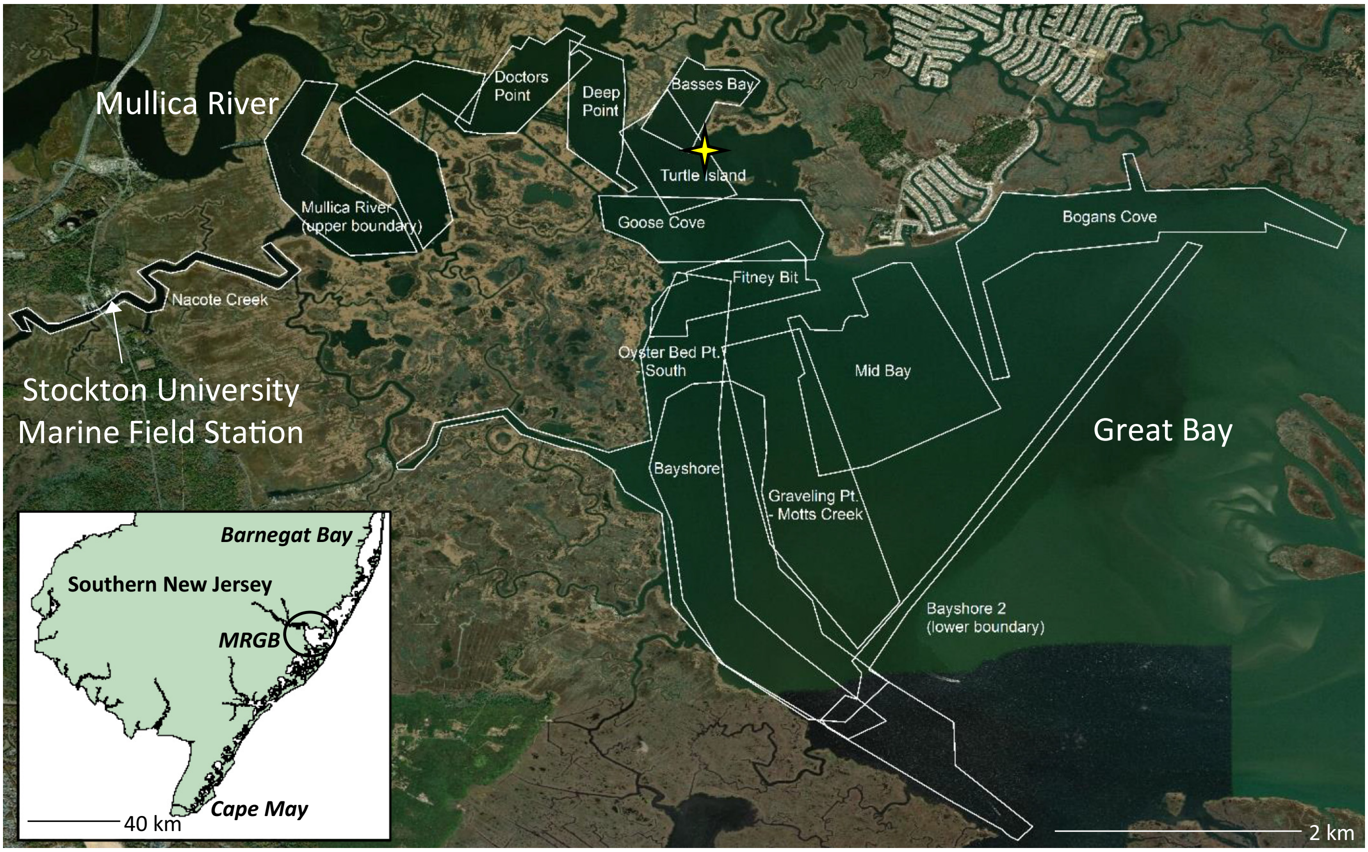

Fig. 2. Pre-restoration survey polygons (white lines) in the MRGB. Yellow star denotes location of Turtle Island side scan sonar detail in Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

directly involving stakeholders (i.e. Havens et al., 2011; Arthur et al., 2014) in the planning, data collection, and recovery components.

2. Materials and methods

2.1. Identification

Side scan sonar systems are effective tools for identifying DFGs in estuarine and/or coastal systems (Kappenman and Parker, 2007; Havens et al., 2008; Maselko et al., 2013). Four winters (2013, 2014, 2016, 2017) of side scan sonar surveys and DFG recoveries were completed in MRGB during the commercial blue crab fishery off-season (December 1–March 14). Broad-scale, side scan sonar surveys were conducted with either a Klein 3900 Digital Side Scan Sonar (Klein Marine Systems, Inc.) or EdgeTech 6205 Combined Bathymetry & Side Scan Sonar (EdgeTech, Inc). The Klein 3900 has selectable frequency capability with a 445 kHz frequency offering excellent range (Fig. 3) and a 900 kHz frequency able to provide high resolution images of targets at position accuracies of 2–3 m. The Edgetech 6205 is a rigid mount system with combined bathymetry and dual frequency side scan sonar. This system represents an increase in shallow water capabilities over the Klein through its ability to provide higher resolution images (1600 kHz) and position accuracies < 0.25 m.

An ~18 km^2 survey area (Fig. 2) within MRGB was selected for DFG identification and recovery work based on the following criteria: 1) known fishing pressure based on direct observation, 2) relative distance to areas of high vessel traffic (commercial partner interviews, S. Evert pers comm). On-site, side scan sonar instrument training (field operations, post-processing, image interpretation) was provided by Vince Capone of Black Laser Learning, Inc. Side scan sonar surveys were conducted using a “mow-the-lawn”-style approach (typically, 445 kHz resolution minimum, 50 m range, 100 m swath, 10 m overlap) at vessel speeds < 5 kts (Fig. 3). Probable DFG target catalogs (comma delimited format) were manually created in the field real-time by Stockton University survey teams (typically led by 2–3 of the co-authors) and full records played back in the lab for target verification (SonarPro, Klein Marine Systems, Inc.) (Fig. 3). Complete, verified target catalogs (definite-to-highly probable DFGs based on target reflectance and acoustic shadow) were uploaded to ArcMap 10.0 (Environmental Systems Research Institute, Inc.) for visualization and saved to SD cards for target reacquisition and removal by commercial partners. Target identification was conservative, surveys likely did not accurately inventory gear completely or partially buried in the sediment (low reflectance and/or lack of acoustic shadow).

2.2. Recovery

Project questionnaires were mailed to 100 permitted commercial crabbers in three southern New Jersey counties (Atlantic, Ocean, Cape May) through the New Jersey Division of Fish and Wildlife to determine the perceived extent and impact of DFG loss, as well as gauge interest in project participation. Response rate was < 10%, with both positive (one group already purchased a sonar unit to tackle the problem themselves) and negative (wariness of new regulations resulting from restoration work) inclinations towards the project. Interested commercial partners were selected for recovery efforts based primarily on reported commercial landings in the MRGB system and percentage of annual income generated from crabbing. Commercial partners P. Andersen, K. & W. Unkert (Years 1–4) and A. Kurtz, G. Leeds (Years 1 & 2) completed a multi-day training workshop at the Stockton University Marine Field Station (Port Republic, NJ) that included a classroom sonar theory and technology overview, safety briefing, and on-the-

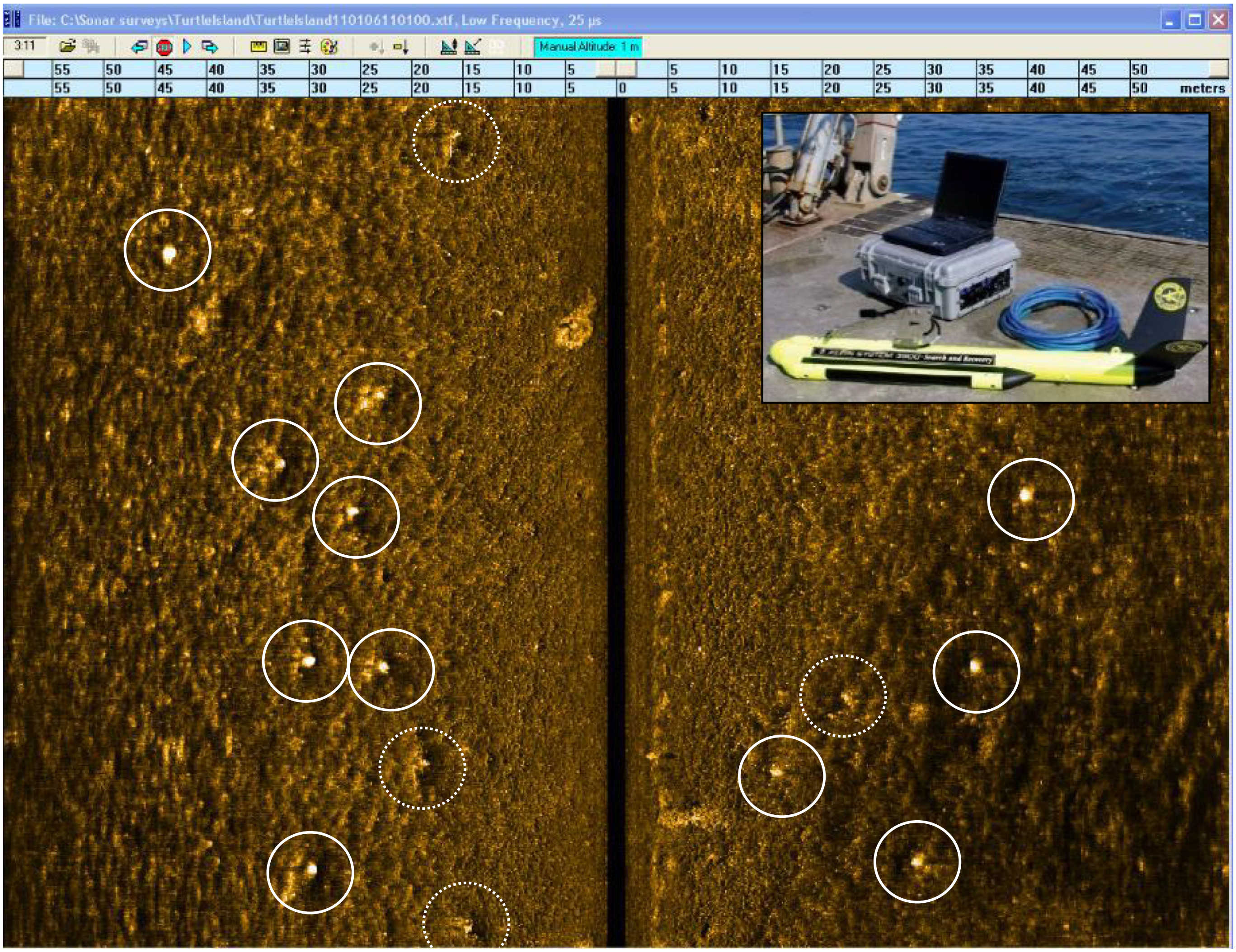

Fig. 3. Klein 3900 side scan sonar (right inset) low frequency (445 kHz) record from Turtle Island (MRGB) with probable (white solid circles) and possible (white dashed circles) DFG targets shown. Scale bars at top of figure represent distance on either side of instrument in meters. Overall portion of record depicted represents an area of ~10,800 m^2 (water depth: 2 m; bottom type: mud, silt).

water training exercise. Commercial partners utilized their own industry vessels (typically < 8 m length, shallow draft, limited hauling capabilities) during recovery operations and were paid for approximately ten days of work each season ($300–$350/day).

Reacquisition of probable DFGs by commercial partners was accomplished with Humminbird 898C SI Combo Side Imaging Sonar (Johnson Outdoors Marine Electronics, Inc.) pre-loaded with target waypoints (GPX converted to HWR files) from the broad-scale sonar surveys (Fig. 4A). Commercial partners initially traveled to areas of dense waypoints to maximize on-the-water efficiency. Targets were verified by slowly passing over a waypoint with the Humminbird sonar screen active (some partners then elected to mark the target with a small surface buoy). The recovery of thin wire mesh Chesapeake-style crab traps (in particular) from shallow, soft-sediment systems (such as MRGB) is challenging given traps become firmly embedded in silt and mud over time due to surface wave action. Depending on commercial partner preference (and typically with sonar screen active), a single grapple hook (5 kg grapple anchor attached to a length of line ~4 × water depth) or hook system (bent nails or grapple hooks in line on weighted 30 m ropes – modified from Havens et al., 2011) was used to engage a target on subsequent vessel passes (Fig. 4B). Once engaged with grapple(s), the target was pried loose from the sediment under vessel power and sediment cleared by steering the vessel in a circular fashion (Fig. 4C). This process, while essential for successful recoveries, likely introduced bias into the bycatch results (see Section 3.3 Impact). Targets at the surface with sediment removed were visually verified as DFGs and lifted on board by hand to complete the recovery (Fig. 4D).

All recovered debris was immediately photographed (depending on project year), assigned a recovery number, and tagged using a color-coded system unique to each commercial partner. Associated finfish and macroorganisms were removed from DFGs, placed in a large bin containing a metric ruler and a second tag, and photographed for future ID confirmation and length determination in the laboratory (Fig. 4E). Data recorded in the field by commercial partners was limited to (for efficiency): date, time, recovery coordinates, and presence or absence of bycatch. Commercial partners returned to the Stockton University Marine Field Station at the end of each day to unload recovered items as well as submit SD cards (Humminbird, digital camera) and field data sheets. SD cards and associated data were used to update identified/recovered databases and verify commercial partner effort. Critically, commercial partners were encouraged to use Humminbird sonars during the active crabbing season to recover traps immediately after loss and help break the cycle of gear loss in this system. Associated data for this study component was limited to recording “successful recovery” only to limit additional data collection burdens in-season.

Fig. 4. A. Humminbird 898C SI Combo Side Imaging Sonar/External GPS unit used by commercial partners for re-acquisition of DFG targets and in-season recoveries. B. 2–4 kg single grapple used for shallow water DFG recoveries from silt/mud habitats. C. Example of typical industry vessel (< 8 m length, shallow draft, limited hauling capacity) used for shallow water DFG recoveries. D. Successful DFG recoveries after mud and silt removed. E. Bycatch photograph example with 3 blue crabs, 1 rock crab, metric ruler, trap ID (KU-64), and Image Pro overlay shown. F. Refurbished recovered traps (n = 39) worth $1560 ($40 each). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. *Impact*

Ecological and economic impacts of DFGs in MRGB were quantified using combinations of data sets collected primarily post-recovery at the Stockton University Marine Field Station. At the end of each recovery season (typically mid-April), a DFG processing day event was held to collect additional information from recovered DFGs and either return fishable gear to the local commercial community (Fig. 4F), detach subsets of parts for reuse (rebar frames, excluder panels), or completely recycle gear as scrap. Processing day participants consisted of commercial partners, project scientists, and community volunteers (including undergraduate and high school students). Data recorded from each recovered DFG included: type, weight, fishery (commercial or recreational), condition (intact–able to fish; dented–able to fish; rusted or collapsed-unable to fish; partial or decomposed-unable to fish), depth of DFG in sediment (as evidenced by epifaunal coverage limit), as well as probable DFG orientation on bottom (right-side up, upside down, side).

Ecological impacts of DFGs were investigated using digital images of species removed from DFGs in the field and processing event data. Detailed bycatch analysis was conducted for the first two project years only (2013, 2014) as subsequent years (2016, 2017) were characterized by a higher percentage of lower condition DFGs (see Section 3.3 Impact for rationale) and uneven bycatch documentation on the water. Digital images were loaded into an image analysis program (Image-Pro Plus 7, Media Cybernetics, Inc.) and calibrated using the embedded metric ruler as reference. Species were identified and measured to the nearest millimeter from calibrated images (Fig. 4E). These data sets, in combination, helped determine whether individuals present in DFGs may represent true bycatch (i.e. unable to escape) or species associating with gear as habitat (i.e. freely able to move between gear and environment). Economic impacts of DFGs were investigated on the individual commercial partner level (recovery pay, savings from recovered gear) as well as the scale of the fishery (indirect savings from crabs “returned” to the fishery through DFG removal).

3. Results

3.1. *Identification*

Over four years of survey work (2013, 2014, 2016, 2017), 2218 probable DFG targets were imaged in MRGB with a Klein 3900 and/or

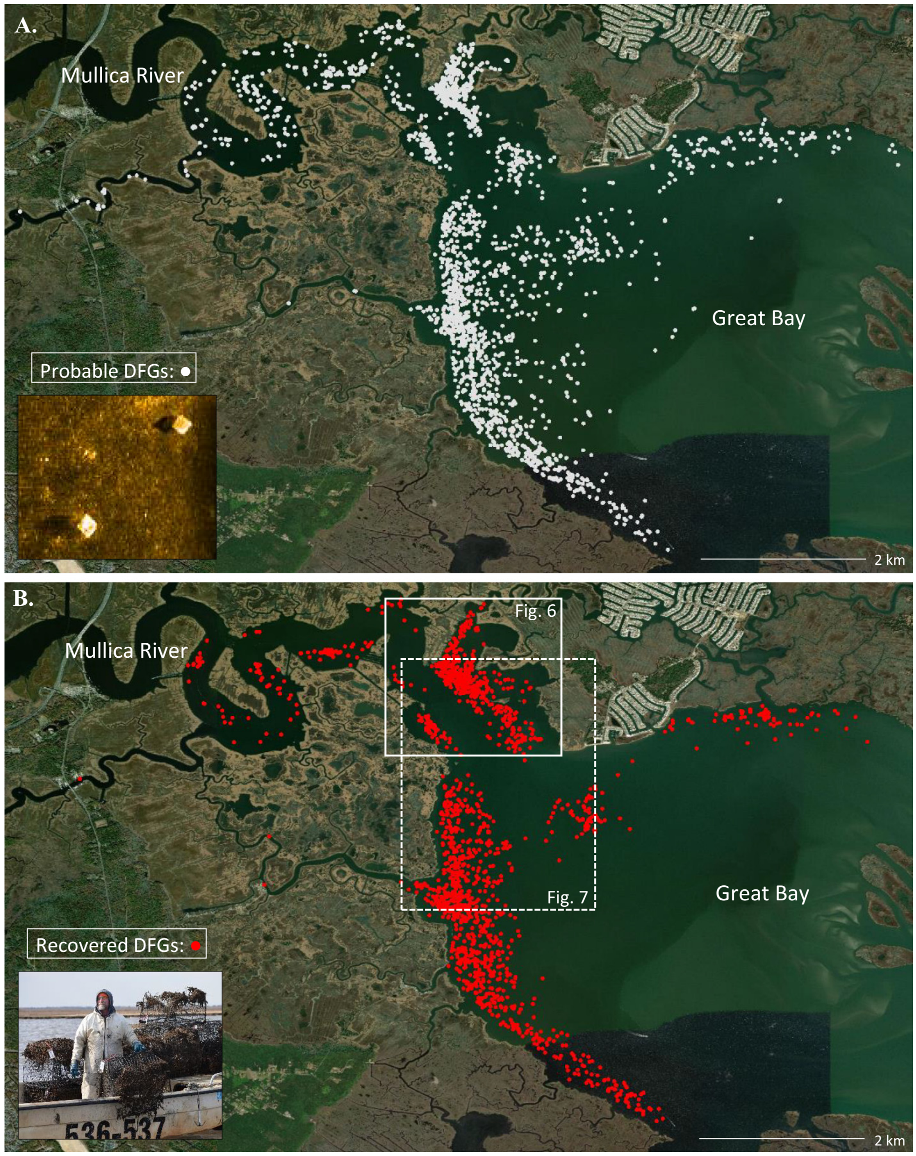

Fig. 5. A. Probable DFGs (white circles) in MRGB from scientific grade side scan sonar surveys. B. Recovered DFGs (red circles) in MRGB. White, solid rectangle denotes area detail in Fig. 6. White, dashed rectangle denotes area detail in Fig. 7. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Edgetech 6205 side scan sonar system covering a total surveyed area of 20.78 km^2 (north of Nacote Creek, in the Mullica River to Main Marsh Thoroughfare, south, in Great Bay; Fig. 5A; Table 1). Densities of probable DFGs in high loss areas (Turtle Island, Basses Bay - high crabbing activity, high vessel traffic) were 333–335 DFGs/km^2. By way of contrast, the lowest densities of probable DFGs (27–48 DFGs/km^2) were found in areas of minimal crabbing activity (Mid Bay, Graveling Pt–Motts Creek), deeper water (Deep Point), and restored oyster reefs (Fitney Bit). Reported survey densities are likely conservative in heavily fished locations given the criteria used to identify DFGs from sonar records (shape, acoustic shadow) as well as the dominant bottom type (silt, anoxic mud). Gear completely buried as well as subsets of partial gear may have gone undetected during survey work (but later successfully retrieved by commercial crabber partners). In multiple locations, DFGs belonging to commercial crabbers not participating in the project may have continued to accumulate after original survey work was complete. Overall, the overall magnitude of DFGs surveyed between locations generally mirrored pre-survey predictions of loss based on commercial crabber interviews and local scientific knowledge (known fishing pressure from direct observation, relative distance to locations of high vessel traffic).

3.2. Recovery

Over four years of recovery work (2013, 2014, 2016, 2017), 1776 DFGs were recovered by participating commercial partners as well as Stockton University recovery teams off-season (Fig. 5B). The percent breakdown of DFG by gear type was as follows: 89% commercial Chesapeake-style crab traps, 7% recreational crab traps, 2% fish traps, 1% whelk pots, 1% other (clam screens, anchors, fishing tackle). Non-fishing related marine debris items recovered (with similar sonar acoustic signatures to DFGs) included beach chairs, rectangular totes, and concrete blocks. Densities of recovered DFGs in high loss locations (Turtle Island, Basses Bay) approached 318–404 DFGs/km^2 (Figs. 5B, 6; Table 1). These values were equal to or higher than the probable DFG predictions from survey work - with higher values likely resulting from a combination of undetected original DFGs and newly accumulated DFGs post survey. Low densities of confirmed DFGs (2–32 DFGs/km^2) were recovered in Nacote Creek, Graveling Pt-Motts Creek, Deep Point, and Mullica River. Recovered DFG numbers at these sites were lower

Table 1
Densities of probable and recovered DFGs from side scan sonar survey locations in the MRGB (see Fig. 2 for survey polygons). Large recovery deviations (−/+) from survey expectations are discussed in Section 3.2 Recovery.

Survey location	Area surveyed (km^2)	Probable DFGs (#/km^2)	Recovered DFGs (#/km^2)
Mullica River (upper bound)	1.85	108.65	32.97
Nacote Creek	0.34	71.12	2.96
Doctors Point	0.64	79.77	70.38
Deep Point	0.58	48.26	15.51
Basses Bay	0.46	335.67	318.35
Turtle Island	0.63	333.06	404.77
Goose Cove	1.09	121.18	106.49
Fitney Bit	0.67	27.91	67.16
Oyster Bed Pt - South	3.24	198.20	227.49
Bayshore	3.21	117.28	190.69
Graveling Pt - Motts Creek	2.41	42.75	9.96
Mid Bay	2.31	39.75	27.65
Bogans Cove	1.78	62.85	42.09
Bayshore 2 (lower bound)	1.56	42.87	46.71

than survey predictions – likely due to reduced recovery effort (Nacote Creek, Graveling Pt.-Motts Creek) and increased water depth (Deep Point, Mullica River). A system-wide average density of recovered DFGs was not calculated as not all areas were surveyed and/or chosen for recovery work. A geographically weighted regression (GWR) approach may be a useful next step for estimating DFG densities in unsurveyed habitats (Bilkovic et al., 2016).

Given ideal combinations of appropriate weather conditions, recovery gear upgrades, and dense fields of DFG targets (Fig. 7 – 2-5-12 vessel track) – commercial partners were able to recover ~20–30 DFGs per day in high density areas. Critically, an improved grapple configuration for MRGB allowed for finer-scale targeting of removals, less incidental interaction with bottom habitat (the majority of locations sampled were within JCNERR and/or alongside NOAA restored oyster beds), and a quicker turn-around time. Commercial partners typically moved on to new locations when transit time between probable DFGs increased and frequency of high quality Humminbird sonar images decreased (Fig. 7 – 3-11-14 track). Given commercial partners were paid a daily rate for their efforts, DFGs remained unrecovered in certain locations to maximize the economic efficiency of the project.

Commercial partners were loaned Humminbird side-imaging sonar units for use on industry vessels during the active commercial crabbing season. Over four summers, commercial partners were able to recover 225 additional DFGs (immediately – 48 h; often within 20 min) after recognizing loss had occurred. On several occasions, commercial partners witnessed gear loss first hand (via recreational vessel traffic, pers comm) while checking active traps.

3.3. Impact

Of the recovered DFGs selected for detailed bycatch analysis (n = 1030), 27% contained associated macroorganisms. When considering higher condition DFGs only (intact–able to fish, dented–able to fish) this percentage rose to 47%. Analysis in the laboratory (using ImagePro software) of DFG bycatch photos taken in the field by commercial partners identified 825 total associated macroorganisms (average: 2.9 individuals/DFG, min: 1, max: 20; mainly fish, crustaceans, and mollusks - small mud crabs and attached epifauna excluded, Fig. 8). The top three species, respectively, were rock crab or Jonah crabs, *Cancer* sp. (n = 317); oyster toadfish (n = 167); tautog, *Tautoga onitis* (n = 107). Sixty target individuals (i.e. blue crab) were collected. Several species followed clear patterns with respect to occupying higher condition vs. lower condition gear (see processing event results below). Diamondback terrapin, *Malaclemys terrapin*, whelks of multiple species; *Cancer* sp.; and the target species, blue crab – accumulated in higher condition gear (Fig. 9 – Inset A). Alternatively, the majority of tautog and oyster toadfish (primarily age 1 based on average total length; Hostetter and Munroe, 1993; Wilson et al., 1982) appeared to be occupying lower condition gear as habitat rather than as true bycatch (Fig. 9 – Inset B). When considering these results, it is critical to

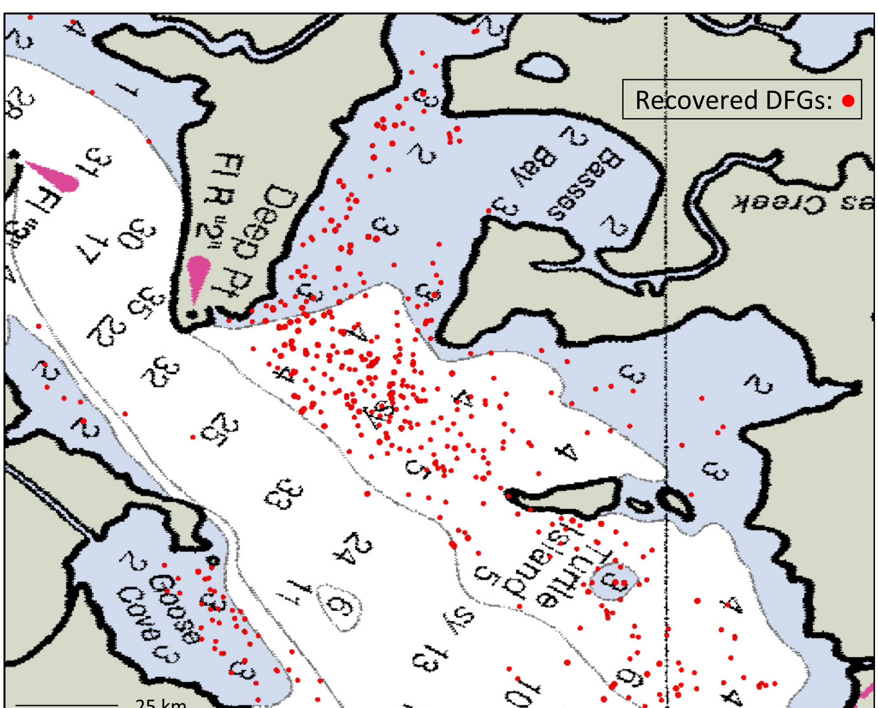

Fig. 6. Detail of locations (Basses Bay, Goose Cove, and Turtle Island) with high densities of recovered DFGs (red circles). Water depths noted on navigational chart in feet. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

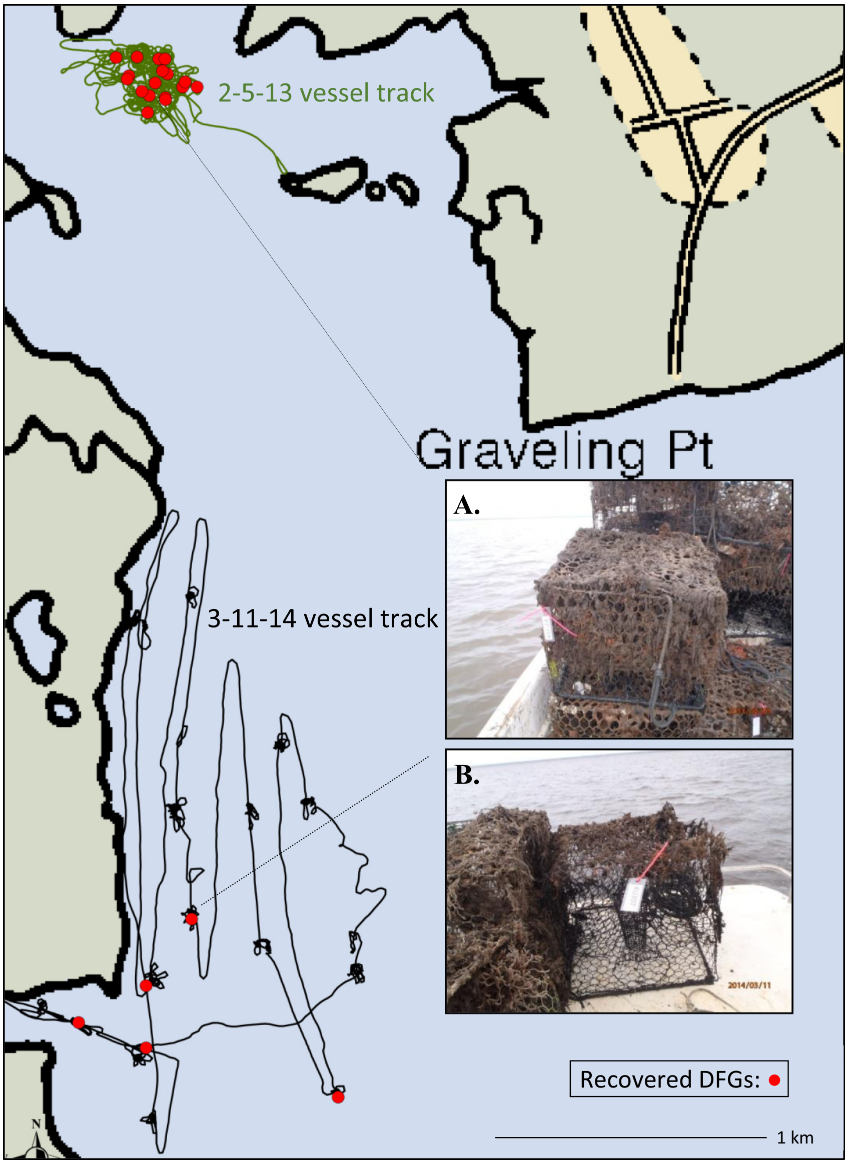

Fig. 7. Contrasting modes of recovery as restoration efforts progress. Green line (top) denotes vessel track on second day of project recoveries in target rich habitat. Recovered DFGs in red (n = 18). Inset A.: Recovered DFG KU-24 with majority of retrievable mesh above sediment surface. Black line (bottom) denotes vessel track during final week of Year 2 recoveries in target limited environment. Note fewer successfully recovered DFGs (n = 5) due to poor quality targets. Inset B.: Recovered DFG KU-307 with majority of retrievable mesh below sediment surface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

recognize the following caveats: (1) Collections were made primarily from January–March when MRGB system-wide species diversity is low (2) Gear was often modified in situ by grapples (mesh torn, panels dislodged) during the retrieval process (3) Gear was frequently towed behind vessels to rid mesh of excess sediment before recovery (likely losing entire individuals and remains in the process). Given these three factors, it is difficult to quantify true "bycatch" in this study as well as accurately gauge the percentage of DFGs containing bycatch (i.e. bycatch in certain scenarios was lost before the DFG was inspected at the surface). Thus, results on associated DFG macroorganisms should be interpreted with caution.

Recovered DFG processing events held in mid-to-late April of each recovery season gathered additional data from recovered gear and either set aside fishable gears (intact–able to fish; dented–able to fish) for possible re-use or broke down unfishable gear (rusted or collapsed-unable to fish; partial or decomposed-unable to fish) for scrap recycling. Overall, the condition breakdown was as follows: 12% (intact–able to fish), 11% (dented–able to fish), 51% (rusted or collapsed), 26% (partial or decomposed-unable to fish).Of the 1030 evaluated DFGs during Year 1 & 2, 203 (~20%) were ultimately deemed acceptable and returned to commercial partners and the local crabbing community. Of the 746 evaluated during Year 3 & 4, only 62 (~8%) were returned (reflecting the poor condition/poor sonar imagery of Year 3 & 4 vs. Year 1 & 2 recoveries). Excluding partial pieces, the average DFG recovered was buried in 20 cm of muddy, silty sediment depending on location (Fig. 10). The poorer condition the DFG, the longer it had likely been in the system and deeper it was found buried in sediment (up to a maximum of 54 cm – or almost the entire trap profile – Figs. 10 & 11). Collaborating commercial partners (pers comm) recovered some DFGs > 10 years old (identified by trap style and configuration).

Economic impacts to the fishery and commercial crabbing community were estimated alongside the ecological impacts (Table 2). At approximately $40 each, the estimated total value of off-season and in-season recovered Chesapeake-style crab traps totaled $19,600 over four years of work. This value does not include additional benefits from reusable parts (re-bar, escape panels) and unfishable DFGs recycled as scrap. Aside from project funds used to directly pay commercial partners for their retrieval efforts ($42,373 total over the course of 4 years), these benefits represent an additional, major return on the initial investment. On the fishery-wide scale, a study in the Lower York River, Virginia indicates 50 crabs/DFG/year might be "returned" to the fishery for each DFG recovered (Havens et al., 2008), thus recovered DFGs in this study (deemed reusable by commercial partners, n = 490) have the potential to add > 24,000 mature blue crabs back into MRGB (Table 2).

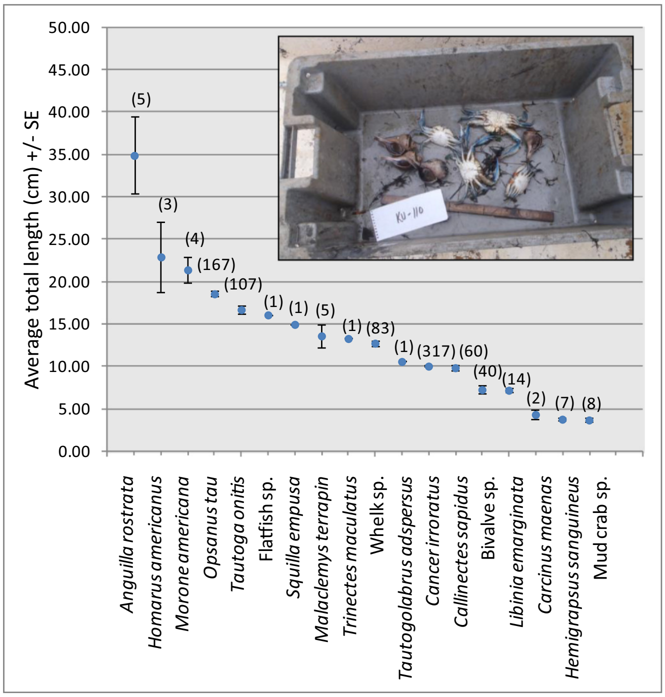

Fig. 8. Species quantified from recovered DFGs (X-axis; total number in parentheses) and average total length in cm +/− SE (Y-axis). Inset: macro-organism examples (whelks, blue crabs) from trap KU-110. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

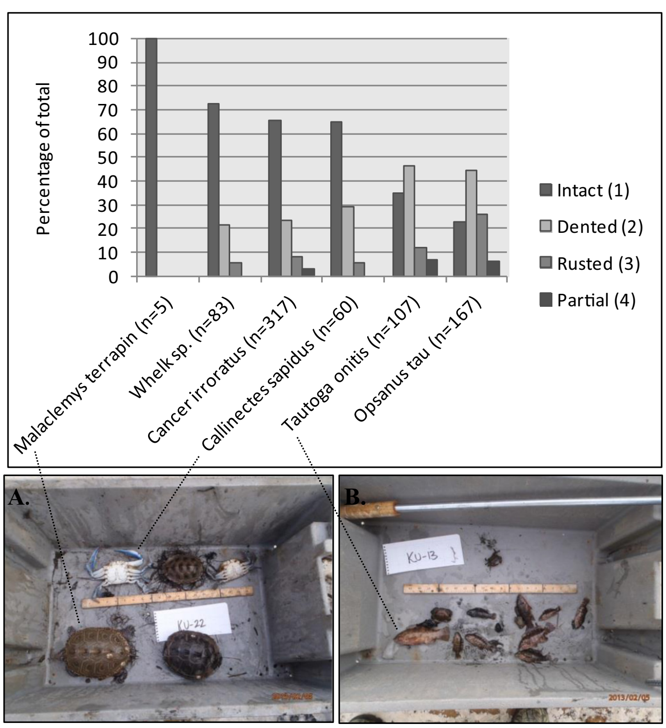

Fig. 9. Percentage of select species found in DFGs by DFG condition value. Species ordered left to right, according to accumulation in higher condition (potential true bycatch – A) or lower condition DFGs (using degraded DFG as habitat – B). Images A & B (DFG IDs KU-22, KU-13) were recovered from the same location (Basses Bay), but represent an intact vs. rusted trap, respectively.

4. Discussion

This work revealed the magnitude and distribution of DFGs in a small, coastal system (MRGB) historically accessed by a handful of stakeholders (8–10 licensed commercial crabbers). Compared to a recent overview of DFG studies in U.S. coastal waters (Arthur et al., 2014), the maximum confirmed DFG densities in MRGB (Table 1) may be up to 3-5× higher than locations reported in Maryland - Chesapeake Bay (Giordano et al., 2010) and Southeast North Carolina (Voss et al., 2015). The highest density DFG locations in MRGB (Turtle Island, Basses Bay, Oyster Bed Pt – South; Fig. 5A) overlap with peak levels of commercial crabbing activity and recreational vessel traffic (the latter factor driven by a popular dockside restaurant and marina/boatyard at these locations). As opposed to larger systems, the size of MRGB creates a bottleneck that aggregates fishing effort into a handful of productive habitats that typically do not vary widely from year-to-year (commercial partners, pers comm).

4.1. Verifying patterns of gear loss

The efficiency and cost-effectiveness of the MRGB recovery effort was contingent on understanding overall patterns of system loss a priori. Anecdotal, historical information (i.e. stakeholder interviews, local scientific knowledge) was useful for planning purposes. However, an initial survey using a high resolution side scan sonar system (i.e. Klein 3900, Edgetech 6205) was critical for defining areas of system-wide loss as well as verifying DFG hotspots to maximize efforts on the water (i.e. Kappenman and Parker, 2007; Havens et al., 2008; Maselko et al., 2013). Multiple locations coincided with anecdotal patterns of loss (in particular, intersections of commercial crabbing activity, navigable channels, and vessel traffic – Basses Bay, Oyster Bed Pt. - South), while others did not (Mid Bay, Graveling Point - Motts Creek). Although the majority of MRGB habitats consist of silt/mud substrates, DFGs may move over time on more consolidated materials leading to decoupling of fishing effort and recovery (Uhrin et al., 2014). In verified dense areas (> 100 DFGs/km^2), commercial partners used low-cost sonar units (i.e. Humminbirds) to reacquire targets opportunistically (i.e. Havens et al., 2011; Voss et al., 2015). As gear was removed from the system, community partners moved on to lower density locations requiring exact waypoints for efficient recovery (Fig. 7A, B). For studies where on-the-water days are limited due to weather, seasonal open fisheries, funding, etc. - efficient use of time is crucial for a successful recovery effort.

4.2. System-specific recovery challenges

All estuaries are not created equal from a habitat standpoint – requiring system-dependent recovery solutions. MRGB, which houses JCNERR (Psuty et al., 1993), is a predominantly shallow, soft-sediment system accessed by commercial crabbers in shallow draft vessels with limited hauling capacity (Fig. 4C). In this study, recovered commercial Chesapeake-style crab traps (the dominant DFG) were buried, on average, 20 cm in soft mud and up to 54 cm in extreme cases (thus, only several cm of mesh was exposed for effective grappling; Fig. 10). Silting-in of thin wire mesh traps in soft sediment systems creates unique recovery challenges - using excessive force and/or dragging arrays of grapples often results in torn mesh and/or failed recoveries. A percentage of the partial DFGs (unable to fish) recovered in this study likely represent detached mesh, rather than a full recovery (i.e. sections of gear remain embedded in mud). Open communication between scientists and commercial partners was critical for improved technique development (in this case, a single grapple, corkscrew approach) that ultimately resulted in efficient DFG removal that was vessel/personnel appropriate and minimized damage to surrounding EFH (seagrass, oyster beds). This single-target technique provided commercial partners with the experience to accurately recover lost gear in-season among

Fig. 10. DFG KU-7 depicting a typical depth-in-sediment demarcation line (epifaunal growth above, "clean" surface below). Bar on right denotes the height of the top of the entry funnel in a typical Chesapeake-style crab trap (16 cm), the average depth in sediment (20 cm), max (54 cm), and min (0 cm) of recovered DFGs (excluding partial DFGs).

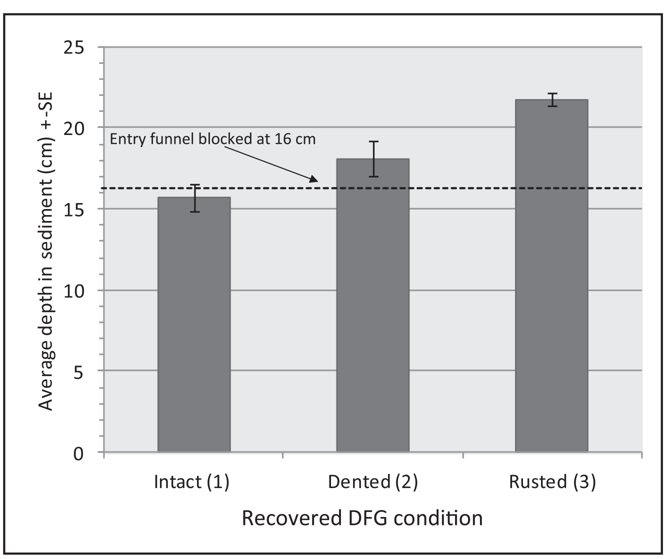

Fig. 11. Average depth of DFGs in sediment by condition. Partial DFGs (4) omitted (i.e. tear-outs or pieces of full DFGs). Dashed line denotes height of entry funnel in typical Chesapeake-style crab trap (16 cm).

dense fields of active traps.

4.3. Preventing future loss and bycatch

Commercial fishing communities trained by collaborating scientists can significantly reduce additional gear loss via low cost sonar systems (i.e. Humminbird) used in-season to immediately recover DFGs. Commercial partners in the present study, once comfortable with sonar operations, were able to immediately search for lost gear once discovered missing. In most cases, DFGs were relocated < 20 m from the origin of loss and retrieved in < 20 min. Cumulatively, 225 DFGs were recovered in this manner, while simultaneously preventing additional loss to the system. Arthur et al. (2014) note that short term and/or one-time clean-up efforts are unlikely to have lasting impacts given consistent annual loss rates in most systems. Low cost sonar use in-season can help break the cycle of continued gear loss in these fisheries.

A second advantage of in-season ("immediate") recoveries includes the removal of gear that likely generate the highest amount of true bycatch. The bycatch and gear condition results from this study reveal an obvious, but critical finding (Fig. 9). Priority removal of higher condition DFGs (which are easier to locate with sonar and recover without tearing) leads to lower percentages of true bycatch and a higher return on commercial crabber time investment (recovered DFGs are more likely to be reused). In this study, higher condition DFGs likely contributed disproportionately to bycatch of the target species (blue crabs) as well as other commercially valuable species (whelks) through initial baiting, but also through entry funnels that remain open for multiple seasons. Degraded DFGs, while important to remove as

Table 2
Economic and ecological project benefits, totals, and notes from MRGB restoration efforts.

Project benefit	Benefit total	Benefit notes
MRGB area surveyed	20.78 km^2	High resolution side scan sonar
DFGs recovered off-season	1776 DFGs	Includes full and partial DFGs
Off-season DFGs reused	265 DFGs	Selected at processing day events
DFGs recovered in-season and reused	225 DFGs	Located with low cost sonar
Estimated value of reused DFGs	$19,600	DFGs reused (n = 490) × $40 (~new trap cost)
Direct pay to commercial partners	$42,373	~10 days/vessel/year @ $300–350/day
Blue crabs "returned" to fishery	24,500 crabs	DFGs reused (n = 490) × 50 crabs/DFG

navigation hazards and marsh habitat threats (Uhrin and Schellinger, 2011) in shallow systems, do not typically contribute to the continued accumulation of bycatch (due to properly functioning escape panels, silted in entry points, and/or degraded mesh). In fact, the present study likely removed a percentage of DFGs that could be considered artificial EFH for juvenile tautog and oyster toadfish. Average total lengths obtained for tautog and oyster toadfish in this study (Fig. 8) suggest individuals recovered from DFGs consisted primarily of age 1 individuals for both species (Hostetter and Munroe, 1993; Wilson et al., 1982). Whether these individuals are occupying DFGs as habitat or true bycatch is equivocal given the series of caveats discussed in Section 3.3 Impact.

Thus, the absolute best practice scenario for a commercial crabber in the MRGB is to remove a DFG immediately after discovering loss. Tools to accomplish this goal were implemented and extend beyond the end date of formal off-season removals. An education program and website (www.wecrabnj.org) developed for recreational boaters, recreational and commercial crabbers, and shore visitors aims to stem future loss by emphasizing lost gear is an issue all user groups can help prevent together. With an initial investment in low-cost sonar technology, smaller-scale systems may be able to avoid future costly restoration efforts involving survey vessel time, personnel, and higher-end sonar technologies.

4.4. Value of collaborative research

Cooperative research programs bringing together commercial partners and scientists provide a unique opportunity for iterative communication and enhanced mutual understanding (Hartley and Robertson, 2009). However, for these partnerships to extend into the future once formal project work is complete, additional incentive for stakeholders is needed (commercial partners, pers comm). Participating commercial partners realized numerous economic benefits from the MRGB restoration efforts (Table 2) – direct pay, reusable gear, as well as probable increased blue crab harvest in the future (i.e. Scheld et al., 2016). All told, direct (pay) and indirect (value of recovered traps) benefits to stakeholders for this work totaled in excess of $61,973. Further, subsets of an estimated 18 km^2 area of habitat, including EFH close to oyster and seagrass beds, was restored. These benefits extend to a wide variety of associated estuarine species as well as human user groups unaffiliated with crabbing – thus, creating a win-win-win scenario. Including stakeholders directly in project planning and on-the-ground research helped facilitate a best practice model for this system. Given the above, identification and removal of DFGs in the MRGB is more appropriately defined as "collaborative research" between stakeholders and scientists, which ultimately helps achieve a more sophisticated level of knowledge integration than cooperation alone (NRC, 2004; Hartley and Robertson, 2009).

Author contributions

Mark Sullivan – corresponding author, article preparation, data analysis lead, co-PI.

Steven Evert – article preparation, field operations lead, commercial partner liaison, co-PI.

Peter Straub – article preparation, wecrabnj.org lead, sonar surveys, co-PI.

Melanie Reding – DFG processing day event lead, education and outreach, co-PI.

Nathan Robinson – Humminbird training lead, sonar surveys, DFG recovery support.

Elizabeth Zimmermann – DFG processing day event support, sonar surveys.

David Ambrose – sonar surveys, DFG recovery support.

Conflict of interest

The authors declare that there is no conflict of interest regarding publication of this paper.

Abbreviations

EFH	Essential Fish Habitat
HAPC	Habitat Areas of Particular Concern
DFG	derelict fishing gear
MRGB	Mullica River–Great Bay Estuary
JCNERR	Jacques Cousteau National Estuarine Research Reserve

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