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Ageing abandoned, lost, and discarded lobster fishing gear based on fouling assemblages.

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ABSTRCT

1. Abandoned, lost, or otherwise discarded fishing gear (ALDFG) is a byproduct of many fisheries. ALDFG impacts extend beyond the targeted species and include bycatch, habitat degradation, and increased plastic in the environment. In particular, ALDFG such as lobster gear attracts a succession of fouling organisms increasing species diversity and productivity.
2. In Cape Cod Bay, Massachusetts, USA, a seasonal lobster gear closure occurs for the protection of North Atlantic right whales (*Eubalaena glacialis*), allowing for the removal of ALDFG. In this study, the percentage cover of fouling organisms on recovered gear was used to model the age of recovered gear of indeterminate ages (gear with missing tags).
3. Between 2017 and 2021, a total of 379 traps were photo documented, of which 223 were of known ages (1-22 years) and 156 were of unknown ages. The age of the unknown traps was modelled utilizing a random forest algorithm using traps with a known age as a training library.
4. High correlations between modelled ages and known ages (R^2=0.634 $P < 0.001$*) slightly underestimated the age of the traps by 1.2 to 1.8 years but are sufficient for developing an age distribution. The majority (79%) of traps were recovered off Provincetown and

averaged 10-11 years old. Approximately 50% of traps recovered in Cape Cod Bay were deposited or lost between 2005-2010.

5. Calculating the age of ALDFG aids in determining the loss rate of and in identifying high concentrations of untended gear that can be recycled or reused. This analysis allows practitioners to understand the scale of the problem, helps quantify the amount of gear in the ocean, and helps identify the areas most affected. This information improves the effectiveness of removal efforts by focusing on discrete areas of recurring and recent gear loss.

Key words: biofouling, derelict fishing gear, marine debris, ALDFG, lobster trap, random forest, ocean, management, succession

1. INTRODUCTION

Fishing is a culturally and economically important activity across the globe that generates a wide range of ecological impacts. Abandoned, lost or otherwise discarded fishing gear (ALDFG) accounts for a large proportion of marine debris identified in the ocean and contributes significantly to the plastic load in the marine ecosystem (Uhrin, Matthews & Lewis, 2014; Pawar, Shirgaonkar & Patil, 2016; Agamuthu et al., 2019; Renchen, Butler & Matthews, 2021). The removal of ALDFG has evolved as a mechanism to reduce impacts to the ecosystem, and large items such as nets and traps, which are readily identifiable and relatively straightforward to remove, have been targeted by many marine debris recovery and disposal programmes across the globe (Gilman et al., 2021; Goodman et al., 2021). Prioritization of recovery efforts is essential to long term programmatic success as annual budgets only allow for a fraction of gear to be recovered in any given year.

The negative impacts of ALDFG extend beyond the gear's intended target species (Renchen et al., 2014; Goodman et al., 2019; Stevens, 2020; Goodman et al., 2021). Lost gear can continue to catch many species through "ghost fishing", and lines and nets can entangle whales, turtles, fishes and other marine organisms (Asmutis-Silvia et al., 2017; Richardson et al., 2019). In particular, trap gear for fishes or crustaceans has a direct impact on the benthic community, especially across highly sensitive benthic habitats such as reefs or submerged aquatic vegetation (Uhrin et al., 2005; Stevens, 2020). Although the specific footprint of any single trap is small, thousands are fished at any given time and each can be easily moved by storm action and currents resulting in impacts to areas well beyond their initial location (Lewis et al., 2009; Renchen et al., 2014; Stevens, 2020). Traps and their associated lines can also tangle with other fishing gear, causing the propagation of ALDFG and compounding related impacts. In addition, the recovery and retrieval of active gear or ALDFG may cause the gear to drag along the substrate, impacting the benthic habitat as the gear is hoisted (Lumsden, 2007; Schweitzer, Lipcius & Stevens, 2018). Furthermore, commonly used PVC-coated wire traps and synthetic line and net may slowly break down due to physical and/or photo-degradation, releasing microplastics into the surrounding environment and contributing to the total amount of microplastics identified in the ecosystem (Agamuthu et al., 2019; Stevens, 2020; Gilman et al., 2021).

The impacts of abandoned, lost, or derelict traps are difficult to assess but are generally understood to have a negative effect on the ecosystem (Stevens, 2020). Over time, a succession of organisms will attach and grow on the surface, and in certain cases, a trap can become a *de facto* artificial reef (Clark et al., 2012; Renchen et al., 2014; Stevens, 2020). Traps can also bury in unconsolidated sediment, causing them to become immobile. This prompts the question as to whether heavily encrusted or immobilized traps that have lost the ability to 'ghost fish' should be prioritized last, in favour of recovery of newer gear that does not support structure-oriented organisms, and which could be recycled or reused, and are mobile (potentially impacting areas beyond their current location).

Understanding the relationship between the age of the trap and the fouling organisms has two intrinsic values (Clark et al., 2012). First, it allows managers who are planning future recovery efforts to prioritize areas for the recovery of gear based on the potential of its negative ecosystem effects relative to the ecosystem services it provides (i.e. structure to act as an artificial reef, potential damage to sensitive benthos and vegetation, and potential to be recycled or reused) (Clark et al., 2012; Goodman et al., 2019). Second, quantifying the demographics of recovered gear can assist with understanding the current and past rates of gear loss, allowing for recovery practitioners to understand the magnitude of the problem and their recovery efforts, just as understanding the age distribution and quantity of traps in different locations allows for the identification of priority areas (e.g. areas with many new traps have a higher priority over that of older traps). Assessment of community succession of fouling organisms has been used to identify both age and location of origin of lost buoys and gear (Saldanha et al., 2003; Clark et al., 2012; Enrichetti et al., 2021). Here the recovery of gear and the quantification of fouling communities were used to model the age of traps found in Cape Cod Bay and predict the age of those traps of unknown ages (i.e. traps recovered without tags).

2. MATERIALS AND METHODS

2.1 Study Site

Cape Cod Bay, Massachusetts, USA, is in the southernmost portion of the Gulf of Maine (Figure 1) and is home to a long tradition of fishing for American lobster (*Homarus americanus*) using relatively common lobster traps (Figure 2). This area is seasonal habitat for the highly endangered North Atlantic right whale (*Eubalaena glacialis*) and a seasonal closure for fixed gear fisheries to prevent entanglement is implemented from February 1 to approximately May 1 annually (M.G.L. c. 130 and 322 CMR Cape Cod Bay Large Whale Trap Seasonal Trap Gear Closure) while the whales are in residence (Nichols, Kenney & Brown, 2008; Mayo et al., 2018). (The closure maybe extended if the whales have not yet vacated Cape Cod Bay by May 1). This allows for an opportunity to safely locate, remove, and quantify ALDFG, and understand its impacts on the ecosystem without interfering with actively fished gear.

2.2 Trap Recovery

During the seasonal closure when ALDFG recovery is permitted, information was received from the local fishing community as to where lost gear was likely concentrated. Based on this anecdotal information, sidescan sonar surveys were conducted to verify more precisely where traps were located. From the sidescan sonar surveys, areas of interest were identified, and in collaboration with local lobster fishermen lost gear were recovered, recycled, disposed of, or if in good condition with proper identification, returned to the owner.

Traps in this fishery are deployed as singles or in trawls of up to 20 traps long. Recovery efforts are focused on non-buoyed gear where a weighted grapple dragged along the sea floor snags the trap or trawl line and allows the gear to be hauled back to the vessel.

Once each trap was retrieved from the ocean floor, a photo of the top and two sides from a minimum of one representative trap per trawl was collected using a Sony Cybershot ® or GoPro Hero 5® for analysis of the fouling community. A minimum of one representative trap per trawl was documented when the number of traps being recovered was occurring at a high rate or in rough seas, in which case it can be either unsafe or impractical to photo catalogue every trap.

The recovery process may damage a trap beyond its use for analysis. A trap was considered representative of an entire trawl when it appeared most like the other traps in the trawl and was least damaged by the hauling action. Grappling locations were documented using a Garmin GPSMAP® 76 handheld GPS receiver, and ancillary data about bottom type, depth, and condition of the trap (crushed, buried) were recorded.

2.3 Photo Processing

Each trap was photographed on the top and two respective sides (unless crushed, in which case a single photograph of the overall trap was taken). A 30 cm graduated reference bar was placed in each photograph for scale. The state of each trap was assessed using the following metrics: condition (whole, partially crushed, or crushed), the level of burial (fully buried, half buried, quarter buried or only the base buried), and orientation when on the sea bed (upside down or right side up). Using a customized library in Coral Point Count with Excel Extension®, 25 random points were overlaid onto cropped photos (up to three photos of the top, long side, short side) of each trap (Kohler & Grill, 2006). If the point fell within the space between the trap mesh the assessor identified the fouling constituents on the nearest piece of trap. If the point fell outside of the trap or on the reference bar, it was removed from the percentage cover analysis (Figure 3). The total number of points for the three sides were used to calculate the percentage cover of the encrusting categories (e.g. if assessment points distributed on 18 mussel, 22 seaweed, 15 attached sponge, 15 bare traps, and 5 reference bars, the total percentage cover would be out of 70 assessment points with 25.7% mussel, 31.5% seaweed, 21.4% attached sponge, and 21.4% bare trap). The fouling constituents were identified as gross categories of encrusted and attached organisms, including “Bare Trap”, “Attached Hydrozoan”, “Attached Sponge”, “Encrusting Sponge”, “Sea Anemone”, “Red Algae”, “Fouling Matrix”, “Kelp”, “Seaweed”, “Barnacle”, “Encrusting Bryozoan”, “Blue Mussel”, “Tunicate”, and “Other”. The category “Fouling Matrix” was assigned to a general fouling community where individual components dead or alive (algae, sponge, bryozoan, barnacle) could not be differentiated and were an encrusting matrix of growth. "Other" is characterized as very rare organisms such as a sea star.

2.4 Age Assessments

Each trap retrieved was examined for permit tags which identify the permit owner and the year the tag is valid (and which indicate the most recent year the trap was tagged and legally set). Tags from multiple years were often found attached, in which case the most recent tag was used to assign ages to the traps; if in a trawl, the most recent tag year was applied to all traps for age estimation. Traps that were fully buried, upside down, or had other unusual circumstances (e.g. ripped apart due to grappling) were removed from the analysis.

Data exploration and analysis were performed using the statistical open-source software R (R Core Team, 2022). Traps with known ages were used to develop a model of age predicted from their fouling community. Recursive partitioning methods, such as random forest, are a popular tool to classify datasets with large numbers of predictor variables with complex interactions and can be used to predict outcomes (Strobl, Malley & Tutz, 2009). Random forest models have proven to handle datasets with a large number of variables of different quality (e.g. missing values, high noise) with high accuracy even when presented with multicollinearity (Stroble et al., 2009; Antoniadis et al., 2021). Random forest works by creating a set of classification decision trees by calculating cut points to create binary outputs. In random forest, this is conducted for many permutations, creating a forest of decision trees (in this case 1,000) by either bootstrapping or subsampling the training dataset across each permutation and a set of predictor variables are randomly restricted in each split. This combination of restrictive splits and bootstrapped/subsampling during multiple permutations creates an improved model even from weak splits (Strobl et al., 2009). Random forest models were developed using the R package "RandomForest" (Liaw & Wiener, 2014).

3. RESULTS

Between 2017 and 2021, a total of 379 traps were photo documented during the seasonal closure of Cape Cod Bay. Of the 379 traps, 223 were of known age ranging between 1-22 years (Table 1) and 156 were of unknown ages (Table 2). As 79% of the traps were recovered from Provincetown waters, in which there is a known concentration of ALDFG, the ages of Provincetown-recovered traps were compared to those recovered elsewhere in Cape Cod Bay to identify trends in these areas (Figure 4). Previous recovery efforts by this programme (the only programme in the state) in 2013 and 2014 did not include photo documentation. These efforts removed 282 and 304 traps respectively and 49% were dated between 1999-2014. The average ages of the traps were 4.0 and 5.4 years for 2013 and 2014 respectively (Figure 4). Traps deployed prior to 2005 represented 11%, between 2005-2010 represented 39%, and traps deployed between 2011-2013 were 50% of total traps recovered.

Fouling community percentage cover ranged greatly (6-100% fouled) with general trends of succession occurring with organisms such as barnacles and sea anemones having higher abundances for younger traps; sponges peaking within the middle of the age distribution and the fouling matrix; and blue mussels increasing their cover over time (Table 1). Out of 75 possible assessment points per trap, between 0-10 points were occasionally removed due to placement on the reference bar or placement that prevented accurate assessment.

Models were developed and certain variables were combined when they were positively correlated with each other (Spearman's Rank) such as attached sponges, encrusted sponges and fouling matrix, resulting in reduced noise and improving the model. Year zero traps were added to improve the model as 100% bare traps, which represent initial trap conditions (a 100% bare trap has no fouling organisms attached). After removal of outliers (i.e. traps destroyed or majority of the organisms removed during the recovery process) and fully buried traps, the final model developed included, in order of importance; "Sponge and Fouling Matrix", "Bare Trap", "Crushed", "Depth", "Bottom Type", "Survey Year", and "Blue Mussel" (Figure 5). A final decision tree was created, identifying how the variables split at each break (Figure 6). To test the accuracy of the model, a randomly selected 15% of the known traps were omitted from the model and instead used as a test set (Table 1). A linear model was used to identify the relationship between predicted and actual ages ($R^2=0.602$ $P< 0.001$*). Ages of traps under 9 years old were overestimated, while ages of traps older than 9 years were underestimated. To reduce this error, a constant was applied based on the error identified as "*Model Age Estimation* * (0.90) * (sqrt(*Model Age Estimation*/9))". The outputs of the model with the addition of this constant improved the average estimation error from -1.8 years to -1.2 years difference and improved the R^2 value to 0.634 (Figure 7).

Known trap ages averaged 9.7 years (n=46) in 2017, 10.6 years (n=43)s in 2019, 11.3 years (n=58) in 2020 and 10.2 years (n=77) in 2021 (Figure 8). Modelled ages for unknown traps followed a similar age distribution pattern: 9.4 years (n=35) in 2017, 10.4 years (n=41) in 2019, 11.05 years (n=61) in 2020, and 9.82 years (n=46) in 2021 (Figure 8).

4. DISCUSSION

While fouling community composition data are intrinsically noisy, the random forest's utility to decipher the smallest patterns enabled the lobster traps recovered from the ocean to be confidently aged. Although estimation of individual trap age accuracy may differ from the actual age, the overall performance of the model to describe the population of traps to within 2 years allowed for a greater understanding of both the efforts to remove traps from the ocean and the annual input of lost gear. Ageing gear by tag year is not a perfect approach, as more recent tags may fall off, leaving older tags to convey an earlier loss date, which may partially explain the approximately 1-2 year deviation in the model. The loss of a newer tag would result in the next oldest tag assigning the age to the trap as many fishermen who deploy traps do not remove old trap tags each year. In addition, traps deployed and lost at the start of the season (May) or the end of the season (December) would have the same tag year, changing the initial succession of organisms attached. These variables of seasonal organisms during the first year and a large (8--month) window explain some of the deviation in the model from the known ages based on the tags.

Approximately 50% of the traps recovered between 2017 and 2021 were known to have been deposited in the bay between 2005 and 2010, indicating that the population of ALDFG traps after 2010 were deposited at a slower rate (compared to 2005-2010), and that traps lost prior to 2005 were either deposited at a slower rate, or have disintegrated. In addition, the traps that were recovered in 2013 and 2014 were on average 4-5 years old and 39% were deployed between 2005-2010, supporting the findings of this analysis. These findings are significant when put in the context of regulations implemented in 2005 requiring the use of sinking ground lines for the prevention of whale entanglement. These regulations went into effect on January 1, 2007, and as with any new regulation a period of adjustment to the newly mandated gear was required. In addition, the seasonal gear closure was implemented starting in 2015, thereby removing traps that are likely to be subject to loss from winter storms.

From the perspective of debris removal, identifying pulses and rates of gear loss aids in resource (boat time and funds) allocation and allows for more efficient and effective removal efforts by identifying areas with gear that can be either recycled or reused. To verify this, long-term monitoring would be needed to identify the longevity of ALDFG in Cape Cod Bay. Traps recovered in Provincetown appeared to be on average 4-5 years old deployed in 2013-2014 and 10-11 years old from 2017 to 2021, indicating that there has been a steady deposition of traps after 2017 as the age demographic is neither increasing nor decreasing.

Conversely, traps recovered elsewhere have been increasing in age, indicating that there were years with many traps deposited; and the rate of trap deposition has slowed as fewer new traps are being recovered (Figure 9) either from effective recovery efforts or better management of gear. It is generally understood that marine debris removal efforts are an imperfect solution to gear loss, with volume of debris deposition often outpacing removal rates. The Massachusetts recreational and commercial lobster fleets were surveyed and were estimated to lose 2,633 to 6,951 traps per year in Cape Cod Bay alone (MA DMF, 2012). This indicates that current efforts here are removing only a small fraction of gear lost in Massachusetts waters.

Developing more efficient methods to prioritize trap removal should be undertaken as resources for removal are limited. Understanding the demographics of a derelict trap population and the localized impacts they have will help managers focus efforts in the long-term (Clark et al., 2012; Agamuthu et al., 2019; Stevens, 2020). For example, traps deposited in sensitive habitat such as a reef or submerged aquatic vegetation should be prioritized with strategic recovery (recovery involving divers, or in a manner that avoids dragging the trap across the habitat) to prevent further damage to the habitat and to prevent the trap from moving. Traps which can move due to storm or entanglement in other gear would pose a continuous threat to the system they reside in (Clark et al., 2012), or degrade into smaller parts making it more difficult to identify or access. Conversely, traps lost may begin to bury and pose little risk of moving and may provide structure for organisms. Although the natural soft sediment beds provide important habitat for sediment dwellings organisms such as polychaetes and bivalves, the structure provided by artificial reefs is known to increase the species diversity of both benthic and reef dwelling micro- and macroinvertebrates as well as fishes and attached submerged aquatic vegetation (Babcock et al., 2020, Harrison & Rousseau, 2020). For example, examination of wrecks and structures in the Stellwagen Bank National Marine Sanctuary, 10 kilometres north of the study site, indicates that the unplanned creation of artificial reefs from shipwrecks provides important habitat in the sanctuary and should be preserved, while removal could damage the ecosystem (Meyer-Kaiser et al., 2022). Although these traps may not provide the same value of habitat as a shipwreck, when presented with limited funding, a programme could prioritize the removal of gear that can be recycled or reused over that which is encrusted and increasing the biodiversity in an area.

Species-of-importance have been identified growing on ALDFG, particularly on lost lobster traps. These species groups include sponges, bivalves and submerged aquatic vegetation such as kelp, among other reef dwelling organisms (Eno et al., 2001; Lumsden et al., 2007; Schweitzer et al., 2018). Traps are known to provide structure for juvenile fishes and for attachment of eggs of squid, skates, gastropods, and fishes (Renchen et al., 2014; Enrichetti et al., 2021). In the recovery described here, several species were documented (minimum count =16) using these traps as habitat including the Ocean Pout (*Zoarces americanus*) which is a protected species. The role of derelict lobster traps as hard structures and the potential ecosystem services they provide should be further explored in the context of artificial reefs.

Artificial reef programmes in many regions aim to supplement the loss of hard and rugose substrate that have been lost to anthropogenic impacts (e.g. sedimentation, dredging, and nutrification). Artificial reef programmes restore or create habitats by seeding areas with artificial structures as a foundation for organisms to grow on (Pickering, Whitmarsh & Jensen, 1999; Lima, Zalmon & Love, 2019; Harrison & Rousseau, 2020). Lost gear such as immobilized traps can perform this exact function by allowing desirable organisms such as bivalves, sponges, and submerged aquatic vegetation to exist in areas otherwise devoid of those organisms. These "reefs" have been shown to support diverse fish communities and increase the biodiversity of an area. Removal of traps can also influence the surrounding substrate through excavation if the traps are buried or partially buried (Schweitzer et al., 2018; Goodman et al., 2021). The excavation can be extensive, damaging and result in scouring of the benthic habitats for tens of metres, causing damage that can last if it occurs in slow-to-recover habitats such as reefs or seagrasses.

A problem with considering lost gear's role as an artificial reef is the uncontrolled placement of the traps, which can pose a risk for navigation and conflict with other fisheries (Paxton et al., 2022). The decay of gear can release microplastics into the ecosystem, a global problem that has come to light in recent years (Pawar et al., 2016; Schuyler et al., 2018; Agamuthu et al., 2019). In addition, the line associated with lost trap gear provides no known benefits and also can degrade into microplastics (Stevens, 2020). By ageing and quantifying the condition of gear present, practitioners can identify areas with newly deposited trap gear which should be prioritized as they pose the greatest risk for entanglement or entrapment, possess the greatest likelihood for recycling, are the easiest to remove, and likely will release the smallest amount of microplastics into the system during removal.

The data from this analysis are currently being utilized by the recovery programme for their 2023-2024 recovery efforts. The purpose of this programme is to remove gear that is unmarked and untended, and either recycled or returned to the owners. As this programme reaches 10 years of work, the data provided in this study allow for places that have high numbers of traps continuously being deposited to be identified (i.e. Provincetown) and that efforts to remove the gear in the remainder of Cape Cod Bay have been successful in removing gear faster than it is being deposited (rising average age). This has allowed the limited time and funds to be focused in the Provincetown area where there are known high abundances of traps (through mapping and grappling efforts) in the 2023-2024 season. Once the trend in trap ages starts to increase in age off Provincetown, it will be time to reassess efforts and choose additional locations to collect gear.

5. IMPLICATIONS FOR CONSERVATION

Removal of gear has two intrinsic values to conservation. First, it can prevent damage to habitat caused by their movement during storm events, which impacts the benthos and creates a consequent breakdown of plastics into the environment. Second, the recovered gear can be either recycled or reused in the fishing fleet, reducing waste and costs. However, the removal of gear needs to be strategic. If the gear is no longer mobile (buried) and is heavily encrusted and degraded, it can no longer be reused and recycled. The removal of gear in this state may damage the substrate or break the traps up, further re-suspending microplastics. This study presents a means for ongoing recovery efforts to prioritize areas based on the age demographics of the gear being recovered.

Calculating the age of a derelict lobster trap population aids in identifying the rate of lost gear and identifying areas to be prioritized for future recovery. The rate of fishing gear being lost in the ocean is an important metric for conservation efforts. Understanding the scale of the problem helps quantify the amount of gear in the ocean, the areas most affected, and the impact it has on marine wildlife. This information can be used to prioritize conservation efforts at large scales and improve the effectiveness of removal efforts at finer scales. Additionally, knowing the rate of loss of fishing gear can help identify hotspots where lost gear accumulates, and develop solutions to reduce its impact. Mitigating the impacts of lost fishing gear can help protect marine ecosystems and wildlife, reduce ghost fishing, and improve the sustainability of fishing practices. Understanding the age demographic of ALDFG allows managers to prioritize mitigation and removal strategies. Removal of gear that can be recycled or returned to the owners should be the focus of trap removal. Traps of any age which are in sensitive habitats or pose a risk to navigation or fishing should be addressed in a strategic manner. Old traps with extensive fouling may provide some ecosystem services and could be a lower priority. Overall, removal of gear is not a long-term solution; and prevention of ALDFG has the greatest implications for conservation.

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FIGURE LIST

Figure 1 Cape Cod Bay, Massachusetts, USA and location of recovered traps in this study. Known trap ages indicated in Black and traps with modeled ages in Red.

Figure 2 A trap deployed for 12 years and recovered with fouling community attached (note 30 cm graduated scale bar).

Figure 3 Examples of traps of known ages from 1-16 years (age identified on each image) deployed and an example of the random point distribution for the percentage cover assessment.

Figure 4 Mean age of traps recovered in Provincetown and the rest of Cape Cod Bay across each survey year.

Figure 5 The importance of variables based on permutation in the final model with seven features ranked from most important to least important: sponge and fouling matrix, bare trap, crushed, depth, bottom type (mud, sand, or a mix), survey year, and blue mussels.

Figure 6 A decision tree example of breaks in variables (sponge and fouling matrix, bare trap, crushed, depth, bottom type (mud, sand, or a mix), survey year, and blue mussels) for age classification based on benthic cover. The outputs (end of branches) are the model age of the traps.

Figure 7 Modelled ages (x) and actual ages (y) from the 15% of traps randomly selected to test the model, indicating a linear relationship (R^2=0.634) (red).

Figure 8 Smoothed distributions of modelled ages of unknown traps (top) and known traps (bottom) across each survey year. Distributions smoothed (loess) in ggplot.

Figure 9 Year each trap was lost from back calculating ages from both the model traps and known traps across each. Peak trap loss occurred between 2005-2010 for all years traps were recovered. Distributions smoothed (loess) in ggplot.