



Ecosystem-Service Scaling Techniques to Evaluate the Benefits of Marine Debris Removal

Adam Domanski¹ · Amanda L. Lavery²

Received: 20 November 2021 / Accepted: 17 March 2022 / Published online: 1 April 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract

While knowledge of the ecological impacts of marine debris is continually advancing, methods to evaluate the comparative scale of these impacts are less well developed. In the case of costly environmental restoration in marine and coastal environments, quantifying and comparing the ecological impacts of diverse forms of ecosystem injuries can facilitate a more efficient selection of restoration projects. This article proposes evaluating marine debris removal projects in an ecological service equivalency analysis framework that can be used to compare marine debris removal to other types of environmental restoration. Drawing on existing spatial and temporal data with respect to marine debris impacts on habitats and resources, we demonstrate how resource managers and organizations involved in marine debris removal can quantify the ecological service benefits of a removal project and use it to comparatively select between projects based on present value ecological benefits. This valuation can be useful in natural resource damage assessment restoration selection, and for directing limited funds to marine debris removal projects which produce the greatest gains in ecological services. This ecological scaling framework is applied to a seagrass injury case study to demonstrate its application for scaling marine debris removal as compensatory restoration.

Keywords Marine debris · Ecosystem services · Natural resource damage assessment · Habitat-based resource equivalency analysis · Habitat equivalency analysis · Resource equivalency analysis

Introduction

Marine debris is the cause of significant ecological and economic harm. It can scour, break, and smother marine habitats and cause significant damage (Derraik 2002; Browne et al. 2015; Sheavly and Register 2007); it can entangle, trap, or be ingested by wildlife, which can lead to serious injury, illness, suffocation, starvation, and death (Derraik 2002; Gall and Thompson 2015; Laist 1987); and, it can also present navigational hazards for ships and result in costly vessel damage (Sheavly and Register 2007). Along shorelines, marine debris can impact beach recreation

(Leggett et al. 2018; McIlgorm et al. 2011; Newman et al. 2015) and can cause physical damage to important habitats including marshes, coral reefs, and the benthos (Browne et al. 2015; Gilardi et al. 2010; Uhrin et al. 2005; Lewis et al. 2009; Uhrin and Schellinger 2011). Debris can also damage submerged aquatic vegetation (SAV) and their associated communities by shading, crushing, or suffocating plants for long periods of time (Lord-Boring et al. 2004; Uhrin et al. 2005; Uhrin et al. 2014). Because SAV buffers wave energy, stabilizes sediments, prevents erosion, and recycles nutrients, these scouring impacts are often a source of significant loss in ecological services (Lord-Boring et al. 2004; Whitfield et al. 2002). Further, debris in these sensitive habitats can become recurrently displaced and grounded during tidal cycles or storm events, which can greatly increase the area of impact beyond the typical debris footprint (Lewis et al. 2009; Uhrin et al. 2005; Whitfield et al. 2002).

Debris also has numerous direct impacts to animals. Entanglement and ingestion have been recorded in tens of thousands of individuals and at least 395 species, including all known species of sea turtles, 54 percent of marine

✉ Adam Domanski
domanski@enduringecon.com

¹ Enduring Econometrics, 1455 NW Leary Way Ste. 400, Seattle, WA 98107, United States

² National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Office of the Chief Financial Officer, Program Analysis Branch, 1335 East West Highway, Silver Spring, MD 20910, USA

mammal species, and 56 percent of seabird species (Gall and Thompson 2015). Wildlife entanglement in derelict nets, fishing lines, ropes, and other debris can create significant risks ranging from external wounds to strangulation and death (Gall and Thompson 2015). Derelict fishing gear can also continue to catch and kill ocean life for years by ghost fishing, which can also be described in terms of economic loss (Brown and Macfadyen 2007; Masompour et al. 2018). For example, Scheld et al. (2016) combined spatially resolved data on derelict pot removal with commercial blue crab harvest and showed that removing 34,408 derelict pots led to 13,504 metric tons in additional harvest, valued at \$24.9 million.¹

To help address these impacts, NGOs and local, state, and federal governments worldwide have funded numerous removal efforts. For instance, from 2006 to 2014, the National Oceanic and Atmospheric Administration's Marine Debris Program awarded nearly \$14 million through 137 competitive grants that removed over 7000 tons of debris and logged over 258,000 volunteer hours (NOAA, 2019). The majority of these removals focus on derelict fishing gear and abandoned and derelict vessels. Many removal projects report the type and mass of debris removed, but there are limited established methods to compare the relative ecological gains from marine debris removal to other options for improving environmental conditions. Generally, the information captured in final reports are tons of debris removed, acres or linear miles cleaned, and numbers of volunteers and hours logged. While these measures provide an impressive glance at the magnitude of removal efforts, they provide limited information on the ecological services gained from removal and serve as an incomplete proxy for environmental benefit.

Ecological service equivalency analysis approaches, such as Habitat Equivalency Analysis (HEA), Resource Equivalency Analysis (REA), and the Habitat-Based Resource Equivalency Method (HaBREM) can be applied to better evaluate the benefits of removal projects using a common set of metrics (Baker et al. 2020). These equivalency approaches are regularly employed to evaluate the amount of restoration required to compensate the public from a natural resource injury by applying information on the spatial and temporal change in ecological services resulting from an oil spill, hazardous waste contamination, or ecological restoration (Dunford et al. 2004; Thur 2007; Zafonte and Hampton 2007). Also known as service-to-service and resource-to-resource scaling, these approaches use information on habitat baseline conditions, time periods of injury, and the spatial extent of injury to measure the

relative decline or gain in ecological services from an injury or restoration across space and time. This translates the flow of ecological services over time into a present value stock. Given that the services lost from an injury are of equivalent or known value to those gained from restoration (known as the equivalent-value assumption), these values can then be compared across restoration project alternatives (Desvougues et al. 2018). HEA and REA have a wide variety of existing uses and we demonstrate their application to marine debris removal. In this paper, we describe the data needs and mechanics of HEA and REA, as well as available existing data on the impacts of marine debris, specifically derelict fishing gear. We also apply equivalency approaches to a hypothetical seagrass injury and restoration scenario, and finally conclude with a discussion of the results and implications for future work.

Methods

Ecological Service Equivalency Analysis

Ecological services are broadly defined in the literature as societal benefits from ecosystem provided resources and processes (e.g., food, climate regulation, recreation, and primary production) (National Research Council 2013). When these services need to be quantified and compared, equivalency approaches relate the relative health and function of a given habitat/resource to another unimpacted habitat/resource of the same type. For example, when natural resources are injured by an oil spill or hazardous waste contamination, natural resource Trustees often use ecological service equivalency analysis approaches to determine the amount of compensatory restoration required to replace the lost ecological services that would have been provided by the injured resource (Baker et al. 2020). Trustees utilize a set of ecological indicators to determine the relative level of ecological services lost due to a spill, as well as the services provided by a given restoration project. These approaches have found broad application from evaluating oil spills (Kim et al. 2017; Li and Wang 2012; Penn and Tomasi 2002), hazardous waste contamination (Cacela et al. 2005), biodiversity credits (Bruggeman et al. 2005), environmental policy evaluation (Roach and Wade 2006), coral reef restoration (Viehman et al. 2009; Milon and Dodge 2001), wildfires (Hanson et al. 2013), invasive species (Johnston et al. 2015), the cost effectiveness of restoration (Scemama and Levrel 2016), storm protection benefits (Wellman et al. 2017), rainforest destruction (Pavanelli and Voulvoulis 2019), and compensation ratios for tribal cultural resources (Duffield et al. 2021). Their application to evaluating impacts from marine debris, as we propose here, is a natural extension.

¹ All dollar values reported in this paper have been adjusted to 2021 values using the U.S. Bureau of Labor Statistics' Consumer Price Index for all Urban Consumers (CPI-U).

Habitat Equivalency Analysis

When applied to habitats, this approach (HEA) uses metrics representing the set of ecological services flowing from a habitat (and their relative change as a percentage of total services provided) over time as inputs.² Using a fixed discount rate r ,³ the present value stock of services, S , from a given habitat, h , is calculated as the integral of discounted service flows over time, t , multiplied by the spatial area, A_h , from which those services are generated. This value, for a given habitat, is referred to as discounted service acre years ($DSAYS_h$) and is calculated as:

$$DSAYS_h = A_h \cdot \int_t^T e^{-rt} \cdot (S_{h,0}(t) - S_{h,1}(t)) dt \quad (1)$$

The approach measures both the loss of ecological services caused by an injury as well as the gain in services from a given restoration project. The restoration project is then scaled to provide restoration of an appropriate magnitude so that the DSAYs lost equal the DSAYs gained. An example is displayed in Fig. 1 below. The red line indicates the decline in ecological services as a result of an oil spill, hazardous waste contamination, or vessel grounding. After the event, the habitat slowly recovers back to the baseline condition that would have been present without the injury. The total injury is represented by the area A. In year 2, a restoration project such as a new or improved wetland is constructed that creates ecological services that are the same type and value as those lost due to the injury. This restored wetland continues to produce services over its lifetime, which in this example is 10 years. The restored wetland is large enough so that the ecological services gained, represented by the area B, is equal to the ecological services lost (area A).

The impact that a piece of marine debris has on the ecological services provided by a habitat can also be calculated in terms of $DSAYS_h$ if the spatial area, decline in percentage of services provided, and temporal extent of impacts are known. The spatial area can be quantified by the footprint of the debris' impact (e.g., the area smothered or scoured). The change in services can be measured using one or more ecological service indicators such as faunal abundance, vegetation density, or some other measure of ecological function compared to baseline (converted to a percentage basis). The temporal

extent of impacts can be measured by the time it takes for the habitat to fully recover once a piece of debris is removed. The net benefits of the debris removal is characterized by the change in $DSAYS_h$ relative to the ecological services provided by the habitat in an unimpaired baseline state.

Resource Equivalency Analysis

When applied to marine fauna, this approach (REA), functions in a similar fashion, however it now captures the flow of ecological services provided by an animal over its lifetime. For instance, the general set of ecological services provided by an animal for any year related in present value terms is a discounted-species-year, or DSY . These services are provided in a binary condition by the existence of the animal, so marginal declines in services are not applied in a REA. $DSYs$ for a given species are calculated:

$$DSYs_a = \int_t^T e^{-rt} \cdot (Q_{a,0}(t) - Q_{a,1}(t)) dt \quad (2)$$

where $Q_a(t)$ is the quantity of animal-years in a given state. This approach can also incorporate information on the life history (e.g., survival and fecundity) of the species.

Many types of marine debris cause both habitat and resource impacts. Derelict fishing gear can smother, scour, or degrade sensitive habitats, while also continuing to capture and kill animals (ghost fishing) (Brown and Macfadyen 2007; Uhrin et al. 2005). These impacts can be evaluated using the equivalency framework, with information on the habitat area affected, number of animals (of various species and life stages) killed by ghost fishing, and duration of impacts informing the respective inputs in Eqs. 1 and 2 above. Additional information on the timing of removal and ultimate natural degradation of the debris is necessary to calculate the benefits (e.g., forgone injury) of removing debris.

For example, a piece of derelict fishing gear will cause impacts to the surrounding habitat, reducing the flow of ecological services normally provided. This is indicated in Fig. 2 below by the initial reduction in services. Over time, marine debris may degrade to the point at which the impacts cease (Lewis et al. 2009). At this point, the habitat can slowly recover, indicated by the return to baseline in the figure between years eight and ten. The total ecological service loss as a result of the debris is the total area between the injury curve (in red) and baseline (zero), indicated by the area C + D. If this piece of derelict fishing gear were found and removed at year two, the habitat begins to recover sooner, and the total ecological service loss would only be the area C. The area D, in this example, represents the benefits (i.e., injury foregone) of removing the debris.

² The HaBREM approach is a similar habitat-based assessment technique that can be applied to the measurement of impacts from marine debris, however the scaling metric applied is some objective measure of habitat productivity rather than the degree of ecological services provided. Additional discussion can be found in Baker et al. (2020).

³ A description of the choice of the discount rate in HEA and REA can be found in Julius (1999).

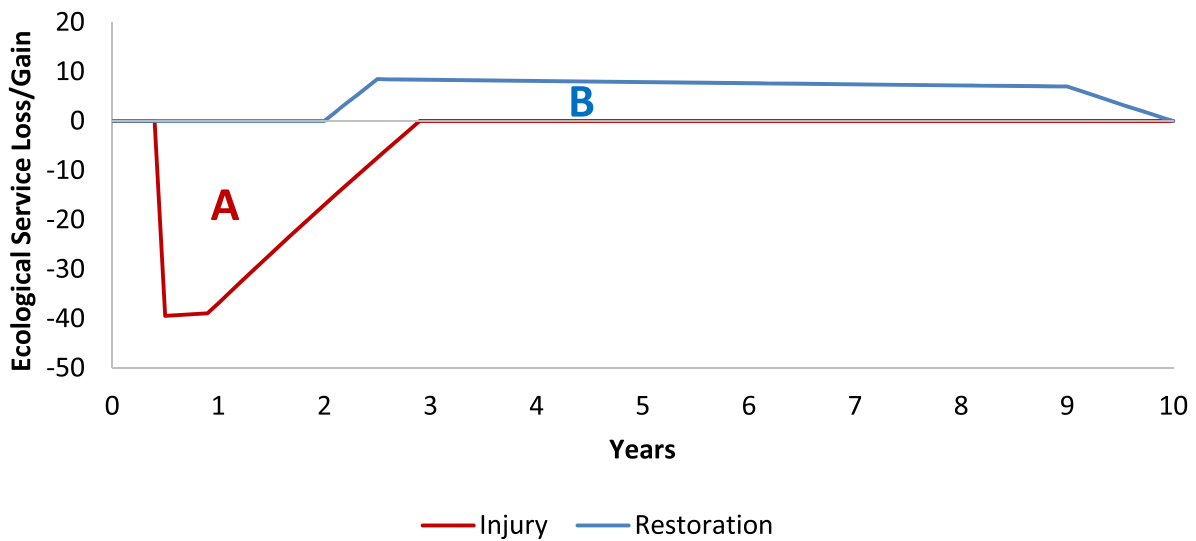


Fig. 1 Injury/Restoration Scaling with Traditional Habitat Enhancement. NOTE: The cumulative habitat injury is denoted by the area “A,” while the cumulative compensatory restoration is denoted by the

area “B.” The HEA approach determines the amount of compensatory restoration needed (often in acres), such that the restoration benefits fully offset the losses such that areas “A” and “B” are equal

Fig. 2 Derelict Fishing Gear Habitat Impacts. NOTE: The cumulative habitat injury without any trap removal is denoted by the areas “C” and “D.” Finding a trap and removing it will prevent injury denoted by the area “D”

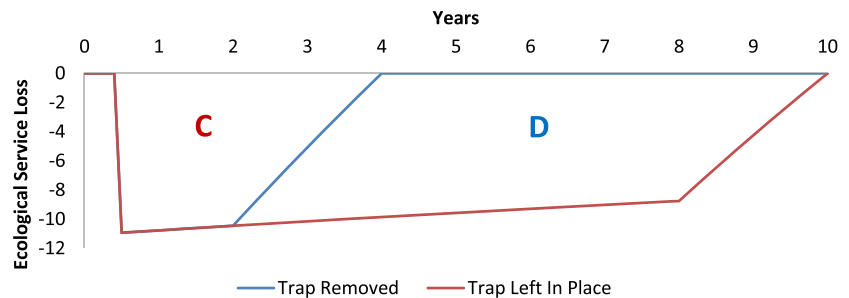
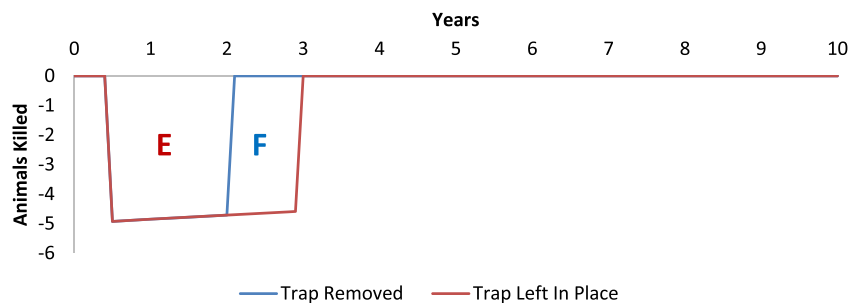


Fig. 3 Derelict Fishing Gear Ghost Fishing Impacts. NOTE: The cumulative animals killed via ghost fishing without any trap removal is denoted by the areas “E” and “F.” Finding a trap and removing it will prevent injury denoted by the area “F”



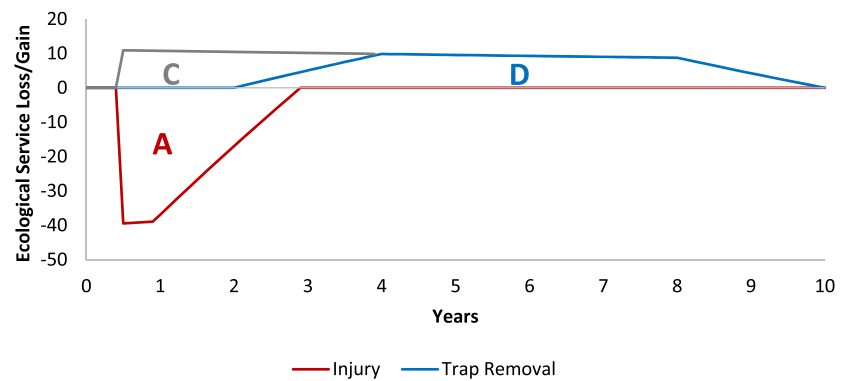
A similar framework applies for evaluating ghost fishing impacts of the same piece of debris. Derelict fishing gear has the capacity to continue to catch and kill animals until it degrades or is removed (Arthur et al. 2020; Butler and Matthews 2015; Matsuoka et al. 2005). Fig. 3 below indicates the lost resource services from derelict fishing gear (area E + F), and the benefits (injury foregone) of removing the same piece of derelict gear at year 2 (area F). In this example, the ghost fishing injury ends before the habitat injury because, generally, derelict fishing gear stops ghost fishing before the gear completely disintegrates (through the use of elements like a degradable panel that allow animals

to escape when left on the seafloor for an extended period) (Bilkovic et al. 2016). Additionally, in this model, there is no gradual recovery in resource impacts because the ghost fishing impacts are measured by animals killed. When a trap stops ghost fishing, animals stop being killed and the service losses end.⁴

To demonstrate how marine debris removal can compensate for an ecological injury, we combine Fig. 2 with the injury scenario from Fig. 1. To scale the benefits of removal

⁴ REAs also can incorporate reproductive services, losses, and effects. For an example and discussion, see USFWS (2016).

Fig. 4 Habitat Injury/Restoration Scaling with Trap Removal. NOTE: The benefits of a trap removal program are denoted by the area “D.” Removal projects can be designed such that the scale of benefits fully offsets some other injury, denoted by the area “A.” The area “C” denotes injury caused by derelict traps before they are removed, and this is not considered in the compensatory calculations



to an injury, Fig. 2 is inverted and placed above the injury in Fig. 1, as indicated in Fig. 4 below. Area A remains the ecological injury from an oil spill, hazardous waste contamination, or vessel grounding. Area C + D is the total habitat injury from derelict fishing gear that is not removed. Area C is the portion of the debris injury that occurs before the derelict fishing gear is removed. This injury occurs independent of the spill/release and the benefits of debris removal accrue from avoided debris-caused injury. Area D represents the benefits of removing the derelict fishing gear, and a sufficient amount of gear is removed so that areas A and D are equal.

The approach for identifying the relevant inputs to perform restoration scaling for marine debris removal is detailed in the next section.

Marine Debris Impacts

To demonstrate the data needs of equivalency approaches, we focus on the known impacts of derelict fishing gear, specifically the habitat scouring impacts of traps and the ghost fishing impacts of traps and nets.

Review of Literature and Data Sources

There is a large and growing literature on the impacts of marine debris on habitats and resources. In this paper, we limited the scope of review of the current literature to only English-speaking publications and included only papers published in academic journals or official reports – excluding books, chapters of books, and conference proceedings. We identified a series of keywords and used various combinations of the following Boolean search terms in Google Scholar: HEA, REA, marine, pollution, debris, habitat, animal, impacts, net, trap, ghost, abandoned, lost, discarded, derelict, fishing, and gear. The literature search was also complemented by contacting relevant experts in the field and by checking articles that cited other individual studies.

Habitat Scouring - Traps

Marine debris stranded in a wetland or benthic habitat, can cause direct impairment via smothering or scouring.⁵ Uhrin and Schellinger (2011) showed that wire blue crab traps and vehicle tires resting on top of salt marsh plants (*Spartina alterniflora*) for extended periods cause stems and blades to become broken, abraded, or crushed. The sustained injuries vary considerably between the two debris types. Tires caused an immediate (within 3 weeks) and long-term impact to salt marsh plants as measured by declines in stem density and stem height. In contrast, crab pot impacts were not as immediate, and recovery was quicker (less than 10 months) than recovery for tires (greater than 14 months). After thirteen weeks of crab pot deployment, the study found that live seagrass stem height and live stem density were significantly decreased (57% and 67%) (Table 1). Following crab pot removal, stem density took twice as long to recover than stem height (Uhrin and Schellinger 2011). Uhrin et al. (2005) determined that commercial spiny lobster traps left beyond 6 weeks inflicted substantial injuries on seagrass beds.

Other studies that do not evaluate marine debris also provide information that can inform recovery rates following marine debris removal (Table 1). For example, scarring has been shown to significantly lower total macrofaunal and species abundance, while also leaving remaining seagrass habitat susceptible to erosion (Hammerstrom et al. 2007; Uhrin and Holmquist 2003; Whitfield et al. 2002). Recovery in scour areas that are more than 20 centimeters deep take two to five years longer than recovery in shallower disturbances that are less than 10 centimeters deep (Hammerstrom et al. 2007). Recovery may also depend on location and species. For tropical and sub-tropical seagrass species, injuries to turtle grass (*Thalassia testudinum*) displayed slower rates of recovery in an estuary in Tampa Bay

⁵ Marine debris also has the potential to provide habitat enhancement in some areas by serving as hard bottom substrate (Havens et al. 2008). A full accounting of ecological service changes must net out all losses and gains.

Table 1 Habitat Impacts of Derelict Traps and Vessels

Reference	Gear Type	Habitat	Region	% Decline	Time to Full Recovery	Gear Footprint
Butler and Matthews 2015	Spiny Lobster Traps	Seagrass and Sandy Bottom	FL	–	–	0.49 m ²
Dawes et al. 1997	Propeller and Artificial Scars	Seagrass	FL	–	3.5–4.1 yrs. (propeller); 7.6 yrs. (artificial)	–
Kenworthy et al. 2002	Propeller Scars	Seagrass	FL	–	<2.6 yrs. (<i>S.filiforme</i> , <i>H.wrightii</i>); 8.5–13.5 (<i>T.testudinum</i>)	–
Lewis et al. 2009	Spiny Lobster Traps	Hardbottom and Reef	FL	14% (4 m) 10% (8 m) 6% (12 m) (Percent Cover)*	–	0.45 m ²
Uhrin and Schellinger 2011	Wire Blue Crab Traps	Saltmarsh	NC	57.3% (Stem Height) 67.4% (Stem Density)	<10 months (<i>S.alterniflora</i>)	0.37 m ²
Uhrin et al. 2005	Spiny Lobster Traps	Seagrass	FL	>20% (Shoot Density)	4 months (<i>T.testudinum</i>) >8 months (<i>S.filiforme</i>)	0.9 m ²
Zieman 1976	Propeller Scars	Seagrass	FL	–	2–5 years	–

Note: This table describes some existing literature values that can inform a scaling of the habitat benefits of trap removal

*Percent cover of sessile fauna is the difference between control areas and experimental sites along the trap movement path for both buoyed and unbuoyed traps at three depths (4, 8, 12 m)

(Dawes et al. 1997; 3.5–7.6 years) when compared to estimates for the Florida Keys (Zieman 1976; 2–5 years).

If a trap is not removed, it may eventually degrade, assimilate into benthic structure, or move due to storms and wind events, resulting in further damage beyond the trap footprint (Lewis et al. 2009; Uhrin et al. 2005). There are a limited number of studies that have evaluated the persistence of derelict traps and their impacts on habitat. Many studies focus instead on the duration of ghost fishing impacts and incidentally measure trap degradation. For example, Butler and Matthews (2015) determined that wooden and hybrid traps remain intact and continue to ghostfish from 1 to 2 years, while wire traps did so for two or more. Additionally, they showed that offshore traps decayed more rapidly than inshore or bay locations, providing evidence that location and depth can also impact decay rates. Lewis et al. (2009) conducted trap movement studies and showed that some traps were reduced to wooden slats and concrete slabs, but noted that plastic and plastic coated fishing materials likely persist in the environment indefinitely. Empirical studies of long-term trap degradation and the resulting relationship to ecological service impacts, however, are limited, particularly when considering the wide variety of trap types, materials, and habitats.⁶ Further research on the ultimate disposition of traps and their relationship to habitat function is warranted.

⁶ Most studies to date have focused on ghost fishing impacts rather than the degradation of traps in their entirety.

Ghost Fishing – Traps

A number of studies have evaluated ghost fishing impacts from derelict crab and lobster traps using various techniques to determine the quantity of trap debris including side scan sonar, diver tows, deployed cameras, SCUBA surveys, and modeling (Antonelis et al. 2011; Clark et al. 2012; Havens et al. 2008; Maselko et al. 2013). Some studies assessed the number of dead animals using diver surveys of ghost traps (Maselko et al. 2013) while others used field experiments (Antonelis et al. 2011; Clark et al. 2012; Havens et al. 2008). Rates of ghost fishing vary by a variety of factors including, but not limited to, trap design, location, season, depth, substrate, and relative abundance of organisms susceptible to capture (Antonelis et al. 2011; Butler and Matthews 2015; Clark et al. 2012; Gilman et al. 2016; Maselko et al. 2013). The amount of time traps continue ghost fishing was evaluated in various studies by ongoing monitoring or estimating ages of recovered derelict gear (Antonelis et al. 2011; Clark et al. 2012; Maselko et al. 2013).⁷

Across all studies reviewed (Table 2), the estimated number of individuals of target species captured and killed via ghost fishing in a given year ranged from 3 to 74.4

⁷ We use the age of derelict gear recovered as a lower bound for injury duration. Additional research is needed to quantify the time it takes for a trap to degrade to the point at which ghost fishing impacts end.

Table 2 Ghost Fishing Impacts of Derelict Traps

Reference	Gear Type	Region	Taxa	% of Traps Ghost Fishing	Total # of Animals Killed Per Trap Annually	Time Until Impacts End
Antonelis et al. 2011	Dungeness Crab Traps	WA	Dungeness Crab	–	21	>2 years
Bilkovic et al. 2014	Blue Crab Traps	VA	Blue Crab	35	18	–
Bilkovic et al. 2016	Blue Crab Traps	VA	Blue Crab	–	23	–
Butler and Matthews 2015	Spiny Lobster Traps	FL	Spiny Lobster	–	6.8 ± 1.0 (Florida Bay); 6.3 ± 0.88 (Atlantic Inshore); 3.0 ± 0.69 (Atlantic Offshore)*	480 ± 142 days (Hybrid); 509 ± 97 days (Wooden); 779.5 ± 273.5 days (Wire)
Clark et al. 2012	Wire Fish Traps	USVI	Fish	5	–	3.59 ± 0.51 months
Giordano et al. 2010	Blue Crab Traps	MD	Blue Crab	~40	20	>14 months
Guillory 1993	Blue Crab Traps	LA	Blue Crab	–	25.8	–
Maselko et al. 2013	Dungeness Crab Traps	AK	Dungeness Crab	32.5	–	>7 years
June 2007	Dungeness Crab Pots	WA	Dungeness Crab	37	74.4	>1 year
Uhrin et al. 2014	Spiny Lobster Traps	FL	Spiny Lobster	18	–	–
Whitaker 1979	Blue Crab Traps	SC	Blue Crab	–	20–60	–

Note: This table describes some existing literature values that can inform a scaling of the ghost fishing benefits of trap removal

*Butler and Matthews (2015). Total number of animals is the estimated number of lobster mortality by location. There was no significant difference in lobster mortality among trap types

(mean = 24) per trap, most commonly crustaceans and fish. The number of derelict traps found to be ghost fishing ranged between 5 and 40 percent of the total derelict traps observed (mean = 28 percent; Table 2). Antonelis et al. (2011) estimated ghost fishing persistence based on the decomposition of escape cords. They estimated that ghost fishing persistence ranged from about four months for traps with escape cords and 2.2 years or until trap degradation for traps without escape cords. Other studies have found that derelict fishing gear continues to ghost fish from 0.3 years to up to 7 years, with most studies averaging between 1 and 3 years (Table 2). Even if traps stop ghost fishing, they may still serve as aggregating devices and continue to compete with actively fishing traps (Scheld et al. 2016; 2021).

Ghost Fishing - Nets

Derelict fishing nets impair ecosystems in a functionally similar, yet quantitatively different way. The extent of ghost fishing that occurs after net loss depends on seabed conditions, habitat type, depth, abundance of fauna in a given area, presence of features upon which the gear can become entangled, and the environmental conditions to which the gear is exposed (Gilman et al. 2016; Matsuoka et al. 2005; Stelfox et al. 2016). Nets that become entangled yet remain suspended in the water column around a reef, for example, will maintain or increase the initial extent of ghost fishing for much longer periods of time than a net

that becomes balled up on the seafloor (Gilman et al. 2016; Matsuoka et al. 2005).

Mortality has been measured by conducting dive surveys and observing dead animals in nets over time (Gilardi et al. 2010), or by counting the number of animal carcasses present in nets at the time of removal (June 2007). The total number of animals killed per net varies between studies due to the measurement approach. Mortality may be reported for one given species (June 2007) or for all species observed in a net (Gilardi et al. 2010). These variations limit the ability to generate uniform estimates of ghost fishing impacts from nets. Of the studies we compared, the mean number of dead animals found per net in a given year was 287 with a range of 2.4 to 839 (Table 3). These nets were found to be ghost fishing for an average of approximately 515 days after loss, after which they break apart, become extensively colonized by biota, or are buried (Table 3).

Monte Carlo Simulation of Scaling Approach

To demonstrate how HEA and REA can be used to evaluate the ecological service benefits of debris removal, we perform two simulations using the data on traps gathered above. The first demonstrates how the approaches can compare among marine debris removal projects, while the second demonstrates the application of marine debris removal in a seagrass injury NRDA context.

Table 3 Ghost Fishing Impacts of Derelict Nets

Reference	Gear Type	Region	Taxa	Total # of Animals Killed Per Net*	Time Until Impacts End
Erzini et al. 1997	Gillnets; Trammel-Nets	Portugal	Fish; Crustaceans	344* 221*	15–20 weeks
Gilardi et al. 2010	Gillnets	United States	Invertebrates; Seabirds; Fish; Mammals	336.7 (Annually)*	>10 years
Kaiser et al. 1997	Gillnets; Trammel-Nets	United Kingdom	Fish; Crustaceans	226–839* 78–754*	70–136 days 22–136 days
Nakashima and Matsuoka 2004	Gillnets	Japan	Fish	455	142 days
Nakashima and Matsuoka 2005	Gillnets	Japan	Fish	191	>3 years
Sancho et al. 2003	Tangle Nets	Spain	Fish	2.37	224 days
Santos et al. 2003	Gillnets	Portugal	Fish	87.6	248 days

Note: This table describes some existing literature values that can inform a scaling of the ghost fishing benefits of removal. Reported values for the total number of animals killed per net are not standardized by the size of the nets. *Erzini et al. 1997. Total number of animals per net after a maximum of 120 days, when the daily catch rate began to approach zero. *Gilardi et al. 2010. Total number of animals per net annually was calculated by converting the daily catch rates to yearly catch rates, and then dividing by the four nets sampled. *Kaiser et al. 1997. Total number of animals per net after a maximum of 136 days, when the daily catch rate began to approach zero

Table 4 Inputs for Hypothetical Trap Removal Scenario

Trap Type	Habitat Type	Time Until Ghost Fishing Impacts End (Days)	Decline in Ecological Services	Habitat Recovery Time (Days)	Total # of Animals Killed Per Trap, Per Year
Wood	Seagrass	509 ± 97	20%	183 ± 30	29
Wire	Salt marsh	779.5 ± 94.5	60%	146 ± 30	2
	Seagrass		20%	183 ± 30	29
Hybrid	Seagrass	480 ± 142	20%	183 ± 30	29

Note: Other inputs common to all trap/habitat types: 3% discount rate, habitat impact persistence is three times as long as the ghost fishing persistence, each trap has an impact footprint of 0.49 m², and traps are found with equal probability over time. Certain types of traps are only used and found in certain habitats

Comparing Marine Debris Removal Projects

Resource managers are often faced with funding limitations. When choosing what type of marine debris removal project to support, it is important to consider the magnitude of ecological benefits from one type of project versus another. Suppose that a resource manager has funds to remove up to 1000 derelict traps, however, these traps vary in both type (i.e., wire, wood, or hybrid) and the habitat in which they are located (i.e., seagrass or salt marsh). Using the approaches and inputs described earlier, we conducted a HEA and a REA to determine which type of traps located on which habitat would generate the greatest ecological service benefits. Table 4 below lists all the necessary inputs for the analysis. To simplify this analysis, we assume equal spatial distribution and searcher efficiency across all types of traps and habitats. Ghost fishing duration values are applied from Butler and Matthews, 2015 by trap and habitat type. Because there have been no long-term studies focused on trap degradation, we use a simplifying assumption that traps would stop causing habitat impacts in about three times the amount of time spent

ghost fishing.⁸ This estimate will ultimately vary with the gear type, the probability of self-baiting, the prevalence of degradable escape panels, and the conditions of the environment to which it is released (Gilman et al., 2021). For the purposes of this demonstration, we consider this estimate valid because it meets the conditions that a) habitat impacts occur longer than ghost-fishing impacts, and b) the rate of trap degradation varies by trap and habitat type.

A trap removal program has inherent variability in benefits. Some of this is captured in the set of inputs in Table 4. For instance, the amount of time it takes for ghost fishing impacts to end, the time for a trap to degrade to the point where habitat impacts end, and the time necessary for a habitat to fully recover all have natural variation. The amount of time a trap sits on the bottom before it is found can also vary. A trap could be recovered a long time after it

⁸ We use this assumption for purposes of demonstrating the application of HEA to derelict fishing gear impacts. Additional research is needed to quantify the time it takes for a trap to degrade to the point at which habitat impacts end.

Fig. 5 Comparative Duration of Impacts from Trap Removal Program. NOTE: This figure displays which components of habitat and ghost fishing impacts are prevented from removal of a derelict trap

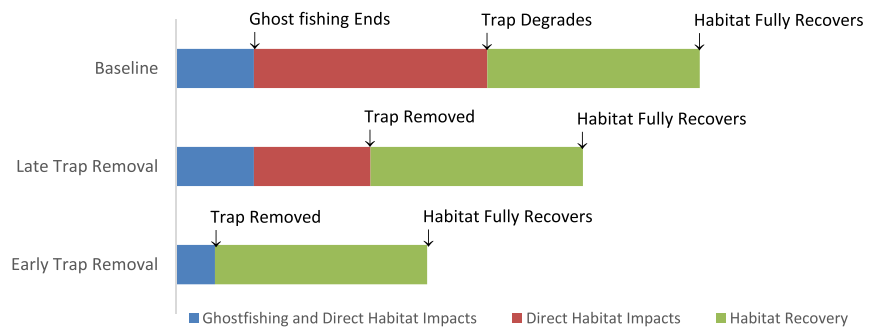


Table 5 Trap Removal Comparison Scenario Results (Per 1000 Traps)

Trap Type	Habitat Type	HEA		REA	
		Mean Dsays Gained	% Injury Reduced	Mean Days Gained	% Injury Reduced
Wood	Seagrass	0.05	42.9%	17.7	16.2%
Wire	Salt marsh	0.21	46.1%	1.9	16.3%
	Seagrass	0.07	43.7%	26.1	16.0%
Hybrid	Seagrass	0.04	41.7%	14.9	14.7%

Note: Results are reported in acre-year and animal-year terms for a 1000-trap removal project of each type-habitat combination. The relative values of seagrass and saltmarsh habitats, as well as those of fauna that die as a result of ghost fishing in either habitat are assumed to be equal in this simulation

is lost, and longer than the duration of ghost fishing impacts, as illustrated in the second bar in Fig. 5 below. In this scenario, removal leads to reductions in habitat impacts, but no reduction in ghost fishing. Alternatively, a trap could be found shortly after it is lost, leading to a reduction in both ghost fishing and habitat impacts (as illustrated in the third bar in Fig. 5).

To account for this variability in our hypothetical scenario, a Monte Carlo analysis was conducted that simulated the removal of 1000 traps from within each habitat type. Habitat recovery time was drawn from a gaussian normal distribution with means and standard deviations for each trap type set to the values in Table 4. The persistence of ghost fishing was drawn from an exponential distribution across the range of the standard deviation around the means in Table 4 for each trap type to allow for the share of traps ghost fishing to decline over time, as observed in Maselko et al., 2013. It is assumed that traps are found with equal probability over time, and thus the trap removal time was drawn from a uniform distribution across the range between trap loss and trap degradation. The habitat recovery time for wood traps was drawn from a normal distribution (of means and standard deviations in Table 2) and applied additively to the point in time at which the trap either degraded or was found and removed. This approach allows consideration of uncertainty regarding trap-specific impacts and searcher efficiency. This simulation is performed independently and results are presented in Table 5 below, per 1000 traps of each type-habitat combination removed. Generally, wire

traps took longer to degrade, habitat ecological service declines were more pronounced, but recovered more quickly on salt marsh habitat, and ghost fishing impacts were greater in seagrass.⁹

This simulation provides several objective measures of project benefits. Wire traps removed from salt marsh provide the largest benefits compared to all other trap and habitat type combinations for targeted removal. In fact, approximately four wood traps located in seagrass would have to be removed to convey the same habitat benefits as one wire trap in salt marsh.¹⁰ Even among the same trap type, three wire traps removed from salt marsh would generate the same habitat benefits of removing one trap in seagrass.¹¹ Similar comparative results are reached when evaluating the resource benefits of reduced ghost fishing, albeit with different benefits by trap-type given the

⁹ An important component of ecological service equivalency analysis is the known or equivalent value between different habitats and resources impacted. The analysis presented here assumes an equivalent ecological value between salt marsh and seagrass habitat, as well as the species and life stage affected by ghost fishing in each (e.g., terrapins and mammals in salt marsh, and fish and crustaceans in seagrass). Assuming that these habitats and fauna are fungible (i.e., exchangeable) but not of equal value, an additional scaling factor can be introduced to account for the relative value of each.

¹⁰ Calculation: $0.21 \text{ DSAYs per salt marsh-wire trap} / 0.05 \text{ DSAYs per seagrass-wood trap} = 4.2$ seagrass-wood traps removed to equal the benefits of one salt marsh-wire trap removal.

¹¹ Calculation: $0.21 \text{ DSAYs per salt marsh-wire trap} / 0.07 \text{ DSAYs per seagrass-wire trap} = 3$ seagrass-wire traps removed to equal the benefits of one salt marsh-wire trap removal.

dynamics of ghost fishing. Removal of a wire trap in seagrass habitat conveys nearly 14 times the resource benefits (i.e., reduction in ghost fishing measured on a per-individual basis) of a wire trap removed from saltmarsh.^{12,13}

It should also be noted that the method of retrieval of derelict gear differs based upon gear type as well as the habitat the gear is to be retrieved from. In some cases, it may be necessary to weigh the potential impacts to the ecosystem if the gear is left in the environment versus the potential impacts sustained by the ecosystem through removal (Jeffery et al. 2016). Trap removal should be targeted depending on the resource manager's needs, the relative value of the various habitats and species injured by ghost fishing, as well as the number of derelict traps and cost to recover them.

Seagrass Injury Case Study

The ecological service equivalency analysis approach can not only make comparisons between marine debris projects, but also between other types of injuries and restoration projects. We now apply the methodology described above to a natural resource damage assessment scenario.

On an annual basis, there are approximately 650 reported vessel groundings within the Florida Keys National Marine Sanctuary and an estimated 30,050 acres of scarred seagrasses, which reflect an increase in groundings over the past two decades (Kirsch et al. 2005). When vessels run aground in sensitive seagrass habitat, physical disturbances caused by impacts from the hull (including “blowholes” created by the propeller in efforts to dislodge the vessel) can alter the sea bottom habitat and bathymetry. Under the National Marine Sanctuaries Act, these injuries are subject to natural resource damage assessment and restoration. To investigate the extent of resource injury, NOAA and the Florida Department of Environmental Protection (FL-DEP) previously used a set of procedures and protocols to assess vessel injuries to seagrass beds (Kirsch et al. 2005). The goal of this assessment approach was to determine the scale of compensatory restoration needed to fully compensate the public for lost services. When a seagrass injury occurred, NOAA and FL-DEP used field assessments to determine the extent of injury. Field assessments included mapping the injury perimeter resulting from a vessel grounding,

¹² Calculation: 26.1 DAYs per seagrass-wire trap/1.9 DAYs per saltmarsh-wire trap = 13.7 saltmarsh-wire traps removed to equal the benefits of one seagrass-wire trap removal.

¹³ This approach takes into account the interaction between the duration and intensity of marine debris impacts, but it does not distinguish between the relative value of individuals affected by a ghost fishing trap in a salt marsh (e.g., terrapins and mammals) and in seagrass (e.g., crabs and fish), but assumes they are fungible. An additional scaling factor can be introduced to account for this difference in value if it is known.

characterizing the habitat in terms of benthic community composition, percent cover, and density (both within the injury and at reference areas adjacent to the injury) and conducting a bathymetric survey to factor in the three-dimensional aspect (depth) typical of seagrass injuries perpetrated by vessel groundings (Kirsch et al. 2005).

Based on the field assessments, a recovery model can be created to determine the time it would take for the injury to return to pre-injury conditions (Fonseca et al. 2000; 2004). In the example described in Kirsch et al. (2005), it requires 30 years for a blowhole of an area of 14.26 m² with a volume of 7 m to fully recover to reference levels of the seagrass species *Thalassia testudinum* (turtle grass) under ideal conditions. Finally, after evaluating the extent and severity of injury and the habitat recovery time, a HEA can be performed to calculate the size of a seagrass restoration project needed to compensate for lost services (Kirsch et al. 2005).

This approach uses seagrass planting (and re-grading the seabed, if needed) to compensate for physical injuries to the same type of habitat. Since we know that removing marine debris from seagrass conveys benefits of a similar type, we can simulate and compare the relative magnitude and cost of seagrass planting with marine debris removal. Table 6 below lists the inputs that are used in our simulation, with seagrass injury and restoration parameters derived from Kirsch et al. (2005), and the marine debris parameters derived from Table 1 above.

This hypothetical scenario involves a vessel running aground in a seagrass bed in 2018 and causing a 60.15 square meter scar and blowhole. Baseline conditions are defined by the vegetation density (measured as percent cover) that would have existed but for the vessel grounding and is determined through the evaluation of adjacent reference sites. Without any action, this habitat will take 22.5 years to fully recover to baseline conditions (Kirsch et al. 2005). A seagrass restoration project is proposed that identifies a suitable area and plants seagrass that takes five years to reach maturity.¹⁴ Without any other disturbances, this new seagrass bed should provide compensable and creditable ecological services for 30 years.¹⁵

¹⁴ There are many considerations of site location necessary when determining the most suitable restoration site. On-site and in-kind restoration has the greatest chance of providing equivalent ecological services to those that were lost (see our discussion of the “equivalent-value assumption” in the introduction). However, off-site restoration may be preferred to minimize costs or to improve the probability of restoration success. See Ruhl et al., 2008 for a discussion of the Section 404 Compensatory Mitigation Program established by EPA and the U.S. Army Corps.

¹⁵ The duration of restoration benefits is often truncated by other environmental stressors, including climate change, sea level rise, invasive species, or other types of habitat destruction.

Table 6 Seagrass Injury and Restoration HEA Inputs

Parameter	Value
Injury	
Habitat Area Injured	60.15 m ²
Initial Service Loss	100%
Time to Full Recovery	22.5 years
Year of Injury	2018
Seagrass Restoration	
Initial Service Level	0%
Time to Full Function	5 years
Seagrass Restoration Success (% survival)	38%
Time Horizon of Benefits	30 years
Year Restoration Begins	2020
Marine Debris Removal	
Trap Footprint	0.5 m ²
Service Loss from Trap	20%
Time to Recovery Following Removal	0.5 years
Time to Trap Degradation	6.4 years
Time Until Ghost Fishing Ends	780 Days
Share of Traps Ghost Fishing	28%
Time to Find a Trap	Random Uniform
Trap Deposition	Random Uniform within the last year
Year Debris Removal Occurs	2020

Note: This table describes the set of inputs used to compare seagrass restoration and marine debris removal projects to offset a seagrass injury

However, restoration success must also be taken into consideration, since the percent survival of planted seagrasses has been shown to be quite variable, ranging from 11% to 41.3% (median, 38.0%) (Bayraktarov et al. 2016). This range is not unexpected, as baseline and ambient conditions in a given location greatly affect the probability of success for all types of restoration projects. Furthermore, as the magnitude of restoration needs grows, the availability of suitable locations diminishes, which is often reflected in the ultimate long-term restoration success. Within the HEA/REA framework, this affects the ultimate full-service provision of restored seagrass habitat, and benefits can be increased by performing appropriate site selection and assessment of ambient conditions (Mitsch, Wilson (1996); Valdez et al. 2020; Zhao et al. 2016).

An alternative marine debris removal project is also proposed that targets derelict spiny lobster traps resting on seagrass. These traps affect vegetative habitat through smothering and scouring. Using measures of vegetation decline caused by smothering drawn from Table 4, these traps cause a 20% decline in ecological function to a half square meter footprint below and around each trap.

Table 7 Seagrass Injury and Restoration HEA Results

Parameter	Value
Seagrass Injury	
DSSMYs Lost	579
Seagrass Restoration	
DSSMYs Gained per Square Meter	6.4
Square Meters of Restoration Needed	91
Marine Debris Removal	
DSSMYs Gained per Trap Removed	1.36
Number of Traps Removed Needed	427

Note: To aid in comparison, results are reported in discounted-service-square-meter-years (DSSMYs) as opposed to the traditional discounted-service-acre-years (DSAYs)

Following removal of a trap, this vegetative habitat will recover in the course of half of a year. If a trap is not removed, we assume that it will take an average of 6.4 years for the trap to naturally degrade¹⁶. Either restoration project will be initiated in 2020. The HEA approach can determine how many square meters of restoration or how many traps must be removed to fully compensate for the injury. Since the area of the injury is measured in square meters, all calculations are performed in terms of Discounted Service Square Meters Years (DSSMYs).

The HEA results indicate that each square meter of seagrass planting project generates ~6.4 DSSMYs (Table 7). In order to fully compensate for the 579 DSSMY injury, 91 square meter seagrass planting project must be completed (Table 7). Each derelict lobster trap removed from seagrass generates an average of 1.36 DSSMYs, meaning that 427 traps must be removed to full compensate for the injury (Table 7).

In most cases, natural resource Trustees are able to exercise their discretion in the choice of restoration. However, in addition to other factors described in NRDA regulations, the comparative cost of a restoration option must always be considered. Seagrass restoration can be a costly undertaking and can vary significantly based on site, volunteer engagement, and project size. In the United States, the most expensive seagrass planting projects have varied between \$1 million (McNeese et al. 2006) and \$5.3 million per hectare (Lewis et al. 2006) depending upon location, extent of restoration, and techniques applied. Bayraktarov et al. (2016) found that the most cost-effective seagrass restoration project was the transplantation of seagrass cores or plugs (\$38 thousand per hectare in a developed country), while the least cost-effective project used

¹⁶ This calculation only includes the habitat benefits of marine debris removal and does not include any calculation of the ghost fishing benefits, since those are not directly relatable to the hypothetical seagrass injury.

mechanical transplantation of seagrass (\$1.5 million per hectare in a developed country). Further, they reported that the median survival of restored habitat was highest for saltmarshes (64.8%) and coral reefs (64.5%), and lowest for seagrass (38.0%) (Bayraktarov et al. 2016). Depending on the technique and tools implemented, some seagrass restoration projects exhibit very low costs between \$132 and \$382 thousand per hectare (Bergstrom 2006), while others with sustained monitoring cost between \$1.1 and \$1.7 million per hectare (Fonseca 2006). Based on the midpoint of this middle range, (\$784,000 per hectare), the 91 square meter restoration project would cost approximately \$7134, but could range from \$1201 to \$15,470.

For comparison, NOAA's Marine Debris Program has funded a number of derelict trap removal projects across the country. These projects are generally multi-faceted and include removal, prevention, and outreach components. Although they are generally broader projects, they can serve as an indication of the trap removal cost. Of the 22 projects that removed traps between 2006 and 2014, the average cost per trap ranged from \$30 to \$1574 per trap. Using these values, it could potentially cost between \$12,810 and \$672,098 to remove 427 traps and fully compensate for the hypothetical seagrass injury. It is important to note that purely target trap removal that would be funded through an NRDA might not include the prevention, outreach, and education components regularly incorporated into Marine Debris Program funded removals, meaning that the cost per trap removed may be significantly lower, particularly if strategic removal methods are implemented (Scheld et al. 2021). The comparative ranges of restoration costs are presented in Table 8 and Fig. 6 below.

Due to the variability in project costs, neither derelict trap removal nor seagrass restoration is the clear cost-effective restoration project for all situations. Any marine debris removal project that could remove derelict traps at less than an average of \$36 per trap could potentially be a more cost-effective solution than seagrass planting.¹⁷ It also may convey additional resource value if the ecological benefits of reduced ghost fishing were considered. A REA performed on the same scenario calculates that each ghost fishing trap removed will generate 7.02 discounted lobster years.¹⁸ If only 28% of traps were actively ghost fishing, removing 427 traps will save approximately 840 future lobsters. Resource benefits (e.g., reduced ghost fishing) as well as the potential economic benefits of the removal

Table 8 Restoration Cost Ranges

Cost Per Square Meter of Seagrass Restoration		Square Meters	Project Cost
Low	\$13	91	\$1201
High	\$170		\$15,470
Cost Per Trap Removal		Traps	Project Cost
Low	\$30	427	\$12,810
High	\$1574		\$672,098

Note: Results are reported across the potential full range of restoration costs, for the amount of seagrass restoration or trap removal necessary to offset the hypothetical injury

should be taken into consideration and may justify selection of the removal project, even at a relatively higher cost.

Conclusions

Addressing and removing marine debris is becoming an increasingly policy and research rich topic. Marine debris, including derelict fishing gear, can be found in many marine environments, including all coastal areas and remote beaches, throughout the open ocean and water column, and on the sea floor. This global and pervasive issue is important because debris can severely injure sensitive marine species and their habitats. While extensive research has been conducted on the harm marine debris can cause to habitats and resources there are still many environmental impacts that are less understood or remain to be identified, such as impacts from microplastics or plastic associated chemicals. Even more so, methods to comparatively evaluate impacts across different geographic locations, habitats, and types of debris have not been fully developed. By utilizing an ecological service equivalency analysis framework, marine debris removal projects can be targeted from an ecological service perspective, which would allow managers to prioritize removal efforts and maximize return on investment. The framework discussed in this paper can be applied to better evaluate the comparative ecological service benefits of removing marine debris by using a common set of metrics across multiple projects.

It should be noted that the results highlighted in this paper are designed to be demonstrative of the application of an ecological service equivalency analysis framework and are limited by available published estimates of ecological service impacts and their duration. Differences in the magnitude of debris removal benefits are likely intuitive. Traps and nets that are larger, more durable, and used in more ecologically productive habitats likely produce greater benefits from removal. Estimates of benefits likely vary

¹⁷ Calculated by dividing the high-cost range of the seagrass planting project (\$15,470) by the number of traps needed to be removed to compensate for the injury (427).

¹⁸ This accounts for the time-value of killed lobsters, as described in section 2. Since the life history of lobsters is not included in the analysis, this term can also be interpreted as "discounted-lobsters."

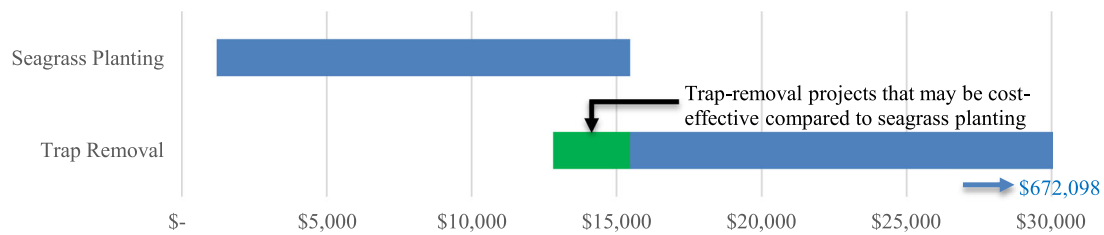


Fig. 6 Restoration Cost Ranges. NOTE: The overlapping portion of the cost ranges in green demonstrate the range of trap removal projects that may be cost-effective compared to seagrass restoration

based on both the trap type and where they tend to be used (e.g., blue crab traps, lobster pots, Dungeness crab pots). The same logic applies to nets (e.g., fixed gillnets, drift gillnets, fixed purse nets, trawl nets).

To further this work, more targeted research and monitoring should be performed to collect data that can be utilized in this framework. Specific data needs include but are not limited to: impaired habitat footprint per debris item removed; percent decline in ecological services over that area; age of debris removed or the time that the debris would continue causing impacts; and the species and number of animals killed by gear in a given year. Much of this information can be collected through targeted research studies or additional monitoring before and after removal efforts. Additional comparisons of vegetation and faunal abundance and diversity surrounding lost debris and reference sites across time can inform the degree of impairment and rate of recovery critical to measuring the change in ecological services. In-situ monitoring of derelict traps and nets can inform the rate at which ghost-fishing impacts change over time, serving as a key input to REA modeling. Additionally, even hydrologic modeling can inform the fate and transport of marine debris in a variety of high and low energy environments. These studies should be expanded to produce estimates specific to habitats, regions, and gear types.

As more informative data emerge from research, monitoring, and removal projects, they should be applied to advance both the NRDA process and restoration science. This approach can continue to draw on existing literature, including socioeconomic literature, which will allow a resource manager to apply the most up-to-date information following an event that damages a habitat. Marine debris removal can then be scaled for restoration efforts and evaluated for resource cost benefits, ultimately serving governmental and non-governmental agencies, project managers, external resource managers, and other parties in decision-making. The greatest challenge now is to capture needed information in broadly accepted metrics that are cost-effective to obtain. Based on what we know from existing literature and the potential provided by the ecological service equivalency analysis framework, the specific

data needs outlined here provide a reliable starting point and standard for applying this method moving forward.

Disclaimer

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect the views of NOAA or the Department of Commerce.

Acknowledgements We appreciate the NOAA Marine Debris Program's support for the inception and formulation of the original project, as well as review of the manuscript. We are also thankful for helpful review and comments from Amy V. Uhrin, Jason Murray, Mary Baker, session participants at the Sixth International Marine Debris Conference, and three anonymous reviewers.

Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

- Antonelis K, Huppert D, Velasquez D, June J (2011) Dungeness crab mortality due to lost traps and a cost–benefit analysis of trap removal in Washington State waters of the Salish Sea. *North Am J Fish Manag* 31(5):880–893
- Arthur C, Friedman S, Weaver J, Van Nostrand D, Reinhardt J (2020) Estimating the benefits of derelict crab trap removal in the Gulf of Mexico. *Estuaries Coasts* 43(7):1821–1835
- Baker M, Domanski A, Hollweg T, Murray J, Lane D, Skrabis K, DiPinto L (2020) Restoration scaling approaches to addressing ecological injury: the habitat-based resource equivalency method. *Environ Manag* 65(2):161–177
- Bayraktarov E, Saunders MI, Abdullah S, Mills M, Beher J, Possingham HP, Lovelock CE (2016) The cost and feasibility of marine coastal restoration. *Ecol Appl* 26(4):1055–1074
- Bergstrom P (2006) Species selection success and costs of multi-year, multi-species submerged aquatic vegetation (SAV) planting in Shallow Creek, Patapsco River, Maryland. *Seagrass Restoration: Success, Failure and the Costs of Both*, eds SF Treat and RR III Lewis (Valrico, FL: Lewis Environmental Services, Inc.) 49–58

- Bilkovic DM, Havens K, Stanhope D, Angstadt K (2014) Derelict fishing gear in Chesapeake Bay, Virginia: Spatial patterns and implications for marine fauna. *Mar Pollut Bull* 80(1–2):114–123
- Bilkovic DM, Slacum Jr HW, Havens KJ, Zaveta D, Jeffrey CF, Scheld AM, Stanhope D, Angstadt K, Evans JD (2016) Ecological and Economic Effects of Derelict Fishing Gear in the Chesapeake Bay 2015/2016 Final Assessment Report
- Brown J, Macfadyen G (2007) Ghost fishing in European waters: Impacts and management responses. *Mar Policy* 31(4):488–504
- Browne MA, Underwood AJ, Chapman MG, Williams R, Thompson RC, van Franeker JA (2015) Linking effects of anthropogenic debris to ecological impacts. *Proc R Soc B: Biol Sci* 282(1807):2014–2929
- Bruggeman DJ, Jones ML, Lupi F, Scribner KT (2005) Landscape equivalency analysis: methodology for estimating spatially explicit biodiversity credits. *Environ Manag* 36(4):518–534
- Butler CB, Matthews TR (2015) Effects of ghost fishing lobster traps in the Florida Keys. *ICES J Mar Sci* 72(suppl_1):i185–i198
- Cacela D, Lipton J, Beltman D, Hansen J, Wolotira R (2005) Associating ecosystem service losses with indicators of toxicity in habitat equivalency analysis. *Environ Manag* 35(3):343–351
- Clark R, Pittman SJ, Battista TA, Caldwell C (2012) Survey and impact assessment of derelict fish traps in St. Thomas and St. John, US Virgin Islands
- Dawes CJ, Andorfer J, Rose C, Uranowski C, Ehringer N (1997) Regrowth of the seagrass *Thalassia testudinum* into propeller scars. *Aquat Bot* 59(1–2):139–155
- Derraik JG (2002) The pollution of the marine environment by plastic debris: a review. *Mar Pollut Bull* 44(9):842–852
- Desvousges WH, Gard N, Michael HJ, Chance AD (2018) Habitat and resource equivalency analysis: a critical assessment. *Ecol Econ* 143:74–89
- Duffield J, Neher C, Patterson D (2021) Estimating compensation ratios for tribal resources within a habitat equivalency framework. *Ecol Econ* 179:106862
- Dunford RW, Ginn TC, Desvousges WH (2004) The use of habitat equivalency analysis in natural resource damage assessments. *Ecol Econ* 48(1):49–70
- Erzini K, Monteiro CC, Ribeiro J, Santos MN, Gaspar M, Monteiro P, Borges TC (1997) An experimental study of gill net and trammel net ‘ghost fishing’ off the Algarve (southern Portugal). *Mar Ecol Prog Ser* 158:257–265
- Fonseca MS, Julius BE, Kenworthy WJ (2000) Integrating biology and economics in seagrass restoration: How much is enough and why? *Ecol Eng* 15(3–4):227–237
- Fonseca MS, Whitfield PE, Judson Kenworthy W, Colby DR, Julius BE (2004) Use of two spatially explicit models to determine the effect of injury geometry on natural resource recovery. *Aquat Conserv: Mar Freshw Ecosyst* 14(3):281–298
- Fonseca MS (2006) Wrap-up of seagrass restoration: success, failure and lessons about the costs of both. *Seagrass Restoration: Success, Failure and the Costs of Both*, eds SF Treat and RR III Lewis (Valrico, FL: Lewis Environmental Services, Inc.) 169–175
- Gall SC, Thompson RC (2015) The impact of debris on marine life. *Mar Pollut Bull* 92(1–2):170–179
- Gilardi KV, Carlson-Bremer D, June JA, Antonelis K, Broadhurst G, Cowan T (2010) Marine species mortality in derelict fishing nets in Puget Sound, WA and the cost/benefits of derelict net removal. *Mar Pollut Bull* 60(3):376–382
- Gilman E, Chopin F, Suuronen P, Kuemlengan B (2016) Abandoned, lost and discarded gillnets and trammel nets: methods to estimate ghost fishing mortality, and the status of regional monitoring and management. *FAO Fisheries and Aquaculture Technical Paper*, (600), I
- Giordano S, Lazar J, Bruce D, Little C, Levin D, Slacum Jr HW, Dew-Baxter J, Methratta L, Wong D (2010) Quantifying the Effects of Derelict Fishing Gear in the Maryland Portion of Chesapeake Bay. Final Report to the NOAA Marine Debris Program. National Oceanic and Atmospheric Administration Silver Spring, MD
- Guillory V (1993) Ghost fishing by blue crab traps. *North Am J Fish Manag* 13(3):459–466
- Hammerstrom KK, Kenworthy WJ, Whitfield PE, Merello MF (2007) Response and recovery dynamics of seagrasses *Thalassia testudinum* and *Syringodium filiforme* and macroalgae in experimental motor vessel disturbances. *Mar Ecol Prog Ser* 345:83–92
- Hanson DA, Britney EM, Earle CJ, Stewart TG (2013) Adapting habitat equivalency analysis (HEA) to assess environmental loss and compensatory restoration following severe forest fires. *For Ecol Manag* 294:166–177
- Havens KJ, Bilkovic DM, Stanhope D, Angstadt K, Hershner C (2008) The effects of derelict blue crab traps on marine organisms in the lower York River, Virginia. *North Am J Fish Manag* 28(4):1194–1200
- Jeffrey CF, Havens KJ, Slacum HW, Bilkovic DM, Zaveta D, Scheld AM, Willard S, Evans JD (2016) Assessing Ecological and Economic Effects of Derelict Fishing Gear: a Guiding Framework. Virginia Institute of Marine Science, College of William and Mary. <https://doi.org/10.21220/V50W23>
- Johnston MW, Purkis SJ, Dodge RE (2015) Measuring Bahamian lionfish impacts to marine ecological services using habitat equivalency analysis. *Mar Biol* 162(12):2501–2512
- Julius B (1999) Discounting and the Treatment of Uncertainty in Natural Resource Damage Assessment. NOAA Technical Paper 99-1 <https://casedocuments.darrp.noaa.gov/northeast/athos/pdf/NOAA%201999.pdf> Accessed 14 March 2019
- June, J (2007) A cost-benefit analysis of derelict fishing gear removal in Puget Sound, Washington. Natural Resources Consultants, Report prepared for the Northwest Straits Foundation, Seattle
- Kaiser MJ, Bullimore B, Newman P (1997) Catches in ghost fishing set nets. *Oceanographic Lit Rev* 6(44):626
- Kenworthy WJ, Fonseca MS, Whitfield PE, Hammerstrom KK (2002) Analysis of seagrass recovery in experimental excavations and propeller-scar disturbances in the Florida Keys National Marine Sanctuary. *J Coastal Res* 37:75–85
- Kim TG, Opaluch J, Moon DSH, Petroliia DR (2017) Natural resource damage assessment for the Hebei Spirit oil spill: An application of Habitat Equivalency Analysis. *Mar Pollut Bull* 121(1–2):183–191
- Kirsch KD, Barry KA, Fonseca MS, Whitfield PE, Meehan SR, Kenworthy WJ, Julius BE (2005) The Mini-312 Program—an expedited damage assessment and restoration process for seagrasses in the Florida Keys National Marine Sanctuary. *J Coastal Res* 40:109–119
- Laist DW (1987) Overview of the biological effects of lost and discarded plastic debris in the marine environment. *Mar Pollut Bull* 18(6):319–326
- Leggett CG, Scherer N, Haab TC, Bailey R, Landrum JP, Domanski A (2018) Assessing the economic benefits of reductions in marine debris at Southern California beaches: a random utility travel cost model. *Mar Resour Econ* 33(2):133–153
- Lewis CF, Slade SL, Maxwell KE, Matthews TR (2009) Lobster trap impact on coral reefs: Effects of wind-driven trap movement. *NZ J Mar Freshw Res* 43(1):271–282
- Lewis RR, Marshall MJ, Bloom SA, Hodgson AB, Flynn LL (2006) Evaluation of the success of seagrass mitigation at Port Manatee, Tampa Bay, Florida. Valrico: Lewis Environmental Services
- Li JM, Wang XL (2012) A model based on the resource equivalency analysis method to evaluate marine ecological damage by oil spill. *Marine Sciences*

- Lord-Boring C, Zelo II, Nixon ZJ (2004) Abandoned vessels: impacts to coral reefs, seagrass, and mangroves in the US Caribbean and Pacific territories with implications for removal. *Mar Technol Soc J* 38(3):26–35
- Maselko J, Bishop G, Murphy P (2013) Ghost fishing in the Southeast Alaska commercial Dungeness crab fishery. *North Am J Fish Manag* 33(2):422–431
- Masompson Y, Gorgin S, Pighambari SY, Karimzadeh G, Babanejad M, Eighani M (2018) The impact of ghost fishing on catch rate and composition in the southern Caspian Sea. *Mar Pollut Bull* 135:534–539
- Matsuoka T, Nakashima T, Nagasawa N (2005) A review of ghost fishing: scientific approaches to evaluation and solutions. *Fish Sci* 71(4):691
- McIlgorm A, Campbell HF, Rule MJ (2011) The economic cost and control of marine debris damage in the Asia-Pacific region. *Ocean Coast Manag* 54(9):643–651
- McNeese PL, Kruer CR, Kenworthy WJ, Schwarzschild AC, Wells P, Hobbs J, (2006) Topographic restoration of boat grounding damage at the Lignumvitae Submerged Land Management Area. *Seagrass Restoration: Success, Failure and the Costs of Both*, eds. SF Treat and RR III Lewis (Valrico, FL: Lewis Environmental Services, Inc.) 131–146
- Milon JW, Dodge RE (2001) Applying habitat equivalency analysis for coral reef damage assessment and restoration. *Bull Mar Sci* 69(2):975–988
- Mitsch WJ, Wilson RF (1996) Improving the success of wetland creation and restoration with know-how, time, and self-design. *Ecol Appl* 6(1):77–83
- Nakashima T, Matsuoka T (2004) Ghost-fishing ability decreasing over time for lost bottom-gillnet and estimation of total number of mortality. *Bull Japan Soc Sci Fisher (Japan)* 70(5):728–737
- Nakashima T, Matsuoka T (2005) Ghost-fishing mortality and fish aggregation by lost bottom-gillnet tangled around fish aggregation device. *Bull Japan Soc Sci Fisher (Japan)* 71(2):178–187
- National Research Council (2013) *Education for life and work: Developing transferable knowledge and skills in the 21st century*. National Academies Press
- Newman S, Watkins E, Farmer A, ten Brink P, Schweitzer JP (2015) *The economics of marine litter*. *Marine Anthropogenic Litter*. Springer, Cham, 367–394
- NOAA (2019) *Marine Debris Clearinghouse*. <https://clearinghouse.marinedebris.noaa.gov/>. Accessed 02/06/2022
- Pavanelli DD, Voulvoulis N (2019) Habitat Equivalency Analysis, a framework for forensic cost evaluation of environmental damage. *Ecosyst Serv* 38:100953
- Penn T, Tomasi T (2002) Calculating resource restoration for an oil discharge in Lake Barre, Louisiana, USA. *Environ Manag* 29(5):691–702
- Roach B, Wade WW (2006) Policy evaluation of natural resource injuries using habitat equivalency analysis. *Ecol Econ* 58(2):421–433
- Ruhl JB, Salzman J, Goodman I (2008) *Implementing the New Ecosystem Services Mandate of the Section 404 Compensatory Mitigation Program-A Catalyst for Advancing Science and Policy*. *Stetson L Rev* 38:251
- Sancho G, Puente E, Bilbao A, Gomez E, Arregi L (2003) Catch rates of monkfish (*Lophius spp.*) by lost tangle nets in the Cantabrian Sea (northern Spain). *Fish Res* 64(2–3):129–139
- Santos MN, Saldanha HJ, Gaspar MB, Monteiro CC (2003) Hake (*Merluccius merluccius L., 1758*) ghost fishing by gillnets off the Algarve (southern Portugal). *Fish Res* 64(2–3):119–128
- Scemama P, Levrel H (2016) Using habitat equivalency analysis to assess the cost effectiveness of restoration outcomes in four institutional contexts. *Environ Manag* 57(1):109–122
- Scheld AM, Bilkovic DM, Havens KJ (2016) The dilemma of derelict gear. *Sci Rep*. 6(1):1–7
- Scheld AM, Bilkovic DM, Havens KJ (2021) Evaluating optimal removal of derelict blue crab pots in Virginia, US. *Ocean Coast Manag* 211:105735
- Sheavly SB, Register KM (2007) Marine debris and plastics: environmental concerns, sources, impacts and solutions. *J Polym Environ* 15(4):301–305
- Stelfox M, Hudgins J, Sweet M (2016) A review of ghost gear entanglement amongst marine mammals, reptiles and elasmobranchs. *Mar Pollut Bull* 111(1–2):6–17
- Thur SM (2007) Refining the use of habitat equivalency analysis. *Environ Manag* 40(1):161–170
- Uhrin AV, Fonseca MS, DiDomenico GP (2005) Effect of Caribbean Spiny Lobster Traps on Seagrass Beds of the Florida Keys National Marine Sanctuary: Damage Assessment and Evaluation of Recovery. *Am Fisher Soc Symposium* 41:579–588
- Uhrin AV, Holmquist JG (2003) Effects of propeller scarring on macrofaunal use of the seagrass *Thalassia testudinum*. *Mar Ecol Prog Ser* 250:61–70
- Uhrin AV, Schellinger J (2011) Marine debris impacts to a tidal fringing-marsh in North Carolina. *Mar Pollut Bull* 62(12):2605–2610
- Uhrin AV, Matthews TR, Lewis C (2014) Lobster trap debris in the Florida Keys National Marine Sanctuary: distribution, abundance, density, and patterns of accumulation. *Mar Coast Fish* 6(1):20–32
- USFWS (2016) “Appendix C: Resource Equivalency Analysis (REA) Models.” *Draft Midwest Wind Multi-Species Habitat Conservation Plan*
- Valdez SR, Zhang YS, van der Heide T, Vanderklift MA, Tarquinio F, Orth RJ, Silliman BR (2020) Positive ecological interactions and the success of seagrass restoration. *Front Mar Sci* 7:91
- Viehman S, Thur SM, Piniak GA (2009) Coral reef metrics and habitat equivalency analysis. *Ocean Coast Manag* 52(3–4):181–188
- Wellman E, Sutton-Grier A, Imholt M, Domanski A (2017) Catching a wave? A case study on incorporating storm protection benefits into Habitat Equivalency Analysis. *Mar Policy* 83:118–125
- Whitaker JD (1979) *Abandoned crab trap study*. South Carolina Wildlife and Marine Resources Department
- Whitfield PE, Kenworthy WJ, Hammerstrom KK, Fonseca MS (2002) The role of a hurricane in the expansion of disturbances initiated by motor vessels on seagrass banks. *J Coastal Res* 37:86–99
- Zafonte M, Hampton S (2007) Exploring welfare implications of resource equivalency analysis in natural resource damage assessments. *Ecol Econ* 61(1):134–145
- Zhao Q, Bai J, Huang L, Gu B, Lu Q, Gao Z (2016) A review of methodologies and success indicators for coastal wetland restoration. *Ecol Indic* 60:442–452
- Zieman JC (1976) The ecological effects of physical damage from motor boats on turtle grass beds in southern Florida. *Aquat Bot* 2:127–139