

Recovery of eelgrass *Zostera marina* following conversion of conventional block and chain moorings to conservation mooring systems in Massachusetts: context dependence, challenges, and management

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Abstract

Eelgrass (*Zostera marina*) meadows and boat mooring fields co-occur in near-shore, relatively sheltered embayments. Traditional chain moorings create denuded scars in eelgrass meadows due to repeated and chronic scour of the seafloor by the chain, impacting meadow contiguity and quality. This study assessed the recovery of eelgrass into mooring scars following the conversion of traditional chain moorings to floating rode conservation mooring systems (CMS) in three Massachusetts harbors. The magnitude and rate of eelgrass recovery following conversion to floating rode CMS was contingent on the location (e.g., site specific environmental conditions) and the size of the scar associated with the mooring. Eelgrass recovery was inversely correlated with exposure and tidal range, and positively correlated with original scar size. While most scars started to revegetate within two years of mooring conversion, few experienced complete recovery, with a two meter denuded halo persisting around mooring anchors five years post-conversion. In some cases, scar sizes increased where floating rode CMS dragged on the seafloor due to inadequate depth, oversizing of gear, or fouling. Transplanting vegetative eelgrass shoots into scars following conversion to floating rode CMS did not increase the extent or quality of eelgrass habitat restored. We show that floating rode CMS can be an important tool for eelgrass conservation and restoration, however, challenges pertaining to site-specific design, installation, long-term maintenance, and public perception must be addressed to fully realize this potential.

Introduction

Human activities heavily impact coastal marine ecosystems, and human impacts along coasts continue to increase as a growing global population looks to the ocean to provide food, energy, and recreational opportunities (Davenport and Davenport 2006, Halpern et al. 2019). Seagrass meadows are one of the most important coastal marine ecosystems (UNEP 2020) because of the many valuable, well documented ecosystem functions and services they provide including buffering wave energy, stabilizing sediments, sequestering carbon, and creating habitat for numerous marine species including commercially and recreationally important fish and shellfish (Williams & Heck, 2001; Barbier et al. 2011), but they are also among the most vulnerable and heavily impacted (Halpern et al. 2008; Halpern et al. 2019) and, as a result, the rate of seagrass loss has accelerated over recent decades (Waycott et al. 2009; Dunic et al. 2021). Recreational boating is one of the anthropogenic activities that has contributed to seagrass declines (Orth et al. 2006; Grech et al. 2012, Unsworth et al. 2017). In particular, the mooring of recreational boats frequently threatens seagrass because the sheltered near shore waters where seagrass thrive are also the most attractive mooring sites for boating communities around the world (Grech et al. 2012).

Recreational boat moorings damage seagrass through a variety of mechanisms. A conventional swing or single-point boat mooring typically consist of a large concrete block, pyramid anchor, or mushroom anchor connected to a heavy chain, followed by a lighter chain with a floating mooring ball at the surface (Fig. 1A). The mooring anchor smothers seagrass and is an unsuitable substrate for recolonization, but it is the mooring chain that is typically the most damaging component to seagrass (Sagerman et al. 2020).

Installed with enough scope to span the water column at the highest tides and with additional length of heavy chain that permanently drags on the seafloor to increase the total holding power, mooring chains scour the benthos around the anchor point as the tides and winds shift, uprooting seagrass (Milazzo et al. 2004, Bourque et al. 2015, Unsworth et al. 2017). As long as the chain scour persists, these circular mooring scars are unable to revegetate (Valdemarsen et al. 2010).

Mooring impacts may also extend beyond the swing of the mooring chain. The increased suspension of sediments and nutrients resulting from chain scour and the loss of sediment stabilizing services provided by seagrass may contribute to wider reaching water quality declines (Williams & Heck 2001, Serrano et al. 2016, Unsworth et al. 2017). In mooring fields, where scars from multiple closely spaced moorings combine, the extent of degradation may disrupt self-reinforcing feedbacks that promote seagrass growth (e.g., sediment stabilization; van der Heide et al. 2011), decreasing seagrass resilience to other stressors, reducing seagrass recovery capacity, and ultimately precipitate the loss of the ecosystem functions and services seagrass meadows provide (Hastings et al. 1995; van der Heide et al. 2011, Sagerman et al. 2020).

A variety of mooring system designs have been developed as alternatives to conventional chain moorings with the objective of minimizing impacts to seagrass by eliminating chain scour and reducing anchor footprint. Several harbors around the world have installed these 'environmentally friendly', 'eco-mooring', or 'conservation mooring' systems, here called CMS for brevity (Egerton 2011, Sagerman et al. 2020). In Australia "cyclone" CMS, three chains fed through a central ring before extending in different directions on the seabed, generally developed more extensive scars than conventional moorings (Walker et al. 1989, Hastings et al. 1995, Demers et al. 2013). In contrast, "screw" CMS, a small moving rod that is elevated from the bottom, decreased impacts to seagrass (Demers et al. 2013). Trials of CMS in the UK also provided mixed results (Egerton 2011, Luff et al. 2019, Unsworth et al. 2022). Installation of "Seaflex" CMS, an elastic rode attached to a helix anchor, led to seagrass recovery in one harbor, but not another (Egerton 2011). In a separate study, installation of a "Stirling" CMS, a chain elevated by small floats, led to increased seagrass density and blade length (Luff et al. 2019). "Rope" CMS in Puerto Rico, southern England, and north Wales did not damage seagrass (Unsworth et al. 2022). In the northeast US, installation of "floating rode" CMS, a buoyant rode connecting a helical anchor to a surface buoy (Fig. 1b), resulted in partial recovery of eelgrass into mooring scars after one year (McManus et al. 2017). For other CMS designs and regions, implementation has outpaced research (Luff et al. 2019, Sagerman et al. 2020). Additionally, there are regional examples of harbor regulations now explicitly including CMS policies. In Portland, Maine, any new mooring installed in seagrass must be a CMS and all moorings in seagrass must either be converted to a CMS or removed (<https://portlandharbor.org/harbor-info/mooring-info>). Despite the increasing implementation of CMS, assessments of their efficacy in eliminating mooring impacts and promoting seagrass recovery are limited to only a small subset of available designs and a fraction of the regions and seagrass species in which they are currently used (Luff et al. 2019, Sagerman et al. 2020). These knowledge gaps represent a challenge to utilizing CMS as a tool for seagrass conservation or compensatory mitigation as the variation in the impacts reported among the

few existing studies suggest we cannot reliably predict the effects of implementing unstudied CMS designs in disparate regions (Urban Harbors Institute 2013, Unsworth et al. 2019, Sagerman et al. 2020).

The present study was conducted along the Massachusetts (MA) coastline in the northeast US. The northeast US coast is a hotspot for human impacts (Halpern et al. 2019) and seagrass vulnerability (Turschwell et al. 2021). The situation in MA is consistent with these regional trends: the majority of the population lives along the coast, coastal areas experienced the fastest population growth in the state over the past decade (US Census Bureau 2021), and the majority of harbors in the state historically supported the temperate seagrass species *Zostera marina*, commonly known as eelgrass (<https://www.mass.gov/guides/eelgrass-mapping-project>). Indeed, eelgrass decline in MA was documented more than a decade ago (Costello and Kenworthy 2011) and have continued highlighting the urgent need for effective conservation measures.

In the northeast US, floating rode CMS (Fig. 1B) are the most common CMS design and have been installed in over half a dozen harbors (<https://www.ecomooringsystems.com/>). However, this is the first peer reviewed assessments of their efficacy in this region. This study seeks to further our understanding of the utility of floating rode CMS as a tool for eelgrass conservation in the northeast by investigating how supplemental restoration and installation location effect the extent to which floating rode CMS promote eelgrass recovery. Specifically, in *Field Experiment I*, we tested how transplanting vegetative eelgrass within mooring scars following conventional mooring conversion to floating rode CMS affected the extent and quality of eelgrass recovery. We hypothesized that eelgrass would recover into both planted and control scars following conversions, but planted scars would show increased eelgrass recovery into the scar area. In *Field Experiment II*, we tested how the location of floating rode CMS conversions (i.e., harbor) affected the extent and quality of eelgrass recovery. For each harbor, we characterized environmental conditions that affect the growth rate of eelgrass (e.g., light availability) and those we hypothesized could affect floating rode CMS function (e.g., tidal amplitude, wave exposure, and sediment type) to look for patterns between environmental conditions and eelgrass recovery. We hypothesized the extent of eelgrass recovery following floating rode CMS conversion would differ among harbors and specifically that eelgrass recovery would be greatest in harbors with smaller tidal amplitudes because of impairment of CMS function documented in other systems with strong tidal influence (Egerton 2011). Finally, to assess the utility of floating rode CMS as an eelgrass restoration or mitigation tool in MA we (1) modeled the relationship between scar size, harbor, and the number of floating rode CMS mooring conversions estimated to restore one acre of eelgrass, (2) tracked floating rode CMS retention rates in six harbors across MA, and (3) quantified the acreage of intersection between historic eelgrass extents and mooring areas in MA.

Methods

Study location

Boston, Gloucester, Manchester, Onset, Quissett, and West Falmouth Harbors are located along the Massachusetts coast in the northeast US (Fig. 2). All six harbors support busy seasonal recreational boating activity from May through September. During the active boating season, many boats in these harbors are stored on conventional swing moorings (Fig. 1A) as is common practice in this region. All the moorings selected for this study are swing moorings in shallow, protected areas that are subject to tidal influence and support eelgrass (Fig. 2).

Experiment I

Conservation Mooring System installation and eelgrass transplant. We identified 20 volunteer boat owners (ten in Manchester Harbor and ten in West Falmouth Harbor) to participate in the study. In Manchester Harbor and West Falmouth harbor we randomly selected seven and eight owners respectively to have their conventional block and chain systems converted to floating rode CMS. The remaining three moorings in Manchester Harbor and two moorings in West Falmouth Harbor were left as conventional block and chain systems. We then selected three of the moorings converted to floating rode CMS in each harbor to receive eelgrass transplants to create three mooring treatments: planted floating rode CMS, unplanted floating rode CMS, and conventional block and chain. Four CMS in Manchester Harbor and five CMS in West Falmouth Harbor remained un-planted.

Floating rode CMS in Manchester Harbor were installed by a local boat shop in partnership with the Manchester Harbormaster and the mooring manufacturers in October 2010. Floating rode CMS in West Falmouth were installed by local mooring installers in partnership with the West Falmouth Harbormaster and the mooring manufacturers in May 2013. Helical anchors were installed in existing scars, but in many cases the concrete anchors associated with block and chain systems were left in place due to the combination of their weight and burial. The Hazelett® and Eco-mooring® type floating rode CMS that were installed are made of proprietary braided polyester line with a rubber shock-absorbing interior core and represent two of the most common commercially available floating rode CMS designs in the northeast US. We confirmed that floating rode CMS systems remained in place over the full study duration by visual assessments via SCUBA in 2011, 2012, and 2013 in Manchester Harbor and 2014 in West Falmouth Harbor. During visual assessments, we recorded photos, videos, and notes on the condition of the mooring equipment. Specifically, we noted whether the mooring rode was floating, fouled, tangled, dragging, or if any components had been altered.

In July 2011, nine months following floating rode CMS installations in Manchester Harbor, and in May 2014, 12 months following floating rode CMS installations in West Falmouth Harbor, we transplanted eelgrass shoots into the mooring scars of three floating rode CMS moorings per harbor. Eelgrass shoots from adjacent meadows were transplanted via the horizontal rhizome method, where two shoots are planted in opposite directions, with bamboo skewers anchoring the rhizomes to the sediment (Davis and Short, 1997). In each cardinal direction radial to the mooring anchor, two 1m² quadrats were planted, with 24 shoots per quadrat, totaling 192 shoots per scar.

Characterizing eelgrass recovery

We monitored the planted and unplanted floating rode CMS and conventional moorings using SCUBA along four radial transects beginning at the anchor, passing through the mooring scar, and continuing beyond the mooring scar to unimpacted eelgrass (Fig. 3). We oriented transects in the cardinal directions (0° , 90° , 180° , and 270°) using a magnetic dive compass. To estimate the mooring scar radius, we took the average of the distances measured from the anchor to the edge of the mooring scar along each transect. We defined the edge of the mooring scar as the transition point from $< 20\%$ eelgrass to $\geq 20\%$ eelgrass cover. We chose this definition for the eelgrass edge because eelgrass cover $< 20\%$ was representative of areas with single seedlings that are unlikely to persist beyond a growing season and these low cover, ephemeral eelgrass areas do not perform the same ecological functions as consistent high coverage eelgrass more typical of unimpacted eelgrass areas in these harbors (Bologna and Heck 1999, Koehler 2022). For both harbors, we measured initial mooring scar radii during the first complete eelgrass growing season following floating rode CMS installation- July 2011 in Manchester Harbor and May 2014 in West Falmouth Harbor. In West Falmouth Harbor, we observed failure of all floating rode CMS in August 2014 and abandoned further eelgrass monitoring in this harbor. In Manchester Harbor, we measured final mooring scar radii in July 2013. We calculated the change in mooring scar radii over the duration of the experiment as the difference between initial and final mooring scar radii.

During the final monitoring of planted and unplanted floating rode CMS in Manchester Harbor, we also measured eelgrass characteristics in three distinct zones along each transect based on mooring impact history: the remaining mooring scar, the recovered eelgrass (i.e., the area between the initial mooring scar edge and the current mooring scar edge), and unimpacted eelgrass (i.e., the area one meter beyond the edge of the initial mooring scar). In each zone, we counted eelgrass shoots, estimated percent cover, and measured canopy height in 0.25m^2 quadrats (Fig. 3).

Statistical Analyses: We used a one-way analysis of variance (ANOVA) to examine the effect of mooring treatment on the change in scar radius. We restricted this analysis to moorings from Manchester Harbor due to the improper installation of floating rode CMS in West Falmouth compromising the mooring treatments in this harbor. We also excluded three moorings from Manchester Harbor from the final analyses: two unplanted floating rode CMS moorings, one of which we could not confirm was installed in the same location as the conventional block and chain mooring it replaced and the other which was converted back to a conventional block and chain mooring, and one conventional block and chain mooring that was moved during the experiment. We test that all data met the assumptions of normality and homogeneity of variances.

We used two-way ANOVAs to examine the independent and interactive effects of mooring treatment, planted or unplanted floating rode CMS, and mooring impact zone, remaining mooring scar, recovered eelgrass, and unimpacted eelgrass, on eelgrass shoot density, percent cover, and canopy height. Prior to analysis, we tested that all data met the assumptions of normality and homogeneity of variances. We log transformed shoot density and arcsine transformed percent cover to meet these assumptions. For significant ANOVA results, we ran Tukey honest significance post-hoc tests to identify differences among treatments.

Experiment II

Conservation Mooring System installation: In 2014 and 2015, the Massachusetts Port Authority (Massport) sponsored the conversion of 285 block and chain mooring systems to floating rode CMS in six harbors across Massachusetts as mitigation for permitted impacts to eelgrass in MA state waters (Fig. 2). Mooring conversions to floating rode CMS were fully subsidized at \$3,320 per conversion. Moorings were converted from traditional block and chain to Eco-mooring® and Stormsoft® type floating rode CMS in July and August 2014 by local mooring installers selected by the mooring owners and with input from harbormasters and the mooring manufacturer. We received funding from MassPort to monitor at least 10% of moorings in each harbor, for a total of 39 moorings converted to floating rode CMS distributed across the six harbors. Twenty-one of these moorings had complete datasets usable for the eelgrass recovery analysis: five in Manchester Harbor, eight in Quissett Harbor, and eight in West Falmouth Harbor.

Characterizing harbor conditions

We characterized each harbor by depth, fetch, tidal amplitude, substrate type, and percent surface irradiance at the bottom (Table 1; See Supplement 1 for detailed methods). We chose this suite of factors because of their hypothesized importance to the performance of floating rode CMS (depth, fetch, and tidal amplitude; Egerton 2011) or eelgrass growth (% surface irradiance; Duarte 1991) or both (substrate type; Kenworthy et al. 2013, Egerton 2011).

Table 1
Harbor conditions where eelgrass recovery was monitored.

Harbor	Depth MLW (m)	Fetch (m)	Surface Irradiance (%)	Tidal Amplitude (m)	Sediment
Manchester	3.5	12,310 ± 3015	20.7	3.4	Sand
Quissett	1.4	1007 ± 477	41.9	1.2	Fine silt
West Falmouth	2.1	1658 ± 242	25.5	1.2	Fine silt

Characterizing eelgrass recovery

We monitored moorings using SCUBA along eight radial transects beginning at the floating rode CMS helix anchor, passing through the mooring scar, and continuing beyond the mooring scar to unimpacted eelgrass (Fig. 3). We oriented transects in the cardinal (0°, 90°, 180°, and 270°) and ordinal (45°, 135°, 225°, and 315°) directions using a magnetic dive compass. Similar to Experiment I, we estimated mooring scar radii by taking the average of the distances measured from the anchors to the edge of the mooring scars. We again defined the edge of the mooring scar as the transition point from < 20% eelgrass to ≥ 20% eelgrass cover. We omitted transects from averages that did not have a mooring scar edge that met this definition. All moorings had at least seven radial transects with defined scar edges. For all three

harbors, we measured initial mooring scar radii within a month of floating rode CMS installation and final mooring scar radii in August of 2019; five years post conversion to floating rode CMS. We calculated the change in mooring scar radii over the duration of the experiment as the difference between initial and final mooring scar radii. We confirmed that floating rode CMS systems remained in place over the full study duration by annual visual assessments of each mooring via snorkel or SCUBA from 2014–2019 during which we recorded photos, videos, and notes on the condition of the mooring equipment.

As in Experiment I, for the final sampling in August of 2019, we characterized the eelgrass in three mooring impact zones: the area of the remaining mooring scar (RS) (when present), the area of recovered eelgrass (RE), and the area of unimpacted eelgrass (UE) along transects radiating in the four cardinal directions from the anchor. In each zone, we counted eelgrass shoots and estimated percent cover in 0.25m² quadrats (Fig. 3).

Statistical Analyses

We used a two-way analysis of covariance (ANCOVA) to examine the independent and interactive effects of harbor (i.e., Manchester, Quissett, and West Falmouth) and initial scar radius on the change in scar radius. We tested that all data met the assumptions of normality and homogeneity of variances.

We estimated mean eelgrass expansion rates using data from moorings with initial scars greater than 3.5 meters in West Falmouth Harbor (n = 3), Quissett Harbor (n = 3), and Manchester Harbor (n = 2) to minimize the inhibitory effects of mooring gear close to the anchor point.

We used two-way ANOVAs to examine the independent and interactive effects of harbor (i.e., Manchester, Quissett, and West Falmouth) and mooring impact zone, remaining mooring scar, recovered eelgrass, and unimpacted eelgrass, on eelgrass shoot density and percent cover. Prior to analysis, we tested that all data met the assumptions of normality and homogeneity of variances. We log transformed shoot density and arcsine transformed percent cover to meet these assumptions. For significant ANOVA results, we ran Tukey honest significance post-hoc tests to identify differences among treatments. We performed all analyses in R 4.1.0 (R Core Team 2021).

Modeling floating rode CMS Conversions per Acre of Eelgrass Recovery

To visualize our results in a context relevant to managers and decision makers we used the data collected in Experiment II to estimate the number of floating CMS necessary to restore an acre of eelgrass over five for each harbor (Manchester, Quissett, and West Falmouth) within the range of observed initial scar sizes (0–8 meters). First, we used the coefficients from the Experiment II ANCOVA model to parameterize linear models that estimated the change in scar radius as a function of initial scar radius and harbor specific intercepts:

$$\Delta R_i = m * R_{initial} + \beta_i [1]$$

Here $R_{initial}$ represents the initial length of the scar radius, m the change in scar radius per initial scar radius, and β_i the harbor specific change in scar radius of moorings that had no initial scar (Table 2). When the estimated change in scar radius was greater than the initial scar radius we set the change in scar radius to the initial scar radius value because recovery cannot exceed the initial scar extent. We then calculated final scar radius as the difference between initial scar radius and the change in scar radius:

Table 2
Coefficients from the Experiment II ANCOVA used to model the change in scar radius.

Parameter (units)	Value
m (meters * meter initial scar size ⁻¹)	-0.57
$\beta_{Manchester Harbor}$ (meters)	1.68
$\beta_{Quissett Harbor}$ (meters)	0.90
$\beta_{West Falmouth Harbor}$ (meters)	-0.05

$$R_{final,i} = R_{initial} - \Delta R_i [2]$$

We estimated initial and final scar area from the initial and final scar radii for each harbor using the equation for the area of a circle because conventional chain moorings generally form close to circular scars (e.g., Unsworth et al. 2017) and then we estimated the area of eelgrass recovery per conventional block and chain mooring converted to floating rode CMS from the difference of these areas:

$$Area_{initial} = \pi * R_{initial}^2 [3a]$$

$$Area_{final,i} = \pi * R_{final,i}^2 [3b]$$

$$\Delta Area_i = Area_{initial} - Area_{final,i} [4]$$

Finally, we then converted our harbor specific eelgrass recovery estimates ($\Delta Area_i$) to the number of conventional block and chain mooring conversions to floating rode CMS estimated to yield an acre of eelgrass recovery. When our model estimated increases in scar size following conversion, $\Delta Area_i < 0$, (e.g., moorings with small initial scar sizes in Quissett and Manchester Harbors) we set the number of mooring conversions to floating rode CMS to ∞ to indicate these are conditions under which no amount of conversions to floating road are predicted to lead to eelgrass restoration:

$$No. CMS_i \left(\frac{conversions}{acre} \right) = \frac{4046.86 m^2}{1 acre} * \frac{1}{\Delta Area_i \left(\frac{m^2}{CMS conversion} \right)} [5]$$

Because of the assumptions we made regarding the shape of the mooring scars, predictions from this analysis should be considered suggestive. The numbers of conservation moorings necessary to restore an acre of eelgrass predicted are estimates.

Reversion of Floating rode CMS to conventional chain moorings

To assess the rate of retention of floating rode CMS following conversion from conventional block and chain mooring systems we followed all moorings converted from conventional block and chain to floating rode CMS from Experiments I and II, as well as an additional sixteen moorings converted from conventional block and chain to floating rode CMS in 2014 and 2015 in three additional harbors: Boston (three moorings), Gloucester (four moorings), and Onset (six moorings), through the summer of 2019. For each mooring, we confirmed the identity of the mooring system by visual assessments via snorkel or SCUBA during which we recorded photos, videos, and notes on the mooring components. Across all experiments, a total of 52 moorings were monitored (i.e., 15 from Experiment I, 21 from Experiment II, 16 from Reversion monitoring) within a year of conversion from conventional block and chain to floating rode CMS and all but three moorings that we were unable to locate (two in Manchester Harbor and one in Gloucester Harbor) were monitored again in the summer of 2019. Throughout monitoring, we met with harbormasters and mooring owners to receive their feedback on the floating rode CMS.

Estimating the Extent of Eelgrass Impacted by Moorings

We used ArcGIS Pro to calculate the overlap of mooring fields in Massachusetts with historically mapped eelgrass meadows. The oldest and most comprehensive eelgrass extent layer, the 1995 survey conducted by MassDEP, was downloaded from the MassGIS (Bureau of Geographic Information (<https://www.mass.gov/orgs/massgis-bureau-of-geographic-information>), while the Massachusetts mooring field layer (2007) was taken from the Massachusetts Coastal Zone Management's (CZM) Massachusetts Ocean Resource Information System (MORIS) (<https://czm-moris-mass-eoea.hub.arcgis.com/#Search>). We intersected the two layers to calculate the area of impacted eelgrass.

Results

Experiment I

Extent of eelgrass recovery

Planting eelgrass in mooring scars following the installation of floating rode CMS in Manchester Harbor did not affect the area of eelgrass that recovered into the scars two years post-planting (Fig. 4A, Table 3). The mean initial radius of the scars associated with moorings converted to floating rode CMS was 4.2 meters $\pm$ 0.2 SE, and the mean final radius was 3.6 meters $\pm$ 0.4 SE. Scars at four of the five moorings converted to floating rode CMS decreased in radius. In contrast, radii of the scars at moorings that continued to use conventional chain increased slightly.

Table 3
One-way blocked ANOVA table of the change in radius, testing for difference between mooring type (CMS, CMS with planting, chain).

	Source	df	MS	F	P
Change in Radius	Mooring Type	1	1.407	3.431	0.123
Residuals		5	0.410		

Characteristics of recovered eelgrass

Eelgrass recovered following mooring conversion to floating rode CMS in Manchester Harbor had similar characteristics to unimpacted eelgrass in reference areas (Fig. 4B-D, Table 4). Shoot density ($113 \text{ shoots/m}^2 \pm 34 \text{ SE}$), percent cover ($32\% \pm 9 \text{ SE}$), and canopy height ($83.7 \text{ cm} \pm 3.5 \text{ SE}$) of recovered eelgrass did not differ from shoot density ($106 \text{ shoots/m}^2 \pm 17 \text{ SE}$), percent cover ($39\% \pm 5 \text{ SE}$), and canopy height ($87.6 \text{ cm} \pm 5.1 \text{ SE}$) of unimpacted eelgrass. Eelgrass characteristics in the remaining mooring scar area differed from recovered and unimpacted eelgrass (Fig. 4B-D, Table 4). Shoot density ($1 \text{ shoot/m}^2 \pm 0.8 \text{ SE}$), percent cover ($0.2\% \pm 0.2 \text{ SE}$), and canopy height ($4.8 \text{ cm} \pm 0.2 \text{ SE}$) of eelgrass in the remaining mooring scar were lower than recovered and unimpacted eelgrass.

Table 4
Two-way blocking ANOVA of shoot density, percent cover, and canopy height, testing for difference between planting treatments (planted and non-planted), eelgrass zone (Remaining Scar, Recovered Eelgrass, and Unimpacted Eelgrass), and the interaction.

	Source	df	MS	F	P
Shoot Density	Mooring Type	1	479.06	4.02	0.0758
	Zone	2	1218.12	10.23	0.00482*
	Mooring Type x Zone	2	131.29	1.102	0.373
	Residuals	9	119.11		
Percent Cover	Mooring Type	1	340.88	2.055	0.185
	Zone	2	2109.02	12.71	0.00239*
	Mooring Type x Zone	2	102.37	0.617	0.561
	Residuals	9	165.88		
Canopy Height	Mooring Type	1	254.1	5.35	0.0460*
	Zone	2	11699.3	246.35	1.37e^{-8} *
	Mooring Type x Zone	2	52.9	1.11	0.369
	Residuals	9	47.5		

Experiment II

Extent of eelgrass recovery

Harbor and size of the initial mooring scar influenced the area of eelgrass recovery following floating rode CMS installation (Fig. 5, Table 5). Specifically, the reduction of mean scar radii five years after conversion to floating rode CMS in West Falmouth Harbor ($2.2 \text{ m} \pm 0.6 \text{ SE}$) was greater than in Manchester Harbor ($0.0 \text{ m} \pm 0.9 \text{ SE}$) and reduction in scar radii in Quissett Harbor ($0.6 \text{ m} \pm 0.6 \text{ SE}$) was intermediate and did not differ from either of the other two harbors. Scars with larger starting radii also recovered more eelgrass. Six of the seven moorings where scars increased in size had initial scars of one meter or less and no scars increased in size at moorings with initial scars greater than 3.5 meters. At the final monitoring, mean scar radii remained at 2.04 meters and only one mooring scar completely revegetated with eelgrass across all three harbors.

Table 5
Two-way ANCOVA of the change in radius, testing for difference between harbor locations, initial scar radius, and the interaction between the two.

Source		df	MS	F	P
Change in Radius	Harbor	2	9.053	8.77	0.003*
	Initial Radius	1	33.66	32.62	4.12e^{-5} *
	Harbor x Initial Radius	2	0.18	0.17	0.841
	Residuals	15	1.032		

Eelgrass expanded at a rate of $78 \text{ cm yr}^{-1} \pm 29$ (mean $\pm$ SE) in West Falmouth Harbor, $38 \text{ cm yr}^{-1} \pm 14$ in Quissett Harbor, and $23 \text{ cm yr}^{-1} \pm 10$ in Manchester Harbor.

Characteristics of recovered eelgrass

Floating rode CMS resulted in recovered eelgrass with similar habitat quality to unimpacted eelgrass in their respective harbors (Fig. 6A and B, Table 6). Shoot density ($69 \text{ shoots m}^{-2} \pm 18 \text{ SE}$) and percent cover ($24\% \pm 6 \text{ SE}$) of recovered eelgrass did not differ from shoot density ($106 \text{ shoots m}^{-2} \pm 26 \text{ SE}$) or percent cover ($38\% \pm 8 \text{ SE}$) of unimpacted eelgrass respectively. Eelgrass shoot density ($21 \pm 8 \text{ SE}$) and percent cover ($7 \pm 3 \text{ SE}$) in the remaining mooring scar was less than in recovered and unimpacted eelgrass.

Table 6

Two-way ANOVA of shoot density, and canopy height, testing for difference between harbor locations (West Falmouth, Manchester, and Quissett), eelgrass zone (Remaining Scar, Recovered Eelgrass, and Unimpacted Eelgrass), and the interaction.

	Source	df	MS	F	P
Shoot Density	Harbor	2	12.66	14.73	4.73e ⁻⁵ *
	Zone	2	11.25	13.088	0.000106*
	Harbor x Zone	4	2.18	2.54	0.0625
	Residuals	27	0.85		
Percent Cover	Harbor	2	0.43	10.066	0.000542*
	Zone	2	0.57	13.63	8.09e ⁻⁵ *
	Harbor x Zone	4	0.044	1.042	0.404
	Residuals	27	0.042		

Eelgrass characteristics differed among the harbors studied (Table 6). Shoot density in West Falmouth Harbor (99 shoots m⁻² ± 16 SE) was greater than in Quissett Harbor (21 shoots m⁻² ± 7 SE). Shoot density in Manchester Harbor (73 shoots m⁻² ± 35 SE) was intermediate. Eelgrass percent cover in West Falmouth Harbor (35% ± 6 SE) was greater than in Quissett Harbor (9% ± 4 SE) and Manchester Harbor (21% ± 8 SE).

Modeling floating rode CMS Conversions per Acre of Eelgrass Recovery

The model predicted the number of mooring conversions to floating rode CMS necessary to restore an acre of eelgrass in five years ranges from 25 to ∞ depending on the harbor and initial scar radius (Fig. 7). Differences in predicted floating rode CMS mooring conversion effort per acre of eelgrass recovery among harbors are strongest at smaller initial mooring scar radii. No eelgrass recovery is predicted for moorings with initial scar radii less than 1.68 m in Manchester Harbor and 0.9 m in Quissett Harbor. In West Falmouth Harbor, the model predicted eelgrass recovery following mooring conversion to floating rode CMS at all initial scar sizes. For moorings with the largest scars in our study (8 m initial scar radii), the model predicted only 25–34 mooring conversions to floating rode CMS would be necessary to restore an acre of eelgrass. For the mean initial scar in our study (3.14 m initial scar radii), the model predicted that 158, 269, and 1901 moorings would need to be converted to floating rode CMS to achieve an acre of eelgrass recovery in West Falmouth, Quissett, and Manchester Harbors respectively.

Reversion of floating rode CMS to conventional chain moorings

The proportion of floating rode CMS reverted to conventional block and chain moorings varied among harbors (Table 7). In Boston Harbor, all monitored floating rode CMS were reverted to conventional chain moorings. In contrast, all floating rode CMS monitored in West Falmouth, Quissett, and Onset Harbors were retained as floating rode CMS throughout the study. Most moorings also were retained as floating rode CMS in Gloucester Harbor (67%) and Manchester Harbor (85%), although in some cases their design was altered to add an additional section of floating rode or change the style of floating rode.

Table 7

Summary of floating rode CMS retained throughout the duration of our study across the six harbors monitored.

Harbor	No. floating rode CMS monitored through summer 2019	No. floating rode CMS converted back to a conventional chain mooring by summer 2019	No. floating rode CMS retained through summer 2019	Percent floating rode CMS retained through summer 2019
Boston	3	3	0	0%
Gloucester	3	1	2	67%
Manchester	13	2	11	85%
Onset	6	0	6	100%
West Falmouth	16	0	16	100%
Quissett	8	0	8	100%
Total	49	6	43	88%

Estimating the extent of eelgrass impacted by moorings

Mooring fields in Massachusetts impact 267 hectares (660 acres) of mapped eelgrass, or 1.7% of the mapped eelgrass extent. These impacts to eelgrass are spread across 31 mooring fields, with areas of overlap between moorings and eelgrass ranging from 0.0076 acres to 51.03 acres. Because these results are based on a 2007 data layer showing approximate mooring field extent, we anticipate the actual overlap is greater.

Discussion

We found converting conventional block and chain moorings to floating rode CMS can be an effective tool to restore eelgrass to scars created by chain scour in MA, but the amount of eelgrass recovery depended on both the harbor where moorings were converted to floating rode CMS and the size of the scar at the time of conversion. Less eelgrass recovered under floating rode CMS in the deepest, most exposed harbor with the greatest tidal range and at moorings with smaller initial scars (Fig. 5, Table 1). Notably, transplanting vegetative eelgrass shoots into scars following conversion to floating rode CMS did not increase the extent or quality of eelgrass habitat recovered, indicating mooring conversions to

floating rode CMS need not be supplemented by planting to achieve eelgrass restoration (Fig. 4). We also observed challenges associated with the installation and retention of floating rode CMS moorings in MA. Improper installation compromised the function of half the moorings converted to floating rode CMS in Experiment I, and of the moorings converted to floating rode CMS that we tracked through 2019, retention of floating rode CMS also varied considerably among harbors from complete retention to complete reversion back to conventional block and chain moorings (Table 7). We found mooring fields overlap with hundreds of acres of eelgrass in MA and conversion of moorings to floating rode CMS resulted in eelgrass recovery, indicating floating rode CMS can be an important tool for eelgrass conservation and restoration in the state. However, challenges regarding site-specific design, installation, long-term maintenance, and perception must be addressed to fully realize this potential.

Effects of Harbor

The amount of eelgrass recovery following conversion to floating rode CMS differed among harbors (Fig. 5), which may be due to a variety of factors that impact the performance of the mooring system and/or the growth rate of eelgrass. Observations of “Seaflex” CMS in the United Kingdom noted increased wave exposure and tidal influence decreased the system’s ability to prevent bottom scour, but performance improved with increasing mooring depth (Egerton 2011). In contrast, “rope” CMS, used to moor small vessels, eliminated damage to seagrass among harbors of varying depths and tidal amplitudes (Unsworth et al. 2022). We found eelgrass recovery following conversion to floating rode CMS was greatest in West Falmouth Harbor (Fig. 5), where moorings were more protected from wave action and experienced a smaller tidal range, suggesting floating rode CMS performance may be negatively related to wave exposure and tidal amplitude (Table 1). The relationship between floating rode CMS performance and depth was more complex. Moorings in Manchester Harbor, where we observed the least eelgrass recovery (Fig. 5), were on average located a meter deeper than in West Falmouth Harbor (Table 1). Quissett Harbor, which has similar exposure and tidal range as West Falmouth Harbor, but is a meter shallower, had eelgrass recovery intermediate of West Falmouth and Manchester Harbors (Fig. 5, Table 1). Together, these results suggest depth may only impair floating rode CMS function below a threshold (less than two meters), possibly because in very shallow areas the ability of buoyancy to lift the mooring rode off the eelgrass canopy or even the seafloor becomes limited by the water surface. Indeed, in a previous study that observed successful performance of a “Stirling” CMS, which also used buoyancy to reduce scour, the mooring was in water deeper than two meters (Luff et al. 2019). For these shallow mooring areas, which are typically only accessible to small vessels, the lighter weight and more streamlined design of “rope” CMS may cause less damage to eelgrass than bulkier floating rode CMS, however, further research comparing the impacts of these CMS designs on eelgrass is needed (Unsworth et al. 2022). Importantly, these differences in mooring efficacy among harbors are not trivial. Predictions from a model parameterized using our data indicate restoring an acre of eelgrass in Manchester Harbor would likely require thousands more mooring conversions than would be needed to restore the same acreage in West Falmouth Harbor (Fig. 7), highlighting the need for additional monitoring of floating rode

CMS over a broader combination of conditions to disentangle the context dependence of floating rode CMS performance.

It is difficult from our data to ascertain the degree to which variable eelgrass growth rates among harbors influenced the extent of eelgrass recovery following floating rode CMS installation. Light availability, a key factor regulating eelgrass growth, was above the minimum threshold for eelgrass growth at all sites (Duarte 1991), but was highest at Quissett and West Falmouth Harbors. However, finer sediments, in which eelgrass has higher light requirements for growth (Kenworthy et al. 2013), were present at Quissett and West Falmouth Harbors. Further, direct estimates of eelgrass growth rates into mooring scars are confounded by the presence of floating rode CMS rodes which we observed inhibiting the expansion of eelgrass into areas close to the anchor or even increasing the size of some smaller scars (radii < 3.5 meter, Fig. 5). If we restrict our analyses to the few scars with initial radii greater than four meters to minimize the influence of rode impacts on eelgrass expansion, West Falmouth Harbor had the greatest eelgrass expansion rates, $78 \pm 29 \text{ cm yr}^{-1}$, followed by Quissett, $38 \pm 14 \text{ cm yr}^{-1}$, and then Manchester, $23 \pm 10 \text{ cm yr}^{-1}$, Harbors. Interestingly, eelgrass expansion rates via clonal propagation range from $22\text{--}32 \text{ cm yr}^{-1}$, indicating the recovery at West Falmouth and Quissett Harbors was probably supplemented by seed-based recruitment (Marba and Duarte, 1998). In contrast, the eelgrass expansion in Manchester Harbor fell within typical eelgrass clonal propagation rates and was also comparable to eelgrass recovery rates via clonal propagation measured following propellor scouring or mussel dragging, similar physical disturbances (Neckles et al. 2005; Orth et al. 2017). In Manchester Harbor, the harbor with the most exposure and largest tides of the three harbors we studied (Table 1), waves and current may have been too strong for seeds to recruit or survive in mooring scars (Oreska et al. 2021). In contrast to expansion rates, recovered eelgrass had similar characteristics to adjacent unimpacted eelgrass at all harbors (Fig. 6A and B). Many of the key ecosystem functions provided by eelgrass are closely tied to the height and density of eelgrass shoots, including habitat provisioning (McCloskey and Unsworth, 2015; Yeager et al. 2017) and sediment stabilization (Peterson et al. 2004). Thus, eelgrass recovery is likely indicative of a return of these ecosystem functions to pre-disturbance levels.

Effects of mooring scar size

The amount of eelgrass recovered following conversion to floating rode CMS was positively correlated with the size of the initial mooring scar (Fig. 5). This correlation is not surprising given larger scars simply have more area available for eelgrass to recolonize. However, a closer examination suggests additional factors may also be at play. For example, eelgrass only completely revegetated one mooring scar and, on average, unvegetated areas with radii of two meters remained around the helix anchors five years after conversions (Fig. 5). While complete eelgrass revegetation of larger initial scars could be limited by the rate of eelgrass expansion (Marba and Duarte, 1998), suggesting full recovery would occur eventually, unvegetated areas remained in smaller scars as well. In fact, no eelgrass recovered into scars with initial radii of one meter or less (Fig. 5). Instead, these smaller scars all increased in size following mooring conversion to floating rode CMS. Further, during annual monitoring we observed that in some cases floating rodes and subsurface buoys were heavily fouled by marine algae and invertebrates causing them

to lose buoyancy and drag on the bottom. In other cases the rode was floating but the short length of chain connecting the rode to the helix anchor was hitting the bottom due to the weight of the shackle that attached it to the floating rode section. These observations in combination with our eelgrass recovery data, indicate areas within one to two meters of the helix anchor still experience enough scour from floating rode CMS gear to prevent eelgrass recovery. Incomplete seagrass recovery due to continued scour impacts was also observed following installation of “screw” CMS in Australia and “Seaflex” CMS in the United Kingdom, however, these failures were attributed to insufficient water depth (Egerton 2011, Demers et al. 2013). While water depth may also have affected floating rode CMS performance, as discussed above, and could interact with fouling to exacerbate floating rode CMS impairment, we observed fouled CMS dragging on the bottom and incomplete eelgrass recovery at all three sites, suggesting fouling impairs floating rode CMS function and prevents complete eelgrass recovery across a variety of contexts. Control of fouling organisms via increased frequency of conservation mooring system maintenance (e.g., monthly or biannual cleanings or application of antifouling paint to shackles, rodes, and subsurface buoys) may further reduce or eliminate impacts from conservation moorings on eelgrass, but further research into the costs and benefits of these strategies is needed. Antifouling paints in particular are toxic to a number of marine organisms (Amara et al. 2018). In sum, floating rode CMS, while reducing the total area of eelgrass impacts from single system chain moorings, still preclude eelgrass colonization in the immediate vicinity of the helix anchor.

Transplanting into mooring scars

Contrary to our hypothesis, transplanting vegetative eelgrass shoots into scars around moorings following conversion to floating rode CMS did not increase the amount of eelgrass restored compared to those that did not receive supplemental planting (Fig. 4A). We failed to observe increases in the amount of eelgrass recovery into mooring scars in part due to poor survival and growth of our eelgrass transplants (Figure S1). This result is not too surprising in light of estimates that only 37% of eelgrass transplant trials are successful (van Katwijk et al., 2009; Bayraktarov et al., 2016). In particular, the small scale of our transplant effort (192 shoots transplanted per mooring scar) may have contributed to our lack of success (van Katwijk et al. 2009). Eelgrass transplanted in small quantities have reduced survival and population growth rate which van Katwijk et al. (2009) attributed to environmental variability and positive density dependence. The presence of large areas of natural eelgrass within meters of our transplants suggest a lack of self-facilitation processes (e.g., sediment stabilization; van der Heide et al. 2011) did not affect the success of our plantings. However, our field observations point towards environmental variability, specifically related to hydrodynamic conditions and the distribution of macroalgal and detrital mats, as key determinants of transplant success in Manchester Harbor. The MA coastline regularly experiences severe winter storms. Winter storms create strong current velocities capable of uprooting small eelgrass transplants (Paulo et al. 2019). Hydrodynamic stress is also stronger along more exposed coastlines, and Manchester Harbor is a relatively exposed mooring field (Calumpong and Fonseca, 2001; Table 1). Though we anchored individual eelgrass shoots with bamboo skewers, we observed some skewers lying on the sediment surface during subsequent monitoring, indicating this technique may have been insufficient to hold against the hydrodynamic forces present at some of the

mooring scars. Hydrodynamic forces also influence the distribution of drift macroalgae and detritus, known to inhibit eelgrass through shading, physical damage, and eutrophication (Canal-Verges et al. 2014). Storm wave action moves sediment from unvegetated areas into surrounding eelgrass, creating depressions in the seafloor that attract drift macroalgae and detritus (Canal-Verges et al. 2014; Collins et al. 2010). Similarly, we noted the mooring scars we monitored were often eroded relative to the surrounding meadow bathymetry, forming depressions which trapped mats of macroalgae and detritus. Finally, in line with these observations, moorings that received eelgrass transplants had the most variable eelgrass recovery outcomes (Fig. 4A), further suggesting microvariability in environment among transplant locations affected transplant performance.

The relatively short duration of our transplanting study (2.5 years) and the limited replication of each mooring system treatment may also have contributed to our failure to detect increases in eelgrass recovery among moorings converted to floating rode CMS that received eelgrass transplants and those that did not, and between moorings converted to floating rode CMS and those remaining as conventional block and chain (Fig. 4A). Perennial grasses typically follow a 'sleep, creep, leap' growth pattern over the first three growing seasons following planting, and growth trajectories of eelgrass adult shoots transplanted at nearby restoration sites did not increase in density until as many as three growing seasons later (Schenck 2022). Though our sample size limited the power of our statistical analyses, the trends in the data suggest differences in eelgrass recovery among treatments would have been apparent had we been able to increase the replication of our treatments. For example, we observed eelgrass recovery into four out of five moorings converted to floating rode CMS, but at neither of the conventional block and chain controls (Fig. 4A), demonstrating once the impacts from the chain scour are removed eelgrass starts revegetating mooring scars within two years of conversion to floating rode CMS. Further, two of the three planted mooring scars had more eelgrass recovery than their unplanted CMS counterparts (Fig. 4A). However, these differences were relatively small, around half a meter greater eelgrass recovery than their unplanted counterparts, and, as noted above, inconsistent. Planting more eelgrass in mooring scars would likely increase transplant success and thus improve eelgrass recovery (van Katwijk et al. 2009), however, because bare space is more limited in mooring scars than at a typical eelgrass restoration site this may not always be an option or the most effective use of resources. In addition, characteristics of recovered eelgrass (e.g., canopy height, shoot density, and percent cover) that are closely linked to the ecosystem functions eelgrass provide (e.g., habitat provisioning; McCloskey and Unsworth, 2015; Yeager et al. 2017), while comparable to unimpacted eelgrass, did not differ among planted and unplanted floating rode CMS (Fig. 4B-D). Further, when we tracked eelgrass recovery following mooring conversion to floating rode CMS at sites that did not receive planting over a longer time (e.g., 5 years, *Experiment II*), we found natural colonization was typically sufficient to revegetate areas where scour disturbance had been alleviated, especially in more protected harbors where seed-based recruitment appears to contribute to recovery, indicating any benefits of supplemental planting would only be temporary and may only be present in more exposed harbors where recovery is limited to vegetative propagation (Fig. 5). Thus, any ecological benefits of supplementing mooring conversions

with eelgrass planting are minimal, temporary, and likely context dependent in comparison to simply converting conventional block and chain moorings to floating rode CMS.

Challenges to Floating Rode CMS Installation and Retention

Proper installation was critical to the success of floating rode CMS as a tool for eelgrass restoration. Improperly installed floating rode CMS uprooted the eelgrass we transplanted in West Falmouth Harbor. Specifically, floating rode CMS were installed without subsurface buoys, resulting in the bottom shackles scouring the seafloor around the helix anchor. In addition, the rodes were improperly sized for the depth of the harbor, leading them to tangle, drag, and further scour the bottom. After reporting these issues to the Harbormaster, subsurface buoys were added and rode lengths adjusted. During subsequent SCUBA surveys, we observed the floating rode CMS functioning properly. However, these corrective actions were too late to prevent impacts to the eelgrass transplants, demonstrating the potential for improperly installed floating rode CMS to damage eelgrass. Adjustments to improve functioning of floating rode CMS were also needed following installations in Quissett and Manchester Harbors. Similar challenges involving “screw”, “Seaflex”, and “EzyRider” CMS installations were also observed in Moreton Bay, Queensland, Australia, where CMS required adjustments following installation to function properly under the local environmental conditions (Dunn, 2014). All together, these observations emphasize the importance of accounting for environmental conditions (e.g., depth) during CMS installations. In addition, because installation errors (e.g., omission of subsurface buoy) can occur and optimal gear adjustment (e.g., rode length) may be difficult to anticipate prior to installation, especially in new environments, monitoring and adjustment of CMS following installation is key to achieving optimal performance.

Another obstacle to the successful restoration of eelgrass following mooring conversion to floating rode CMS was reversion of floating rode CMS back to conventional chain moorings by the owner. Even if floating rode CMS are optimally sited and installed, mooring owners are ultimately responsible for the equipment they use to moor their boats, and despite rules to the contrary, we found that some mooring owners put out chain in place of their floating rode CMS, particularly in preparation for a storm or if the floating rode CMS needed replacement (Table 7). Interestingly, owner retention of floating rode CMS differed considerably among harbors. For example, owners retained all floating rode CMS in Onset, Quissett, and West Falmouth Harbors, but none were retained in Boston Harbor and retention was mixed in Manchester and Gloucester Harbors. From the feedback we received from harbormasters and mooring owners we identified three main factors underlying owners decisions to revert to chain moorings: (1) owners did not trust floating rode CMS to safely secure their boats, (2) owners were advised by professional mooring installers to revert their moorings to conventional chain, and (3) owners were not aware of the requirement for a permit through the US Army Corps of Engineers (US Army Corps of Engineers, Massachusetts General Permit, GP2, 2018), and in some municipalities through local bylaws as well, to revert their moorings from floating rode CMS back to conventional chain systems in eelgrass. Targeted conservation guidance, incentives, and increased societal recognition of seagrass importance are key to achieving the behavioral responses and social acceptance needed to successfully restore eelgrass via CMS (Parry-Wilson et al. 2019, Unsworth et al. 2019). In our study, the initial costs to owners

for the conversion of moorings from traditional chain to floating rode CMS were completely subsidized, however, these subsidies did not extend to the subsequent replacement costs which may have reduced floating rode CMS retention. Nonetheless, in most harbors we had over 50% retention of floating rode CMS, which we attribute to a strong community-driven conservation management ethos developed through in person presentations and meetings with local boaters and harbormasters (Parry-Wilson et al. 2019). Future CMS initiatives could also direct outreach and education efforts towards local professional mooring installers to further promote the retention of floating rode CMS. In addition, some owners remained skeptical of the safety of this new technology even when presented with evidence that floating rode CMS provide equal or greater strength and holding capacity when compared to conventional chain moorings (*reviewed in* Urban Harbors Institute 2013). Thus, providing boat owners with alternative CMS designs that integrate chain or other materials that increase owner's perception of the safety of the CMS system, may also improve CMS retention among owners concerned about boat safety, however, further study of such alternative designs is needed to confirm their efficacy in preventing damage to eelgrass in Massachusetts harbors (Luff et al. 2019). Finally, explicit and consistent regulation enforcement at the municipal, state, and federal level would improve compliance.

Opportunity, Feasibility, and Costs of Eelgrass Restoration and Conservation Via Floating Rode CMS

Mooring impacts are both highly localized around the anchor (e.g., chain scour), and extend into the established meadow (e.g., turbidity associated with destabilized sediments). An estimated 334 hectares of eelgrass overlap with mapped mooring fields in Massachusetts and the use of floating rode CMS may enhance restoration and minimize associated impacts to that entire area (Williams & Heck 2001, Serrano et al. 2016, Unsworth et al. 2017). Further, our assessment of mooring areas was limited to clusters of ten or more contiguous moorings, but many boat moorings in Massachusetts are distributed in smaller aggregations or even in isolation. Finally, our assessment is based on a 2007 data product, and thus we have likely underestimated the potential for floating rode CMS as a tool for eelgrass restoration.

Seagrasses are among the most expensive coastal marine habitats to restore. The median total restoration costs per hectare of seagrass is US\$383,672 (2010) (Bayraktarov et al. 2016). While these costs are not specific to eelgrass, eelgrass is by far the most common seagrass species restored and thus seagrass restoration costs are likely reflective of eelgrass restoration costs (van Katwijk et al. 2016). It is difficult to assess the cost of restoring an equivalent area of eelgrass by converting moorings to floating rode CMS because the efficacy of floating rode CMS in restoring eelgrass was contingent on the location and the size of the scar associated with the mooring (Fig. 5). However, if we consider West Falmouth Harbor, the location where floating rode CMS where most effective in restoring eelgrass, the capital cost (e.g., purchasing and installation) of converting the 390 existing moorings to floating rode CMS predicted to restore a hectare of eelgrass (Fig. 7) is US\$1,192,244 (2010), approximately three times the median cost using traditional restoration strategies. Further, we did not obtain permitting and operating cost estimates (e.g., maintenance, monitoring, repair, and replacement) from mooring owners, but if these costs were included, the total cost of implementing floating rode CMS would be greater. Notably, these

already high costs would increase for harbors where floating rode CMS were less effective in restoring eelgrass and thus additional mooring conversions would be needed to achieve equivalent restoration acreages (Fig. 7). In contrast, the capital cost of converting the 62–84 moorings to floating rode CMS (depending on the harbor) with large scars (8 m radius) predicted to restore a hectare of eelgrass (Fig. 7) is US\$188,646 – US\$256,559 (2010). These hypotheticals highlight that, by targeting moorings with large scars, conversion of moorings to floating rode CMS can be a cost effective and logistically feasible means to restore eelgrass.

Conversion of moorings to floating rode CMS may also help protect existing eelgrass meadows by increasing their resistance to climate stressors such as temperature and sea level rise. The suspension of sediments and nutrients from areas denuded and persistently disturbed by conventional chain moorings decreases water quality and thus the amount of light available to eelgrass (Williams & Heck 2001, Serrano et al. 2016, Unsworth et al. 2017). Critically, maintaining water quality at the status quo may not provide sufficient light for eelgrass to persisted under projected sea temperatures and sea levels (Dunic et al. 2023). Conserving existing eelgrass meadows is paramount because of the high cost and high failure rate of restoration (Bayraktarov et al. 2016, van Katwijk et al. 2016). Once eelgrass meadows are lost they often are unable to recover due to the absence of self-reinforcing feedbacks, like wave buffering and sediment binding provided by the established meadow (van der Heide et al. 2007; Carr et al. 2010). Future investigation into the potential for floating rode CMS to improve coastal water quality and thus increase eelgrass resistance to climate associated stressors is needed to fully assess the value of converting moorings to floating rode CMS.

Takeaways and Recommendations for CMS as a Tool for Eelgrass Restoration

The following points summarize what we have learned by studying eelgrass recovery following conversion of conventional chain moorings to floating rode CMS in Massachusetts and apply these results to identify best practices for using CMS as a tool for eelgrass restoration.

1. Floating rode CMS reduce impacts to eelgrass compared to conventional chain systems. Floating rode CMS or alternative CMS designs of equal or lesser impact to eelgrass should be required for all existing moorings in eelgrass habitat.
2. Floating rode CMS do not eliminate impacts to eelgrass. Therefore, we recommend no new moorings be permitted and installed in eelgrass..
3. More eelgrass recovered at moorings with larger scars. To maximize eelgrass restoration, conventional chain moorings with large scars should be prioritize for floating rode CMS conversion.
4. Eelgrass recovery did not differ among moorings converted to floating rode CMS that received eelgrass transplants and those that did not. Conversion of conventional chain moorings to floating rode CMS need not be accompanied by eelgrass transplants.
5. Improper installation, reversion to conventional chain moorings, and fouling of floating rode CMS reduced eelgrass recovery.

- a. Visual inspections and maintenance of floating rode CMS should be performed monthly throughout the boating season to confirm optimal system performance, make gear adjustments to achieve optimal system performance as needed, and remove fouling organisms.
- b. Conversion of conventional chain moorings to CMS should be accompanied by (i) education and outreach directed towards the local boating community, including boat owners, harbor masters, and professional mooring installers, and (ii) monetary incentives to encourage conversion to and retention of CMS.
- c. Boat owners should be provided with alternative CMS designs to improve CMS retention. Additional research into these alternative CMS designs should be supported to assess their efficacy as a tool for eelgrass restoration.
- d. Municipal, state, and federal rules and regulations should be updated to include clear and consistent recommendations and guidance on CMS based on the best available science.

Our study demonstrates that converting conventional chain moorings to floating rode CMS results in eelgrass recovery into mooring scars. However, the extent of eelgrass restored depends on the location and the extent of mooring impact. In addition, eelgrass recovery was often incomplete due to continued scour impacts close to the anchor from floating rode CMS mooring gear and was further inhibited in some cases by improper installation and maintenance of floating rode CMS. Encouragingly for eelgrass conservation and restoration, the participation in this study along with the use of floating rode CMS and other CMS designs regionally and globally suggests motivation for action exists among boating communities (Egerton 2011; Dunn 2014). However, our results highlight the need for more studies on the influence of environmental conditions and installation and maintenance techniques on CMS performance (Unsworth et al. 2019, Sagerman et al. 2020). Understanding where to locate and how to install and maintain floating rode CMS to most effectively restore eelgrass will help decision makers (e.g., resource managers and harbor masters) and stakeholders (boat owners and conservation groups) identify areas to prioritize for CMS conversions and protocols to achieve optimal CMS performance. We also identified challenges in the retention of floating rode CMS. Alternative CMS designs should continue to be developed and assessed to find options that are more palatable to boat owners. In light of increasing pressure to provide infrastructure for growing coastal populations, sustainable environmental stewardship will require us to continue to innovate- developing, testing, and adopting new means of coexisting alongside coastal ecosystems.

Declarations

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Figures

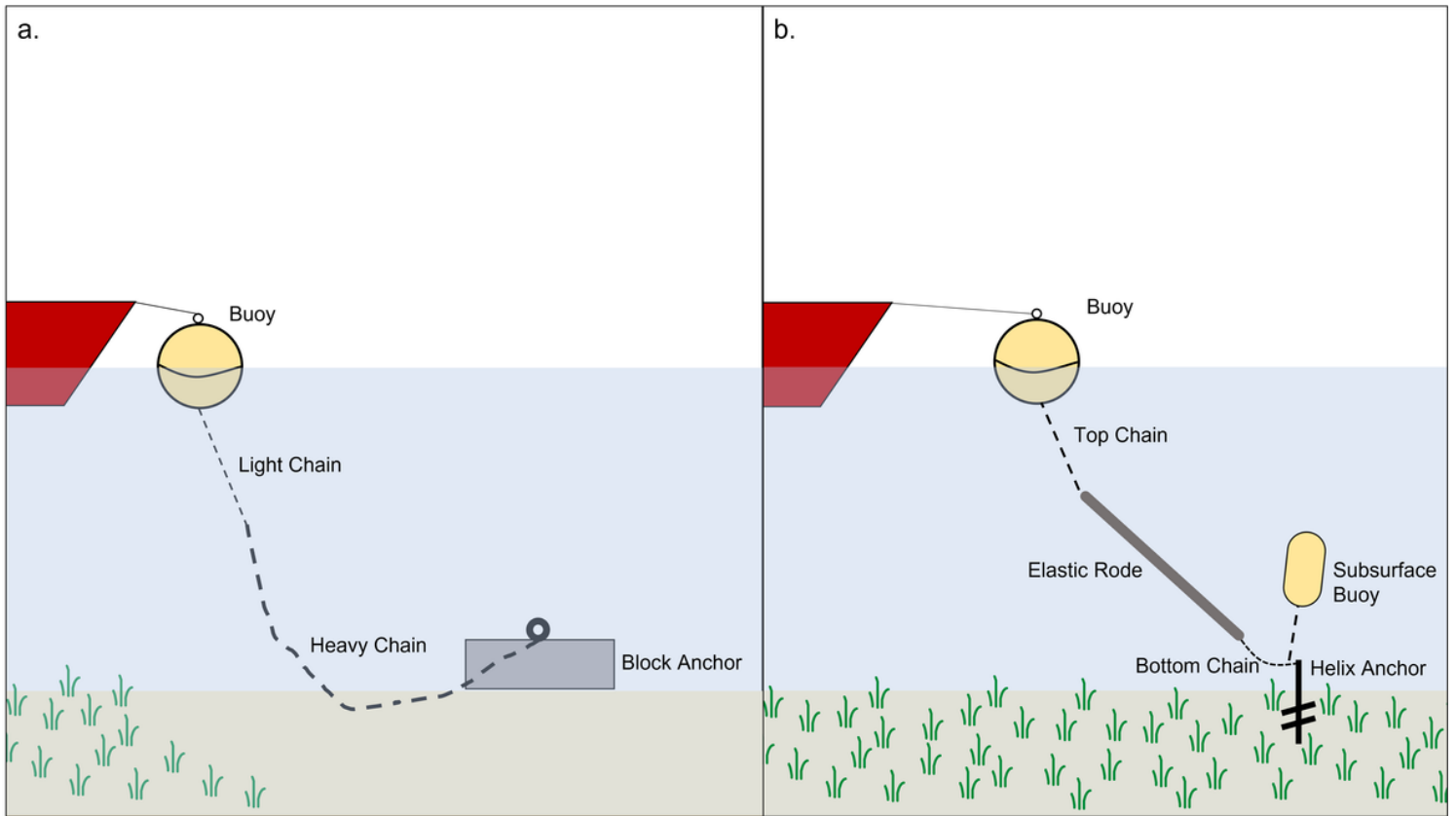


Figure 1

(a) Diagram of a conventional block chain mooring. (b) Diagram of a “floating rode” conservation mooring system (CMS)

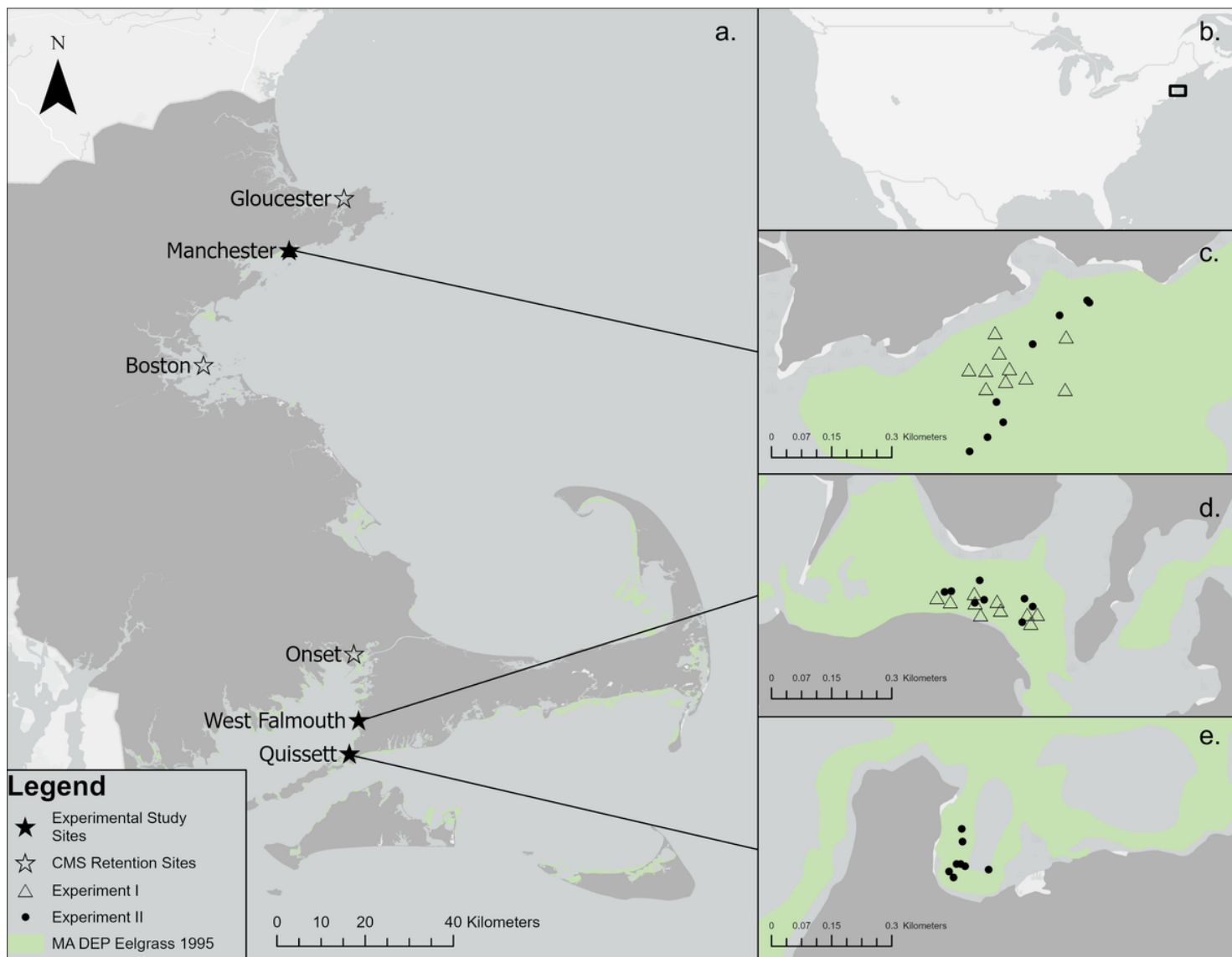


Figure 2

(a) Map of study sites surveyed. **(b)** United States of America, with study area shown. **(c, d, e)** Manchester, West Falmouth, and Quissett harbors showing mooring locations from Experiment I and II over mapped eelgrass meadows

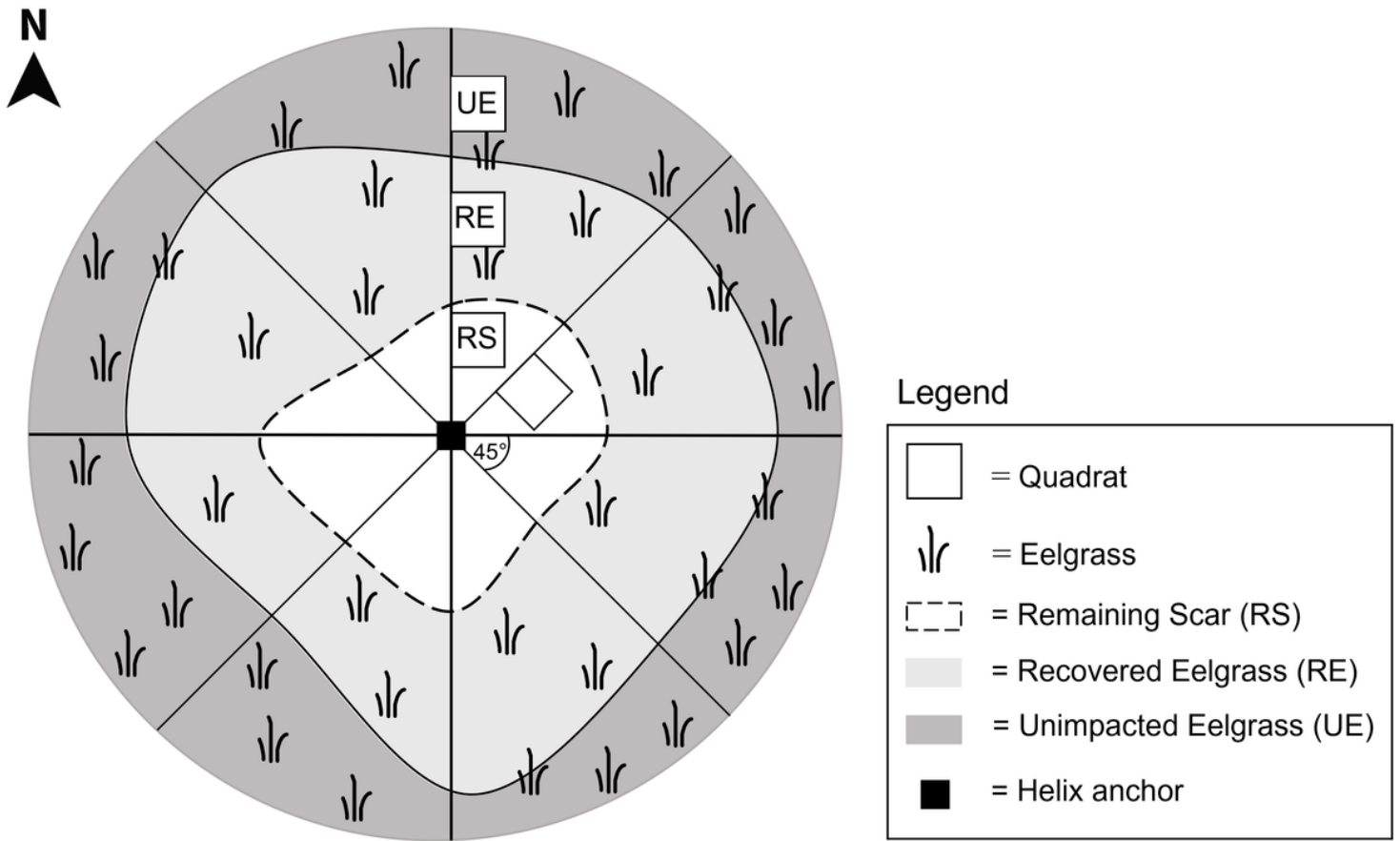


Figure 3

Diagram of the three eelgrass zones: Remaining Scar (RS), Recovered Eelgrass (RE), and Unimpacted Eelgrass (UE), and eight transect lines along which divers measured eelgrass characteristics at each mooring

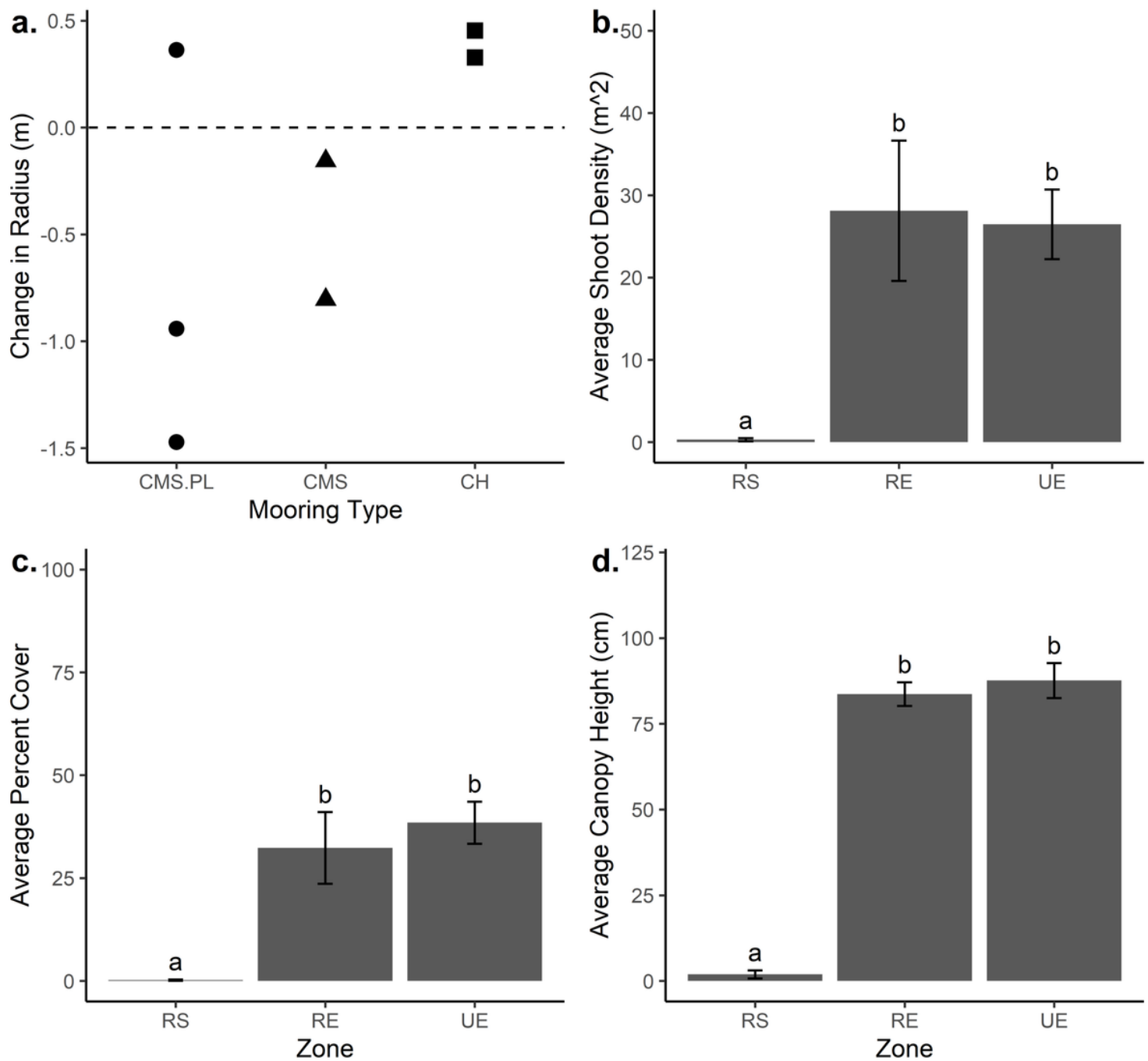


Figure 4

(a) Change in radius plotted against the three mooring types: CMS with planting (circle), CMS (triangle), and chain (square). Dashed line denotes no change in radius from 2011 to 2013. Differences in **(b)** shoot density, **(c)** canopy height, and **(d)** percent cover, between the Remaining Scar (RS), Recovered Eelgrass (RE), and Unimpacted Eelgrass (UE) zones

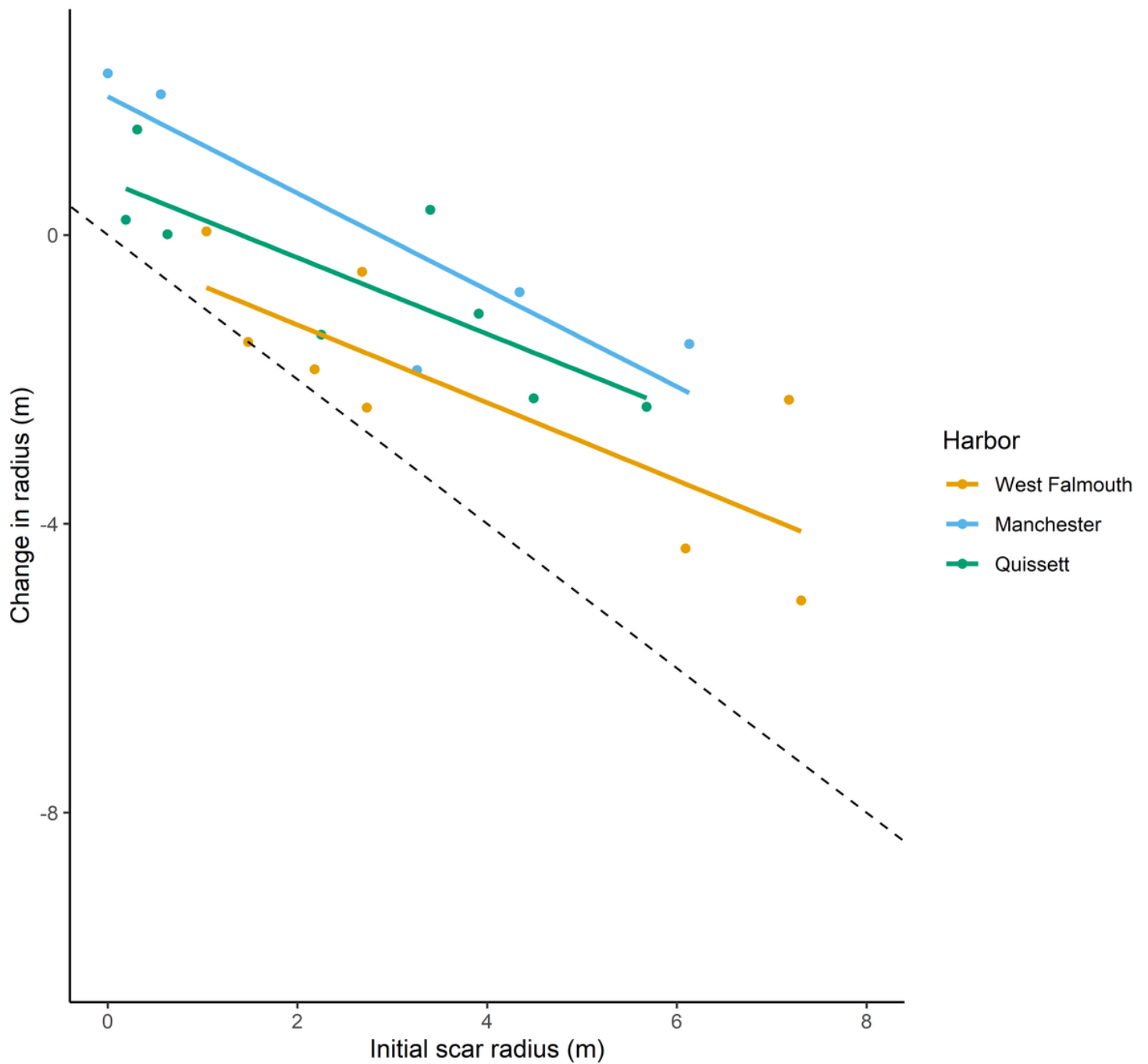


Figure 5

Change in mooring scar radius (final scar radius – initial scar radius) plotted against initial mooring scar radius per harbor. Dashed line denotes the change in radius (i.e., eelgrass recovery) associated with complete revegetation the mooring scar

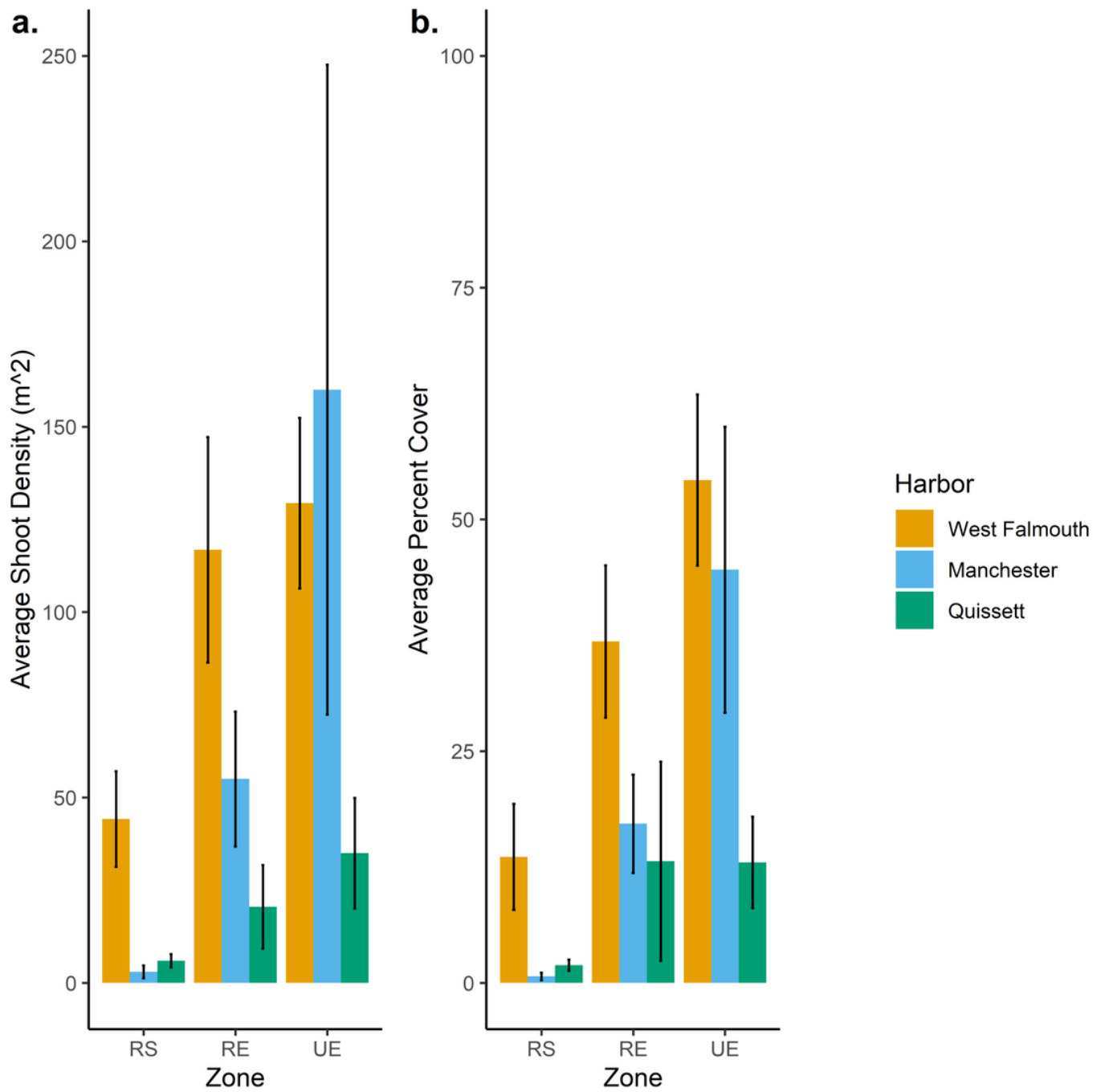


Figure 6

Differences in **(a)** shoot density, and **(b)** percent cover, between the Remaining Scar (RS), Recovered Eelgrass (RE) and Unimpacted Eelgrass (UE) zones in West Falmouth, Manchester, and Quissett Harbors

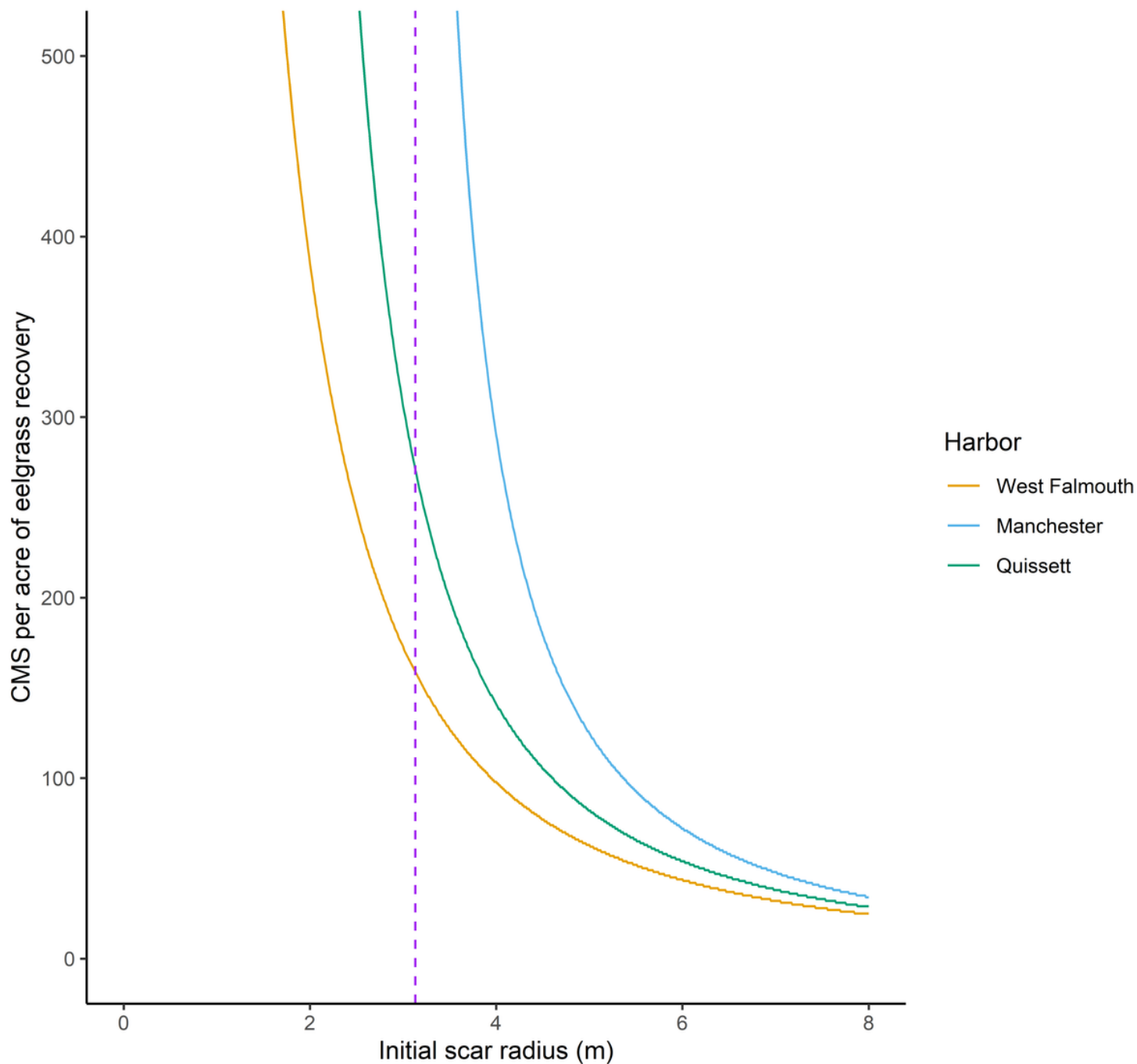


Figure 7

Estimated number of CMS conversions necessary to restore an acre of eelgrass in Manchester, Quissett, and West Falmouth Harbors plotted against initial scar radius. Dashed line denotes overall average initial scar radius from this study

Supplementary Files

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