Fantastic Wetlands and Why to Monitor Them: Demonstrating the Social and Financial Benefit Potential of Methane Abatement through Salt Marsh Restoration

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Abstract

Salt marsh restoration has the potential to reduce greenhouse gas emissions thereby providing an opportunity for blue carbon crediting, but implementation has been limited to date because of insufficient data and validation. Freshening salt marshes are sources of methane emissions, which present an opportunity for states to address this source of potent greenhouse gas emissions if restored to their more naturally saline state. In this paper, we demonstrate the potential scale of methane emissions that could be avoided if salinity-reducing impairments are mitigated by applying findings from six salt marsh restoration sites in Massachusetts combined with a meta-analysis of the salt marsh salinity-methane relationship. Of the six sites selected, restorations at two sites were successful in improving salinity. Our approach and findings demonstrate the potential benefits in developing consistent accounting methodologies to better track, prioritize, and implement wetlands restoration strategies to mitigate methane emissions and contribute toward state-level emissions reduction targets across at least a percentage of the 475 Massachusetts salt marches with an existing tidal restriction. A significant limitation in estimating benefits, however, is the lack of coordinated, widespread monitoring strategies relevant to methane emissions. While not insurmountable, these challenges will need to be addressed for methane emissions reduction and carbon sequestration through salt marsh restoration to be accepted as an effective strategy. We conclude that while carbon crediting may offer benefits to marsh restoration and state greenhouse gas emissions reduction targets, there remain significant limitations because of a lack of project monitoring and data validation, which could undermine the social benefits that carbon crediting would afford. In the worst case, this could result in the offsetting of actual greenhouse gas emissions with credits that are supported by indirect and less-than-rigorous monitoring data.

KEYWORDS: Salt Marsh Restoration, Carbon Crediting, Carbon Markets, Social Benefit Value, Methane Emissions Mitigation

Introduction: Fantastic Wetlands and Why to Monitor Them

Salt marshes are critical ecosystems and are being actively restored for many reasons including habitat provision and flooding abatement, but the co-benefits of these restorations as they relate to greenhouse gas (GhG) mitigation are often overlooked. States have an opportunity to optimize methane mitigation in salt marsh restoration planning and to better catalogue these systems' emissions reductions to contribute toward state-level GhG emissions reduction targets. To achieve these ends, better, more comprehensive monitoring and data collection is needed to inform these efforts. Once this data becomes available and more widely collected, this paper outlines a straightforward calculation to assess the GhG mitigation potential and the social benefits of salinity-increasing salt marsh restorations using available data that could be applied at other restoration sites in Massachusetts or elsewhere. As we will discuss, the primary limitation to such an application remains data availability and lack of low-cost widespread monitoring techniques, which will be required to make this approach widely applicable and to improve validity.

Salt marshes are critical habitats that host numerous plant and animal species and provide valuable ecosystem services. Healthy salt marshes provide benefits to surrounding communities through the coastal resilience they provide against tidal surge during storms. Salt marshes also act as a carbon sink and store a significant amount of carbon in their soils (Burden et al., 2013). This carbon is sequestered for hundreds of years provided the marsh remains intact. However, should salt marshes become degraded or impaired, they can become a net source of GhGs rather than a sink as they can emit methane, another potent GhG (Hirota et al., 2007). One driver of excess methane emissions from salt marsh in New England is a transition from saline to fresher water in the system resulting from inadequate flushing of seawater, often due to human-induced tidal restrictions such as a narrow culvert for road/rail construction through salt marshes. Diminished salinity activates a natural microbial process that produces methane as a byproduct, thereby turning freshening salt marshes into enhanced methane sources (Dean et al., 2018; Kroeger et al., 2017).

In the United States, thousands of narrow culverts that are aging or outdated impact the streams and natural areas surrounding the culvert and sometimes flood roads and other developments (MassDOT, 2020). Culvert widening, a practice used by many coastal communities' transportation departments for road maintenance and improvement, can help to reverse the process of marsh freshening by allowing increased tidal flushing to restore salinity levels in the system, thereby reducing methane emissions. For tidal salt marsh, salinity has a negative relationship with methane emissions (Poffenberger et al.; Hiraishi et al., 2013; 2011; Holm Jr. et al., 2016; Kroeger et al., 2017; Doroski et al., 2019; Qu et al., 2019) and a positive relationship with carbon sequestration (Morrissey et al., 2013; Qu et al., 2019) such that, as salinity increases above 18 psu (practical salinity units), methane emissions from tidal salt marsh potentially decrease and its capacity for carbon sequestration potentially increases.

Methane is 28 (100-year global warming potential) to 81 times (20-year) more potent as a greenhouse gas than carbon dioxide (CO_2; IPCC, 2014). Methane also has a shorter half-life than CO_2 (roughly 10 years compared to 30+), so with methane mitigation, there is potential for reducing GhG effects within a shorter timeframe, possibly even within a decade. Globally, our window to act on climate change by reducing excess GhG emissions is dwindling (Canadell et al., 2021). Addressing methane emissions as quickly and from as many sources as possible, including culvert widening and other marsh restoration efforts, could afford the global community time to address more persistent sources of GhG pollution that are less susceptible to rapid remediation (McGrath, 2021).

There are 1.7 million extant hectares of salt marsh throughout the United States (U.S. Fish and Wildlife, 2021), which face myriad environmental stressors; an unknown percentage of which might serve as a source of excess methane emissions due to freshening. If these marshes are to be protected or restored to mitigate rather than produce methane, there are a number of data needs to understand the scale of benefits. These include a need to identify the spatial extent of degraded marshes, estimate the relative annual methane contributions from each marsh, identify the source of degradation (for example, a tidal restriction that prevents adequate flushing), and deploy a pre- and post-restoration monitoring plan to determine the efficacy of that restoration. Salinity is currently applied as a relatively cost-effective metric to track the efficacy of salt marsh restoration. Further, salinity can also be used to estimate the methane emissions from a given salt marsh (Hiraishi et al., 2013, Poffenberger et al., 2011, Kroeger et al., 2017). Though direct methane capture is a better indicator of methane emissions, using salinity as a proxy for methane emissions can scope and inform policy decisions for determining prioritization of salt marsh restoration and for inferring benefits of mitigated methane emissions.

The impact of culvert widening on methane emissions reduction is not being captured at the restoration site or state levels. With many states working to meet mandates on GhG emission reductions, demonstrating the potential scale of salt marsh restoration for reducing methane as a co-benefit of widening could help prioritize and expand these efforts. To demonstrate the GhG emission reductions, a reliable wetland monitoring methodology will need to be implemented to track and confirm the restoration results. A standardized assessment of GhG mitigation in restored wetlands is useful not only for its contribution towards meeting environmental goals and state reduction targets, but also for the ability to count these restorations towards carbon offset crediting initiatives in addition to the ecological benefits that these projects might provide (MassDOT, 2020; Emery and Fulweiler, 2017; Wang et al., 2019; MA EOEA, 2020; Executive Office of the President, 2021). This additional revenue stream could be used to offset the cost of future salt marsh restoration projects or be used to fund the long-term monitoring of restored systems. While state entities are currently barred from applying for offset credits, non-profit partners are not, which could incentivize more public-private partnerships in future salt marsh restoration efforts.

This paper quantifies the potential benefits of methane reduction via salt marsh restoration at six restoration sites in Massachusetts. We estimated methane emission reductions for each site using meta-analyses that use salinity as a proxy for methane emissions (Kroeger et al., 2017; Hiraishi et al.,2013; Poffenbarger et al., 2011). We calculated the social benefit of these avoided emissions based on the 2021 social cost of methane (IWG, 2021). We then discuss alternative revenue sources available to restoration projects such as blue carbon crediting opportunities through voluntary markets and conclude with a discussion on next steps and state-level monitoring strategies.

Methods

Site Selection and Salinity Values

We identified six completed salt marsh restoration projects administered through the Massachusetts Audubon Society[1] that were a part of a decades-long research partnership with local middle schools in Massachusetts, USA. Each of the projects included in this analysis from this larger dataset were those with one definitive restoration action restoring tidal flow (i.e., correction of a tidal restriction, such as culvert widening) and with salinity data available both before and after the restoration project was implemented. The six projects are listed in Table 1, with their corresponding datasets listed in the appendix. The values shown in Table 1 are those calculated by averaging all values provided both before and after the given restoration took place regardless of the depth at which those values were taken. The salt marsh salinity datasets for these projects are hosted by the Massachusetts Audubon Society (Massachusetts Audubon Society, 2022).

For the purposes of this analysis, a restoration project was considered successful for the purposes of greenhouse gas mitigation only if the post-restoration salinity average surpassed 18 psu, which is the level identified in the scientific literature as the point where methane emissions are no longer released (Kroeger et al., 2017). As shown in Table 1, of the six sites included in this analysis, only the Mill Pond and Eastern Point sites met these criteria with the remaining sites excluded. The Cedar Point and Seaview Street sites were excluded because averaged pre- and post-restoration salinity values remained below the 18 psu benchmark. The Town Farm Road and Conomo Point Road sites were excluded because both the pre- and post-restoration salinity values were above the 18 psu threshold, and therefore the restoration project did not result in meaningful new methane emissions reductions.

None of these restoration projects were completed or monitored with the specific intention of methane mitigation or capture, but the pre- and post-restoration salinity data enables the retroactive application of monitoring data to estimate the potential changes in methane emissions.

Table 1: Restored Marsh Name, Location, Size, Salinity Values. A summary table for the six sites selected for analysis from the Massachusetts Audubon Society dataset. Each site includes pre- and post-restoration salinity data with associated standard error at varying times and seasons. Due to this variance, pre- and post-salinity values were averaged without taking temporal considerations into account. Total marsh area for the Essex site was derived from MA CZM records, the Town Farm Road area was obtained by Mass.gov, Seaview Street was derived from NO1 records, Mill Pond was derived from U.S. Fish and Wildlife data. The remaining sites were derived from MA DEP records.

Location	Years Monitored	Date of restoration	Years of Post-restoration Monitoring	Number of Data Points	Avg Salinity pre-rest (ppt)	Avg Salinity post-rest (ppt)	Total Area of Wetland (m^2)	Total Area of Wetland (hectares)
Essex, MA, Conomo Point Road	1998-2015	Tidal Restriction restored November 2000	15	961	18.3 ± 0.94	23.7 ± 0.41	54,197	5.42
Gloucester, MA, Eastern Point	2000-2015	Tidal Restriction restored November 2003	12	764	10.2 ± 0.52	19 ± 0.3	10,955	1.10

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[1] https://www.massaudubon.org/get-outdoors/wildlife-sanctuaries/endicott/salt-marsh-project/results-data/salinity

Ipswich, MA, Cedar Point	1999-2015	Tidal Restriction Phase 1 restored Spring 2000	15	249	12.6 ± 0.75	9.8 ± 0.63	12,869	1.29
Ipswich, MA, Town Farm Road	1996-2015	Tidal Restriction restored spring 2005	10	829	27.4 ± 0.51	25.7 ± 0.36	97,128	9.71
Rockport, MA Seaview Street	1998-2015	Seaview Street tidal restriction restored fall 2003	12	371	17.7 ± 1.7	16.9 ± 0.42	12,141	1.21
Gloucester, MA, Mill Pond	1998-2015	Tidal Restriction - Site flooded when board placed on tide gates spring 2003, killing marsh plants. Tide gates opened beginning spring 2004	11	808	17.4 ± 0.44	19.7 ± 0.32	161,880	16.19

Estimating Methane Emissions Rates and Carbon Sequestration

We estimated annual methane emission rates per square meter pre- and post-restoration using published methane emission factors inferred by salinity measurements in the manner described by the meta-analysis in Kroeger et al., 2017. For the pre-restoration values, we applied two emissions factors (EF): a geometric mean of studies of 19.4 gC-m^{2}year^{-1} for salt marsh with salinity values less than 18 psu (Hiraishi et al. 2013) and a true mean of 41.6 gC-m^{2}year^{-1} (Poffenbarger et al. 2011). For sites with an average salinity value above 18 psu, we applied an emissions factor of 0.46 gC-m^{2}year^{-1} (Poffenbarger et al., 2011).

There is some evidence to suggest that salt marsh restoration projects that address salinity changes can result in increased soil carbon sequestration, likely from increased water flow (Kevin Kroeger, personal communication; Weston et al., 2014). While not included directly in this analysis, we demonstrate how carbon sequestration could be included in a follow-up analysis in the appendix.

Applying the Verified Carbon Standard

The Verified Carbon Standard (VCS) is a program managed by Verra, which developed the 2015 VCS Methodology for Tidal Wetland and Seagrass (VM0033) in partnership with Restore America's Estuaries and Silvestrum (Verified Carbon Standard, 2015). Section 4c of the VM0033 on Tidal Wetlands validates culvert widening as an appropriate practice for credit application provided that pre- and post-restoration values are assessed using one of the approved methodologies. Section 8.1.4.1 allows for the use of proxies to estimate GhG emissions and section 8.1.4.4.3 allows for the use of published values to estimate emissions where proxies or direct capture are not available. Equations 42 and 43 of Section 8.1.4.4.4. allow for the application of a default factor in conjunction with the 100-year global warming potential of methane (GWP-CH_4; VCS, 2015).

The 100-year GWP-CH_4 as compared to the warming effects of CO_2 over a 100-year timeframe is somewhat in flux. The U.S. Environmental Protection Agency recommends a GWP-CH_4 range between 28-36 (U.S. EPA, 2021), whereas the 100-year GWP-CH_4 assessed by the IPCC has varied across successive assessment reports, with the most recent providing a value of 27.2 ± 11, as shown in Table 2. For the purposes of this analysis, we applied the GWP-CH_4 of 27.2, identified in the 2021 IPCC AR6 report to the calculation of verified carbon units (VCUs) using the VM0033 methodology described previously.

Table 2: Change in IPCC Global Warming Potentials. Change in IPCC global warming potentials (GWP) for methane (CH_4) and nitrous oxide (N_2O) across assessment reports (AR) 4, 5, and 6.

		100-year GWP			20-year GWP		
Greenhouse Gas (GhG)	Lifetime[a] (years)	AR4 (2007)	AR5 (2014)	AR6 (2021)	AR4 (2007)	AR5 (2014)	AR6 (2021)
CO_2	Multiple	1	1	1	1	1	1
CH_4 (non-fossil)	11.8 ± 1.8	25	28[b]-34[c]	27.2 ± 11[d]	21	84[b]-86[c]	80.8 ± 25.8[d]
N_2O	109 ± 10	298	265[b] -298[c]	273 ± 130[d]	310	264[b]-268[c]	273 ± 118[d]

[a]Compound lifetime values were reported in IPCC AR6.
[b]Non-inclusive of climate change feedback, as reported in AR5
[c]Inclusive of climate change feedback
[d]AR6 was the only report to include error ranges

To estimate the VCUs for avoided methane emissions from salt marsh, as shown in Equation 1, annual post-restoration emissions were subtracted from annual pre-restoration emissions to calculate total avoided annual emissions from each site, assuming the effects of each restoration can be applied equally throughout the area of the marsh. These emissions were converted to carbon dioxide emissions (CO_2e) by applying the average global warming potential (GWP) of methane as defined by IPCC AR6 (Forster et al., 2021), and then equated to VCUs using a 1:1 ratio (one metric ton of CO_2e is equivalent to one VCU). Consistent with the IPCC AR6 report, we applied a GWP-CH_4 of 27.2. Our findings are summarized in Table 3, where VCUs-yr^{-1} are equivalent to annual methane emissions avoided (as CO_2e).

Therefore, VCUs that could have been generated at the completion of each salt marsh restoration project were estimated using the following equation:

(1)

$$VCU = [E_0 - E_1] * A * GWP_{CH4} + [C_0 - C_1] * A$$

Where:

VCU - Number of Verified Credit Unit credits (equivalent to one metric ton of emissions avoided) per year

E – Emissions (metric tons of methane per square-meter) pre ($_0$) and post ($_1$) restoration

A – Area (m^2) of restoration

GWP_{CH4} - 27.2 the global warming potential of methane (IPCC AR6)

C **–** Additional CO_2e variables[2] (i.e., soil carbon, nitrous oxide, etc.) pre ($_0$) and post ($_1$) restoration

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[2] For the purposes of this study, the only GhG of concern was methane, though a supplemental discussion of soil carbon is included in the appendix.

Calculating Social Benefit of Avoided Methane Emissions and Increased Carbon Sequestration

To estimate the social benefit of avoided GhG emissions, we applied the 2021 Social Cost of Methane (IWG, 2021) to emissions potentially avoided through prior wetland restoration, shown in Equation 2. An analysis of the impact of improved carbon sequestration and its associated social benefits are included in the appendix. In this analysis, we calculate the social benefits of each salt marsh restoration as avoided costs with respect to avoided methane emissions and increased carbon sequestration (discussed in the appendix).

(2)

$$SCM_{2050} = \sum_{i=2021}^{2050} [E_0 - E_1] * A * \ Y_{i,\,a\%}$$

Where:

SCM_{2050} = Cumulative avoided social cost of methane from 2021-2050

E = Emissions (metric tons per square-meter) pre ($_0$) and post ($_1$) restoration

$Y_{i,\,a\%}$= Social cost of methane value for year *i* discounted at *a%* described in the Interagency Working Group SCM technical document addendum (here, *a* is equivalent to 3%)

VCUs are presented in per-year values to agree with the crediting-system logic, while we integrate the social cost values over a time window (2021-2050) to account for the changes in social value over the course of the time window, based on the modeled social damages and discount rate. Values from Equation 2 are reported in Table 4 in 2021 dollars.

In February of 2021, a US Government Interagency Working Group (IWG, 2021) proposed an update to the 2010 Social Cost of Carbon (IWG, 2010), and 2016 addendum to the Social Costs of Carbon and Methane (IWG, 2016). We used these updated Social Cost of Methane values in estimating the benefits of avoided future methane emissions. We applied these updated annualized values to each of the sites included in this analysis to quantify the total potential benefit at each site realized from 2021 – 2050. A truncated list of annualized values is reported in Table 4 in 2021 dollars, with the full tables included in Appendix D.

Because each restoration included in this analysis occurred prior to the 2021 technical documentation or the 2016 SCM and SCC technical documents that preceded it, we were unable to calculate the total benefit of each restoration project from their implementation using the provided annualized data values. Due to this temporal inconsistency, the benefits of avoided emissions at each site were assessed from 2021 to 2050 to demonstrate the future added value from the previously completed restoration projects.

A range of potential benefits are provided using varied discount rates. Both the SCC and SCM technical documents account for uncertainty by including a range of discount rates (2.5%, 3%, and 5%). Discount rates reflect varying assumptions of the degree to which future scenarios impact current decision-making practices. The higher the discount rate, the higher the assumed value of present-day damages compared against future damages, and the lower the total social cost (IWG, 2010).[3] To keep consistent with both the 2010 SCC technical document and the 2016 SCM addendum, a three percent discount rate was treated as the default reported value; however, the full range of values is included in the appendix.

Results

Our analysis yielded an average annual avoided methane emissions rate of 0.19 $MtCH_4$-hectare-year^{-1} and 0.41 $MtCH_4$-hectare-year^{-1}) for the geometric mean and true mean baseline emissions factors, respectively.[4] Across the total monitoring periods for both Gloucester sites (totaling 12 and 11 years, respectively), we calculated the total range of avoided methane emissions from 36 $MtCH_4$ – 79 $MtCH_4$ (17.3 hectares total), which has the equivalent global warming potential of 985 $MtCO_2e$ – 2,140 $MtCO_2e$.

Table 3: Summary of Annual Avoided Emissions. Summary of values from each site calculated using Equation 1, where E are the annual emissions avoided, GWP is the global warming potential of methane, and VCUS-yr are the annual verified carbon units that could have been generated considering the CO_2e potential of both avoided methane and increased carbon sequestered as a result of each restoration assuming that the project was considered for carbon credits via the Verified Carbon Standard. Values are shown using both emissions factors (EF) of 19.4 (geometric mean) and 41.6 (true mean) to demonstrate range of values.

EF 19.4 EF 41.6	Eastern Point	Mill Pond	Total
E-yr^{-1}	0.21 0.45	3.07 6.66	3.28 7.11
GWP_{CH4}	27.2	27.2	27.2
VCUs-yr^{-1}	5.7 12.2	83.5 181.2	89.2 193.4

Estimating VCU Accumulation

We estimated an annual VCU accumulation ranging from 5.2 VCU-hectare-year^{-1} to 11.2 VCU-hectare-year^{-1} when applying the geometric mean and true mean emissions factors, respectively. Carrying this through to the complete post-restoration monitoring periods for Eastern Point and Mill Pond sites (totaling 12 and 11 years, respectively), the cumulative VCU accumulation over this time ranges from 985 VCUs to 2,140 VCUs from avoided methane alone. This translates to a potential revenue generation ranging from $19,700 to $42,800[5] (assuming a market price of $20/metric ton-$CO_2e$) when applied to the emissions factors scenarios previously described. Were these projects to have occurred today (2021), a potential revenue of 2,671 credits ($53,420) to 5,802 credits ($116,040) might have been generated between 2021-2050 across both sites (17.3 hectares), assuming that these restoration projects remain successful and consistent with the project validation requirements described by VM0033 (VCS, 2015), and assuming a rate of $20/$MtCO_2e$. While this is a modest benefit, methane abatement is one of many associated with salt marsh restoration.

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[3] page 9

[4] Excluding the Cedar Point, Town Farm Road, and Seaview Street sites, which did not demonstrate any avoided emissions.

[5] Whereas the social cost of carbon is discounted at a rate of 3%, we did not discount the VCS monetary values.

The Social Benefit of Methane Mitigation

Using a 3% discount rate, we estimate a cumulative social benefit ranging from \$223,253 (EF of 19.4) to \$484,931 (EF of 41.6) by 2050 across the two sites (17.3 hectares) included in this analysis, as shown in Table 4.

The Big Picture

There are potentially 475 salt marshes (932 hectares) throughout Massachusetts with tidal restrictions greater than 50% as identified by McGarigal et al. (2017). At its maximum, the successful remediation of these tidal restrictions could result in the net abatement of 176.6 to 384 $MtCH_4$-$year^{-1}$, and the potential revenue generation of \$114,720 to \$227,328-$year^{-1}$ via carbon offset crediting, assuming \$20/Mt-CO_2e and a discount rate of 3%. By 2050, the social benefit of this avoided methane could range from \$12 - \$26 million if all sites were successfully restored, as shown in Table 4. However, the successful restoration of all sites is improbable. Of the six projects we identified in this study, only 33% - 66% achieved the types of salinity changes that would be indicative of methane abatement (depending on how salinity values are calculated). As such, this estimate likely demonstrates an extreme upper bound.

Table 4: Social Benefit Value of Avoided Methane Emissions. The social benefit value of avoided methane applied to the two sites included in the study, in addition to the 475 (932 hectares) of Massachusetts salt marshes impaired by tidal restrictions, as determined by McGarigal et al. (2017). Benefits calculated with Social Cost of Methane values proposed by the 2021 Interagency Working Group using emissions factors (EF) of 19.4 and 41.6. *This is a truncated table; the full table can be found in the appendix.*

Year	**Avoided social cost of methane (3% average) in 2021 dollars (\$/Mt)**	**Gloucester, MA, Eastern Point**		**Gloucester, MA, Mill Pond**		**All restricted salt marsh in MA (932 hectares)**	
		EF 19.4	EF 41.6	EF 19.4	EF 41.6	EF 19.4	EF 41.6
2021	\$1,500.00	\$311	\$676	\$4,599	\$9,990	\$264,903	\$575,402
2022	\$1,600.00	\$332	\$721	\$4,906	\$10,656	\$282,563	\$613,762
2023	\$1,600.00	\$332	\$721	\$4,906	\$10,656	\$282,563	\$613,762
2024	\$1,700.00	\$353	\$766	\$5,212	\$11,322	\$300,223	\$652,122
2025	\$1,700.00	\$353	\$766	\$5,212	\$11,322	\$300,223	\$652,122
2026	\$1,800.00	\$373	\$811	\$5,519	\$11,988	\$317,884	\$690,482
2027	\$1,800.00	\$373	\$811	\$5,519	\$11,988	\$317,884	\$690,482
2028	\$1,900.00	\$394	\$856	\$5,825	\$12,654	\$335,544	\$728,842
2029	\$1,900.00	\$394	\$856	\$5,825	\$12,654	\$335,544	\$728,842
2030	\$2,000.00	\$415	\$901	\$6,132	\$13,319	\$353,204	\$767,202
2021-2050 Total	-	\$14,151	\$30,737	\$209,102	\$454,194	\$12,044,257	\$26,161,602

Discussion

Dreyfus et al. (2022) describe the focus of short- to long-term greenhouse gas mitigation goals as focused (albeit middling) on carbon dioxide with not enough attention on more non-CO_2 pollutants like methane or nitrous oxide, which are far more potent and less controlled, though less ubiquitous. In this study, we demonstrated how salt marsh restoration by way of tidal restriction removal could contribute towards the mitigation of a portion of these emissions while also increasing the resilience of these critical ecosystems, which have additional benefits such as wave attenuation, erosion control, and the provision of habitat to myriad species. There are more than 123,000 salt marshes in the United States representing 1.7 million acres of habitat, which is 31% of the global total (Mcowen et al., 2017) – a portion of which are likely affected or threatened by freshening. To give these systems the best chance at adaptation, addressing salinity concerns in freshening habitat wherever possible is an important and relatively low-tech application, but affordable monitoring and reliable data to support such efforts are lacking.

More data is needed. The estimates produced in this analysis illustrate how an additional benefit of these systems might be applied once this data becomes available and should not be applied to policy decisions in their current form. Rather, this analysis was an attempt to demonstrate a road map for how such a future valuation might be possible with the appropriate data inputs. Before such an approach can be taken, better, more complete monitoring data is necessary and, to our knowledge and after extensive efforts to attain more, does not yet exist. The best salinity data that we were able to find was a longitudinal study performed by the Massachusetts Audubon Society over decades as part of an educational initiative in partnership with local middle schools. Of the sites included in this dataset, only six were associated with one definitive restoration project with both pre- and post-restoration salinity data available. That the best data currently available are those collected by middle schoolers[6] serves to highlight both the significant need for better data sources and the ease with which these data could be collected at sufficient scale.

Standardized methodologies. There is more than one method to summarize salinity. The decision to average pre- and post-salinity values was only one of several ways that salinity data could have been processed for this analysis. Rather than calculate a pre- and post-restoration mean, we might have also assessed these values with more fine-grained detail by examining the variance in pre- and post-restoration salinity values at different depths or summarized by year.

As demonstrated in field data collection worksheets prepared by the Massachusetts Audubon Society (Mass Audubon, n.d.), salinity measurements were taken across multiple transects at each site at varying depths of “Shallow” (5 – 20cm), “Medium” (35 – 50cm), and “Deep” (65 – 80cm), these values were then aggregated, as shown in Table D-1. If depth is included as a factor in this analysis, then four of the six sites would instead be considered for further analysis. As shown in Table D-1, the first 20cm of soil in the Seaview Street and Conomo Point sites meet the previously described criteria for inclusion, in addition to both Gloucester sites previously included. Because the microbes responsible for methanogenesis are ubiquitous throughout salt marsh soil, we potentially could assume that, in these cases, methane is produced in the shallow layer among these sites and not produced in the layers of soil

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[6] Which is not meant to minimize the students’ contribution to the field.

when salinity remains above the threshold. It is unclear whether the analyses applied by Kroeger et al. (2017) accounted for these differences by depth, so this might be an avenue for further study.

Salinity might also have been summarized by year. As shown in Table D-2, when average salinity values are organized by year, there seems to be a lag phase associated with some of the post-restoration sites. Were annual differences included in our overall analysis, the calculated social and fiscal benefits for each site would have been reduced to only include years in which the average post-restoration salinity was above 18 psu.

Because the salinity datasets used in this paper are intended only to demonstrate the application of a valuation methodology to be applied in future restoration projects (ideally with better data), and because these datasets are middling in their quality, we chose a simplified approach by taking only the mean of pre-and post-restoration salinity, ignoring variance across depth or transect. However, we acknowledge that this methodology is oversimplified, and that future application of the methodology described in this paper should likely include consideration of variance by depth, time, and spatial distribution. Some of the potential revenue from VCS crediting could be used to offset some of the costs. There is a tradeoff between the accuracy of the information that can be derived from a monitoring program and the costs for implementing that monitoring program.

The voluntary market is important but needs tightening. A market-based approach shows potential to mitigate greenhouse gas emissions, but concerns remain in the current use of salinity data to achieve those ends, especially given the recent issues demonstrated by the over-crediting of forestry credits by the California Air and Resource Board described by Badgley et al. (2021) and Song and Temple (2021). While the current literature (and therefore, the VCS methodology) allows for the use of salinity data as a proxy for methane emissions from salt marsh, the application of this proxy is limited only to a range of potential emission values based on its distance from the benchmark of 18 psu. Equations 42 and 43 of the VCS VM0033 seem to compensate for this in recommending more conservative post-restoration emissions factors of 1.1 g CH_4-$m^{-2}y^{-1}$ for wetlands with salinity values greater than 18 psu but less than 20 psu, and 0.56 g CH_4-$m^{-2}y^{-1}$ for salinity values greater than 20 psu compared against the post-restoration emissions factor of 0.46 as applied by Kroeger et al. (2017). Methods for the assessment of the pre-restoration emission factor are not described and therefore dependent on present-day recommendations in the literature. One concern with this approach is that the use of these benchmarks might lead to a higher than acceptable level of inaccuracy that could be avoided if the salinity approach were replaced with more methane-specific monitoring approaches. Given the importance of calculating estimated avoided emissions to potentially inform state-level GhG emissions targets and/or offset the emissions of fossil fuel-intensive activities, the development of more sensitive methods would mitigate the potential pitfalls of blue carbon crediting before it grows in popularity.

An amended approach to blue carbon crediting. Currently, the VCS allows for several approaches to estimate avoided emissions: salinity as proxy, direct methane capture, or new methods supported by the literature. Because more sensitive measurements of methane emissions from degraded wetlands can be costlier and more time consuming, such approaches might be combined with cheaper options to better inform where more sensitive testing might be appropriate. For example, given the ease with which salinity assessments or remote sensing applications could be deployed (once further developed), these assessments could become common practice to assess wider swathes of salt marsh more regularly. In areas where these assessments suggest that a given restoration project was successful at mitigating GhG, (i.e., salinity values of greater than 18 psu or remote sensing instruments that detect flora consistent with higher soil salinity), more sensitive, direct capture tests could then be deployed to confirm their findings, and these more sensitive tests would then inform the allocation of carbon offset credits. Newer, more innovative approaches could still be deployed, such as the use of salt marsh flora as a salinity proxy (Barry et al. 2022; Derby et al., 2022), or remote sensing technologies used to infer soil salinity conditions (Zhang, 2019), but standardized monitoring protocols will increase validity and enable better allocation of credits.

A comparable example can be found in decentralized wastewater technologies. State agencies and regional programs (e.g., Chesapeake Bay Program) currently serve as arbiters of allowable alternative practices for pollution control. Such approval processes for innovative approaches pose what might be considered a useful model for carbon crediting. For non-traditional approaches to be more widely accepted by states for general use, a critical mass of systems must typically be installed in the field and demonstrate that they maintain their performance at or below current acceptable levels. An example of this procedure is the state-level approval process for innovative and alternative septic systems. Here, states encourage innovation in design and approach, but ensure the integrity of the process by requiring that these systems are vigorously tested before they can be approved for general use. Though carbon crediting referees such as VCS do currently require a regular review of proposed project monitoring approaches, these organizations might borrow from the state model of approval for innovative approaches by providing a more rigorous standard for measuring, approving, and auditing novel restoration project monitoring approaches before they become eligible for informing the allocation of carbon credits.

Spatial distribution of findings remains an open question. Salt marsh methane fluxes are dynamic and can be influenced by numerous variables that include the level of the water table, temperature, and salinity, among others (Huertas et al., 2019). Further, methane emissions are not uniform across the entirety of a given salt marsh. Yet, for the purposes of this study, annual methane emissions were estimated from three discrete transects based on the limitations of the dataset and applied across the entirety of the corresponding marsh border. This is not necessarily representative of methane emissions or abatement across the whole salt marsh, yet the current VCS VM0033 methodology suggests that this approach would be valid for blue carbon offset crediting. This demonstrates another area in which the scientific literature and the VCS methodology will need to improve. Even in the case of more sensitive monitoring approaches, extrapolation of direct methane capture in a representative sample would result in a similar degree of error. Short of placing a fume hood over the entirety of a salt marsh, a degree of error will likely always exist; however, a better understanding of dynamic methane fluxes in salt marsh and the application of a representative direct capture sample with these considerations could work to reduce this error.

The importance of getting this right. Beyond their methane fluxes, the boundaries of salt marsh systems are constantly changing in response to numerous stressors, including anthropogenic development, sea-level rise, and more. Upper marsh boundaries become lower marsh boundaries, lower marsh boundaries transition into seagrasses where possible as sea-levels rise, marsh extent migrates, grows, and recedes – none of these transitory properties are captured in this analysis and for our purposes, salt marsh extent was assumed to be fixed. Though many of these stressors are beyond our immediate control, salinity might be among the easiest stressors to address, thereby increasing marshes' resilience against stressors that are less easily alleviated. Aiming to restore salinity will not work in all cases, as evidenced by the proportion of restorations that increased salinity from the data we found (2/6 of the Massachusetts sites).

Funding these projects poses another challenge: salt marsh restoration is expensive, but carbon crediting could offset a portion of the total cost or support long-term monitoring to ensure the restoration remains effective. GhG markets are imperfect but represent a potential opportunity to offset some of the costs of restoration and monitoring and monetize an important co-benefit of restoration.

Culvert repair is already a common, though regulatorily complex, practice among municipal and state departments of transportation for reasons other than greenhouse gas mitigation. In this study, we demonstrate the potential additional value to culvert widening projects. With the proper data inputs, such an approach might one day inform a state or municipality's decision to repair an existing culvert with one of similar type, or to install a wider culvert to better capture the additional long-term benefits on the surrounding salt marsh and the communities they serve through the added benefits of GhG mitigation. Our assessment of salt marsh benefits is not meant to be exhaustive. This analysis covers the benefits of methane emission reduction, but other considerable benefits could include carbon sequestration (see Appendix).

Salt marshes offer a host of ecosystem service benefits that are not captured in this analysis. Rather, this assessment was limited only to the social benefits associated with avoided methane emissions in restored salt marsh. As this retrospective analysis has shown, standardized data for common metrics such as salinity are not readily available or regularly monitored in a way that is easily comparable. Where data does exist, it's unclear to what degree such data can be applied to the marsh it represents – whether to a portion of the marsh area or to its entirety. And yet, this approach is currently acceptable for use in validating the success or failure of a salt marsh restoration project and could result in the assignment of VCUs to be sold in existing voluntary carbon markets. In the worst case, this could result in the offsetting of very real CO_2e emissions with credits that are supported by less-than-rigorous monitoring data and validation processes, as has been the case in the misallocation of forestry credits (Badgley et al., 2021; Song and Temple, 2021). Carbon markets could make a significant impact in stemming the flow of future emissions, especially when considering the number of private companies who have demonstrated interest in boosting their "green" credentials, but proper allocation of credits is critical. To ensure proper allocation means the creation of effective accounting strategies and cataloguing crediting projects in a way that is verifiable and subject to regular auditing by a capable and well-resourced auditing body. If such a validation methodology were to be completed, increased trust in carbon markets could further enable nuanced applications such as the stacking of methane abatement credits with carbon sequestration and resiliency credits to better capture the plurality of benefits that salt marshes provide.

Conclusion

Many states and towns already perform culvert widening or the easement of tidal restrictions for reasons other than greenhouse gas mitigation, but the benefits of this work with respect to climate change have yet to be fully considered. By applying the strategies demonstrated here, in tandem with a reliable, low-cost salt marsh monitoring network, states and towns can better prioritize future restoration work and contribute towards their GhG emissions reduction targets. As demonstrated in this exercise, salt marsh restoration efforts can result in both direct and indirect benefits to local communities. Viewing salt marsh restoration through the lens of greenhouse gas emissions reduction could present an opportunity to further promote salt marsh restoration while also providing a mechanism for states to track and eliminate methane emissions from impaired systems. There are 475 salt marshes with tidal restrictions greater than 50% in Massachusetts alone (McGarigal et al.,2017), each an opportunity for methane emissions reduction.

The goals of carbon crediting can and should be developed but monitoring and validation must take precedence for this approach to realize its intended goals. Voluntary carbon crediting programs could benefit greatly from the more rigorous auditing of monitoring approaches and the development of monitoring requirements that are both accurate and cost-effective without being onerous. Adoption of validation approaches could instill stronger confidence in the carbon market while diminishing administrative costs and increasing the ease of use of a unified carbon market. Until these challenges are addressed, states should prioritize work to capture and realize at least a portion of the theoretical emissions reduction potential shown here for application toward their state-level emissions reduction targets. This work will require standardized monitoring and accounting that could be applied to future crediting programs.

Credit authorship contribution statement

Conceptualization: Reilly, Merrill, Mulvaney, Colarusso; Methodology: Merrill, Reilly, Mulvaney; Formal Analysis: Reilly, Merrill, Mulvaney, Burman, Colarusso; Writing—original draft preparation, Reilly; Writing—review and editing: Reilly, Merrill, Mulvaney, Burman, Colarusso.

Declaration of Competing Interests

The authors declare no conflicts of interest. Reilly, Merrill, Mulvaney, and Colarusso were employees of the U.S. Environmental Protection Agency for the duration of this work. Burman was an Oak Ridge Institute for Science Education Fellow sited at the U.S. Environmental Protection Agency for the duration of this work.

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APPENDIX A: Carbon sequestration:

The Social Benefit of Carbon Sequestration in Massachusetts Marshes

Carbon sequestration values were not measured directly in this analysis; however, it's likely that the rate of carbon sequestration increased in areas where salt marsh restoration projects were successful. Due to limited carbon sequestration data at each of the sites included in this study, we applied a soil carbon sequestration rate of 100 gC-m^{2}year^{-1} for impaired salt marsh and a 200 gC-m^{2}year^{-1} for restored marsh, defined as those marshes with a post-restoration value greater than 18 psu (Kroeger pers.

comm. 2021; Peteet et al., 2020). Though we acknowledge that the question of carbon sequestration rates are far more complex than these benchmark values would suggest.

As explained in the main body of the paper, we identified 475 salt marshes (932 hectares) throughout Massachusetts with tidal restrictions greater than 50% as identified by McGarigal et al., 2017. The successful remediation of these tidal restrictions could result in an upper-limit[7] net abatement of 932 MtC-year^{-1}, assuming all restorations resulted in an increase of system salinity above 18 psu.

We applied the social cost of carbon to this carbon abatement value using the following equation:

$$SCC_{2050} = \sum_{i=2021}^{2050} [E_0 - E_1] * A * \; Z_{i,b\%}$$

Where:

SCC_{2050} – Cumulative avoided social cost of carbon from 2021-2050

E – Emissions (metric tons per square-meter) pre (0) and post (1) restoration

A – Area (m^2) of restoration

$Z_{i,b\%}$ - Social cost of carbon value for year *i* discounted at *b*% as described in the EPA SCC technical documentation (here, *b* is equivalent to either 2.5%, 3%, or 5%).

The estimated social benefits of increased carbon sequestration from saltmarsh restoration, at discount rates of 2.5%, 3%, and 5%, is presented in Table A-1.

Table A-1: Projected Social Benefits of Avoided Carbon 2021-2050. Shown here are the summed annual values at each site using the social cost of carbon. The Essex and both Gloucester restoration projects were successful in increasing salinity above the 18 psu threshold, which is the level assumed to stop production of methane from impaired salt marsh. The social cost of carbon was applied to the avoided emissions at each site as if the restoration projects were completed in 2021. In contrast, the Rockport and both Ipswich restorations were not successful at restoring salinity values above the 18 psu threshold and were therefore excluded from further analysis; and the Conomo Point rd. site presented with a pre-restoration salinity value more than 18 psu. The SCC values shown here are estimates of the social damage that would have been incurred between 2021-2050 from the lower sequestration rate of carbon from these sites if no restoration had taken place, again assuming that the project was completed in 2021. The "all restricted salt marsh in MA" row demonstrates the estimated social benefits of increased carbon sequestration assuming that all sites were successfully remediated and is therefore an overestimation of the possible. This is a truncated table; the remaining table is shown in Appendix B.

	Projected Benefits from 2021 – 2050 using 2021 Social Cost of Carbon		
Location	**Avoided social cost of carbon by 2050 (5% average) in 2021 dollars**	**Avoided social cost of carbon by 2050 (3% average) in 2021 dollars**	**Avoided social cost of carbon by 2050 (2.5% average) in 2021 dollars**
Essex, MA, Conomo Point Road			
Gloucester, MA, Eastern Point	$748	$2,239	$3,187
Ipswich, MA, Cedar Point			
Ipswich, MA, Town Farm Road*			
Rockport, MA Seaview Street			
Gloucester, MA, Mill Pond	$11,056	$33,088	$47,091

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[7] As our previous analysis has shown, of the 6 sites included in our analysis, only 33% - 66% of these restorations were successful (depending on how salinity values are summarized). Therefore, a more apt estimate would likely be 33% - 66% of 932 MTC-year^{-1}.

All restricted salt marsh in MA (932 hectares)	$636,849	$1,905,884	$2,712,435
All restricted salt marsh in MA (conservative estimate, assuming 50%)	$318,425	$952,942	$1,356,218

Like the SCM analysis previously described, these estimates of social benefit value resulting from the future restoration of all tidally restricted salt marsh demonstrate an upper bound of potential social benefits given the limitations associated with salinity rebound in restored salt marsh. All caveats previously described also apply to this SCC analysis.

Using Equation 1 above, we estimated that the restoration of each tidal restriction resulted in an increased carbon sequestration of 191.2 $MtCO_2$ in either EF scenario[8].

Table A-2: Annual emissions savings from avoided methane and increased carbon sequestration. This table summarizes values at each site calculated using Equation 1, where E are the annual emissions avoided, GWP is the global warming potential of methane, C is the increase in soil carbon sequestration, and VCUS-yr are the annual verified carbon units that could have been generated considering the CO_2e potential of both avoided methane and increased carbon sequestered as a result of each restoration assuming that the project was considered for carbon credits via the Verified Carbon Standard.

EF 19.4 EF 41.6	Eastern Point	Mill Pond	Totals
E-yr^{-1}	0.21 0.45	3.07 6.66	3.28 7.11
GWP_{CH4}	27.2	27.2	27.2
C-yr^{-1}	1.1	16.2	17.3
VCUs-yr^{-1}	6.8 13.3	99.7 197.4	106.5 210.7

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[8] Because carbon sequestration was estimated using a value not dependent on an emissions factor, the carbon accretion rate remains constant across either scenario.

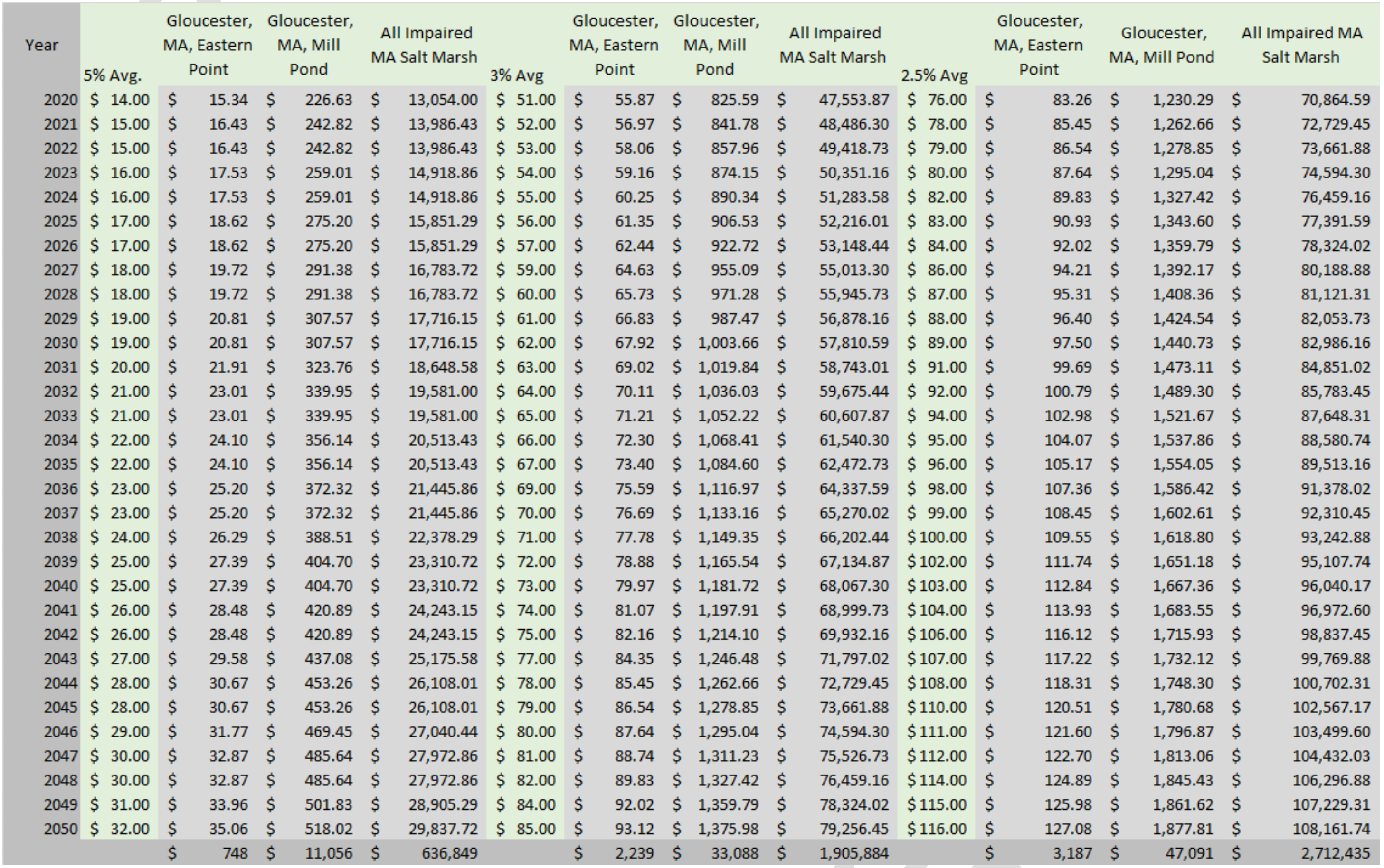
APPENDIX B: Continuation of Tables

Year	5% Avg.	Gloucester, MA, Eastern Point	Gloucester, MA, Mill Pond	All Impaired MA Salt Marsh	3% Avg	Gloucester, MA, Eastern Point	Gloucester, MA, Mill Pond	All Impaired MA Salt Marsh	2.5% Avg	Gloucester, MA, Eastern Point	Gloucester, MA, Mill Pond	All Impaired MA Salt Marsh
2020	$ 670	$ 139	$ 2,054	$ 118,323	$ 1,500	$ 311	$ 4,599	$ 264,903	$ 2,000	$ 415	$ 6,132	$ 353,204
2021	$ 690	$ 143	$ 2,116	$ 121,855	$ 1,500	$ 311	$ 4,599	$ 264,903	$ 2,000	$ 415	$ 6,132	$ 353,204
2022	$ 720	$ 149	$ 2,208	$ 127,153	$ 1,600	$ 332	$ 4,906	$ 282,563	$ 2,100	$ 436	$ 6,439	$ 370,864
2023	$ 750	$ 156	$ 2,300	$ 132,452	$ 1,600	$ 332	$ 4,906	$ 282,563	$ 2,100	$ 436	$ 6,439	$ 370,864
2024	$ 770	$ 160	$ 2,361	$ 135,984	$ 1,700	$ 353	$ 5,212	$ 300,223	$ 2,200	$ 456	$ 6,745	$ 388,524
2025	$ 800	$ 166	$ 2,453	$ 141,282	$ 1,700	$ 353	$ 5,212	$ 300,223	$ 2,200	$ 456	$ 6,745	$ 388,524
2026	$ 830	$ 172	$ 2,545	$ 146,580	$ 1,800	$ 373	$ 5,519	$ 317,884	$ 2,300	$ 477	$ 7,052	$ 406,185
2027	$ 860	$ 178	$ 2,637	$ 151,878	$ 1,800	$ 373	$ 5,519	$ 317,884	$ 2,300	$ 477	$ 7,052	$ 406,185
2028	$ 880	$ 183	$ 2,698	$ 155,410	$ 1,900	$ 394	$ 5,825	$ 335,544	$ 2,400	$ 498	$ 7,358	$ 423,845
2029	$ 910	$ 189	$ 2,790	$ 160,708	$ 1,900	$ 394	$ 5,825	$ 335,544	$ 2,500	$ 519	$ 7,665	$ 441,505
2030	$ 940	$ 195	$ 2,882	$ 166,006	$ 2,000	$ 415	$ 6,132	$ 353,204	$ 2,500	$ 519	$ 7,665	$ 441,505
2031	$ 970	$ 201	$ 2,974	$ 171,304	$ 2,000	$ 415	$ 6,132	$ 353,204	$ 2,600	$ 539	$ 7,972	$ 459,165
2032	$ 1,000	$ 207	$ 3,066	$ 176,602	$ 2,100	$ 436	$ 6,439	$ 370,864	$ 2,600	$ 539	$ 7,972	$ 459,165
2033	$ 1,000	$ 207	$ 3,066	$ 176,602	$ 2,100	$ 436	$ 6,439	$ 370,864	$ 2,700	$ 560	$ 8,278	$ 476,825
2034	$ 1,100	$ 228	$ 3,373	$ 194,262	$ 2,200	$ 456	$ 6,745	$ 388,524	$ 2,800	$ 581	$ 8,585	$ 494,486
2035	$ 1,100	$ 228	$ 3,373	$ 194,262	$ 2,200	$ 456	$ 6,745	$ 388,524	$ 2,800	$ 581	$ 8,585	$ 494,486
2036	$ 1,100	$ 228	$ 3,373	$ 194,262	$ 2,300	$ 477	$ 7,052	$ 406,185	$ 2,900	$ 602	$ 8,891	$ 512,146
2037	$ 1,200	$ 249	$ 3,679	$ 211,922	$ 2,300	$ 477	$ 7,052	$ 406,185	$ 3,000	$ 622	$ 9,198	$ 529,806
2038	$ 1,200	$ 249	$ 3,679	$ 211,922	$ 2,400	$ 498	$ 7,358	$ 423,845	$ 3,000	$ 622	$ 9,198	$ 529,806
2039	$ 1,200	$ 249	$ 3,679	$ 211,922	$ 2,500	$ 519	$ 7,665	$ 441,505	$ 3,100	$ 643	$ 9,505	$ 547,466
2040	$ 1,300	$ 270	$ 3,986	$ 229,583	$ 2,500	$ 519	$ 7,665	$ 441,505	$ 3,100	$ 643	$ 9,505	$ 547,466
2041	$ 1,300	$ 270	$ 3,986	$ 229,583	$ 2,600	$ 539	$ 7,972	$ 459,165	$ 3,200	$ 664	$ 9,811	$ 565,126
2042	$ 1,400	$ 290	$ 4,292	$ 247,243	$ 2,600	$ 539	$ 7,972	$ 459,165	$ 3,300	$ 685	$ 10,118	$ 582,787
2043	$ 1,400	$ 290	$ 4,292	$ 247,243	$ 2,700	$ 560	$ 8,278	$ 476,825	$ 3,300	$ 685	$ 10,118	$ 582,787
2044	$ 1,400	$ 290	$ 4,292	$ 247,243	$ 2,700	$ 560	$ 8,278	$ 476,825	$ 3,400	$ 705	$ 10,424	$ 600,447
2045	$ 1,500	$ 311	$ 4,599	$ 264,903	$ 2,800	$ 581	$ 8,585	$ 494,486	$ 3,500	$ 726	$ 10,731	$ 618,107
2046	$ 1,500	$ 311	$ 4,599	$ 264,903	$ 2,800	$ 581	$ 8,585	$ 494,486	$ 3,500	$ 726	$ 10,731	$ 618,107
2047	$ 1,500	$ 311	$ 4,599	$ 264,903	$ 2,900	$ 602	$ 8,891	$ 512,146	$ 3,600	$ 747	$ 11,038	$ 635,767
2048	$ 1,600	$ 332	$ 4,906	$ 282,563	$ 3,000	$ 622	$ 9,198	$ 529,806	$ 3,700	$ 768	$ 11,344	$ 653,427
2049	$ 1,600	$ 332	$ 4,906	$ 282,563	$ 3,000	$ 622	$ 9,198	$ 529,806	$ 3,700	$ 768	$ 11,344	$ 653,427
2050	$ 1,700	$ 353	$ 5,212	$ 300,223	$ 3,000	$ 622	$ 9,198	$ 529,806	$ 3,800	$ 788	$ 11,651	$ 671,088
	2021-2050	$ 7,100	$ 104,919	$ 6,043,321		$ 14,151	$ 209,102	$ 12,044,257		$ 17,885	$ 264,290	$ 15,223,094

Table B-1: The social benefit of Methane for the two sites included in the study, in addition to the 475 (932 hectares) of Massachusetts salt marshes impaired by tidal restrictions, as determined by *McGarigal et al., 2017*. Benefits calculated with SCM values using an EF of 19.4. Values are shown in $2021

Year	5% Avg.	Gloucester, MA, Eastern Point	Gloucester, MA, Mill Pond	All Impaired MA Salt Marsh	3% Avg	Gloucester, MA, Eastern Point	Gloucester, MA, Mill Pond	All Impaired MA Salt Marsh	2.5% Avg	Gloucester, MA, Eastern Point	Gloucester, MA, Mill Pond	All Impaired MA Salt Marsh
2020	$ 670	$ 302	$ 4,462	$ 257,013	$ 1,500	$ 676	$ 9,990	$ 575,402	$ 2,000	$ 901	$ 13,319	$ 767,202
2021	$ 690	$ 311	$ 4,595	$ 264,685	$ 1,500	$ 676	$ 9,990	$ 575,402	$ 2,000	$ 901	$ 13,319	$ 767,202
2022	$ 720	$ 324	$ 4,795	$ 276,193	$ 1,600	$ 721	$ 10,656	$ 613,762	$ 2,100	$ 946	$ 13,985	$ 805,563
2023	$ 750	$ 338	$ 4,995	$ 287,701	$ 1,600	$ 721	$ 10,656	$ 613,762	$ 2,100	$ 946	$ 13,985	$ 805,563
2024	$ 770	$ 347	$ 5,128	$ 295,373	$ 1,700	$ 766	$ 11,322	$ 652,122	$ 2,200	$ 992	$ 14,651	$ 843,923
2025	$ 800	$ 361	$ 5,328	$ 306,881	$ 1,700	$ 766	$ 11,322	$ 652,122	$ 2,200	$ 992	$ 14,651	$ 843,923
2026	$ 830	$ 374	$ 5,528	$ 318,389	$ 1,800	$ 811	$ 11,988	$ 690,482	$ 2,300	$ 1,037	$ 15,317	$ 882,283
2027	$ 860	$ 388	$ 5,727	$ 329,897	$ 1,800	$ 811	$ 11,988	$ 690,482	$ 2,300	$ 1,037	$ 15,317	$ 882,283
2028	$ 880	$ 397	$ 5,861	$ 337,569	$ 1,900	$ 856	$ 12,654	$ 728,842	$ 2,400	$ 1,082	$ 15,983	$ 920,643
2029	$ 910	$ 410	$ 6,060	$ 349,077	$ 1,900	$ 856	$ 12,654	$ 728,842	$ 2,500	$ 1,127	$ 16,649	$ 959,003
2030	$ 940	$ 424	$ 6,260	$ 360,585	$ 2,000	$ 901	$ 13,319	$ 767,202	$ 2,500	$ 1,127	$ 16,649	$ 959,003
2031	$ 970	$ 437	$ 6,460	$ 372,093	$ 2,000	$ 901	$ 13,319	$ 767,202	$ 2,600	$ 1,172	$ 17,315	$ 997,363
2032	$ 1,000	$ 451	$ 6,660	$ 383,601	$ 2,100	$ 946	$ 13,985	$ 805,563	$ 2,600	$ 1,172	$ 17,315	$ 997,363
2033	$ 1,000	$ 451	$ 6,660	$ 383,601	$ 2,100	$ 946	$ 13,985	$ 805,563	$ 2,700	$ 1,217	$ 17,981	$ 1,035,723
2034	$ 1,100	$ 496	$ 7,326	$ 421,961	$ 2,200	$ 992	$ 14,651	$ 843,923	$ 2,800	$ 1,262	$ 18,647	$ 1,074,083
2035	$ 1,100	$ 496	$ 7,326	$ 421,961	$ 2,200	$ 992	$ 14,651	$ 843,923	$ 2,800	$ 1,262	$ 18,647	$ 1,074,083
2036	$ 1,100	$ 496	$ 7,326	$ 421,961	$ 2,300	$ 1,037	$ 15,317	$ 882,283	$ 2,900	$ 1,307	$ 19,313	$ 1,112,444
2037	$ 1,200	$ 541	$ 7,992	$ 460,321	$ 2,300	$ 1,037	$ 15,317	$ 882,283	$ 3,000	$ 1,352	$ 19,979	$ 1,150,804
2038	$ 1,200	$ 541	$ 7,992	$ 460,321	$ 2,400	$ 1,082	$ 15,983	$ 920,643	$ 3,000	$ 1,352	$ 19,979	$ 1,150,804
2039	$ 1,200	$ 541	$ 7,992	$ 460,321	$ 2,500	$ 1,127	$ 16,649	$ 959,003	$ 3,100	$ 1,397	$ 20,645	$ 1,189,164
2040	$ 1,300	$ 586	$ 8,658	$ 498,682	$ 2,500	$ 1,127	$ 16,649	$ 959,003	$ 3,100	$ 1,397	$ 20,645	$ 1,189,164
2041	$ 1,300	$ 586	$ 8,658	$ 498,682	$ 2,600	$ 1,172	$ 17,315	$ 997,363	$ 3,200	$ 1,442	$ 21,311	$ 1,227,524
2042	$ 1,400	$ 631	$ 9,324	$ 537,042	$ 2,600	$ 1,172	$ 17,315	$ 997,363	$ 3,300	$ 1,487	$ 21,977	$ 1,265,884
2043	$ 1,400	$ 631	$ 9,324	$ 537,042	$ 2,700	$ 1,217	$ 17,981	$ 1,035,723	$ 3,300	$ 1,487	$ 21,977	$ 1,265,884
2044	$ 1,400	$ 631	$ 9,324	$ 537,042	$ 2,700	$ 1,217	$ 17,981	$ 1,035,723	$ 3,400	$ 1,532	$ 22,643	$ 1,304,244
2045	$ 1,500	$ 676	$ 9,990	$ 575,402	$ 2,800	$ 1,262	$ 18,647	$ 1,074,083	$ 3,500	$ 1,577	$ 23,309	$ 1,342,604
2046	$ 1,500	$ 676	$ 9,990	$ 575,402	$ 2,800	$ 1,262	$ 18,647	$ 1,074,083	$ 3,500	$ 1,577	$ 23,309	$ 1,342,604
2047	$ 1,500	$ 676	$ 9,990	$ 575,402	$ 2,900	$ 1,307	$ 19,313	$ 1,112,444	$ 3,600	$ 1,622	$ 23,975	$ 1,380,964
2048	$ 1,600	$ 721	$ 10,656	$ 613,762	$ 3,000	$ 1,352	$ 19,979	$ 1,150,804	$ 3,700	$ 1,668	$ 24,641	$ 1,419,324
2049	$ 1,600	$ 721	$ 10,656	$ 613,762	$ 3,000	$ 1,352	$ 19,979	$ 1,150,804	$ 3,700	$ 1,668	$ 24,641	$ 1,419,324
2050	$ 1,700	$ 766	$ 11,322	$ 652,122	$ 3,000	$ 1,352	$ 19,979	$ 1,150,804	$ 3,800	$ 1,713	$ 25,307	$ 1,457,685
	2021-2050	$ 15,423	$ 227,896	$ 13,126,833		$ 30,737	$ 454,194	$ 26,161,602		$ 38,849	$ 574,070	$ 33,066,424

Table B-2: The social benefit of Methane applied to both sites included in the study, in addition to the 475 (932 hectares) of Massachusetts salt marshes impaired by tidal restrictions, as determined by *McGarigal et al., 2017*. Benefits calculated with SCM values using an EF of 41.6. Values are shown in $2021



Year	5% Avg.	Gloucester, MA, Eastern Point	Gloucester, MA, Mill Pond	All Impaired MA Salt Marsh	3% Avg	Gloucester, MA, Eastern Point	Gloucester, MA, Mill Pond	All Impaired MA Salt Marsh	2.5% Avg	Gloucester, MA, Eastern Point	Gloucester, MA, Mill Pond	All Impaired MA Salt Marsh
2020	$ 14.00	$ 15.34	$ 226.63	$ 13,054.00	$ 51.00	$ 55.87	$ 825.59	$ 47,553.87	$ 76.00	$ 83.26	$ 1,230.29	$ 70,864.59
2021	$ 15.00	$ 16.43	$ 242.82	$ 13,986.43	$ 52.00	$ 56.97	$ 841.78	$ 48,486.30	$ 78.00	$ 85.45	$ 1,262.66	$ 72,729.45
2022	$ 15.00	$ 16.43	$ 242.82	$ 13,986.43	$ 53.00	$ 58.06	$ 857.96	$ 49,418.73	$ 79.00	$ 86.54	$ 1,278.85	$ 73,661.88
2023	$ 16.00	$ 17.53	$ 259.01	$ 14,918.86	$ 54.00	$ 59.16	$ 874.15	$ 50,351.16	$ 80.00	$ 87.64	$ 1,295.04	$ 74,594.30
2024	$ 16.00	$ 17.53	$ 259.01	$ 14,918.86	$ 55.00	$ 60.25	$ 890.34	$ 51,283.58	$ 82.00	$ 89.83	$ 1,327.42	$ 76,459.16
2025	$ 17.00	$ 18.62	$ 275.20	$ 15,851.29	$ 56.00	$ 61.35	$ 906.53	$ 52,216.01	$ 83.00	$ 90.93	$ 1,343.60	$ 77,391.59
2026	$ 17.00	$ 18.62	$ 275.20	$ 15,851.29	$ 57.00	$ 62.44	$ 922.72	$ 53,148.44	$ 84.00	$ 92.02	$ 1,359.79	$ 78,324.02
2027	$ 18.00	$ 19.72	$ 291.38	$ 16,783.72	$ 59.00	$ 64.63	$ 955.09	$ 55,013.30	$ 86.00	$ 94.21	$ 1,392.17	$ 80,188.88
2028	$ 18.00	$ 19.72	$ 291.38	$ 16,783.72	$ 60.00	$ 65.73	$ 971.28	$ 55,945.73	$ 87.00	$ 95.31	$ 1,408.36	$ 81,121.31
2029	$ 19.00	$ 20.81	$ 307.57	$ 17,716.15	$ 61.00	$ 66.83	$ 987.47	$ 56,878.16	$ 88.00	$ 96.40	$ 1,424.54	$ 82,053.73
2030	$ 19.00	$ 20.81	$ 307.57	$ 17,716.15	$ 62.00	$ 67.92	$ 1,003.66	$ 57,810.59	$ 89.00	$ 97.50	$ 1,440.73	$ 82,986.16
2031	$ 20.00	$ 21.91	$ 323.76	$ 18,648.58	$ 63.00	$ 69.02	$ 1,019.84	$ 58,743.01	$ 91.00	$ 99.69	$ 1,473.11	$ 84,851.02
2032	$ 21.00	$ 23.01	$ 339.95	$ 19,581.00	$ 64.00	$ 70.11	$ 1,036.03	$ 59,675.44	$ 92.00	$ 100.79	$ 1,489.30	$ 85,783.45
2033	$ 21.00	$ 23.01	$ 339.95	$ 19,581.00	$ 65.00	$ 71.21	$ 1,052.22	$ 60,607.87	$ 94.00	$ 102.98	$ 1,521.67	$ 87,648.31
2034	$ 22.00	$ 24.10	$ 356.14	$ 20,513.43	$ 66.00	$ 72.30	$ 1,068.41	$ 61,540.30	$ 95.00	$ 104.07	$ 1,537.86	$ 88,580.74
2035	$ 22.00	$ 24.10	$ 356.14	$ 20,513.43	$ 67.00	$ 73.40	$ 1,084.60	$ 62,472.73	$ 96.00	$ 105.17	$ 1,554.05	$ 89,513.16
2036	$ 23.00	$ 25.20	$ 372.32	$ 21,445.86	$ 69.00	$ 75.59	$ 1,116.97	$ 64,337.59	$ 98.00	$ 107.36	$ 1,586.42	$ 91,378.02
2037	$ 23.00	$ 25.20	$ 372.32	$ 21,445.86	$ 70.00	$ 76.69	$ 1,133.16	$ 65,270.02	$ 99.00	$ 108.45	$ 1,602.61	$ 92,310.45
2038	$ 24.00	$ 26.29	$ 388.51	$ 22,378.29	$ 71.00	$ 77.78	$ 1,149.35	$ 66,202.44	$ 100.00	$ 109.55	$ 1,618.80	$ 93,242.88
2039	$ 25.00	$ 27.39	$ 404.70	$ 23,310.72	$ 72.00	$ 78.88	$ 1,165.54	$ 67,134.87	$ 102.00	$ 111.74	$ 1,651.18	$ 95,107.74
2040	$ 25.00	$ 27.39	$ 404.70	$ 23,310.72	$ 73.00	$ 79.97	$ 1,181.72	$ 68,067.30	$ 103.00	$ 112.84	$ 1,667.36	$ 96,040.17
2041	$ 26.00	$ 28.48	$ 420.89	$ 24,243.15	$ 74.00	$ 81.07	$ 1,197.91	$ 68,999.73	$ 104.00	$ 113.93	$ 1,683.55	$ 96,972.60
2042	$ 26.00	$ 28.48	$ 420.89	$ 24,243.15	$ 75.00	$ 82.16	$ 1,214.10	$ 69,932.16	$ 106.00	$ 116.12	$ 1,715.93	$ 98,837.45
2043	$ 27.00	$ 29.58	$ 437.08	$ 25,175.58	$ 77.00	$ 84.35	$ 1,246.48	$ 71,797.02	$ 107.00	$ 117.22	$ 1,732.12	$ 99,769.88
2044	$ 28.00	$ 30.67	$ 453.26	$ 26,108.01	$ 78.00	$ 85.45	$ 1,262.66	$ 72,729.45	$ 108.00	$ 118.31	$ 1,748.30	$ 100,702.31
2045	$ 28.00	$ 30.67	$ 453.26	$ 26,108.01	$ 79.00	$ 86.54	$ 1,278.85	$ 73,661.88	$ 110.00	$ 120.51	$ 1,780.68	$ 102,567.17
2046	$ 29.00	$ 31.77	$ 469.45	$ 27,040.44	$ 80.00	$ 87.64	$ 1,295.04	$ 74,594.30	$ 111.00	$ 121.60	$ 1,796.87	$ 103,499.60
2047	$ 30.00	$ 32.87	$ 485.64	$ 27,972.86	$ 81.00	$ 88.74	$ 1,311.23	$ 75,526.73	$ 112.00	$ 122.70	$ 1,813.06	$ 104,432.03
2048	$ 30.00	$ 32.87	$ 485.64	$ 27,972.86	$ 82.00	$ 89.83	$ 1,327.42	$ 76,459.16	$ 114.00	$ 124.89	$ 1,845.43	$ 106,296.88
2049	$ 31.00	$ 33.96	$ 501.83	$ 28,905.29	$ 84.00	$ 92.02	$ 1,359.79	$ 78,324.02	$ 115.00	$ 125.98	$ 1,861.62	$ 107,229.31
2050	$ 32.00	$ 35.06	$ 518.02	$ 29,837.72	$ 85.00	$ 93.12	$ 1,375.98	$ 79,256.45	$ 116.00	$ 127.08	$ 1,877.81	$ 108,161.74
		$ 748	$ 11,056	$ 636,849		$ 2,239	$ 33,088	$ 1,905,884		$ 3,187	$ 47,091	$ 2,712,435

Table B-3: The social benefit of Carbon applied to both sites included in the study, in addition to the 475 (932 hectares) of Massachusetts salt marshes impaired by tidal restrictions, as determined by *McGarigal et al., 2017*. Benefits calculated with SCC values. Values do not vary by EF so EF excluded. Values are shown in $2021

Appendix C. Salinity data sources

Massachusetts Audubon Society salinity results and values:

Essex, MA Conomo Point Rd.

Gloucester, MA, Eastern Point

Gloucester, MA, Mill Pond

Ipswich, MA, Cedar Point

Ipswich, MA, Town Farm Road

Rockport, MA, Seaview Street (excluding Saratoga Creek)

Appendix D. Variance in Salinity Values

Table D-1: Restored Marsh Salinity Variance by Depth. Shown here is the variance in pre-and post-restoration salinity values with associated standard error by degrees of depth. As described by the Massachusetts Audubon Society, salinity values were measured at discrete depths of Shallow” (5 – 20cm), “Medium” (35– 50cm), and “Deep” (65 – 80cm). When average pre- and post-restoration salinity is corrected by depth, we can see a much stronger change in the first 20cms of soil compared against the remaining 60cms.

		Shallow	Medium	Deep
Essex Conomo Point	Restricted	7.8 ± 0.54	23.6 ± 0.52	22 ± 0.52
	Restored	22.4 ± 0.6	24.4 ± 0.58	24.2 ± 0.58
Gloucester Eastern Point	Restricted	8.1 ± 0.36	10.8 ± 0.34	11.9 ± 0.36
	Restored	19.4 ± 0.47	19.2 ± 0.45	18.4 ± 0.48
Ipswich Cedar Point	Restricted	11.8 ± 0.39	12.8 ± 0.34	13.4 ± 0.27
	Restored	11.7 ± 0.92	11.3 ± 0.79	8.8 ± 0.62
Ipswich Town Farm	Restricted	31 ± 0.5	29.3 ± 0.49	24.8 ± 0.49
	Restored	28.9 ± 0.45	27.1 ± 0.44	24.8 ± 0.44
Rockport Seaview St.	Restricted	17.5 ± 0.59	18.2 ± 0.57	17.4 ± 0.56
	Restored	20.4 ± 0.73	16.1 ± 0.7	13.9 ± 0.69
Gloucester Mill Pond	*Restricted*	*12.4 ± 0.48*	*18.5 ± 0.47*	*21.7 ± 0.48*
	Restored	*22.3 ± 0.44*	*18.4 ± 0.43*	*19.1 ± 0.43*

Table D-2: Restored Marsh Salinity Variance by Year. Of the six sites included in this analysis, shown here is the annual variance in salinity values demonstrated both before and after the first restoration year, which is demarcated by the highlighted cell for each site. As is shown, average annual salinity values vary year-on-year both before and after implementation of the restoration project at each site. Further, this summation demonstrates a definitive lag phase in the Gloucester sites following the completed restoration project. Were this lag phase to have been included in our overall analysis, the total social benefit value for each site would have been reduced to only include years in which the average salinity was above 18 psu. Average pre- and post-salinity values vary here when compared against previous summary tables as these averages represent an *average of the annual averages* rather than an average of the pre- and post-restoration values.

Year	*Essex Conomo Point*	*Gloucester Eastern Point*	*Gloucester Mill Pond*	*Ipswich Cedar Rd.*	*Ipswich Town Farm*	*Rockport Saratoga*
1996					*23.8 ± 1.04*	
1997					*No Data*	
1998	*20.7 ± 1.7*		*21 ± 0.8*		*29 ± 0.96*	*No Data*
1999	*15.7 ± 1.39*		*21.7 ± 1.33*	*12.6 ± 0.75*	*33.6 ± 2.66*	*No Data*
2000	*20 ± 1.72*	*12.1 ± 1.32*	*18.2 ± 0.71*	*10 ± 1.43*	*28 ± 1.28*	*No Data*
2001	*23.4 ± 0.96*	*13.2 ± 1.22*	*14.2 ± 0.68*	*5.1 ± 2.05*	*26 ± 1.3*	*No Data*
2002	*21.7 ± 1.46*	*10.9 ± 0.95*	*No Data*	*No Data*	*29.2 ± 0.96*	*18.2 ± 1.65*
2003	*25.5 ± 1.53*	*No Data*	*No Data*	*No Data*	*30.7 ± 1.12*	*No Data*
2004	*20.6 ± 0.67*	*16.3 ± 0.85*	*21 ± 2.96*	*7.3 ± 0.67*	*21.1 ± 1.12*	*13 ± 1.41*
2005	*23.2 ± 1.04*	*20.5 ± 1.11*	*16.2 ± 0.74*	*11 ± 4*	*24.3 ± 1.36*	*20.2 ± 1.66*
2006	*22.1 ± 1.18*	*18.6 ± 0.59*	*15 ± 0.63*	*8.5 ± 1.28*	*23.6 ± 1.01*	*11.2 ± 1.31*
2007	*24 ± 1.19*	*22.3 ± 1.66*	*18.4 ± 0.58*	*6.9 ± 0.68*	*24.5 ± 1.03*	*16.2 ± 1.29*
2008	*22.5 ± 1.21*	*19 ± 1.45*	*18.8 ± 0.91*	*6.5 ± 0.81*	*23.1 ± 1.16*	*10.2 ± 2.11*
2009	*19.3 ± 1.05*	*17.3 ± 1.15*	*19.3 ± 0.93*	*7.5 ± 1.27*	*23.3 ± 0.99*	*15.8 ± 1.75*
2010	*21.4 ± 0.73*	*19.1 ± 1.47*	*22.5 ± 1.21*	*14.9 ± 1.01*	*26.7 ± 0.96*	*22.3 ± 1.3*
2011	*19.4 ± 0.95*	*16.3 ± 1.59*	*20.7 ± 1.18*	*No Data*	*25.5 ± 1.2*	*12.9 ± 1.42*
2012	*24.6 ± 0.72*	*19.2 ± 1.26*	*16.5 ± 1.32*	*15.6 ± 1.32*	*28.4 ± 1.49*	*13.3 ± 0.98*
2013	*20.9 ± 0.8*	*20.4 ± 2.18*	*18.6 ± 1.04*	*10.9 ± 1.43*	*25.7 ± 0.95*	*17.7 ± 1.07*
2014	*25.8 ± 0.94*	*17.8 ± 1.77*	*22.6 ± 1.23*	*11.2 ± 4.23*	*24.5 ± 0.73*	
2015	*29.1 ± 4.02*	*19.5 ± 1.84*	*25.1 ± 1.32*	*9.9 ± 1.44*	*25.9*	
2016		*20 ± 1.28*	*29.9 ± 0.99*	*6.8 ± 1.23*	*29.8*	
2017		*20.8 ± 1*	*25.1 ± 0.87*	*10.9 ± 1.45*	*27.3*	
2018		*18.5 ± 0.63*	*21 ± 1.12*	*15.1 ± 1.53*	*28.2*	
Avg. Pre	*18.2 ± 1.54*	*12.1 ± 1.16*	*18.8 ± 0.88*	*12.6 ± 0.75*	*27.7 ± 1.31*	*18.2 ± 1.65*
Avg. Post	*22.9 ± 1.25*	*19.2 ± 1.36*	*20.7 ± 1.14*	*9.9 ± 1.63*	*25.9 ± 1.06*	*15.3 ± 1.43*

SUPPLEMENTARY MATERIALS

Excel Model (EPA-only as of 3/2022 – please email authors for access)

Interactive Map (EPA-only as of 3/2022 – please email authors for access)

This map identifies 54,941 acres of wetlands throughout Massachusetts that are near or overlap one of the 2,118 tidal restrictions greater than or equal to 0.5 identified in the 2010 dataset developed by McGarigal et al., 2017. Of the 54,941 acres of wetlands, 943 hectares are classified as salt marsh (marine and estuarine), which correspond to 475 sites. These 475 sites were those included for analysis in this paper.