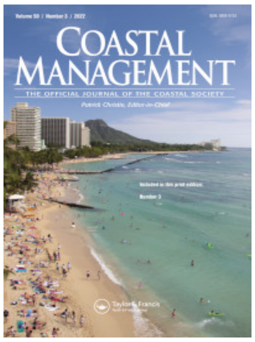

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Economic Value of Salt Marshes under Uncertainty of Sea Level Rise: A Case Study of the Narragansett Bay

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ABSTRACT
Salt marshes are an integral part of coastal ecosystems that are changing rapidly with sea level rise (SLR). Because marshes provide important ecosystem services, such as carbon sequestration and shoreline protection, it is critical to understand how their economic benefit values are likely to be affected by SLR. Such change, however, depends on the capacity of marshes to adapt to flooding by migrating inland. This study provides the economic value of changes in carbon and non-carbon benefits using predicted changes in salt marsh coverage in Narragansett Bay, Rhode Island under three SLR scenarios and two marsh adaptation conditions. We apply regional carbon prices and a value function transfer approach to value other salt marsh service values. Results indicate an average annual value of $1,863/acre for carbon and $2,537/acre for non-carbon ecosystem services. This yields a mean discounted value of $592 million (M) (+14% compared to no change) over 90 years. We discuss alternative management strategies to enhance marshes' capacity to migrate inland, which may accrue as much as $659 M.

KEYWORDS
Carbon sequestration; ecosystem valuation; salt marsh; sea level rise; value function transfer

Introduction

Coastal environments are among the most economically important, yet vulnerable, ecosystems (Barbier et al. 2011). Coastal and estuarine salt marshes provide a diverse spectrum of valuable ecosystem services, including water filtration, nutrient cycling, protection from coastline erosion, wave surge attenuation, fish nursery provision, and the promotion of biodiversity (McGlathery et al. 2007). In addition to ecological value, healthy marsh habitat contributes other significant social, cultural, and recreational benefits within coastal communities (Feagin et al. 2010). More recently, intertidal salt marshes have also been lauded for their potential as "blue carbon" sinks given their ability to capture and store carbon dioxide (CO_2) in their living tissues and underlying peat sediments (Mcleod et al. 2011; Luisetti et al. 2014; Hungate et al. 2017).

Despite the recognized importance of salt marshes' numerous benefits, the degradation and loss of historically abundant marshes have accelerated worldwide within the last

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century (Crooks et al. 2011; Mcowen et al. 2017). In addition to nutrient and sediment disturbances, displacement by invasive species, and vestigial ditching along shorelines, sea level rise (SLR) is a leading cause of marsh degeneration (US EPA 2006). Given adequate environmental conditions, salt marshes have the natural ability to transition landward inland in response to incremental changes in sea level and increased frequency of inundation and can gradually colonize areas which were previously at higher relative elevations (Donnelly and Bertness 2001; Weston 2014; Fagherazzi et al. 2020). Coastal development in densely populated areas, however, often acts as a barrier against landward transgression, which is fundamental to long-term salt marsh survival (Torio and Chmura 2013). Land impoundments caused by urban infrastructure (e.g., pavement, dams, and seawalls) may further restrict adaptive marsh migration unless interventions are coordinated to make these surfaces traversable (Balmford et al. 2008; Kutcher et al. 2018). Moreover, sediment deposition and organic matter accumulation must match or surpass SLR; otherwise, the marsh will decrease in elevation and eventually drown (Reed 1995). To facilitate the adaptation of salt marshes to SLR and other threats, local and state resource managers are beginning to implement proactive measures to ensure that newly submerged areas are accessible for existing marshes to migrate inland.

However, one major challenge for coastal communities is how to characterize the economic benefit of assuring the migration of salt marshes into upland areas and other actions that safeguard these habitats into the future. Although much research has investigated the ecological effects of climate change on coastal ecosystems, much less attention has focused on valuing the changes in their economic benefits over time (Fagherazzi et al. 2019). For example, decisions about what to do with infrastructural impediments that inhibit long-term marsh adaptation to SLR require coastal managers to consider not only the value of the current salt marsh area, but also the value resulting from changes in marsh abundance and distribution in the future. Such value measures are especially salient to coastal planners if practical measures can be taken to maintain or improve marsh persistence into the future. Location-specific value estimates are crucial to local management; projections that are attuned to the local or regional-level are still not often readily accessible to community resource planners, creating additional barriers to effective coastal management (Hanley et al. 2015).

The primary goal of this study is to help fill this valuation gap by quantifying the economic values of ecosystem services from salt marshes in the Narragansett Bay, the largest estuary in New England (NBEP 2017). This study provides per-acre values of carbon and non-carbon benefits of salt marshes, as well as total value of benefits for changes in salt marshes at two spatial scales based on several SLR scenarios and whether upland migration of salt marshes is restricted versus unrestricted. While salt marsh is present in many temperate coastal regions, inherent differences in species composition, environmental inputs, and socioeconomic factors between different regions elicit heterogeneous values of ecosystem services from salt marsh. Thus far, application in the Northeast United States has been limited and, to our knowledge, an extensive valuation of the benefit values of salt marshes in the Narragansett Bay has yet to be conducted to date. Given that the region is experiencing SLR rates much higher than the global average (Oppenheimer et al. 2019), this type of information is valuable to the development and implementation of adaptive management strategies that aim to protect at-risk areas or to restore degraded patches of marsh habitat.

Another key contribution is to provide a range of value estimates that can be used across settings, in part to address uncertainty in the parameter values in both ecological and economic modeling. Establishing these ranges benefits the continued formation of policies that affect salt marshes in the Bay, especially given the growing interest locally, regionally and globally in the ecosystem services they provide. For instance, per acre value ranges of carbon and non-carbon benefits of salt marshes may be used in cost-benefit analyses for marsh restoration projects in the region.

Specifically, we quantify the values of future multiple benefits, including carbon and other non-market ecosystem benefits, provided by marsh coverage from 2010 through the year 2100 using the Sea Level Affecting Marshes Model (SLAMM) simulations generated for the state of Rhode Island (RI) in 2015 (RI CRMC 2015). We evaluate six scenarios that vary in both the mean sea level change (i.e., 1-ft, 3-ft, and 5-ft) and the assumption of whether existing marshes will be able to migrate onto shorelines currently hardened by infrastructure in an "unrestricted" or "restricted" fashion. For each marsh coverage prediction, we calculate the total discounted stream of benefits over the 90-year time horizon by combining a monetization of dynamic carbon storage and sequestration values with a benefit transfer function for non-market service values. Values are estimated separately for carbon and non-carbon benefits and are then combined to yield total discounted value. Finally, we perform three Monte Carlo simulations, each with one million draws, to address the variability in our key parameters and to test the sensitivity of our results to inputs. Although our calculations focus on the change in salt marsh coverage within the Narragansett Bay, we provide a range of unit values of the carbon and non-carbon benefits, which can be used in many settings in coastal New England to assess future projects for the protection or restoration of salt marshes.

Materials and methods

Study site: the narragansett Bay

This study estimates the economic values of hypothetical changes in salt marsh coverage in Narragansett Bay and the associated ponds and estuaries of the State of Rhode Island.[1] The most recently recorded total land cover of salt marshes in this area is 3,164 acres (Figure 1, RI CRMC 2015). New England salt marshes have been vulnerable to the consequences of direct and indirect human interaction since times of early colonization, when their ecosystem services were not yet well understood or appreciated. More than 50 percent of Narragansett Bay's historical salt marshes (over 4,500 acres) are estimated to have been lost due to coastline development, dredging, and other human activities in intertidal waters between the 1800s and the 1970s (Bromberg and Bertness 2005; Nixon and Fulweiler 2012; Roman 2017). In addition, photographic records document the increased shoreline erosion and widening of tidal creeks and channels in the Bay since the 1930s (Niering and Scott Warren 1980; Watson et al. 2014). A recent multi-decadal analysis of aerial imagery suggests that vegetation loss may have been as high as 17.3% from 1939 to 2011 alone (Watson et al. 2017).

Trends of anthropogenic-related marsh loss are expected to accelerate in response to drastically shifting climate conditions across New England (Watson et al. 2016),

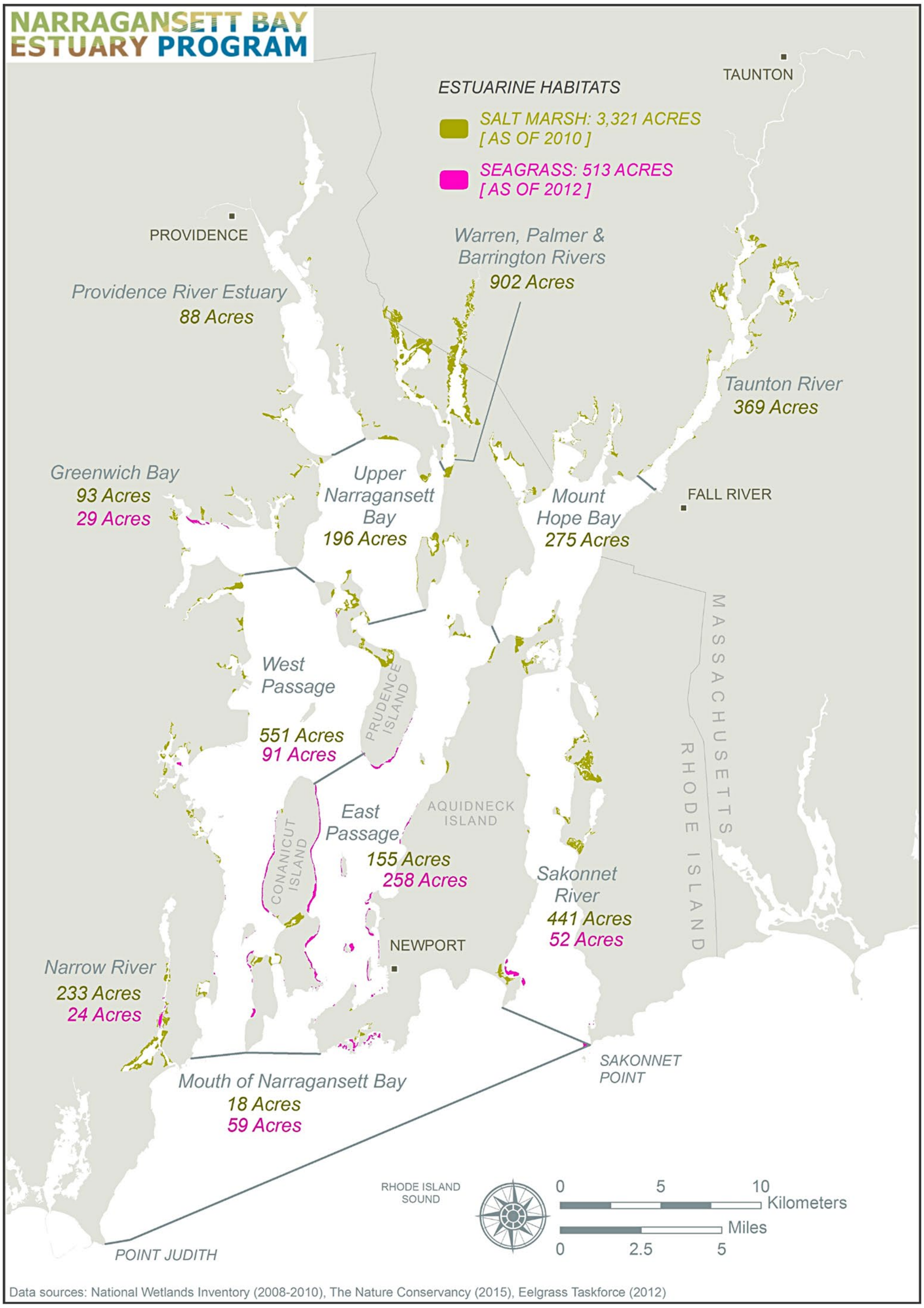

Figure 1. 2016 extent (in acres) of salt marshes (and seagrasses) in the estuarine waters of Narragansett Bay, the RI portion of Little Narragansett Bay, the Southwest Coastal Ponds of RI, and the RI Sounds. [printed in color].*Source*: Narragansett Bay Estuary Program 2016. Data are from Rhode Island Eelgrass Task Force surveys.

although the net change is likely to be location specific and scale dependent. Studies show that a number of factors can influence salt marsh's adaptive process including slope, current land use, and extreme weather events (Fagherazzi et al. 2019). Historically, salt marshes in the Northeastern U.S. have been able to keep pace with SLR through lateral transgression and vertical peat accretion (Raposa et al. 2017). However, reduced sediment resulting from urbanization and other coastal modification in combination with accelerating SLR currently threatens the adaptive capacity of New England marshes to persist in the coming decades (Watson et al. 2017). Between 60-90% of all salt marshes in the Atlantic are not expected to gain elevation at a sufficient rate to endure the magnitude of expected SLR by 2100 (Crosby et al. 2016). Rates of tidal elevation in New England are nearly 50% greater than the global average mean that the Bay's marshes are at even greater threat to be lost via drowning (Cole Ekberg et al. 2017; Watson et al. 2017). While some research had initially been optimistic about New England salt marshes' ability to keep relative pace with future SLR (Charles and Dukes 2009), even the region's more resilient marshes are now expected to die off at extreme levels of inundation without targeted intervention (Donnelly and Bertness 2001; Carey et al. 2017; Raposa et al. 2017; Mariotti et al. 2020). To counter these trends, statewide efforts in the past three decades have aimed to protect or restore RI's marsh habitats by removing or modifying tidal restrictions, improving stormwater treatment and flow to limit sediment deposition in marshes, and installing vegetation buffers to protect marshes from runoff (Save the Bay 2018; Vinhateiro 2021). Ultimately, the net change observed in the future will be determined by a number of factors, including extreme weather events, land use, the slope of the areas intersecting with salt marsh, and human response to marsh migration.

Rhode Island SLAMM scenarios

In 2015, RI Coastal Resources Management Council (RI CRMC) developed the RI SLAMM for statewide use in coastal development and climate change response planning. The model produces land cover projections over time given future uncertainty in mean SLR (Chu-Agor et al. 2011) by assimilating LiDAR and GIS data with data from the National Wetland Inventory. Generally, SLAMMs identify high priority marsh units for the removal of impediments to migration such as old roads, stone barriers, and other vestigial human-made features, as well as areas for land conservation easements to protect certain inland migration areas from future development.

We design six scenarios of hypothetical changes in salt marsh coverage in the Narragansett Bay between 2010 and 2100 from the RI SLAMM (RI CRMC 2014, Table 1). Each scenario assumes one of three levels of SLR (1 ft, 3 ft, or 5 ft) and considers two possible dichotomous marsh conditions:[2] (1) *unrestricted*: assumes the uninhibited capacity for marsh migration inland over newly submerged landscapes that are hardened by human-built infrastructure and (2) *restricted*: assumes migrating marshes are deprived of the opportunity to take root on developed coastlines (RI CRMC 2015). The models consider hardened or developed lands to be those that reflect highly altered upland conditions, such as pavement, parking lots, and seawalls. In restricted scenarios, these physical boundaries delineate areas that are unsuitable for new marsh propagation. The purpose of using two different conditions is to compare how the presence of shoreline

Table 1. Six scenarios for salt marsh area in the Narragansett Bay in 2100 (acres).

	1-ft SLR			
	Total Area	**Migrated Marsh Area**	**Persistent Marsh Area**	**Lost Marsh Area**
S1: Restricted	5,187	1,845	3,340	409
S2: Unrestricted	5,669	2,392	3,277	472
	3-ft SLR			
	Total Area	Migrated Marsh Area	Persistent Marsh Area	Lost Marsh Area
S3: Restricted	4,444	2,610	1,834	1,916
S4: Unrestricted	5,755	3,959	1,796	1,954
	5-ft SLR			
	Total Area	Migrated Marsh Area	Persistent Marsh Area	Lost Marsh Area
S5: Restricted	3,950	3,480	470	3,279
S6: Unrestricted	6,746	6,278	468	3,281

Note: S1-S6 stands for Scenarios 1 through 6.
Source: Rhode Island CRMC (2015)

development will influence the ability of inland marsh migration and to demonstrate the potential for conservation and restoration efforts that would remove these obstacles or otherwise mitigate their effect on marsh transition.

For each combination of SLR and migration capacity, we evaluate corresponding changes in ecosystem service value flows by calculating the discounted annual benefits from ecosystem services summed over 90 years. Beginning with the 2010 estimated area of 3,164 acres (RI CRMC 2015), we calculate the inter-annual change in new, persistent, and lost marsh area and combine all yearly changes to estimate the total net change for each scenario (Table 1, "Total area"). "Migrated marsh area" is the total acreage of migrated marsh that is projected to propagate under each respective SLR outcome subject to the assumption marsh ability of migrating inland. "Persistent marsh area" refers to acres of currently existing marsh that is expected to survive the 90-year time horizon, while "lost marsh area" specifies the acreage that will drown in place.

Overall, the RI SLAMM predicts that the Narragansett Bay will experience substantial land cover change and loss of existing salt marsh area (Table 1). Under the most extreme assumptions of 5-ft SLR over 90 years with restricted migration capacity, the model predicts up to 87% loss in current coverage (~3,000 acres), a 15-fold difference from the same amount of SLR under the unrestricted scenario (~200 acres); however, all six scenarios predict net gains in acreage (RI CRMC 2015).

The large net gain in marsh acreage with SLR may be seemingly counterintuitive and deserves some discussion. It is well documented that with sea level rise, low-lying coastal forests, agricultural fields and suburban areas will retreat and be replaced with salt marshes (e.g., Fagherazzi et al. 2019). In this sense, the magnitude of SLR expected in the Narragansett Bay resembles that of other parts of the U.S., especially in the northeast where sea level is expected to rise more than in other coastal regions of the country. However, the rate and the extent of salt marsh transgression depends on storms, the slope of the marsh-adjoining areas, and land use. At the same time, coastal communities will likely prevent inland marsh migration in many areas because it translates to a loss of agricultural land, residential properties, and infrastructure. The net effect will inevitably vary locally across space and time.

These insights lead to three implications for the future trends of salt marshes in the Narragansett Bay. First, it is plausible that Narragansett Bay will experience a net gain in salt marshes; however, it is highly location and scale specific. Indeed, the model predicts a net gain in the Narragansett Bay as a whole, while some localities are expected to experience a sizable net decrease with SLR. In this study, we estimate the carbon and non-carbon values for each scenario at two spatial scales—one for the entire Bay and the other for specific municipalities for which SLAMM predicts a large net loss in salt marsh. Second, there is a large degree of uncertainty in the predictions from the SLAMM model because it ignores some important factors such as the feedback effect of human response to marsh migration or future extreme weather events and these factors can change the future scenarios. Given the large degree of uncertainty, we emphasize the usefulness of our approach of valuing carbon and non-carbon benefits rather than the aggregate values. Third, it is important to note that RI SLAMM projections express a possibility for at least some existing and migrating marsh to persist despite a rising mean sea level, provided that there is adequate substrate on newly submerged surfaces to support migration. However, existing development along the State's shorelines can greatly impede the ability of existing marshes to migrate landward. Therefore, achieving the unrestricted outcomes put forth by the RI SLAMM in reality will rely on well-coordinated coastal management and community stewardship. We discuss these and other limitations of the model in the Discussion section.

Carbon storage and sequestration

Similar to other coastal vegetation, salt marshes remove atmospheric carbon dioxide (CO_2) through photosynthesis and their anaerobic soils enable the long-term burial of organic carbon (C) (CEC 2013). While a fraction of the carbon is re-released with oxygen and some methane through cellular respiration and oxidation, marshes retain the majority of carbon in two primary pools: living plant biomass (i.e., above- and belowground vegetation) and soil organic carbon (SOC) (Mcleod et al. 2011; Lovelock et al. 2017). While approximately 95 to 99% of total marsh carbon is accumulated in underground sediment, storage is believed to decrease gradually with depth in relation to mean tidal elevation and is considered most concentrated in the superficial soils under marshes up to one meter depth (Murray et al. 2011). In mature marshes, the carbon stored in living plant tissue and in the material built up in near-surface soils will remain relatively constant unless the health of the vegetation changes or the wetland is disturbed (PWA and SAIC 2009). Each year, some amount of carbon is added to the storage pools at an assumed sequestration rate for a marsh area of a given unit size, typically per acre.

The simple aggregation of total carbon as a product of net changes in coverage risks grossly misestimating the amount of carbon stored by a given marsh area and, consequently, the amount at risk for re-release if the area is destroyed or drowned. Following methods used by similar carbon valuation studies (e.g., Murray et al. 2011; Beaumont et al. 2014; Clough et al. 2016; Propato et al. 2018), we calculate total carbon as the equivalent of CO_2 captured by salt marshes in the Narragansett Bay as a function of the RI SLAMM's predictions of migrating, persistent, and lost marsh area. In this process, we take into account carbon held in the top one meter of soil and all living biomass plus all new carbon sequestered each year. It also takes into account the carbon released back into the atmosphere as CO_2 when salt marsh is disturbed or drowned (e.g., when the underlying soil and root systems oxidize). Further details including equations, assumptions, and parameters are available in the Supplementary Material.

The computation of carbon for each scenario uses multiple data sources from different sampling sites and collection methods. Moreover, parameters often have wide ranges with uneven distribution of samples across regions. To address parameter uncertainty, we conduct Monte Carlo analysis for key storage and sequestration parameters across a range of values collected from the literature.

Economic value of carbon

Carbon values for each time period (one year) are monetized by multiplying total carbon for each period by the market price of carbon assuming fixed price over time. We use a mean clearing price of carbon credit auctions conducted by the Regional Greenhouse Gas Initiative (RGGI)—a joint cap-and-trade program between North Eastern states—between 2016 and 2018. Prices are adjusted for inflation to 2010 US$ value using the Consumer Price Index (CPI), yielding a final amount of \$3.39/tCO_2e. We use the range of RGGI clearing prices (\$2.24 to \$4.61) from the same period as the upper and lower bounds in our sensitivity analysis to capture the possible breadth of blue carbon value in current market terms.

Value function transfer of non-carbon ecosystem services

Because primary valuation studies are often costly and time-consuming, value transfer methods are considered a suitable alternative to approximate the value of ecosystem services in different geospatial and temporal settings (Richardson et al. 2015, NOAA 2016). The value function transfer approach allows adjustments to be made in the explanatory variables, which results in a more fine-tuned representation of the target site. It also allows for the incorporation of information from a larger number of relevant studies while controlling for methodological differences across valuation studies (Bateman and Jones 2003). One shortcoming of the value transfer method is that the parameter estimates used in the value transfer come with statistical uncertainty. In light of this, we provide per unit values for blue carbon and non-carbon services separately, so that they can be used by planners to assess the costs of action plans relative to these two types of benefits. We carefully reviewed the meta-regression studies to avoid the double counting of blue carbon benefits.

Specifically, this study applies value function transfer for non-carbon benefits using Brander et al. (2006), adjusted to the context of the Narragansett Bay. Brander et al. (2006) captures the salient features of ecosystem services provided by salt marshes meta-analyses and includes variables to adjust for socioeconomic and geographical characteristics. We also conduct a sensitivity analysis using Brander et al. (2012) (Supplementary Material).

The value transfer function includes salt marsh area, geographic area, wetland type (freshwater marsh, salt/brackish marsh, mangrove), types of ecosystem services (biodiversity, amenity, recreational values), valuation methods, and socioeconomic variables of the study areas (median income and population density, Table S3). Where possible, values for variables were set according to available data for salt marshes in Narragansett Bay. For area coverage of salt marsh, we converted per hectare values to per acre values to match the 2010 baseline coverage estimates of salt marsh in Narragansett Bay used in the RI SLAMM. Median household income and mean population density for the State of RI were obtained from the U.S. Census (U.S. Census Bureau 2020). Relevant variables for which no regional data was available were set using mean estimates from the study's metadata.

The per acre value of non-carbon ecosystem services from Narragansett Bay salt marshes were obtained by aggregating the products of input values and coefficients and calculating the exponential value (Table S3, column 3). We convert economic values from each benefit transfer to 2010 US$ using the appropriate CPI to match the start year of the RI SLAMM, yielding an annual value estimate of $2,136/acre/year and $2,937/acre/year from Brander et al. (2006) and (2012), respectively. In addition to using the average of these two estimates for non-carbon ecosystem services, we use these values as the lower and upper bounds in the Monte Carlo simulations to test the sensitivity of our results to variability in our benefit transfer value.

Discounted value of total economic benefit and social discounting

Total economic benefit consists of two values summed over a 90-year time horizon for each of six scenarios: (1) the total value of carbon benefits, and (2) the total value of other services.[3] For each scenario, the combined value is discounted using a social discount rate to obtain the discounted value of total benefits resulting from 90 years of change in salt marsh coverage. Social discounting aims to incorporate the tradeoffs that society is willing to make between amounts that occur in different time periods (EPA 2010). While there are ongoing discussions about the appropriate rate of social discounting, we follow the recommendation of 3% for environmental analyses set by the U.S. EPA (2010).

Sensitivity analysis

Model specifications, underlying assumptions, and temporal scales are sources of uncertainty in marsh coverage predictions, yet estimation validation remains underexplored in existing current valuation studies of salt marshes. To test the integrity of results against variability and uncertainty, we perform Monte Carlo simulations, each with one million draws. Outcomes from these simulations yield a confidence interval around the estimated discounted stream of benefits. By replicating model predictions over the full range of parameter values, our analysis provides decision makers with more reliable information than using only the point estimates.

For each of the two marsh migration conditions considered (i.e., restricted and unrestricted), we test the robustness of our results to five parameters: (1) the probability of the three SLR scenarios, with higher probability weights on 3-ft and 5 ft scenarios reflecting recent predictions (NOAA 2017); (2) carbon sequestration potential; (3) methane emission rate; (4) non-carbon values; and (5) market prices for CO_2e (Table 2). These parameters are influential and important in our analysis and have a relatively high degree of variability and uncertainty. In each simulation run, each of the three possible SLR outcomes are assigned different probability weights (Table 2). Additionally, we run a separate Monte Carlo analysis for the 'combined' capability state for marsh migration. Finally, this study's long time horizon has intergenerational implications and, in such cases, the literature suggests using a time-declining discount rate (e.g., Arrow et al. 2013). In the Monte Carlo simulations, we test the sensitivity of our findings by applying a broad range of discount rates (between 1% and 20%).

Results

Salt marshes in the Narragansett Bay generate a significant economic value. We obtain a per-acre baseline value of $1,863 (in 2010 US Dollars) for blue carbon and $2,537 for non-carbon services, with a combined value of $4,400 per acre of salt marsh annually (Table 3).

Aggregated results suggest that all SLR scenarios lead to higher economic returns from the combined ecosystem services than the baseline scenario of no change in marsh acreage (Figure 2). The average total value of blue carbon across scenarios is $258 M, which is about 80% of the value derived from all other non-carbon services combined ($330 M). On average, the estimated combined carbon and non-carbon benefit exceeds the baseline of $518 M by +14% over the 90-year period, regardless of migration capacity. Overall, although these estimates are high, they are in line with some existing valuation studies. For example, a 2016 NOAA report estimated an added value of about $2.3 M for a modest change of 142 acres in New Hampshire's Great Bay Estuary (NOAA et al. 2016).

Notably, the total values across the three SLR scenarios exhibit opposite trends between the restricted and unrestricted conditions. This is an unsurprising result

Table 2. Parameter ranges and SLR probability weights for Monte Carlo simulations.

Panel A: SLR probability weights					
Sea Level Rise	Probability	Unrestricted		Restricted	
(ft)		2100 Marsh Acres	Annual Change	2100 Marsh Acres	Annual Change
1	10%	5,668.95	0.57%	5,187.15	0.43%
3	40%	5,754.75	0.59%	4,443.85	0.21%
5	50%	6,745.75	0.89%	3,950.25	0.06%
Panel B: Parameter ranges					
		Annual Sequestration Rate (tCO2e/acre/year)	Annual Methane Emission Rate (tCO2e/acre/year)	Value of Other Services (2010 $/acre)	RGGI Price (2010 $/tCO2e)
Lower bound		0.607	-0.040	$2,136.37	$2.24
Upper bound		3.036	-0.567	$2,937.31	$4.61

Note: See Table A6 for sources for parameter range. Year 2100 salt marsh acreages are derived from RI SLAMM.

Table 3. Per acre value of carbon and non-carbon services of salt marshes in the Narragansett Bay.

Value for salt marsh services (2010 $/acre)		
Carbon	**Other services**	**Total**
$1,863	$2,537	$4,400

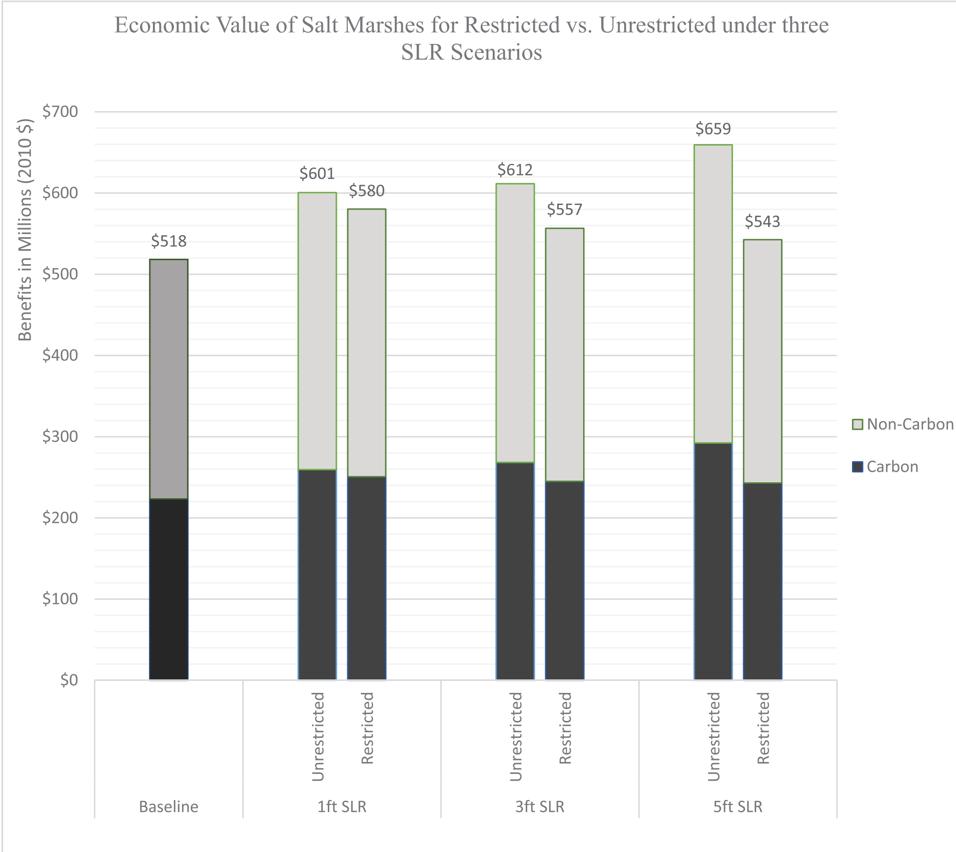

Figure 2. Total economic value of carbon and non-carbon salt marsh benefits by SLR scenario.

given that more marshes are expected to drown under restricted migration conditions. If inland colonization is impossible, the largest benefits occur under the lowest SLR scenario of 1-ft ($580 M). In the restricted 3-ft and 5-ft scenarios, total value estimates are $557 M and $543 M, respectively, reflecting a minimum difference of at least $25 M when compared to the no-change baseline. In contrast, when marshes are permitted to migrate without restriction, we find the largest discounted value of $659 M resulting from the 5-ft SLR scenario, representing an approximate $141 M (+27%) difference from the baseline. With unrestricted mobility, marsh coverage changes in the 1-ft and 3-ft SLR scenarios yield $83 M (+16%) to $94 M (+18%) more value compared to the constant acreage outcome, respectively. This equates to total estimated values of about $601 M and $612 M. In general, these trends suggest that future migration capabilities will play a critical role in determining economic benefits derived from salt marshes.

Although we observe high positive economic value for blue carbon and other services of salt marshes for the entire Narragansett Bay, the SLAMM predicts that at least two coastal communities—Narragansett, RI and Charlestown, RI—are likely to experience net negative changes in salt marsh area for both 3-ft and 5-ft SLR regardless of migration capacity. This negative net area change in the Town of Narragansett leads

Table 4. Total value of salt marshes under two migration scenarios for 5-ft SLR.

	Total value for salt marsh services at 5-ft SLR (in 2010$)					
	Restricted Scenario			Unrestricted Scenario		
	Carbon	Other Services	Total	Carbon	Other Services	Total
Narragansett Bay	$242,945,665	$299,712,445	$542,658,109	$292,367,863	$367,069,444	$659,437,307
Town of Charlestown	-$191,160	-$260,296	-$451,456	-$49,933	-$67,992	-$117,924
Town of Narragansett	-$315,619	-$429,768	-$745,387	-$96,884	-$131,924	-$228,808

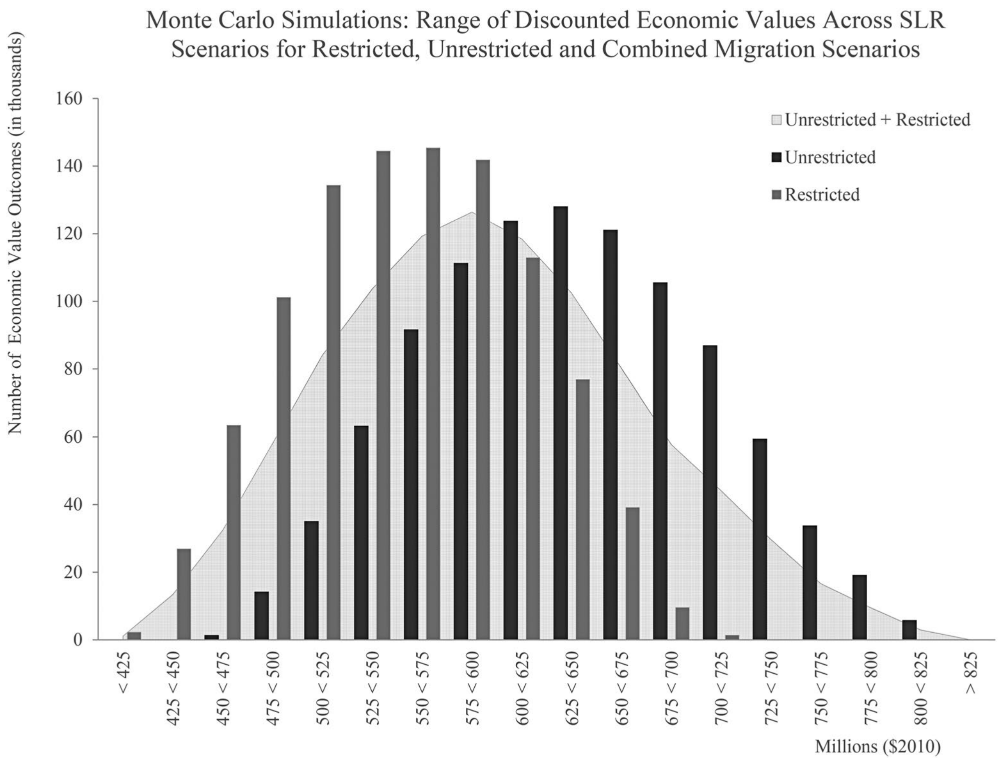

Figure 3. The distribution of discounted value of salt marsh benefits under restricted, unrestricted and combined conditions from Monte Carlo simulations.

to an economic loss greater than -$745,000 under restricted migration conditions and nearly -$229,000 with unrestricted mobility (Table 4). Similarly, for the Town of Charlestown, the loss of salt marsh coverage under a 5-ft SLR scenario leads to a loss of almost -$451,500 for the restricted mobility scenario and -$118,000 for the unrestricted mobility scenario.

The sensitivity analysis using Monte Carlo yields a wide range of total discounted value for the Narragansett Bay. The mean discounted value total is $637 M for the unrestricted scenario (standard deviation = $70 M) and $554 M for the restricted scenario (standard deviation = -$58 M, Figure 3). The total discounted value ranges between $459 M and $823 M for the unrestricted scenario and $413 and $555 M for the restricted scenario. Additional details are provided in Table S6. When we assume a combination of the two migration scenarios (restricted and unrestricted), we obtain

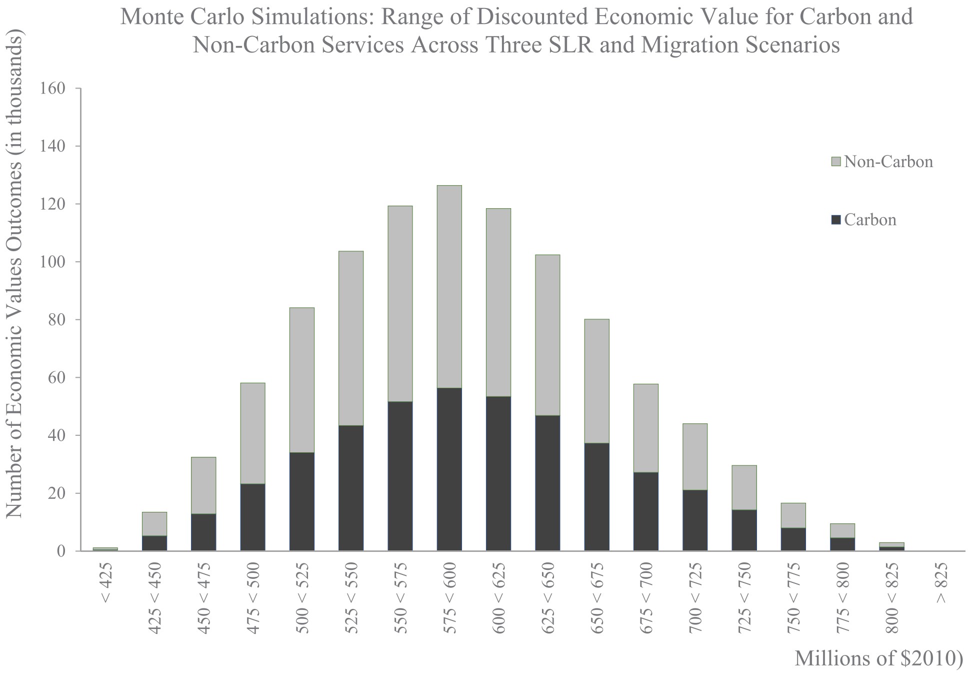

Figure 4 . Proportion of blue carbon versus other services in the frequency distribution of discounted value of salt marshes benefits in the combined conditions simulation.

a mean discounted value of approximately $596 M. The split between blue carbon and other services value is consistent with the baseline scenario at 45% for blue carbon and 55% for the other services (Figure 4). Our results also indicate that even with a high discount rate of 20%, the discounted value of benefits remains large, at $25 M over the 90-year time horizon, and becomes considerably larger at a discount rate of 1% ($1.3 billion, Figure 5).

Discussion

Given current limitations to the literature, this study aims to establish a much-needed foundation upon which to expand economic research of the ecosystem services provided by salt marshes in the Narragansett Bay when more site-specific data become available. While the specific projections based on RI SLAMM are subject to uncertainty, our results provide important indication that salt marsh habitats are uniquely valuable resources that contribute a rich array of critical services to Rhode Island's coastal economy. The per unit area values for carbon and non-carbon benefits demonstrate the potentially significant benefits offered by the active conservation preservation and/or restoration of the state's marsh habitats. Moreover, although the extent of total carbon at risk is both activity- and site-specific, our analysis demonstrates the significant CO_2 release potential of continued marsh loss and degradation in the Narragansett Bay. The magnitude of our estimated blue carbon value alone indicates that the preservation of these salt marshes is still an economically significant reason for policy action.

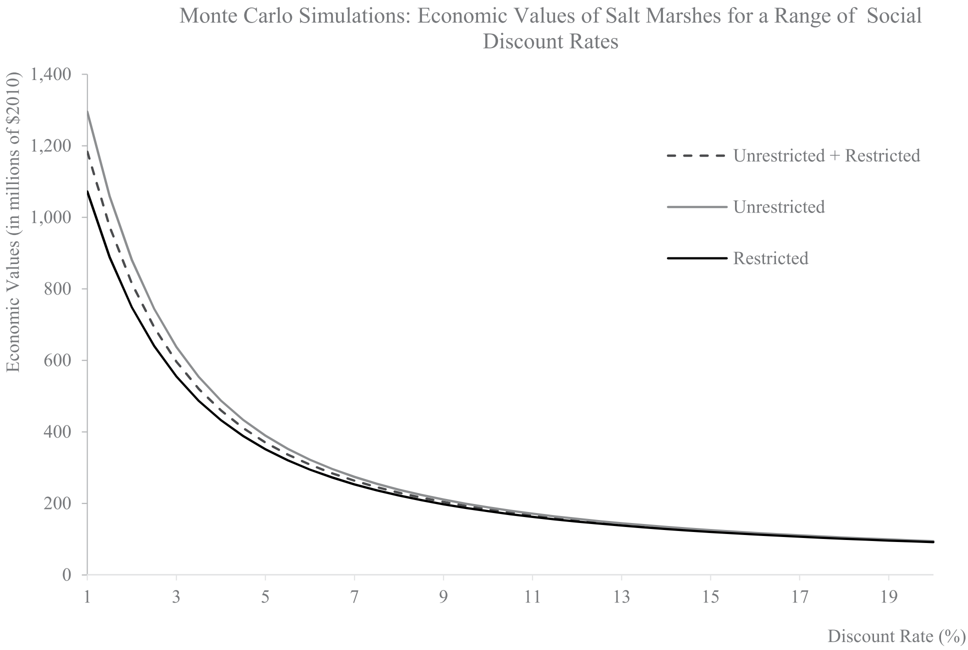

Figure 5. Discounted value of salt marsh benefits for varying levels of discount rate (in millions of 2010$).

The value differences between our restricted and unrestricted scenarios demonstrate the critical need for interventions that facilitate marsh adaptation to SLR and other changing environmental conditions. Ultimately, more extensive consideration of human-made infrastructure as impediments to critical habitat migration and survival will benefit the development of effective long-term coastal management plans. Future policy may therefore include more explicit conservation objectives, such as elevation enhancement initiatives and the prompt removal of, or modification to, impervious surfaces to assist inland marsh migration. As communities grapple with whether to protect current land uses or to allow marshes to migrate by removing barriers such as seawalls, bulkheads, levees, concrete and managed lawns, quantifiable information on the net economic benefit can be instrumental in decision making. Restoration strategies recently implemented in RI include the installation of "living" shoreline, or a natural substrate that stabilizes eroding marsh edges and/or the application of sand or sediment to assist in inland marsh transgression (Sharples et al. 2008; Smith 2013), and runnel (shallow channel) digging (Perry et al. 2021). Paved roads or lots, unused dams, and seawalls that restrict access and reduce sediment flow may also be removed to create additional opportunities for transition (Wigand et al. 2017). Finally, the avoidance of direct habitat conversion or removal is also important to ensure a net positive area scenario.

Moreover, the predictions from RI SLAMM underscore the importance of planning and coordinating coastal management at multiple scales. Despite a forecasted net gain for the entire Bay, the RI SLAMM predicts substantial losses of existing habitat across scenarios at a smaller spatial scale. Planning at the larger spatial scale (e.g., the Narragansett Bay) has the advantage that decision makers have more room to make tradeoffs, allowing for potentially more cost effective decisions (e.g., Roy et al. 2018); however, this can mask proportionally large losses of salt marshes and associated benefits at the local level (e.g., municipalities). Some non-carbon ecosystem services such as shoreline protection and fish habitat may also benefit from greater contiguity of salt marshes, which creates additional rationale for planning and coordination across municipalities and at multiple spatial scales.

As a mechanistic model, SLAMM has several notable limitations. The RI SLAMM incorporates widespread losses of the Bay's extant salt marsh due to SLR-related drowning, but does not consider other causes of loss. For instance, although it takes processes that vary both spatially and through time, such as accretion, sedimentation, and erosion, into account, it does not model the flow of water nor does it track and account for the movement of sediment (RI CRMC 2015). SLAMM also lacks important substrate data and assigns all undeveloped land with equal elevations and flooding frequencies, and the same probability of converting to marsh area when they become submerged by SLR (RI CRMC 2015). The consequence of this is that the output predicts a number of areas along the coast as being able to support salt marsh where none is currently present. Although marsh propagation in these places is plausible, the model may overestimate future marsh coverage (RI CRMC 2015).

Conclusion

This paper presents an integrated framework of economic valuation of salt marshes subject to rigorous sensitivity testing. Our approach uses site-specific land-cover change projections of future salt marsh abundance from RI SLAMM to obtain the combined economic value of both carbon and non-carbon ecosystem benefits over a time horizon of 90 years. The result is a decision-support resource that policy-makers and stakeholders may use to establish or improve feasible adaptation strategies for marsh conservation across coastal communities in the Narragansett Bay. The per-unit values for carbon and non-carbon benefits are applicable elsewhere in the New England region with similar types of population density and income levels.

These estimates equip stakeholders with greater means to incorporate salt marsh protection into coastal community resiliency plans by demonstrating the significant effects of extreme climate scenarios on potential future benefit values. Further, the results of our sensitivity analysis provide robust estimates that local planners can utilize in situations of uncertainty regarding future climate change and in contexts beyond the Narragansett Bay. An effective communication of ecosystem service benefits is another critical next step to ensure the future survival and resilience of coastal marshlands. Management initiatives could involve public outreach that raises awareness of coastal property owners about the value of salt marshes and how private construction, wastewater processing, and other land use decisions influence their future abundance and resiliency.

We highlight several opportunities for future research. In general, the spatial distribution of the marshes can be important for non-carbon services, both in biophysical and economic terms. For instance, changes to a salt marsh ecosystem and its services (e.g., fish habitat, water quality) may vary depending on the surrounding ecological and geomorphological conditions. The value derived from services may also depend on the demand for those services, reflecting the preferences of nearby communities.

Future studies in sites with more heterogeneity may examine the distributional impacts of the scenarios by constructing more spatially explicit scenarios and incorporating different community characteristics in their valuation.

Another important direction is to continue to improve the SLAMM model for more accurate predictions of future trends in salt marshes. The modeling approach may incorporate the flow of water, sediment and erosion, which influence salt marsh migration. Future SLAMMs may be further fine-tuned to identify which marsh habitats are at greatest risk as well as what areas are suitable candidates for restoration projects.

Notes

1. Although a small region of the Bay—about 68 km^2 (~18%) of its total 380 km^2 —extends into the bordering state of Massachusetts, we do not consider salt marsh coverage outside of the RI's portion of the Bay in this evaluation.
2. The RI CRMC uses the terms "unprotected" and "protected" in their report. We substitute these terms in our paper for ease of comprehension.
3. This approach assumes that carbon and all other benefits are strictly additive. Moreover, the meta-analysis models include categories of services as dummy variables. This implies that the willingness-to-pay for one service is a fixed scalar transformation of another service, which is a strong assumption (Bergstrom and Taylor 2006). Although these are conventional approaches in value transfer, we acknowledge that these limitations extend to our study.

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