The Case for and Against Phragmites australis: An Ecosystem Service Cost-Benefit Analysis for Chesapeake Bay Marshes

Elliott Campbell

elliott.cambell@maryland.gov

Maryland Department of Natural Resources

Anthony Campbell

Goddard Space Flight Center

Research Article

Keywords: Phragmites australis, Ecosystem Services, Cost-Benefit, Carbon Sequestration, Nitrogen, Wildlife Habitat

Posted Date: September 30th, 2025

DOI: https://doi.org/10.21203/rs.3.rs-7621664/v1

Additional Declarations: No competing interests reported.

Version of Record: A version of this preprint was published at Wetlands Ecology and Management on March 12th, 2026. See the published version at https://doi.org/10.1007/s11273-026-10120-4.

Abstract

Invasive species are a global issue, occurring virtually everywhere there is a significant human population. It is typically assumed that these invasive species are less preferential to the uninvaded native habitats that they invade and sometimes replace and should be extirpated. This assumption is often made *a priori* to scientific investigation. This work tests that assumption by analyzing the grass *Phragmites australis*, invasive to Chesapeake Bay coastal wetlands, using ecosystem service valuation. We review the literature and analyze published data to estimate the range of carbon sequestration, nitrogen removal, and wildlife habitat that can be expected in a Chesapeake Bay marsh dominated by *Phragmites australis* and a marsh characterized by typically observed high marsh species. *Phragmites* dominated marsh was found to differ from native high marsh (characterized by species such as *Spartina patens*, *Scripus oleneyi*, and *Distichlis spicata)* in the quantity of ecosystem services provided, with *Phragmites* providing greater carbon sequestration and native high marsh having greater nitrogen removal and wildlife habitat quality. The two systems under median conditions were found to provide very similar economic value, with native high marsh providing greater value under optimal conditions for both systems. An analysis considering the net present value of control costs and ecosystem service value indicates that it is not a net economic benefit to control for Phragmites, unless the cost is low to moderate and the benefit is high, i.e. the system is able to maintain or return to optimal wildlife habitat. These results can be used to inform land management decisions in the Chesapeake Bay region.

Introduction

Phragmites australis is the most commonly observed non-native invasive species in tidal marshes throughout the Chesapeake Bay region and is a common invader throughout North American wetlands, spreading dramatically over the past 150 years as a cryptic invader (Saltonstall, 2002, McCormick et al. 2010a, Saltonstall and Meyerson, 2016). *Phragmites australis*, or the common reed, is a large form grass, growing up to 5 meters in height and often forms near monotypic stands, spreading both through seed and rhizomes (Engolener 2009). It is likely one of the most common wetland species globally, occurring on 6 continents with the exception of Antarctica (Tucker 1990; Canavan et al. 2018), and is one of the most studied plant species; the subject of over 35,000 publications since 2010 (Google Scholar search results for *"Phragmites australis"*). It thrives in a variety of conditions, having been observed to thrive in both high and low nutrient (Cott et al. 2018), wave energy (Casahalo et al. 2023), disturbance (Minchinton and Bertness 2003, Baldwin et al. 2010), temperature, and salinity conditions (Sheng et al. 2024). Contributing to this plasticity is that *Phragmites* is a C3-C4 intermediate, although preferentially uses the C4 photosynthetic pathway (Srivastava. 2014), and that the plant typically forms near monotypic stands with a thick rhizome mat (Ketterinig 2010).

In North America two native species of *Phragmites* occur, *Phragmites australis subspecies americanus*, a native haplotype, known to present throughout the United States and Canada and *Phragmites australis var. Berlandieri*, found in the American south and Mexico, both present for at least 40,000 years (Saltonstall 2002). *Phragmites australis* (hereafter referred to as "*Phragmites*") originated in the Middle

East (ibid.) and was likely introduced to North America in the early to mid-19th century. The first confirmed collection of non-native *Phragmites australis* was made in 1883 in Chesapeake Beach, Maryland (US National Herbarium collections, Saltonstall 2002). By 1960 non-native *Phragmites* had become prevalent throughout North America, and has become particularly dominant on the East Coast and Great Lakes regions of the United States while the native subspecies is relatively rare (Mozdzer et al. 2013). Historic observations indicate that the native subspecies was never a dominant component of wetland marsh species assemblages (ibid.). Currently the vast majority of Phragmites observed in the Chesapeake Bay region is the non-native variety, with Tulbure et al. (2012) finding only 14 of 212 patches (~ 7%) sampled to be *Phragmites australis sub. americanus*, verified through genetic analysis. The subspecies can be distinguished by morphological differences observed in the field, in some cases, (i.e. height, stem density, adherence of leaf sheaths, culm color/fungal presence) or in the lab (i.e. measurement of ligule and glumes), but genetic testing may be necessary for identification given that hybridization is possible and that there are multiple sublineages (Meyerson et al. 2010, Mozdzer et al. 2013, Williams et al. 2019).

Similarly to many invasive species, occurrence of *Phragmites australis* is often associated with human disturbance (McCormick et al. 2010b, McCormick et al. 2020). Humans are often the vector for transporting the species, but also typically create conditions that facilitate the spread and dominance of non-native species. It is theorized that this has occurred in the case of *Phragmites australis*, which thrives in disturbed coastal areas, and in high nutrient conditions, common in highly urbanized or agriculturally dominated watersheds (Chambers et al. 2008, Sciance et al. 2016). Kettering et al. (2012) found significant variability in sublineages of introduced *Phragmites* and their ecological impact across North America, with the “short b” variant present in the Chesapeake Bay region found to be the most invasive. *Phragmites* is considered one of the most significant issues for wetland land managers in the Chesapeake Bay region, often targeted for removal (MD DNR 2025, Chesapeake Bay Program 2003). It is notoriously difficult to successfully eliminate, often requiring repeated herbicide spraying over multiple years. Landscape level elimination has proven not to be successful (Martin et al. 2013, Quirion et al. 2018), but small patches in areas with low abundance likely can be controlled (Hazelton et al. 2014, Rohal et al. 2022, Brooks et al. 2024).

In the Chesapeake Bay, a *Phragmites* dominated wetland has different characteristics than a native high marsh, which typically includes species such as *Spartina patens*, *Scripus oleneyi*, and *Distichlis spicata* (these high marsh species are most common in the mesohaline and polyhaline portions of the Chesapeake Bay, tidal fresh and oligohaline high marsh can be much more diverse), with altered wetland functions and associated ecosystem services, or benefits to people. It is typically assumed in the field of invasion ecology or biology that an invaded ecosystem is less preferential, i.e. beneficial, than a native ecosystem, due to decreased ecosystem function and supported diversity in flora and fauna (Correa et al. 2021, Renault et al. 2022). However, this *a priori* assumption has been controversial, with criticism (Guiaşu and Tindale 2018, Sagoff 2018, Sagoff 2019,) support (Ricciardi and Ryan 2018, Warren et al. 2017) and attempts at reconciliation (Cassini 2020, Guareschi et al. 2024) in the literature. For environmental land management, invasive species are almost universally viewed as a negative and framed in this way when communicating to the public and among peers.

This paper examines the assumption that invasive species create a system that is less beneficial to people by conducting an ecosystem function and service assessment comparing a hectare of *Phragmites* marsh to a hectare of native high marsh typical to the Chesapeake Bay region. The results from this analysis are combined with the predicted cost to eliminate *Phragmites* from 1 ha of marsh to estimate the cost-benefit of controlling *Phragmites* in Chesapeake Bay wetlands. Cost-benefit analysis has been suggested as a useful framework for assessing invasive species control (Courtois et al. 2018, Blaalid et al. 2021) and has been applied to specific invasive species, such as the Canada goose in northern Belgium (Reyns et al. 2018), invasive vegetation in the western United States (Munson et al. 2020), and invasive aquatic plants in Florida (Wainger et al. 2018, Weber et al. 2020). However, these approaches typically account for the cost for control and the benefits of the native species, relatively few of these approaches account for the economic benefits of the invaded ecosystem (Hanley and Roberts 2019, Boltozsky et al. 2022). Prior work examining the ecosystem services provided by *Phragmites* include Čížková et al. (2023), focusing on European *Phragmites* marshes and their use for bioenergy, reed materials, hunting, grazing, and fish farming. The work notes techniques for restoring systems to *Phragmites* dominated systems. Kivat (2013) evaluated ecosystem services of invasive *Phragmites* in North America, concluding that it provides valuable services and functions for both humans and other organisms. We provide a data driven approach to informing environmental land management of the Chesapeake Bay's coastal wetlands.

Methods

The review focused on seven ecosystem services: carbon sequestration, methane emissions, nitrogen utilization and removal, other pollutant removal, wave attenuation/storm surge reduction, marsh resilience to loss, and wildlife habitat. We compared these services for the native high marsh and *Phragmites* marsh- by reviewing the literature and synthesizing relevant past studies. It was determined that three of these (carbon sequestration, nitrogen utilization and removal, and wildlife habitat) had sufficient data available to quantify the ecological function and monetary ecosystem service value for native high marsh and *Phragmites* in the Chesapeake Bay region. Landscape context is highly influential on *Phragmites* occurrence and native marsh type, along with ecological function and resulting ecosystem service provision. To reflect this, we present results in the form of low, median, and high to reflect the expected range, roughly corresponding to a normal distribution of observations found in existing data. In order to assess these ecosystem services, the literature was reviewed and synthesized with a focus on work in the Chesapeake Bay region. To perform this review the Google Scholar search engine was prompted with “*Phragmites australis*” combined with the following terms sequentially; “ carbon sequestration”; “methane emissions”; “sea level rise”; “nitrogen utilization"”; “phytoremediation”; “wildlife habitat”; “biodiversity”; “ecosystem services”; “ecology”; “invasion”; and “control”.

Carbon Sequestration

Phargmites australis is extraordinary among marsh plants in its growth, having been observed exceeding rates of 20 mt of carbon per ha per year (Silan et al. 2024, Wang et al. 2022), a rate rivaling that of forests in their most productive age class (Hoover et al. 2021). However, there is a large range in sequestration observations found in the scientific literature, with nitrogen availability being an influential factor (Caplan et al. 2015). Silan et al. (2024) applied a model estimating *Phragmites* production under different growth conditions and assumptions for the percentage of net primary production entering long term storage (i.e. carbon sequestration). They found a minimum of 2.7 tonnes C ha-1 and a maximum of 25.6 tonnes C ha-1, with an average of 14.38 tonnes of annual sequestration. Many factors influence the percentage of NPP that enters long term storage, e.g. climate conditions, lateral flux and export, herbivory, and periodic disturbance. Prior work suggests the range for percent of NPP entering long term carbon storage in the marsh sediment averages 24% for global coastal marshes (Algoni 2020), but regional work suggest the rate is approximately 33% for marshes in the Chesapeake Bay region (Hermann et al. 2015, Najar et al. 2018), and there is some support for *P. australis* having higher than average rates of carbon sequestration, attributed to forming thick rhizome mats and having persistent stalks (Gu et al. 2020). There is growing evidence that lateral flux of carbon to adjacent waterbodies can be a significant component of carbon sequestration (Wang et al. 2016, Rethmair et al. 2023, Song et al. 2023). This flux has high temporal and spatial variability (Santos et al. 2021, Li-Shan 2020), so we present estimates with and without this pathway. Here we present a likely range for carbon sequestration in the Chesapeake Bay region derived from aboveground and belowground biomass data for *Phragmites* and native species (predominately Scirpus olneyi; Spartina patens; and Distichlis spicata) collected at the Smithsonian Environmental Research Center's Global Change Research Wetland (Modzer et al. 2025). The economic value estimate for carbon sequestration is taken from the US EPA's 2023 report on the social cost of carbon (USEPA 2023).

Methane Emissions

When considering the ecosystem service of climate mitigation it can be important to include emissions of greenhouse gases in addition to net CO2 removal from the atmosphere, with methane being the primary GHG emitted from wetlands (Poffenbarger et al. 2011, Holmquist et al. 2018, Arias-Ortiz et al. 2024). Evidence of *Phragmites* invasion impacting methane emissions is mixed, with some results indicating an increase in invaded marsh relative to native marshes (Neubauer and Megonigal 2015; Martin and Moseman-Valtierra 2015), and others a decrease or neutral effect (Yarwood et al. 2016), with Mueller et al. (2016) concluding that innate properties of soil are more influential on methane than the plant community type. Given this mixed evidence and ability of *Phragmites* to exist in a wide range of salinity regimes, methane emissions were not included in the ecosystem service valuation calculations.

Nitrogen Utilization and Removal

Phragmites continues to utilize nitrogen at high loading rates (Chlot 2015, Milke et al. 2020), contributing to its common use for phytoremediation (Rodriguez and Brisson, 2015, Ngyuen et al. 2017, Milke et al. 2020). Nitrogen removal is a particularly important service in the Chesapeake Bay region, as the Chesapeake Bay is often eutrophic with excess nutrients causing issues such as hypoxia. Nitrogen utilization is correlated with primary production, as the primary pathway of nitrogen use is plant growth, but much of this nitrogen eventually reenters the system as plant matter decays. Denitrification by bacteria in marsh soils is a more permanent removal pathway (Cornwell et al. 1999, Martínez-Espinosa et al. 2021). In natural systems the rate of nitrogen utilization and denitrification in wetland soils is highly variable (CBP 2019), varying with factors such as inundation frequency, salinity, plant community, and soil chemistry. High nutrient levels in soil likely facilitates *Phragmites* invasion in certain native systems (Farnsworth and Meyerson, 2003, Kettering et al. 2011, Uddin and Robinson, 2018, Saltonstall and Stevenson, 2007, Piehler and Yacono 2019), with *Phragmites* having been shown to sequester higher nitrogen content in biomass (Farnsworth and Meyerson 2003, Findlay et al. 2003). However, some native species have been shown to be more effective than *Phragmites* in utilizing nitrogen (Cott et al. 2018 and 2020). Additionally, nutrient loading is often confounded with disturbance rates and urbanization (Kettering et al. 2011). Here we assume *Phragmites* and native marsh to provide very similar nutrient removal, and derive the rate for the median values for native marsh from a literature review conducted by the Chesapeake Bay Program Expert Panel on Shoreline Stabilization (CBP 2019) and *Phragmites* low, median, and high estimates from Lopez et al. (2016) and Geurts et al. (2020) that performed experiments observing *Phragmites* nitrogen utilization. The high estimate for native marsh is derived from Cotts et al. (2018) who showed that certain native species (i.e. *Spartina patens*) were able to utilize very high rates of nitrogen in elevated conditions. A caveat to this value is that it is unknown how often native marsh of this type is exposed to very high nitrogen conditions. The economic value is taken from Campbell et al. (2020) estimate for nitrogen removal and updated to 2024 dollars.

Other Pollutant Attenuation

Phragmites has been shown to be effective at removing heavy metals in a treatment wetland context, with Ngyuen et al. (2017) demonstrating its effectiveness in treating iron mine drainage. Many studies (Kleche et al. 2018, Rezania et al. 2018, Milke et al. 2020, Tlili et al. 2023), have reviewed its effectiveness in wastewater treatment with the conclusion it is an effective species for this application due to its ability to remove a wide variety of pollutants and tolerate a wide conditions. This service is not included in the analysis because it is uncertain where and how frequently on the landscape of the Chesapeake Bay marshes are exposed to these pollutants.

Wave Attenuation/Storm Surge Reduction

Phragmites has traits which contribute to reducing wave energy and storm surge, such as large, thick stems which grow close together (Engolener 2009). Prior studies show that *Phragmites* does significantly reduce wave energy and storm surge (Casahalo et al. 2023), but studies differ on if the reduction provided by *Phragmites* marsh is more or less than native marsh, with some evidence that *Phragmites* provides more reduction for large waves but similar reduction for medium and small waves (Sheng et al. 2021, Coleman et al. 2022, Cashallo et al. 2023). Based on this evidence, the ecosystem service value is assumed to be the same for both marsh types. The economic value of marsh related to reduction of damages associated with large storms has been assessed in prior studies (Costanza et al. 2008, Narayan et al. 2017, Rezaie et al. 2020, Sheng et al. 2021,Al-Attabi et al. 2023, Taylor-Burns et al. 2024), with highly variable results based on the chosen methodology and region being analyzed (~$185 - $8240 per ha of marsh per year from these selected studies). Given the large range of values and lack of distinction between the ecosystems this service is not included in the comparison presented here.

Marsh Resilience to Loss

Marsh loss to erosion and sea level rise is a growing issue in the Chesapeake Bay region (Kirwan et al. 2016, Mitchell et al. 2017, Mitchell et al. 2020) that experiences some of the highest rates of relative sea level rise globally (Boesh et al. 2024). *Phragmites* has an uncertain impact on marsh erosion and the ability of marshes to keep up with sea level rise through sediment accretion, but identifying the specific role of the species is difficult given the many factors at play (Kirwan et al. 2025). Studies have found that *Phragmites* has higher than average accretion rates (Rooth and Stevenson, 2000, Weis et al. 2021), but may function as a barrier to migration of native species landward with sea level rise (Smith 2013). *Phragmites* is typically the first wetland species to colonize previous uplands (often coastal forests in the Chesapeake Bay region) as sea level rises (Shaw and Gedan, 2022, Xiong et al. 2024), making understanding its role an important direction for future research. Given the uncertainty and lack of direct comparison between ecosystems marsh resilience to loss was not included in the comparison presented here.

Wildlife Habitat

The decline in habitat quality is almost universally cited as the primary concern related to invasion of *Phragmites* into native marsh. However, when this conclusion is examined it is not clear that *Phragmites* provides low quality habitat for wildlife. When comparing *Phragmites australis* to the native subspecies (*P. australis americanus*) they support very similar microbial, macroinvertebrate, and vertebrate communities and have similar co-occurring plant species in North America and native range (Kivat 2019). *Phragmites australis* invasion has been found to have minimal to no effect on the soil microbial community (Gulis et al. 2006, Song et al. 2014), fish community (Warren et al. 2001), mammal community (Kivat 2011), and amphibian community (Meyer 2003, Tozier and Mackenzie 2019). *Phragmites australis* stands do have lower plant diversity than native high marsh, but do not form monoculture at scales above the individual 1 m^2 plot (Keller 2000, Meyerson et al. 2000). Studies show that *Phragmites* supports an avian community that is similar in species abundance, but lower in overall richness and is different from the native marsh community (Kivat 2011, Lupian and Lavoie 2014). It has been found to provide critical habitat for some nesting wading birds (Parsons 2003).

An important management consideration is that certain species of conservation concern that are dependent on high marsh such as the salt marsh sparrow, willets, and rails, do not prefer *Phragmites* as a habitat and are thought to not nest in *Phragmites* (Benoit and Askins 1999, Meiman et al. 2012, Wiest et al. 2018). Loss of native high marsh to *Phragmites* invasion (along with other loss drivers, sea level rise being the primary concern but also coastal development) is contributing to the decline of these species in the Chesapeake Bay region (Coreel et al. 2017, Hartley, and Weldon 2020). Campbell et al. (2020) created the Wildlife Habitat and Biodiversity Potential Index for Maryland using mapped occurrences of rare species,habitat types (MD DNR 2016), and habitat connectivity (MD DNR 2024). The index was related to the economic value of acquiring land for the primary purpose of wildlife conservation. The overlap of *Phragmites* shoreline occurrence data (VIMS 2024) and the DNR wildlife index was calculated with spatial selection in ArcMap 10.8. The stats package in R version 4.1.2 was used to test the effect of *Phragmites* occurrence on the wildlife indicator. It was assumed that the relationship between habitat quality and *Phragmites* occurrence would hold true for marshes in the Virginia portion of the Chesapeake Bay.

Phragmites Control

Phragmites is a notoriously difficult to control invasive species. Employed methods of control include repeated application of herbicide, typically glyphosate, mechanical removal, and smothering (Rohal et al. 2019). Biological control through grazing has been suggested as an alternative to chemical control (Brundage 2010), but this is not commonly practiced. Studies indicate that control of *Phragmites* is more likely at a small scale (Quirion et al. 2018) and with repeated management (Rohal et al. 2019, Hazelton et al. 2018, Brooks et al. 2024), but large scale regional elimination of *Phragmites* is not seen as a feasible goal (Martin and Blossey 2013). Both landscape and site specific factors influence probability of successfully controlling *Phragmites* and reestablishing a native high marsh, with watershed land use and local site hydrology both influential (Rohal et al. 2019, Rohal et al. 2023). We include costs for *Phragmites* control based on personal communication with DNR biologists who regularly contract for and perform this service (Pers. Comm. 2024). Based on the literature and the experience of DNR biologists it is assumed that in low *Phragmites* pressure, i.e., optimal conditions, one year of control efforts can successfully control *Phragmites*, in conditions with median *Phragmites* pressure control efforts would need to be repeated every 10 years, and in conditions with high *Phragmites* pressure control efforts would need to be repeated every 5 years, for the purposes of calculating the net cost-benefit across this spectrum. Net present value (NPV) is not an ideal economic tool, particularly when applied to ecosystem services (Costanza et al. 2021), but is utilized here for scenario comparison with the specific monetary value being less important for influencing the management decision whether or not to control for *Phragmites* than the relative difference between scenarios.

Results

Ecosystem Service Quantification and Valuation

In total ecosystem service value was found to be very similar between native high marsh and *Phragmites* dominated marsh, with *Phragmites* having a slightly higher median value, \$6,201 ha^{-1} yr^{-1} compared to \$5,827 ha^{-1} yr^{-1} for native high marsh. However, the high end of the range for native high marsh exceeds that of *Phragmites*, at \$10,140 ha^{-1} yr^{-1} compared to \$8,748 ha^{-1} yr^{-1}. These results indicate that in optimal conditions native high marsh would be providing more benefit in processing nitrogen and providing wildlife habitat relative to *Phragmites*, but *Phragmites* sequesters significantly more carbon.

Table 1
Ecosystem Services, 1 ha native high marsh species

	Unit	**Low Estimate**	**Median Value**	**High Estimate**	**Economic Value, \$ per unit**	**Median Economic Value**	**Likely Range**
Carbon sequestration	Mt CO_2e ha^{-1} yr^{-1}	1.4	5.11	7.7	\$ 204	\$1,042	\$ 286-\$1571
Nitrogen Processing	kg N, ha^{-1} yr^{-1}	95	120	261	\$ 24	\$2,880	\$ 2280–6283
Wildlife Habitat	Index	1	2	3	5 is max index value = \$3811 ha^{-1} yr^{-1}	\$1,905	1524–2286
					Total	\$5,827	\$4090–10140

Table 2
Ecosystem Services, 1 ha Phragmites australis

	Unit	Low Estimate	Median Value	High Estimate	Economic Value, $ per unit	Median Economic Value	Likely Range
Carbon sequestration	Mt CO2e ha^{-1} yr^{-1}	7.33	14	22	$ 204	$2,856	$1495–4488
Nitrogen Processing	kg N, ha^{-1} yr^{-1}	81	108	114	$ 24	$2,592	$ 1944–2736
Wildlife Habitat	Index	1	1	2	5 is max index value = $3811 ha^{-1} yr^{-1}	$762	$ 762–1524
					Total	$6,210	$4,201-8,748

Carbon Sequestration

Carbon sequestration values for *Phragmites australis* ranged from 7.33 to 22 Mt CO^2e per ha per year based on observations of aboveground and belowground net primary production made over 28 years of field data collection at the Smithsonian Environmental Research Center’s Global Change Research Wetland (GCRW) (Drake et al. 2025, Mozdzer et al. 2025) and the assumption of 33% carbon sequestered (only burial of carbon in sediments) or 50% (33% carbon burial and 17% lateral flux that enters long term storage). The same assumptions for carbon fate was applied to the GCRW data for native high marsh species NPP (see supplemental materials for full calculations).

Nitrogen Utilization and Removal

While literature values for rates of nitrogen utilization and denitrication in tidal wetlands are highly variable (CBP 2019, Cott et al. 2019) the median rate for native high marsh and *Phragmites* was found to be similar, at 120 and 108 kg ha^{-1} yr^{-1}, respectively. A broader range of values was found for the native high marsh compared to *Phragmites*, resultingly the high estimate for native high marsh is more than double that of *Phragmites*, at 261 compared to 114 kg ha^{-1} yr^{-1}.

Wildlife Habitat

The Wildlife Habitat and Biodiversity Index (Campbell et al. 2020) was evaluated for wetlands with *Phragmites* and those without for the Chesapeake Bay. Coastal marshes were found to be some of the most valuable habitat types in Maryland (Campbell et al. 2020). The median value for both classes was 5 with 81% of the native high marsh and 68% of the *Phragmites* dominated marsh within this category. The distributions of wildlife habitat and biodiversity index significantly differed when comparing the two classes with Chi-Square test X^2 (4, n = 1,012,738) = 16752, $p < 0.001$. To capture this variability in our analysis we examined the data by 5% quantiles to find where the habitats differed. Native high marsh had a value of 3 and 4 for the 10% and 15% quantiles, respectively. While *Phragmites* had values of 2 and 3 for those same quantiles. Therefore, these values were utilized as our low and medium values. While the GIS analysis indicated both native high marsh and *Phragmites* would have high values of 5 we adjusted the *Phragmites* high to be a 4 based on the extensive literature documentation of *Phragmites* not being suitable habitat for certain priority species (Benoit and Askins 1999, Meiman et al. 2012, Wiest et al. 2018).

Other Services

Given the literature evidence *Phragmites* is possibly superior to native high marsh in wave attenuation and storm surge reduction, pollutant removal (other than nitrogen), methane emissions, and resilience to marsh loss. However, prior studies were mixed in their evidence and the economic value of these services was deemed too uncertain to be applied to the Chesapeake Bay region.

Cost-Benefit for *Phragmites* Control

The cost of controlling Phragmites was estimated to be \$150 acre^{-1} (~\$370 ha^{-1}) for aerial application of herbicides, \$500 acre^{-1} (~\$1240 ha^{-1}) for hand application of herbicides from personnel communication with MD DNR staff. Total costs for successful control were estimated at \$1000 - \$2000 acre^{-1} (\$2500-\$5000 ha^{-1}) with a median estimate of \$3000 ha^{-1}. Using our median ecosystem service value (\$ yr^{-1}) control for *Phragmites* would not be cost effective. In our calculations, we assume the site conditions will produce similar results in the range of value for carbon and nitrogen benefits between the two communities. We estimate the maximum potential net benefit for *Phragmites* control to be \$761 ha^{-1} yr^{-1} based on the difference between the mid point estimates for carbon and nitrogen and the difference between optimal native high marsh habitat (index rank 5) and minimal value *Phragmites* marsh (Table 1 and Table 2). This is assumed to be an optimistic outcome for control; prior research shows it is unlikely target native species recover after control actions (Rohal et al. 2023). This optimistic scenario coupled with high control effort results in a negative or very slightly positive net present value (NPV) over a 25 year time period (Fig. 4), low effort and medium effort control exhibit a positive NPV over the three presented discount rates. High effort control is a clear cost-benefit breakpoint and it is more cost effective to take no action. We suggest that future decision support tools be developed to identify *Phragmites* invaded marshes where low or medium efforts control is likely to be successful. Potentially influential site characteristics to consider are elevation, extent *Phagmites*, salinity, historic change, sea level rise, and wildlife habitat.

Discussion

This work finds that, on average, native high marsh in the Chesapeake Bay provide a similar, but slightly lower, ecosystem service value than *Phragmites* marsh when measured through non-market economic metrics. The specific services of carbon sequestration are likely to be higher in *Phragmites* dominated marshes and native high marsh likely provides greater nitrogen removal and wildlife habitat services. The range of values was found to be greater in native high marsh than in *Phragmites*, to be expected given that we included multiple different species assemblages in the native high marsh category. The range of values is expected to vary geographically, and there are likely areas of the Chesapeake Bay region where a *Phragmites* marsh provides greater ecosystem service value than native high marsh species. This finding is particularly important in the Chesapeake Bay region as *Phragmites* is considered to be the primary invasive species of concern in coastal wetlands with land managers spending $4.6 million per year across the United States (Martin and Blossey, 2013) and the Maryland DNR spends thousands of dollars every year on management actions on state lands and restoration projects.

Management Implications

The results of this study have implications for land management decisions.The potential for ecosystem service value to be higher for *Phragmites* than some native high marsh, the cost associated with *Phragmites* control and the uncertainty of long term success of those control measures indicates that *Phragmites* control actions are not likely to be optimal in all situations, from an economic perspective. In certain cases the goals of the land management entity will recommend controlling for *Phragmites* as a general rule, regardless of the economic cost-benefit (e.g. a wetland with known occurrence of certain bird species), but in many other instances it would be beneficial to apply these criteria to the decision whether or not to recommend attempting *Phragmites* removal. For instance, the Maryland DNR currently requires controlling *Phragmites* on lands under conservation easement, in some cases that may not be consistent with the goals of the easement or feasible given the landscape context. Given that the median value for *Phragmites* ecosystem services was found to be higher than the median value for native high marsh, this would indicate that controlling for *Phragmites* would typically not provide an economic benefit. In an area where the value of wildlife habitat ranked the highest, controlling for *Phragmites* does provide a net economic benefit when analyzed over 25 years, if the management effort required is low or medium. A situation requiring high effort, repeating control every 5 years, did not provide a net economic benefit unless there was not a discount rate applied to the future costs and ecosystem service benefits. Future work is necessary to apply these results by spatially analyzing the factors contributing to the likely degree of effort necessary for control and the areas of high priority marsh to suggest areas where control should be prioritized.

A spatial decision tool could help public and private landowners in assessing whether or not controlling for *Phragmites* is 1) feasible given the level of Phragmites abundance and urbanization in the watershed/adjacent shoreline and 2) likely to be a net ecosystem service benefit, considering habitat suitability for target wildlife species. Adjusting governmental policy around requiring *Phragmites* control only in areas with optimal benefits to wildlife and with a reasonable probability of success would allow limited resources to be used more effectively.

Future work to better understand the response of *Phragmites* in conjunction with other species, in the context of the elevation continuum of the coastal ecosystem, will likely be influential in best management practices for these systems. As presented earlier, *Phragmites* appears likely to be better equipped to keep up with sea level rise than other marsh systems, but also may present an impediment to landward migration of other marsh types. A better understanding of landscape level marsh vulnerability and the potential for *Phragmites* to reduce or enhance it would likely influence how land managers approach managing the *Phragmites*. A *Phragmites* marsh is undoubtedly preferable to marsh loss, if that is a binary choice given contemporary observations and future projections of sea level rise.

Other Ecosystem Services

This study is not comprehensive in terms of assessing all ecosystem services associated with coastal wetlands in the Chesapeake Bay region. The additional ecosystem services discussed in the literature review (other pollutant attenuation, marsh loss, and wave attenuation/storm surge reduction) to those that were quantified are likely to be greater for *Phragmites*, but there is evidence that *Phragmites* may have some harmful economic impacts. One study (Isley et al. 2017) found that *Phragmites* occurrence decreased home values, and that there would be a significant economic benefit from removing it from properties. This benefit was associated with the improved view of local water bodies. Anecdotal impacts reported in the grey literature include *Phragmites* not being preferential for hunting or recreational water craft access due to its density impeding navigation, possible increased risk of wildfire due to its tendency to retain aboveground biomass post-growing season, possible risk of road hazards due to its large growth form, and crop shading in agricultural fields, again due to its large growth form. While these impacts bear additional investigation, native species of a similar growth form, such as *Typha spp.* or *Phragmites australis subsp. americanus*, would create the same or very similar issues as the non-native *Phragmites*.

Uncertainty

This study did not calculate the uncertainty associated with the ecosystem functions, GIS analysis, or economic values presented here, but we acknowledge that all elements presented here are uncertain, and uncertainty would undoubtedly be significant if calculated. That said, we believe the values presented here to be representative of the current best state of knowledge and useful to inform decision making.

Implications for Other Invasive Species

While assessing ecosystem service costs and benefits associated with invasive species and their control has been suggested as a useful framework for informing decision making (Courtois et al. 2018, Blaalid et al. 2021), it has been rarely applied. *Phragmites* is an ideal case study for this approach because it has been the subject of extensive scientific study, it has a cosmopolitan distribution, its perception as a great threat to native species and ecological functioning, and the failure of controlling its spread in the region, despite a long history of attempts (Hazelton et al. 2014). A similar approach could be taken in assessing species such as the invasive plant *Hydrilla verticillata* or mollusk *Dreissena polymorpha* in the freshwater aquatic environment of much of the United States or, what is essentially the inverse of this study, the invasion of *Spartina alterniflora* into *Phragmites* marsh that is being experienced in China (Nie 2023). Ideally the subject of this type of analysis would be species with abundant existing literature and a situation where there are both positive and negative impacts of the invasion that can be quantified and economically valued.

Conclusion

Spread of invasive species is typically considered to be a negative for ecosystem functioning, biodiversity, and people, *a priori*. This work shows that objective analysis of ecosystem functioning and economic value resulting from changes in that function can be applied to an invasive species to help guide decisions on how that invasive species should be managed. Given these results a definitive conclusion that can be applied to all cases cannot be made, but we recommend that landscape factors and management goals be considered when making these decisions for marshes in the Chesapeake Bay Region. It is clear that the exotic invasive species *Phragmites australis* provides value to society and the ecosystem in the Chesapeake Bay region; how that value is recognized and incorporated into public perception and decision making remains to be seen.

Declarations

Funding Statement:

No external funding was used for this work.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution

E.C. led the writing of the main manuscript text and performed the ecosystem service valuation and net present value calculation. A.C. edited and contributed to the main manuscript text, performed the data analysis of carbon sequestration values, and geospatial analysis for wildlife habitat value.

Acknowledgement

We would like to acknowledge and thank Patrick Megonigal and the Smithsonian Environmental Research Wetland Global Change Research Wetland research group for answering questions regarding the available data from their long term monitoring.

Data Availability

All data and calculations will be made available as supplementary materials upon publication, or are already publicly available in prior publications or resources.

References

1. Al-Attabi, Z., Xu, Y., Tso, G. and Narayan, S., 2023. The impacts of tidal wetland loss and coastal development on storm surge damages to people and property: A Hurricane Ike case-study. Scientific Reports, 13(1), p.4620.
2. Alongi, D.M. Carbon Balance in Salt Marsh and Mangrove Ecosystems: A Global Synthesis. J. Mar. Sci. Eng. 2020, 8, 767. https://doi.org/10.3390/jmse8100767
3. Baldwin, Andrew H. Karin M. Kettenring, Dennis F. Whigham, Seed banks of Phragmites australis-dominated brackish wetlands: Relationships to seed viability, inundation, and land cover, Aquatic Botany, Volume 93, Issue 3, 2010, Pages 163-169, https://doi.org/10.1016/j.aquabot.2010.06.001
4. Benoit, L.K., Askins, R.A. Impact of the spread ofPhragmites on the distribution of birds in Connecticut tidal marshes. Wetlands 19, 194–208 (1999). https://doi.org/10.1007/BF03161749
5. Blaalid R, Magnussen K, Westberg NB, Navrud S (2021) A benefit-cost analysis framework for prioritization of control programs for well-established invasive alien species. NeoBiota 68: 31-52. https://doi.org/10.3897/neobiota.68.62122
6. Boesch, D. F., Baecher, G. B., Boicourt, W. C., Cullather, R. I., Dangendorf, S., Henderson, G. R., Kilbourne, H. H., Kirwan, M. L., Kopp, R. E., Land, S., Li, M., McClure., K., Nardin, W., & Sweet, W. V. 2023. Sea-level Rise Projections for Maryland 2023. University of Maryland Center for Environmental Science, Cambridge, MD.
7. Boltovskoy, D., Guiaşu, R., Burlakova, L. et al. Misleading estimates of economic impacts of biological invasions: Including the costs but not the benefits. Ambio 51, 1786–1799 (2022). https://doi.org/10.1007/s13280-022-01707-1
8. Brundage, Jennifer. Grazing as a management tool for controlling Phragmites australis and restoring native plant biodiversity in wetlands. University of Maryland, College Park, MS Thesis, 2010.
9. Campbell, Elliott, Rachel Marks, Christine Conn, Spatial modeling of the biophysical and economic values of ecosystem services in Maryland, USA, Ecosystem Services, Volume 43, 2020, https://doi.org/10.1016/j.ecoser.2020.101093
10. Canavan, Kim Iain D Paterson, Carla Lambertini, Martin P Hill, Expansive reed populations—alien invasion or disturbed wetlands?, AoB PLANTS, Volume 10, Issue 2, April 2018, ply014, https://doi.org/10.1093/aobpla/ply014
11. Chambers, Randy & Havens, Kirk & Killeen, Sharon & Berman, Marcia. (2008). Common Reed Phragmites australis Occurrence And Adjacent Land Use Along Estuarine Shoreline In Chesapeake Bay. Wetlands. 28. 1097-1103. 10.1672/07-61.1

12. Cassalho,Felício, Andre de Souza de Lima, Daniel J. Coleman, Martin Henke, Tyler W. Miesse, Gustavo de A. Coelho, Celso M. Ferreira,Projecting future wave attenuation by vegetation from native and invasive saltmarsh species in the United States,Regional Studies in Marine Science,Volume 68,2023,103264, https://doi.org/10.1016/j.rsma.2023.103264
13. Chesapeake Bay Program. 2015 (amended 2019). Recommendations of the Expert Panel to Define Removal Rates for Shoreline Management Projects. Watershed Technical Work Group Report. https://www.chesapeakebay.net/files/documents/short_final_shoreline-management-protocol_11-24-19_final.pdf
14. Chesapeake Bay Program. 2003. Common Reed (Phragmites australis) in the Chesapeake Bay: A Draft Bay-wide Management Plan. The Chesapeake Bay Phragmites australis Working Group Chaired by: Julie A. Thompson USFWS, Chesapeake Bay Field Office https://www.midatlanticpanel.org/wp-content/uploads/2016/04/phragmites_102003.pdf
15. Chlot, S., Widerlund, A. & Öhlander, B. Nitrogen uptake and cycling in *Phragmites australis* in a lake-receiving nutrient-rich mine water: a ^{15}N tracer study. *Environ Earth Sci* 74, 6027–6038 (2015). https://doi.org/10.1007/s12665-015-4626-x
16. Cornwell, J.C., Kemp, W.M. & Kana, T.M. Denitrification in coastal ecosystems: methods, environmental controls, and ecosystem level controls, a review. *Aquatic Ecology* 33, 41–54 (1999). https://doi.org/10.1023/A:1009921414151
17. Correa, Nancy & Guiasu, Radu & Boltovskoy, Demetrio. (2021). Invasion biology: evidence, assumptions, and conservationism. 72. 179-226.
18. Correll, M.D., Wiest, W.A., Hodgman, T.P., Shriver, W.G., Elphick, C.S., McGill, B.J., O'Brien, K.M. and Olsen, B.J. (2017), Predictors of specialist avifaunal decline in coastal marshes. Conservation Biology, 31: 172-182. https://doi.org/10.1111/cobi.12797
19. Costanza, Robert & Pérez-Maqueo, Octavio & Martínez, M. & Sutton, Paul & Anderson, Sharolyn & Mulder, Kenneth. (2008). The Value of Coastal Wetlands for Hurricane Protection. Ambio. 37. 241-8. 10.1579/0044-7447(2008)37[241:TVOCWF]2.0.CO;2.
20. Costanza, Robert. Ida Kubiszewski, Natalie Stoeckl, Tom Kompas, Pluralistic discounting recognizing different capital contributions: An example estimating the net present value of global ecosystem services, Ecological Economics, Volume 183, 2021, https://doi.org/10.1016/j.ecolecon.2021.106961
21. Cott, G.M., Caplan, J.S. & Mozdzer, T.J. Nitrogen uptake kinetics and saltmarsh plant responses to global change. *Sci Rep* 8, 5393 (2018). https://doi.org/10.1038/s41598-018-23349-8
22. Cott, G.M., Jansen, M.A.K. & Megonigal, J.P. Uptake of organic nitrogen by coastal wetland plants under elevated CO2. *Plant Soil* 450, 521–535 (2020). https://doi.org/10.1007/s11104-020-04504-5
23. Courtois, Pierre, Charles Figuieres, Chloe Mulier, Joakim Weill,A Cost–Benefit Approach for Prioritizing Invasive Species,Ecological Economics,Volume 146,2018,Pages 607-620, https://doi.org/10.1016/j.ecolecon.2017.11.037

24. Drake, Bert, Megonigal, Patrick, Duls, Jim, Lu, Meng, Peresta, Andrew, Peresta Gary. Data: CO2, Nitrogen and Marsh Elevation Experiment. https://serc.si.edu/gcrew/nitrogendata Accessed March 2025.
25. Engloner, Attila I. Structure, growth dynamics and biomass of reed (Phragmites australis) – A review,Flora - Morphology, Distribution, Functional Ecology of Plants, Volume 204, Issue 5, 2009, Pages 331-346, https://doi.org/10.1016/j.flora.2008.05.001
26. Farnsworth, E.J., Meyerson, L.A. Comparative ecophysiology of four wetland plant species along a continuum of invasiveness. Wetlands 23, 750–762 (2003). https://doi.org/10.1672/0277-5212(2003)023[0750:CEOFWP]2.0.CO;2
27. Findlay, S.E.G., Dye, S. & Kuehn, K.A. Microbial growth and nitrogen retention in litter of *Phragmites australis* compared to *Typha angustifolia* . *Wetlands* 22, 616–625 (2002). https://doi.org/10.1672/0277-5212(2002)022[0616:MGANRI]2.0.CO;2
28. Guareschi, Simone, Kate L Mathers, Josie South, Laetitia M Navarro, Trevor Renals, Alice Hiley, Marco Antonsich, Rossano Bolpagni, Alejandro Bortolus, Piero Genovesi, Arthertone Jere, Takudzwa C Madzivanzira, Fortunate M Phaka, Ana Novoa, Julian D Olden, Mattia Saccó, Ross T Shackleton, Montserrat Vilà, Paul J Wood, Framing challenges and polarized issues in invasion science: toward an interdisciplinary agenda, BioScience, Volume 74, Issue 12, December 2024, Pages 825–839, https://doi.org/10.1093/biosci/biae084
29. Guiaşu, R.C., Tindale, C.W. Logical fallacies and invasion biology. Biol Philos 33, 34 (2018). https://doi.org/10.1007/s10539-018-9644-0
30. Hanley N, Roberts M. The economic benefits of invasive species management. People Nat. 2019; 1: 124–137. https://doi.org/10.1002/pan3.31
31. Hartley, M.J. and A.J. Weldon, eds. 2020. Saltmarsh Sparrow Conservation Plan. Atlantic Coast Joint Venture, acjv.org/documents/SALS_plan_final.pdf
32. Hazelton, E.L.G., Downard, R., Kettenring, K.M. *et al.* Spatial and Temporal Variation in Brackish Wetland Seedbanks: Implications for Wetland Restoration Following *Phragmites* Control. *Estuaries and Coasts* 41 (Suppl 1), 68–84 (2018). https://doi.org/10.1007/s12237-017-0289-z
33. Hazelton, E.L., Mozdzer, T.J., Burdick, D.M., Kettenring, K.M. and Whigham, D.F., 2014. Phragmites australis management in the United States: 40 years of methods and outcomes. AoB plants, 6, p.plu001. https://doi.org/10.1093/aobpla/plu001
34. Herrmann, M., R. G. Najjar, W. M. Kemp, R. B. Alexander, E. W. Boyer, W.-J. Cai, P. C. Griffith, K. D. Kroeger, S. L. McCallister, and R. A. Smith (2015), Net ecosystem production and organic carbon balance of U.S. East Coast estuaries: A synthesis approach, Global Biogeochem. Cycles, 29, 96–111, doi:10.1002/2013GB004736.
35. James R Holmquist et al 2018 Environ. Res. Lett. 13 115005 DOI 10.1088/1748-9326/aae157
36. Hoover, Coeli M.; Bagdon, Ben; Gagnon, Aaron. 2021. Standard estimates of forest ecosystem carbon for forest types of the United States. Gen. Tech. Rep. NRS-202. Madison, WI: U.S.

Department of Agriculture, Forest Service, Northern Research Station. 158 p. https://doi.org/10.2737/NRS-GTR-202.

37. Isely, Paul; Nordman, Erik E.; Howard, Shaun; and Bowman, Richard (2017) "Phragmites Removal Increases Property Values in Michigan's Lower Grand River Watershed," Journal of Ocean and Coastal Economics: Vol. 4: Iss. 1, Article 5.
38. Kettenring, K.M., McCormick, M.K., Baron, H.M. and Whigham, D.F. (2011), Mechanisms of Phragmites australis invasion: feedbacks among genetic diversity, nutrients, and sexual reproduction. Journal of Applied Ecology, 48: 1305-1313. https://doi.org/10.1111/j.1365-2664.2011.02024.x
39. Kirwan, M. L., D. C. Walters, W. G. Reay, and J. A. Carr (2016), Sea level driven marsh expansion in a coupled model of marsh erosion and migration, Geophys. Res. Lett., 43, 4366–4373, doi:10.1002/2016GL068507
40. Kirwan, Matthew L. and Michael, Holly A. and Gedan, Keryn B. and Tully, Katherine L. and Fagherazzi, Sergio and McDowell, Nate G. and Molino, Grace D. and Pratt, Dannielle and Reay, William G. and Stotts, Stephanie. Feedbacks Regulating the Salinization of Coastal Landscapes. Annual Review of Marine Science. 2025. Volume 17, 202, pp 461-484, https://doi.org/10.1146/annurev-marine-070924-031447
41. Kiviat, Erik 2013 Ecosystem services of Phragmites in North America with emphasis on habitat functions https://doi.org/10.1093%2Faobpla%2Fplt008
42. Martin, L.J., Blossey, B. The Runaway Weed: Costs and Failures of Phragmites australis Management in the USA. Estuaries and Coasts 36, 626–632 (2013).https://doi.org/10.1007/s12237-013-9593-4
43. Martin, R.M. and Moseman-Valtierra, S., 2015. Greenhouse gas fluxes vary between Phragmites australis and native vegetation zones in coastal wetlands along a salinity gradient. Wetlands, 35, pp.1021-1031.https://doi.org/10.1007/s13157-015-0690-y
44. Martínez-Espinosa, Columba Sabine Sauvage, Ahmad Al Bitar, Pamela A. Green, Charles J. Vörösmarty, José Miguel Sánchez-Pérez, Denitrification in wetlands: A review towards a quantification at global scale, Science of The Total Environment, Volume 754, 2021,142398, https://doi.org/10.1016/j.scitotenv.2020.142398
45. Maryland Department of Natural Resources (MDNR). Accessed 2025. Phragmites: Considerations for Management in the Critical Area. Critical Area Commission. Undated. https://dnr.maryland.gov/criticalarea/Documents/Phragmites-Fact-Sheet-Final.pdf
46. McCormick MK Kettenring KM Baron HM Whigham DF, Extent and reproductive mechanisms of Phragmites australis spread in brackish wetlands in Chesapeake Bay, Maryland (USA), Wetlands, 2010a, vol. 30 (pg. 67-74) a10.1007/s13157-009-0007-0
47. McCormick, M.K., Kettenring, K.M., Baron, H.M. and Whigham, D.F. (2010)b, Spread of invasive Phragmites australis in estuaries with differing degrees of development: genetic patterns, Allee

effects and interpretation. Journal of Ecology, 98: 1369-1378. https://doi.org/10.1111/j.1365-2745.2010.01712.x

48. McCormick, M.K., Whigham, D.F., Stapp, J.R. et al. Shoreline modification affects recruitment of invasive Phragmites australis. Wetlands Ecol Manage 28, 909–919 (2020). https://doi.org/10.1007/s11273-020-09757-6
49. Meiman, S., Civco, D., Holsinger, K. et al. Comparing Habitat Models Using Ground-Based and Remote Sensing Data: Saltmarsh Sparrow Presence Versus Nesting. Wetlands 32, 725–736 (2012). https://doi.org/10.1007/s13157-012-0306-8
50. Milke, J.; Gałczyńska, M.; Wróbel, J. The Importance of Biological and Ecological Properties of Phragmites Australis (Cav.) Trin. Ex Steud., in Phytoremendiation of Aquatic Ecosystems—The Review. Water 2020, 12, 1770. https://doi.org/10.3390/w12061770
51. Minchinton, T.E. and Bertness, M.D. (2003), DISTURBANCE-MEDIATED COMPETITION AND THE SPREAD OF PHRAGMITES AUSTRALIS IN A COASTAL MARSH. Ecological Applications, 13: 1400-1416. https://doi.org/10.1890/02-5136
52. Mitchell, M, J. Herman, D. M. Bilkovic & C. Hershner (2017) Marsh persistence under sea-level rise is controlled by multiple, geologically variable stressors, Ecosystem Health and Sustainability, 3:10, 1379888, DOI: 10.1080/20964129.2017.1396009
53. Mitchell, M., Herman, J. and Hershner, C., 2020. Evolution of tidal marsh distribution under accelerating sea level rise. Wetlands, 40(6), pp.1789-1800.
54. Mozdzer, Thomas J. Jacques Brisson, Eric L. G. Hazelton, Physiological ecology and functional traits of North American native and Eurasian introduced Phragmites australis lineages, AoB PLANTS, Volume 5, 2013, plt048, https://doi.org/10.1093/aobpla/plt048
55. Mozdzer, Thomas, Megonigal, Patrick, Duls, Jim, Lu, Meng, Peresta, Andrew, Peresta Gary. Data: Invasive Phragmites Experiment. Accessed February 2025. https://serc.si.edu/gcrew/phragmitesdata
56. Mueller, P., Hager, R.N., Meschter, J.E. et al. Complex invader-ecosystem interactions and seasonality mediate the impact of non-native Phragmites on CH4 emissions. Biol Invasions 18, 2635–2647 (2016). https://doi.org/10.1007/s10530-016-1093-6
57. Munson, S. M., E. O. Yackulic, L. S. Bair, S. M. Copeland, and K. L. Gunnell. 2020. The biggest bang for the buck: cost-effective vegetation treatment outcomes across drylands of the western United States. Ecological Applications 30(7):e02151. 10.1002/eap.2151
58. Najjar, RG; Herrmann, M; Alexander, R; Boyer, EW; Burdige, DJ; Butman, D; Cai, W-J; Canuel, Elizabeth A.; Chen, RF; Friedrichs, Marjorie A.M.; and et al, Carbon Budget of Tidal Wetlands, Estuaries, and Shelf Waters of Eastern North America (2018). Global Biogeochemical Cycles, 32(3), 389-416. 10.1002/2017GB005790
59. Narayan, S., Beck, M.W., Wilson, P. *et al.* The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. *Sci Rep* 7, 9463 (2017). https://doi.org/10.1038/s41598-017-09269-z

60. Nie, Ming, Wenwen Liu, Steven C. Pennings, and Bo Li. 2023. " Lessons from the Invasion of Spartina Alterniflora in Coastal China." Ecology 104(1): e3874. https://doi.org/10.1002/ecy.3874
61. Nikolić L, Maksimović I, Džigurski D, Putnik-Delić M, Ljevnaić-Mašić B. Removal of nitrogen and phosphorus by aboveground biomass of Phragmites australis in Constructed Wetland System under the conditions of temperate continental climate. Int J Phytoremediation. 2023;25(4):483-492. doi: 10.1080/15226514.2022.2090498. Epub 2022 Jul 3. PMID: 35786062.
62. Nguyen Thi Hoang Ha1 and Bui Thi Kim Anh The removal of heavy metals by iron mine drainage sludge and Phragmites australis. 2017. IOP Conf. Ser.: Earth Environ. Sci. 71 01202210. doi.org/1088/1755-1315/71/1/012022
63. Poffenbarger, H.J., Needelman, B.A. & Megonigal, J.P. Salinity Influence on Methane Emissions from Tidal Marshes. Wetlands 31, 831–842 (2011). https://doi.org/10.1007/s13157-011-0197-0
64. Quirion, B., Simek, Z., Dávalos, A. et al. Management of invasive Phragmites australis in the Adirondacks: a cautionary tale about prospects of eradication. Biol Invasions 20, 59–73 (2018). https://doi.org/10.1007/s10530-017-1513-2
65. Reithmaier, G.M.S., Cabral, A., Akhand, A. *et al.* Carbonate chemistry and carbon sequestration driven by inorganic carbon outwelling from mangroves and saltmarshes. *Nat Commun* 14, 8196 (2023). https://doi.org/10.1038/s41467-023-44037-w
66. Renault, David, Manon C.M. Hess, Julie Braschi, Ross N. Cuthbert, Marta G. Sperandii, Manuele Bazzichetto, Olivier Chabrerie, Gabrielle Thiébaut, Elise Buisson, Frédéric Grandjean, Anne-Kristel Bittebiere, Maud Mouchet, François Massol, Advancing biological invasion hypothesis testing using functional diversity indices,Science of The Total Environment, Volume 834, 2022, https://doi.org/10.1016/j.scitotenv.2022.155102
67. Reyns N, Casaer J, De Smet L, Devos K, Huysentruyt F, Robertson PA, Verbeke T, Adriaens T. Cost-benefit analysis for invasive species control: the case of greater Canada goose Branta canadensis in Flanders (northern Belgium). PeerJ. 2018 Jan 29;6:e4283. doi: 10.7717/peerj.4283. PMID: 29404211; PMCID: PMC5793711.
68. Rezaie AM, Loerzel J, Ferreira CM (2020) Valuing natural habitats for enhancing coastal resilience: Wetlands reduce property damage from storm surge and sea level rise. PLOS ONE 15(1): e0226275. https://doi.org/10.1371/journal.pone.0226275
69. Rezania, S., Park, J., Rupani, P.F. et al. Phytoremediation potential and control of Phragmites australis as a green phytomass: an overview. Environ Sci Pollut Res 26, 7428–7441 (2019). https://doi.org/10.1007/s11356-019-04300-4
70. Ricciardi, A., Ryan, R. The exponential growth of invasive species denialism. Biol Invasions 20, 549–553 (2018). https://doi.org/10.1007/s10530-017-1561-7
71. Rodríguez, Mariana, Jacques Brisson, Pollutant removal efficiency of native versus exotic common reed (Phragmites australis) in North American treatment wetlands, Ecological Engineering, Volume 74, 2015, Pages 364-370, https://doi.org/10.1016/j.ecoleng.2014.11.005

72. Rohal, Christine B., Eric L. G. Hazelton, Eliza K. McFarland, Rebekah Downard, Melissa K. McCormick, Dennis F. Whigham, and Karin M. Kettenring. 2023. “ Landscape and Site Factors Drive Invasive Phragmites Management and Native Plant Recovery across Chesapeake Bay Wetlands.” Ecosphere 14(1): e4392. https://doi.org/10.1002/ecs2.4392
73. Rohal CB, Cranney C, Hazelton ELG, Kettenring KM. Invasive Phragmites australis management outcomes and native plant recovery are context dependent. Ecol Evol. 2019; 9: 13835–13849. https://doi.org/10.1002/ece3.5820
74. Rooth, J., Stevenson, J. Sediment deposition patterns in *Phragmites australis*communities: Implications for coastal areas threatened by rising sea-level. *Wetlands Ecology and Management* 8, 173–183 (2000). https://doi.org/10.1023/A:1008444502859
75. Saltonstall, K. Cryptic invasion by a non-native genotype of the common reed, Phragmites australis, into North America, Proc. Natl. Acad. Sci. U.S.A. 99 (4) 2445-2449, https://doi.org/10.1073/pnas.032477999 (2002).
76. Saltonstall, Kristin, J. Court Stevenson,The effect of nutrients on seedling growth of native and introduced Phragmites australis,Aquatic Botany,Volume 86, Issue 4,2007, Pages 331-336, https://doi.org/10.1016/j.aquabot.2006.12.003
77. Saltonstall, K., Meyerson, L.A. Phragmites australis: from genes to ecosystems. Biol Invasions 18, 2415–2420 (2016). https://doi.org/10.1007/s10530-016-1240-0
78. Sagoff,Mark What Is Invasion Biology?,Ecological Economics,Volume 154,2018, Pages 22-30, https://doi.org/10.1016/j.ecolecon.2018.07.023
79. Sagoff, M. (2020), Fact and value in invasion biology. Conservation Biology, 34: 581-588. https://doi.org/10.1111/cobi.13440
80. Santos,Isaac R., David J. Burdige, Tim C. Jennerjahn, Steven Bouillon, Alex Cabral, Oscar Serrano, Thomas Wernberg, Karen Filbee-Dexter, Julia A. Guimond, Joseph J. Tamborski,The renaissance of Odum's outwelling hypothesis in 'Blue Carbon' science, Estuarine, Coastal and Shelf Science,Volume 255,2021,107361, https://doi.org/10.1016/j.ecss.2021.107361
81. Sciance, M. & Patrick, Christopher & Weller, Donald & Williams, Meg & McCormick, Melissa. (2016). Local and regional disturbances associated with the invasion of Chesapeake Bay marshes by the common reed Phragmites australis. Biological Invasions. 18. 10.1007/s10530-016-1136-z
82. Shaw, P., Jobe, J. & Gedan, K.B. Environmental Limits on the Spread of Invasive Phragmites australis into Upland Forests with Marine Transgression. Estuaries and Coasts 45, 539–550 (2022). https://doi.org/10.1007/s12237-021-00980-9
83. Sheng, Wenyi, Lele Liu, Yiming Wu, Meiqi Yin, Qing Yu, Xiao Guo, Huijia Song, Weihua Guo, Exploring salt tolerance and indicator traits across four temperate lineages of the common wetland plant, Phragmites australis, Science of The Total Environment, Volume 912, 2024, 169100, https://doi.org/10.1016/j.scitotenv.2023.169100
84. Smith JAM (2013) The Role of Phragmites australis in Mediating Inland Salt Marsh Migration in a Mid-Atlantic Estuary. PLoS ONE 8(5): e65091. https://doi.org/10.1371/journal.pone.0065091

85. Song, S., Wang, Z.A., Kroeger, K.D., Eagle, M., Chu, S.N. and Ge, J. (2023), High-frequency variability of carbon dioxide fluxes in tidal water over a temperate salt marsh. Limnol Oceanogr, 68: 2108-2125. https://doi.org/10.1002/lno.12409
86. Silan et al. 2024 Dynamics and drivers of carbon sequestration and storage capacity in Phragmites australis-dominated wetlands https://doi.org/10.1016/j.ecss.2024.108640
87. Srivastava. 2014. Environmental perspectives of Phragmites australis (Cav.) Trin. Ex. Steudelhttps://link.springer.com/article/10.1007/s13201-013-0142-x
88. Tan, Li-Shan, Zhen-Ming Ge, Bei-Li Fei, Li-Na Xie, Ya-Lei Li, Shi-Hua Li, Xiu-Zhen Li, Tom Ysebaert, The roles of vegetation, tide and sediment in the variability of carbon in the salt marsh dominated tidal creeks, Estuarine, Coastal and Shelf Science, Volume 239, 2020, 106752, https://doi.org/10.1016/j.ecss.2020.106752
89. Taylor-Burns, R., Lowrie, C., Tehranirad, B. et al. The value of marsh restoration for flood risk reduction in an urban estuary. Sci Rep 14, 6856 (2024). https://doi.org/10.1038/s41598-024-57474-4
90. Tlili, Hiba & Bali, Mahmoud & Chebil, Sabrine & Boukchina, Rachid. (2023). Potential of Phragmites australis in Vertical Flow Constructed Wetland for Heavy metals removal from Urban wastewater. 10.21203/rs.3.rs-2613123/v1.
91. Tulbure, Mirela & Ghioca-Robrecht, Dana & Johnston, Carol & Whigham, Dennis. (2012). Inventory and Ventilation Efficiency of Nonnative and Native Phragmites australis (Common Reed) in Tidal Wetlands of the Chesapeake Bay. Estuaries and Coasts. 35. 1353-1359. 10.1007/s12237-012-9529-4.
92. Tucker, G.C. 1990. The genera of Arundinoidea (Gramineae) in the southeastern United States. Journal of the Arnold Arboretum 71: 14–171.
93. Uddin and Robinson. 2018 Can nutrient enrichment influence the invasion of Phragmites australis? Science of The Total Environment Volumes 613–614, 1 February 2018, Pages 1449-1459 https://doi.org/10.1016/j.scitotenv.2017.06.131
94. Virginia Institute of Marine Science (VIMS) Center for Coastal Resources Management,. 2024. Virginia Shoreline Inventory Database, College of William and Mary, Gloucester Point, Virginia. Retrieved from http://www.vims.edu/ccrm/research/inventory/index.php
95. Wainger, Lisa & Harms, Nathan & Magen, Cedric & Liang, Dong & Nesslage, Genevieve & McMurray, Anna & Cofrancesco, Al. (2018). Evidence-based economic analysis demonstrates that ecosystem service benefits of water hyacinth management greatly exceed research and control costs. 10.7287/peerj.preprints.26617v1
96. Wang, S.; Li, S.; Zheng, S.; Gao, W.; Zhang, Y.; Cao, B.; Cui, B.; Shao, D. Estimating Biomass and Carbon Sequestration Capacity of *Phragmites australis* Using Remote Sensing and Growth Dynamics Modeling: A Case Study in Beijing Hanshiqiao Wetland Nature Reserve, China. *Sensors* **2022**, *22*, 3141. https://doi.org/10.3390/s22093141

97. Wang, Z.A., Kroeger, K.D., Ganju, N.K., Gonneea, M.E. and Chu, S.N. (2016), Intertidal salt marshes as an important source of inorganic carbon to the coastal ocean. Limnol. Oceanogr., 61: 1916-1931. https://doi.org/10.1002/lno.10347
98. Warren RJ, II, King JR, Tarsa C, Haas B, Henderson J (2017) A systematic review of context bias in invasion biology. PLoS ONE 12(8): e0182502. https://doi.org/10.1371/journal. pone.0182502
99. Weber, Matt, Wainger, Lisa & Harms, Nathan & Nesslage, Genevieve. (2020). The economic value of research in managing invasive hydrilla in Florida public lakes. Lake and Reservoir Management. 37. 1-14. 10.1080/10402381.2020.1824047
100. Weis, J.S., Watson, E.B., Ravit, B. et al. The status and future of tidal marshes in New Jersey faced with sea level rise. Anthropocene Coasts 4, 168–192 (2021). https://doi.org/10.1139/anc-2020-0020
101. Wiest, Whitney & Correll, Maureen & Marcot, Bruce & Olsen, Brian & Elphick, Chris & Hodgman, Thomas & Guntenspergen, Glenn & Shriver, Greg. (2018). Estimates of tidal-marsh bird densities using Bayesian networks. The Journal of Wildlife Management. 83. 10.1002/jwmg.21567
102. Yarwood, S.A., Baldwin, A.H., Gonzalez Mateu, M. et al. Archaeal rhizosphere communities differ between the native and invasive lineages of the wetland plant Phragmites australis (common reed) in a Chesapeake Bay subestuary. Biol Invasions 18, 2717–2728 (2016). https://doi.org/10.1007/s10530-016-1144-z
103. Xiong, Biao, Siyuan Han, Tyler C. Messerschmidt, Matthew L. Kirwan, Keryn Gedan, Man Qi, Early detection of invasive Phragmites australis at the tidal marsh-forest ecotone with airborne LiDAR, Ecological Indicators, Volume 167, 2024, 112651, https://doi.org/10.1016/j.ecolind.2024.112651

Supplementary Materials

The Supplementary Material file is not available with this version.

Figures

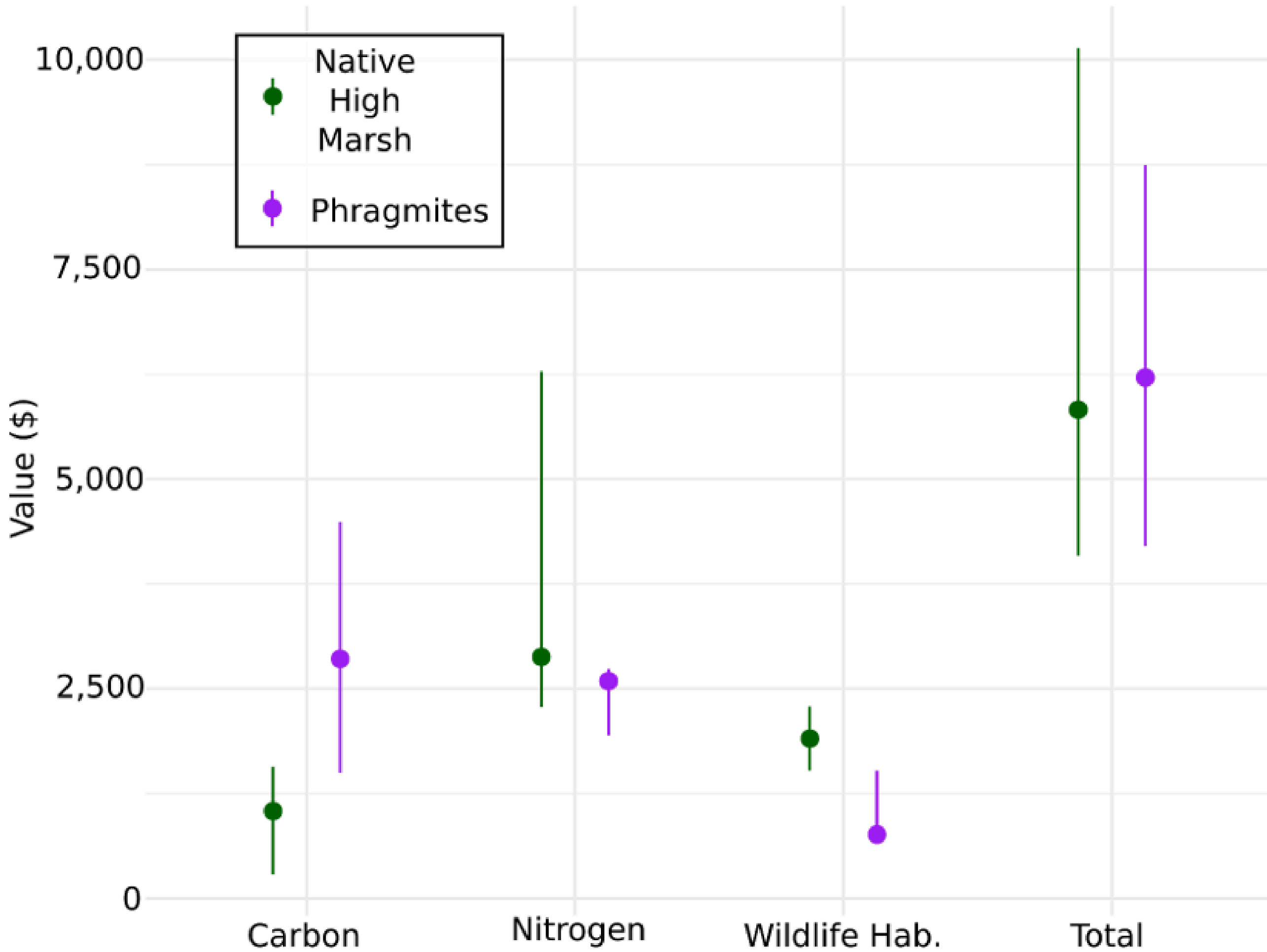

Figure 1

Range of Ecosystem Service Economic Value Estimates, units are $ ha^{-1} yr^{-1}

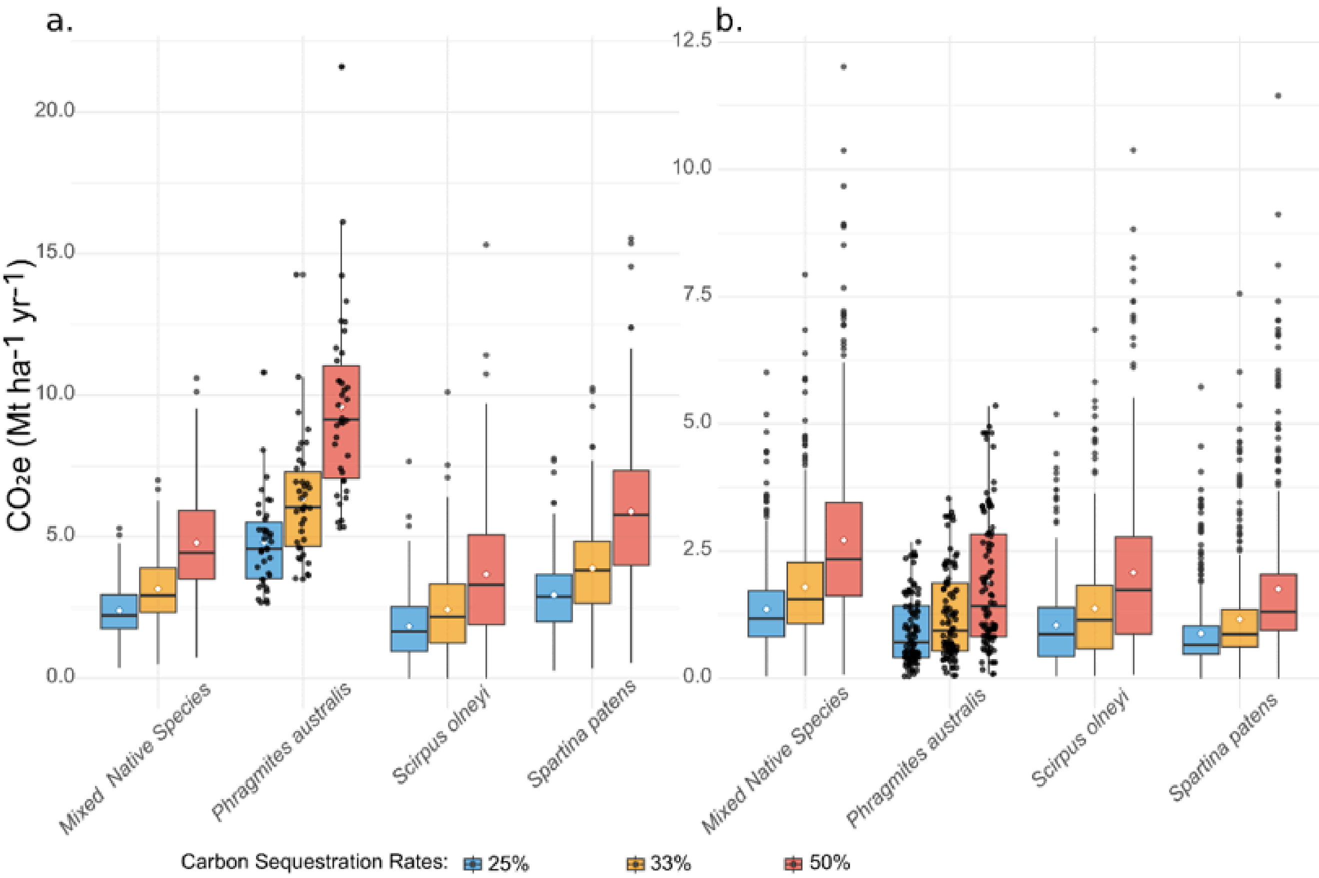

Figure 2

Estimated Annual Carbon Sequestration per Ha from Smithsonian GCRW data (Drake et al. 2025, Mozdzer et al. 2025). Panel a is Aboveground Biomass (agb). Panel b is below ground biomass (bgb)

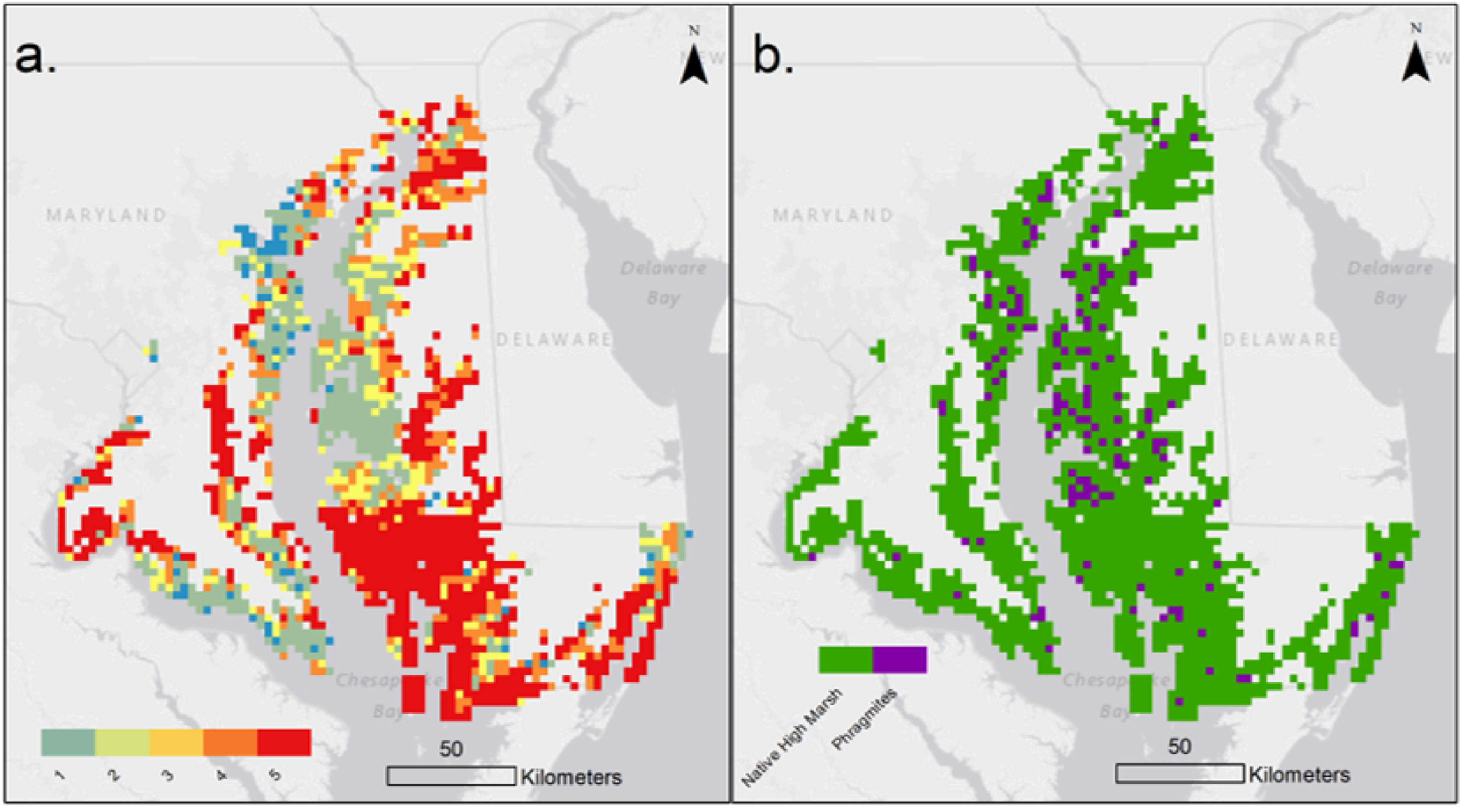

Figure 3

Comparison of Wildlife Habitat and Biodiversity Index (panel a) and occurrence of *Phragmites australis* (panel b) in the Chesapeake Bay region.

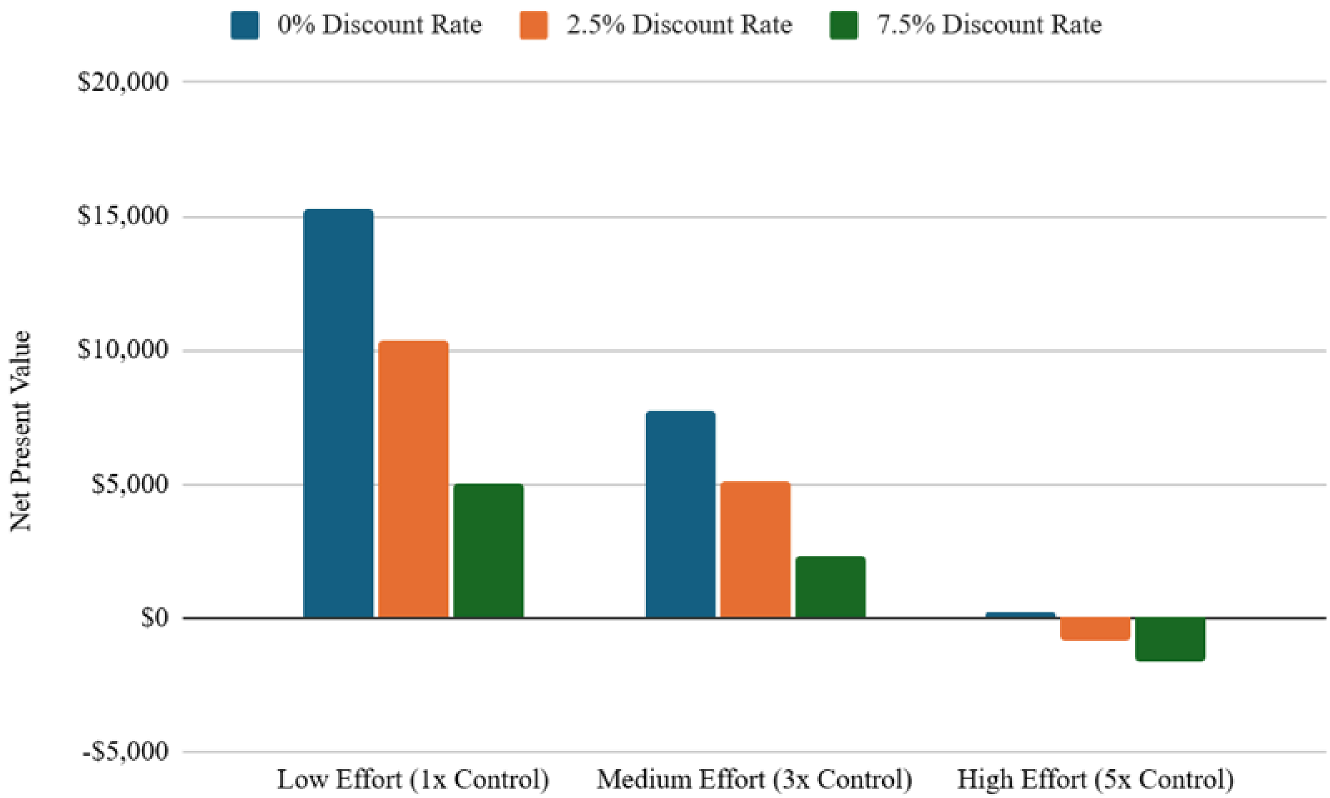

Figure 4

Net Present Value Over 25 Years for the Optimal Difference in Ecosystem Service Value Resulting from Control of Phragmites and Successful Establishment of Native High Marsh, under 3 Scenarios of Control Effort Required.