# Impacts of Prescribed Burns on Tidal Marsh Ecosystem Services

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# Executive Summary

This document is a literature review summarizing the current state of knowledge of the impact of removing the invasive common reed, *Phragmites australis* (hereafter *Phragmites*), via prescribed burning on a suite of tidal salt marsh ecosystem services. *Phragmites*-invaded marshes are considered degraded due to *Phragmites* aggressive growth in Mid-Atlantic salt marshes and perceived impacts on marsh biological and recreational ecosystem services. Prescribed burns paired with herbicide applications are a common strategy employed in Delaware and the Mid-Atlantic region to remove *Phragmites* and restore native habitat and the natural landscape. Through a literature review, we assess the previously observed and documented or expected impacts of *Phragmites* burn restorations (intended to replace *Phragmites* with native vegetation) on marsh ecosystem services important to end users within the state of Delaware. Assessments of positive, neutral, negative, or unknown impacts of *Phragmites* burning on individual ecosystem services are offered for the purpose of informing marsh management decisions based on the priorities defined by individual managers. Each assessment is paired with a confidence score, an evaluation of the strength of the evidence leading to the impact assessment. The results of the literature review reveal very few studies that directly and definitively assess the effects of prescribed burns on marsh services. As a result, many of the assessments are asserted with low confidence demonstrating the need for longer and more thorough pre- and post-prescribed burn monitoring that will test some of the more speculative ecosystem service impact assessments.

Impacts of prescribed burns on biogeochemical ecosystem services are variable depending on the nutrient or pollutant service of interest. Carbon storage has been reported to be greater in burned wetlands than unburned wetlands suggesting that prescribed burns may offer a carbon sequestration ecosystem service that recoups some of the carbon storage benefits that are lost when *Phragmites* is removed. Studies examining char in thin layer placements suggest that the removal of reactive nitrogen via denitrification may be reduced when *Phragmites* is removed via burning leading to potential increases in nutrient loading that could impair water quality issues. Denitrification studies that study the effects of burning directly are needed, however. Studies show no effect of prescribed burns on phosphorus storage ecosystem services. Biochar has been shown to store pollutants like heavy metals and PAHs in lab studies, but field studies that directly examine the effects of burns or biochar applications in marshes are needed. Studies show greenhouse gas emissions increase in the short term after burning, but long term impacts are highly uncertain and require longer term monitoring.

Biological ecosystem services are similarly variable with responses to burning often depending on the species of interest. Removing *Phragmites* by burning and herbicide applications has been shown to have a neutral to positive impact on native vegetation. Invertebrate, fish, and bird communities overall benefit from *Phragmites* removal, however, individual species' responses to burning are variable. Species with generalist feeding strategies are generally unaffected, and may even benefit, by the presence of *Phragmites*, while the responses of marsh specialist species can depend on habitat preferences and environmental factors. Given the sometimes species-specific response to burning, land managers will want to target their burning decision to species of highest priority to their stakeholders.

Physical marsh ecosystem services aid in coastal resilience and also show variable responses to prescribed burns. Sedimentation services that aid in the vertical accretion of marsh allowing it to keep pace with sea level have been shown to show differential responses to burning that depend on organic versus mineral content. Sedimentation is reduced after burning in marshes with high organic sediment sources but increased after burns in marshes with higher relative amounts of mineral sediment sources. *Phragmites* has also been shown to accrete more sediment than native grasses, so restoration may reduce sedimentation. Burning *Phragmites* has had contradicting effects on marsh elevation depending on treatment timing and duration. Prescribed burns will not themselves impact tidal flow, but replacement of *Phragmites* with native grasses will enhance tidal inundations. Literature reports ultimately also show conflicting results in terms of the effects of burns on coastal resilience as defined as the reduction in flood and wave impacts to coasts by marshes. There are conflicting results in the literature of how native grass and *Phragmites* impact wave attenuation and shoreline stability. Notably, any vegetation is substantially more effective in maintaining these physical ecosystem services than removing vegetation entirely.

Recreational and Cultural salt marsh ecosystem services have not been examined specifically in the context of prescribed burning in salt marshes. These impacts are likely determined by the response of biological and physical services influencing animal presence and the prevention of marsh loss.

A prescribed burn conducted at Woodland Beach Wildlife Area in 2011. *Credit: Jay Davis, DNREC.*

# 1. Introduction

Tidal marsh ecosystems, vegetated environments that are periodically inundated with water due to lunar tidal cycles, cover an estimated 9 million hectares globally (Murray et al., 2022) and 71,343 acres within the state of Delaware (DNREC, 2022). These ecosystems provide a wide range of ecosystem services to humans in the form of recreational opportunities, habitat for wildlife and commercially important species, protection from erosion, and biogeochemical services for water quality and climate (see Ecosystem Services section for a detailed description of notable ecosystem services). Studies have valued tidal marshes at $15,491-69,549/ha/year within the Delaware River Basin (Kauffman, 2016) and $193,845/ha/year globally (de Groot et al., 2012) making them important targets for conservation.

Of great concern to coastal land managers, tidal marshes have been subject to significant potential or realized degradation and habitat loss that diminish their value. Past agricultural (Sebold, 1998), infrastructural (Roman and Burdick, 2012), and pest control strategies have altered the natural hydrology of salt marshes (Gedan et al., 2009; Philipp, 2005) leading to habitat loss and/or invasion by the common reed, *Phragmites australis* (hereafter referred to as *Phragmites*). Anthropogenic agricultural fertilizer use, wastewater effluent, and increases in watershed impervious surface provide a biogeochemical stressor in the form of excessive nutrient loads that have been linked with *Phragmites* invasion (Bertness et al., 1999) and eutrophication that can reduce high-marsh vegetation in favor of low-marsh species (Pennings et al., 2002). These habitat losses are exacerbated by sea level rise associated with the combined effects of rising global temperatures and natural land subsidence which converts marsh habitats into open water areas at the seaward edge of a marsh (FitzGerald et al., 2008) and leads to species die-offs as saltwater intrusion eliminates salt-intolerant vegetation at the landward edge (Fagherazzi et al., 2019). Under natural conditions, the continuum of salt-tolerant to salt-intolerant species would simply migrate inland; however, anthropogenic development at the landward edge of marshes provides a barrier for marsh migration creating a ‘coastal squeeze’ that results in habitat loss (Adam, 2019; Nevermann et al., 2023).

All of the above factors are relevant to Delaware marshes historically or currently (Tiner et al., 2011). Between 2007 and 2017, Delaware has lost 238 acres of vegetated tidal wetland with much of the losses due to erosion and sea level rise as well as development, transportation, land clearing, and agriculture (DNREC, 2022). Additionally, in that same decade, 3,979 acres of vegetated tidal wetlands shifted to non-vegetated (DNREC, 2022). Results generated from Mid-Atlantic Tidal Rapid Method estimates conducted within the past 15 years reveal ~15% of Delaware tidal wetlands to be severely stressed and an additional ~45% to be moderately stressed (Rogerson et al., 2010, 2011, 2013; Jennette et al., 2014; Smith et al., 2016; Dorset et al., 2017, 2018, 2019, 2020).

A commonality to the majority of marsh disturbances in the United States Mid-Atlantic region is the invasion of *Phragmites*, an invasive common reed originally from Eurasia that has rapidly spread throughout wetlands in North America outcompeting native vegetation including cordgrass species and the native *Phragmites* genotype (Hazelton et al., 2014). In the Delaware estuary, the initial establishment of invasive *Phragmites* dates back to the 1950s (Philipp and Field, 2005). Since its introduction, *Phragmites* has continued to encroach upon salt marshes along the East Coast of the United States, leading to declines in native vegetation, altered hydrology, and degradation of habitats for native wildlife (Benoit and Askins, 1999; Chambers et al., 1999; Kimball and Able, 2007; Marks et al., 1994). Tidal wetland assessments in Delaware marshes following the Mid-Atlantic Tidal Rapid Method frequently show the lowest scores

**Figure 1.** A comparison of a *Phragmites* stand (tall, brown-tipped reed to the right) and native *Spartina* grasses in the St. Jones National Estuary Research Reserve.

for "Habitat" (compared with "Hydrology" and "Buffer" categories) with invasion by *Phragmites* being a significant factor in the low "Habitat" scores (Rogerson et al., 2010, 2011, 2013; Jennette et al., 2014; Smith et al., 2016; Dorset et al., 2017, 2018, 2019, 2020). Because of its impacts on tidal marsh habitat, the control or removal of *Phragmites* via any of several mechanisms is a target of tidal marsh management plans within state (Rogerson et al., 2010, 2011, 2013; Jennette et al., 2014; Smith et al., 2016; Dorset et al., 2017, 2018, 2019, 2020; DNREC WMAP, 2022), federal (U.S. Fish and Wildlife Service), and privately-owned (including Delaware Wild Lands, the Nature Conservancy, individual landowners) marshes within Delaware and throughout the United States (Hazelton et al., 2014).

Recognizing their value to humans, land managers have sought to protect and restore tidal marshes via one of several methods to remove *Phragmites* and restore native vegetation. Efforts to remove *Phragmites* include some combination of nutrient reductions, hydrological restoration, contaminant elimination, and physical removal (Broome et al., 1988; Kutcher et al., 2018; Neckles et al., 2015; Zedler and Leach, 1998). The physical removal of *Phragmites* can be achieved via simple approaches such as mowing or using cattle grazers (Brundage, 2010; Tesauro and Ehrenfeld, 2007), but the application of herbicides is the most widespread approach, a practice often used in conjunction with prescribed burns (Hazelton et al, 2014), the focus of this report.

Regardless of the restoration method, it is vital to evaluate the efficacy of the restoration. All of these interventions come at a cost, and stakeholders will benefit from an evidence-based approach for assessing the value of restoration projects. Notably, despite the threat posed by *Phragmites*, its eradication is challenging, and recent work suggests it may offer ecosystem services (e.g., nutrient and pollutant remediation, carbon sequestration, storm resilience, and more) at rates equal to or exceeding native species (Hershner and Havens, 2008; Kiviat, 2013; Sheng et al., 2021; Theuerkauf et al., 2017). For example, *Phragmites* stores more carbon in its biomass and soils than native vegetation and can increase denitrification (Duke et al., 2015; Gu et al., 2020; Yacano et al., 2022). Further, recent work suggests that repeated herbicide applications can cause conversion of *Phragmites* habitat to open water (Hollis and Turner, 2019; Lane et al., 2016) resulting in a loss of all (native or *Phragmites*) marsh ecosystem services. Given the challenges and costs of removing *Phragmites* and replacing it with native vegetation, assessments of restoration impacts on ecosystem services are needed to ensure optimal outcomes.

## Goals and Objectives

With this document, we seek to place the role of prescribed burns into a climate-adaptive tidal marsh restoration framework. While there are studies assessing how prescribed burns impact individual ecosystem properties and/or services, we are unaware of reports that assess how the herbicide-burn restoration approach impacts a larger suite of physical, biogeochemical, recreational, cultural, and socio-economic ecosystem services. Thus, the goal of this document is to assess the state of knowledge of the effect of tidal marsh restorations that employ prescribed burns on ecosystem service categories identified as important to end users within the state of Delaware. The document intends to be of value to land managers and policymakers exploring solutions for marshes impacted by *Phragmites* invasion and who may consider the use of burns for *Phragmites* removal. No specific recommendations as to whether managers should or should not employ prescribed burns are made herein; instead, the known and unknown impacts of prescribed burns are cataloged such that land managers can make an educated assessment based on their own set of priorities.

An experimental plot frame placed on the marsh before vegetation was trimmed and amendments were added at St. Jones Delaware National Estuarine Research Reserve in Dover, DE, in June 2022.

# 2. Background

## Prescribed Burns

Prescribed burns are controlled burns used to achieve a management objective. The state of Delaware more specifically defines prescribed burning as the open burning of undisturbed vegetation for the specific purpose of conservation practices; wildlife habitat management; or plant, pest or disease control under such conditions that the fire is confined to a predetermined area (personal communication, Gerald Mood, DNREC Division of Air Quality). Within tidal marshes, prescribed burns are primarily used 1) for the removal of invasive *Phragmites* to restore native vegetation and associated habitat ecosystem services (e.g., improve waterfowl, fur-bearing animal habitat), 2) to reduce fuel loads from accumulated dead biomass and protect citizen lives and property from the risk of wildfires at the wildlife urban interface. The former application (*Phragmites* removal) is the primary focus of this document.

## Regulatory, Safety, and Environmental Considerations

Safe and effective prescribed burns require significant planning and are subject to regulatory, weather, safety, and personnel considerations. In the state of Delaware, the DNREC Division of Air Quality restricts prescribed burns to the period between October 1 and April 30. Emissions of particulate matter (PM2.5, PM10), nitrogen oxides, carbon monoxide and volatile organic compounds from prescribed burns react in the atmosphere to form ozone, a major influence on air quality. The longer daylight and higher temperatures between May 1 and September 30 allow for higher ozone formation from the emitted precursors, and burns are thus banned during this period to meet National Ambient Air Quality Standards set by the EPA in compliance with the Clean Air Act. Burns are further restricted to between the hours of 8:00 AM and 4:00 PM for safety considerations. Additionally, burning cannot occur on lands where trapping leases are active; those leases extend until March 15th further shortening this burn window. Land managers must submit an online application to DNREC (https://dnrec.delaware.gov/air/open-burning/prescribed-burns/) justifying that the prescribed burn a) is the most effective method for meeting their approved land management objective and b) does not impact a person's health or enjoyment of their property. Proximity of a proposed fire to human activity (e.g., residences, commercial businesses, schools, medical facilities, infrastructure) may thus play a role in application approval. Data on the number of prescribed fires conducted in Delaware are not easily attainable, but within a recent 5-year period 9 of the 14 fires intended to burn more

**Figure 2.** An example of prescribed burning of *Phragmites* in Delaware. Source: https://dnrec.delaware.gov/air/open-burning /prescribed-burns/

than 70 acres were marsh burns (personal communication, Gerald Mood, DNREC Division of Air Quality).

Burn effectiveness and safety are influenced by a variety of personnel, meteorological, and environment-specific factors. A team (~10-14 individuals) of experienced burn practitioners is required to safely perform prescribed burns. Temperature, wind speed, wind direction, recent precipitation, relative humidity, airmass stability, soil moisture, fuel moisture, and topography all influence burn safety and effectiveness (Waldrop and Goodrick, 2012). These factors further narrow the time window for conducting burns. Readers are directed to further reading for more details on how these various factors influence burn decisions (Waldrop and Goodrick, 2012). Briefly, slow (<20 mph), steady winds that allow for burn containment and transport burn emissions up in the atmosphere and away from humans are desirable. Relative humidities within the range of 30-55% and fuel moistures of 10-20% are optimal to ensure that fuel will burn but not spread beyond the containment area. Damp to wet soil moistures ensure maintenance of soil microbial communities and soil integrity (resistance to erosion).

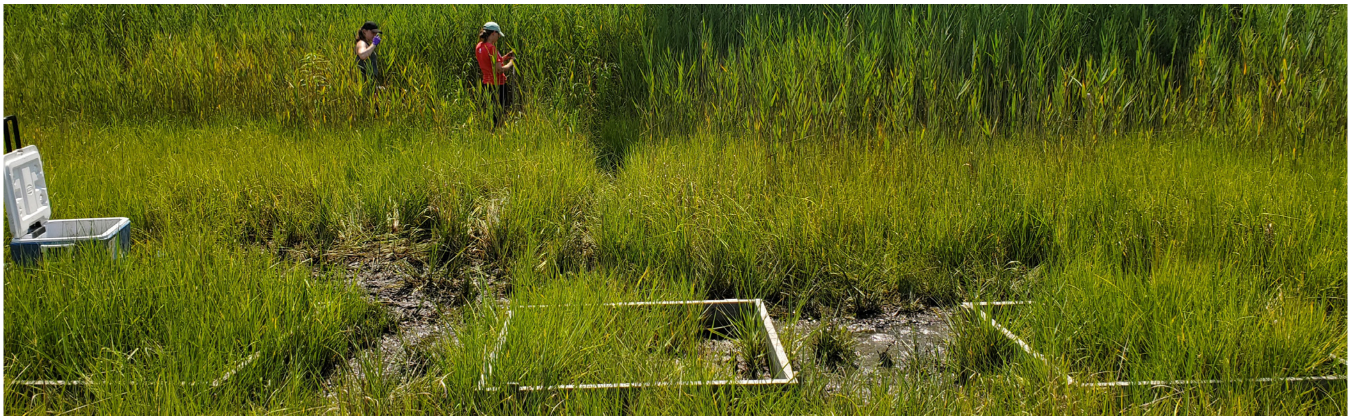
## Herbicide-Burn Tidal Marsh Restorations

Burns of *Phragmites* will kill aboveground biomass, but damp marsh soils prevent extensive damage to the rhizomes, and *Phragmites* will recover quickly. Consequently, prescribed burns are paired with additional control methods (e.g., cutting, mowing, herbicides) aimed at killing *Phragmites*. A common strategy is to pair herbicide applications pre- and/or post-burn, a strategy employed by DNREC and other entities in the Mid-Atlantic region. Burning after spraying removes the dead plant material to allow for the establishment of vegetation. Therefore, for the purposes of this document, we assume prescribed burns are paired with herbicide applications.

Given their use prior to burns, the impacts of herbicides to salt marsh wildlife must also be considered. Reported impacts of glyphosate-based herbicides include endocrine disruption in larval and juvenile frogs, genotoxicity and potential carcinogenicity to lab rats, and reproductive toxicity to mammals (Kiviat, 2009). Kiviat (2009) also documents imazapyr-based herbicides to cause human eye damage, fish toxicity, and potential carcinogenicity. An Australian study found that a phenoxy herbicide was mildly toxic to common salt marsh worm and amphipod species in the lab, but there were no impacts to invertebrate abundance after field herbicide application (Kleinhenz et al., 2016). Further, the herbicide was not acutely toxic to snails and was associated with an increase in crustacean abundance, which was attributed to soils rich in organic matter from decaying vegetation providing a food source (Kleinhenz et al., 2016). Glyphosate-based herbicide treatment paired with mowing resulted in greater abundances of small fish and crustaceans in untreated *Phragmites* relative to a treated area, but there was no difference in invertebrates which likely benefited from the litter supplied by mowing (Fell et al., 2006). That litter would be removed by burning, and the reduction in litter may be expected to reduce these populations.

Below, our assessments of burn impacts on ecosystem services assume a successful restoration, defined as a restoration that removes *Phragmites* and replaces it with native vegetation. In actuality, data on restoration success is infrequently reported (Gucker, 2008) with results varying depending on factors discussed below in the Biological ecosystem service section. Many managers, including DNREC (DNREC WMAP, 2022), often opt for repeated herbicide-fire treatments on varying timescales, but there is little information on the effects of repeated burns on *Phragmites* control and marsh ecosystem services.

# 3. Ecosystem Services



Emma Leaseburg and Jackalyn Wyrobek collecting samples from biochar amendment experiment plots at St. Jones Delaware National Estuarine Research Reserve in Dover, DE, in July 2023.

An ecosystem service is broadly defined as the "goods" or "benefits" that people derive from ecosystems (Barbier, 2007; MEA, 2005). These services are generated through both the direct and indirect impacts that they have on human society (US EPA, 2009); thus incorporating both intermediate and final end services. It should be noted that how ecosystem services are defined and categorized varies among practitioners. For example, the Millenium Ecosystem Assessment (MEA, 2005) categorized services as supporting (such as soil formation, primary production, and nutrient cycling and storage), regulating, (such as climate regulation, erosion control, and coastal protection), provisioning (such as fisheries, habitat, and agriculture), and cultural (including recreation, tourism, and spiritual importance; Adams et al, 2021; MEA, 2005), while de Groot et al. (2012) omit supporting services in favor of habitat services. For the purposes of this document, the authors and Biochar in Marsh Restoration Advisory Committee have elected to separate marsh ecosystem services into five main categories: Biogeochemical, Biological, Physical, Recreational, and Cultural. These sub-groupings allow us to focus on more specific "goods" and "services" provided by tidal marshes.

The myriad of ecosystem services offered by coastal marshes can be economically valued for their contributions to both natural systems and human well-being. Economic valuations have been of great interest to land managers and policymakers especially since the widely circulated Costanza et al. (1997) article on ecosystem services and natural capital. Methodologies for these valuations vary and are outside of the scope of this document. Interested readers are referred to literature describing contingent (or willingness to pay; Himes-Cornell et al., 2018; Mitchell and Carson, 1989) and replacement cost (or avoided-cost; Daily, 1997; Grabowski et al., 2012; Tietenberg and Folmer, 2005) approaches.

Several states, including Delaware, have conducted valuations for either state or region-wide ecosystem services (Barbier et al., 2011; Hauser and Bason, 2022; Kauffman, 2016; Santoni et al., 2017) with tidal marshes within the Delaware River Basin recently valued at $15,491-69,549/ha/year (Kauffman, 2016). These assessments evaluate current benefits derived from an ecosystem and give recommendations for restoration practices that will improve ecosystem structure and economic value. Recognizing and quantifying these ecosystem services enable policymakers and stakeholders to make informed decisions about marsh conservation and sustainable resource management. Importantly, these valuations are dependent on an understanding of how marsh systems respond to perturbations, including *Phragmites* invasion and restoration efforts.

## Ecosystem Service Assessments

Within this section, the peer-reviewed literature is reviewed for each marsh ecosystem service category within the context of how prescribed burns for the purpose of *Phragmites* removal and restoration of native vegetation will impact that service. Where possible, economic valuations of ecosystem services are described for added context. In several instances, there have been no definitive studies directly assessing prescribed burn impacts on an ecosystem service. In those situations, we note the absence of direct assessments and add educated speculation on potential impacts along with a recommendation for further research. A major challenge for assessing the effects of burning is a lack of data measuring the success of the burns for permanently removing *Phragmites* and restoring native vegetation. At the end of each section, we include an assessment of how prescribed burning for the removal of *Phragmites* and replacement with native vegetation impacts each tidal marsh ecosystem service affected by *Phragmites* invasion and management. The assessments follow the framework detailed in Tables 1 and 2 where burning *Phragmites* can have a negative (-), positive (+), no (0), or unknown (?) impact and are scored for our confidence (1= low confidence, 2 = moderate confidence, 3 = high confidence) in the assessments. The assessments for each ecosystem service are compiled below in Table 3 in the Summary section.

**Table 1.** Ecosystem Service Assessment Impact Scores

| Score | Description | Reasoning |
|---|---|---|
| - | Negative Impact | Available data demonstrate net negative impacts on the service of interest. |
| + | Positive Impact | Available data demonstrate net positive impacts on the service of interest. |
| 0 | No Impact | Available data demonstrate no net impacts on the service of interest. |
| ? | Unknown Impact | There are no data currently available that sufficiently assess burning impact on the service of interest OR available data demonstrate both positive and negative impacts. |

**Table 2.** Ecosystem Service Assessment Confidence Levels

| Score | Description | Reasoning |
|---|---|---|
| 1 | Low Confidence | Little to no data is available on the service of interest. Little to no regional or prescribed burn-specific data available. |
| 2 | Moderate Confidence | Sufficient data is available on the service of interest. Regional and prescribed burn specific data on the service of interest may be available as well |
| 3 | High Confidence | Sufficient data are available. Regional and prescribed burn related data on the service of interest are available as well. |

Recognizing that end users value ecosystem services differently and will want to manage marshes to maximize their value systems, these assessments are intended as a resource for interested stakeholders and managers who can incorporate this knowledge into their decision making strategy. We recommend that readers interpret these assessments through the lens of their own prioritization matrix and marsh systems of interest. Important caveats regarding these assessments include:

1) The ecosystem service assessments assume that burns are paired with herbicide treatments and that the restoration attempt is successful, resulting in the removal of all *Phragmites* and the subsequent recruitment of native vegetation. This assumption does not always hold true and likely depends on marsh-specific conditions but is necessary for making the ecosystem service assessments here.
2) The concomitant impacts of herbicide application alongside prescribed burns are included when assigning assessment impact scores.
3) Assessments are primarily based on available peer-reviewed scientific studies and quantitative evidence. Anecdotal evidence (non-quantitative, qualitative reports), although useful, is weighted with lower confidence than peer-reviewed scientific evidence.
4) The ecosystem impact scores should be viewed as net scores. Though an herbicide-burn restoration may score a net positive impact for a given class of ecosystem services, there will be cases where negative impacts on that service are observed due to marsh-specific conditions or to differential impacts on sub-classes of an ecosystem service (e.g., specialist bird species may benefit while generalist bird species may not).

Salt marsh at St. Jones Delaware National Estuarine Research Reserve in Dover, DE, in June 2022.

## Biogeochemical

The biogeochemical services provided by tidal marshes relate to how these environments cycle, store, and transform major biologically relevant elements including carbon, nitrogen, and phosphorus (Tobias and Neubaeur, 2019), trace metals (e.g., arsenic, cadmium, copper, manganese, lead, zinc, nickel; Reboreda and Caçador, 2007; Teuchies et al., 2013), and pollutants. The high productivity of salt marsh systems allows for the incorporation of carbon, nitrogen, and phosphorus into marsh vegetation biomass, and high sedimentation rates and euxinic (no oxygen, high sulfide) conditions leads to efficient burial of those elements in marsh soils thereby reducing the export of inorganic forms of nitrogen and phosphorus that could otherwise contribute to eutrophication issues in estuaries (Conley et al., 2009; Ryther and Dunstan, 1971; Sousa et al., 2012; Fig. 3). The same burial processes lead to the retention of trace metals and pollutants in soils (Bianco et al., 2021; Cai et al., 2020; Li et al., 2013; Ramos and Ashworth, 2024; Zheng et al., 2022).

*Phragmites* typically has much higher biomass than the native *Spartina* species in Mid-Atlantic tidal marshes (Kiviat, 2013; Windham, 2001) so removing *Phragmites* in favor of native vegetation may actually reduce the provision of these biogeochemical services. Prescribed burn interventions may offset losses in these additional biogeochemical services through the introduction of biochar, a material with unique sorptive and refractory physicochemical properties that results from burning (Fig. 4). The beneficial use of biochar has garnered significant interest for carbon sequestration and nutrient and pollutant mitigation (Majumder et al., 2023; Pignatello et al., 2017; Smernik, 2012) including recent work examining the potential benefits of prescribed burns for biogeochemical ecosystem

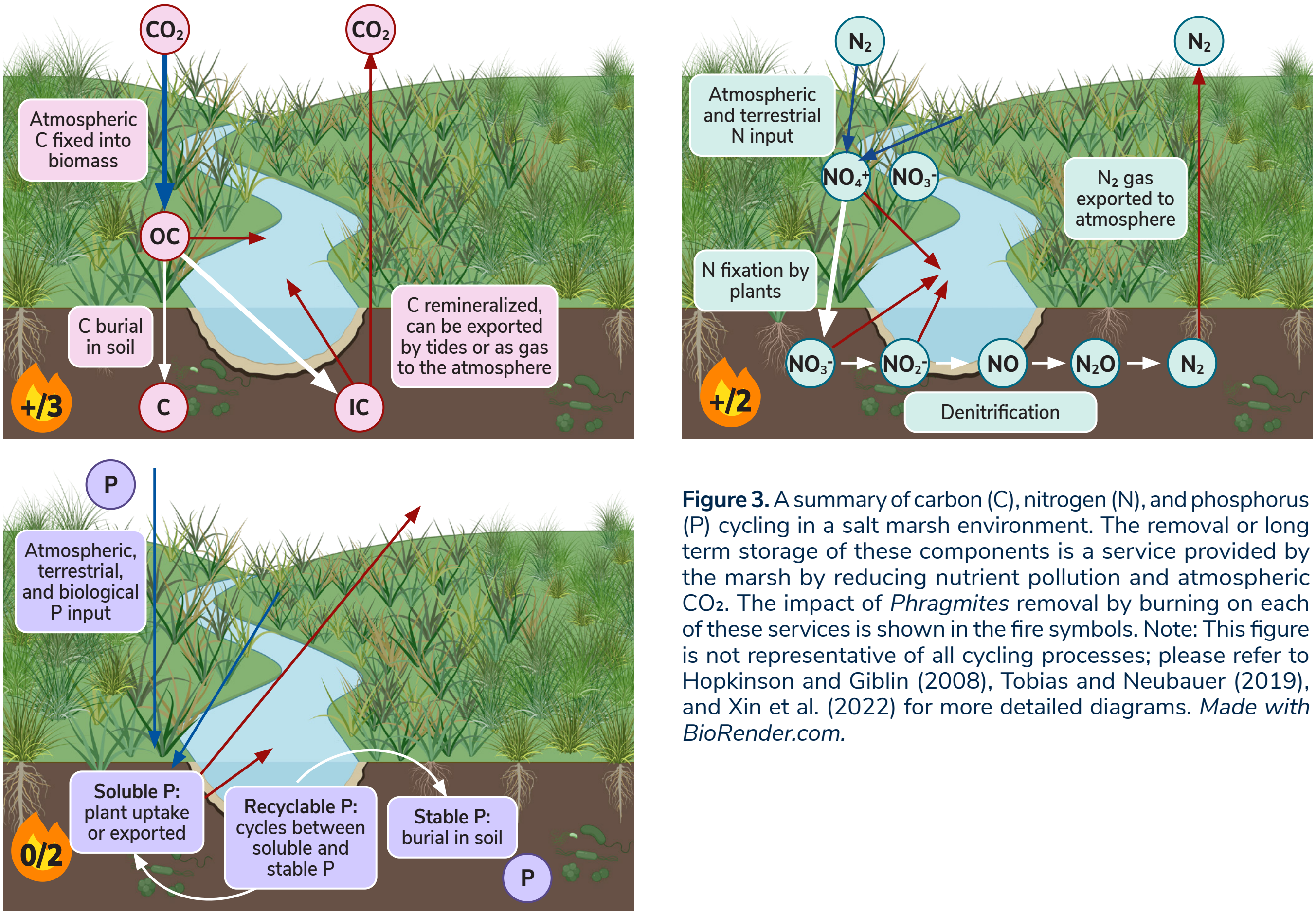


**Figure 3.** A summary of carbon (C), nitrogen (N), and phosphorus (P) cycling in a salt marsh environment. The removal or long term storage of these components is a service provided by the marsh by reducing nutrient pollution and atmospheric $CO_2$. The impact of *Phragmites* removal by burning on each of these services is shown in the fire symbols. Note: This figure is not representative of all cycling processes; please refer to Hopkinson and Giblin (2008), Tobias and Neubauer (2019), and Xin et al. (2022) for more detailed diagrams. *Made with BioRender.com.*

services (Edris, 2024; Kelly, 2023; Leaseburg, 2024). This is due to the resistance of biochar's aromatic molecular compounds to microbial degradation and its ability to sorb carbon, nutrients, and pollutants due to its characteristic high porosity, high surface area, and its surface chemistry (Bolton et al., 2019; Coppola et al., 2022; Lian and Xing, 2017; Zhang et al., 2019). The studied impacts of *Phragmites* removal via prescribed burning to carbon, nitrogen, and phosphorus storage as well as pollutant removal and greenhouse gas emissions are summarized below and in Figure 3.

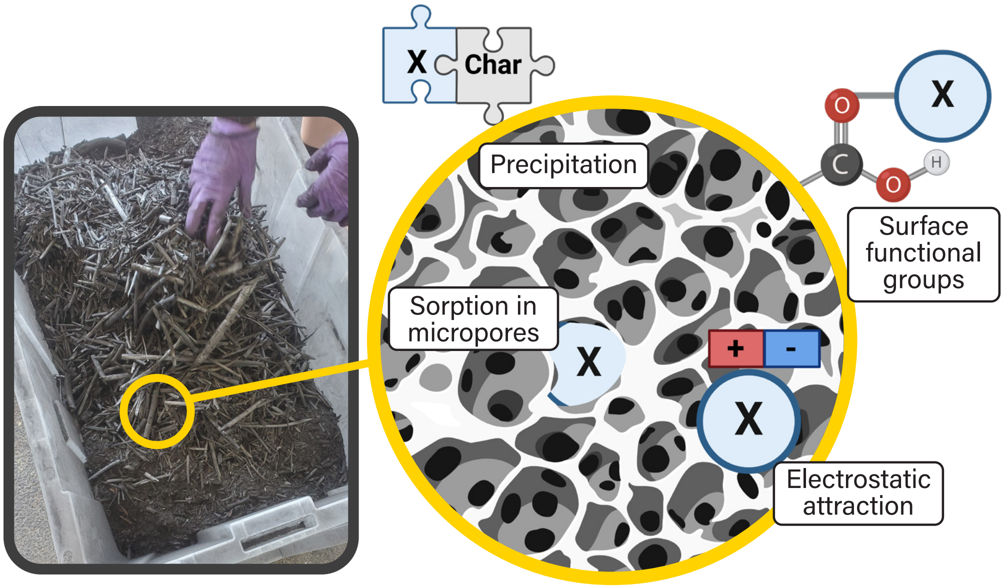


**Figure 4.** Left: An example of biochar produced from the common reed, *Phragmites australis*. Right: Biochar sorbs components like N, P, metal pollutants, and organic pollutants (collectively represented as X) through physical sorption (sorption in micropores) and chemical sorption (electrostatic attraction, hydrogen bonding, and precipitation). *Made with Biorender.com.*

Biochar-amended sediment mixture at an experimental setup at St. Jones Delaware National Estuarine Research Reserve in Dover, DE, in June 2022.

## Economic Benefits of Carbon and Nutrient Markets

Carbon and nutrient storage services provided by marshes also have economic benefits via payment for ecosystem service schemes like carbon markets and water quality trading (Canning et al., 2021; Heberling et al., 2018; Jenkins et al., 2010; McLeod et al., 2011; Raffensperger et al., 2017; Salzman et al., 2018). These alternative management techniques are thought to be cost effective and amount to $45 billion (2024 USD) in payments annually, but specific valuation and maintenance costs remain unclear, particularly due to variability in nutrient cycling processes in marshes (CPI Inflation Calculator; Mulvaney et al., 2022; Raffensperger et al., 2017; Salzman et al., 2018). Using incentives to increase participation, reducing barriers like high transaction costs, and using smart market optimization techniques for dynamic valuation would increase the value of nutrient credits and better contribute to reducing nutrient runoff (Heberling et al., 2018; Raffensperger et al., 2017). For example, restoring agricultural land to wetlands in the Mississippi Alluvial Valley is estimated to be worth $1,488/ha/yr (2024 USD) when considering the potential market value of greenhouse gas mitigation, nitrogen mitigation, and waterfowl recreation (CPI Inflation Calculator; Jenkins et al., 2010).

## Carbon Storage

High primary production and sedimentation rates bury and sequester organic carbon at high rates in tidal wetlands (Chmura et al., 2003) keeping that carbon from being transformed and returned to the atmosphere in the form of greenhouse gasses (carbon dioxide, methane). This marsh carbon sequestration is of increasing interest to land managers in the context of "blue carbon" markets that offer economic benefits for climate mitigation offsets (McLeod et al., 2011). Data from Delaware marshes suggest that burned marshes store more carbon than adjacent unburned marshes (Fig. 5, Kelly, 2023). Specifically, the burned marshes show higher accumulation of recalcitrant char materials that can be expected to be sequestered on centennial timescales (Kelly, 2023). Burned wetlands in China showed similar increases in soil carbon stocks (Wang et al., 2019; Zhao et al., 2012), and Leonard et al. (2010) observed that burning regimes in Chesapeake Bay tidal marshes led to increased above and below-ground vegetation growth. This could be attributed to the physicochemical properties of biochars, including its ability to sorb nutrients (Lian and Xing, 2017). Thus, while *Phragmites* is effective at carbon fixation (Caplan et al., 2015), a portion of the carbon storage ecosystem service that is lost to *Phragmites* removal may be recouped via char carbon inputs via their contributions to carbon stocks and their influence on belowground carbon storage. Thus, prescribed burning of *Phragmites* is rated to yield a positive impact to carbon storage with high confidence.

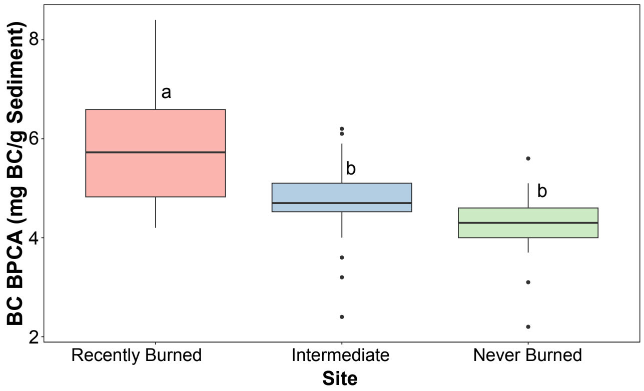


**Figure 5.** Box plots of black carbon concentrations—a recalcitrant carbon form and proxy for biochar input—compared across three marsh sites with varying burn frequencies ($n$ = 30–28). The most recently burned site has greater [black C] than the intermediate and never-burned sites, as indicated by 'a' and 'b' notations (ANOVA, $p < 0.001$; Kelly, 2023).

## Nitrogen Removal

Nitrogen is a necessary but highly limiting nutrient in many salt marsh systems and in excess can negatively impact sensitive estuarine waters. While nitrogen can enter the marsh system through a variety of terrestrial and marine channels, uptake of reactive nitrogenous compounds into vegetation and microbial biomass can immobilize it prior to its entering vulnerable estuarine and coastal waters. Denitrification processes (conversion of nitrate to $N_2$(g)) occurring in tidal wetland anoxic soils provide an additional biogeochemical service by further reducing the potential nitrogen pollution load (Martin et al., 1999; Yao et al., 2018). The presence of vegetation facilitates the denitrification process through increased organic matter accumulation and root zone oxygenation. Furthermore, studies have found that the type of vegetation present within a marsh also impacts the rate of denitrification. *Phragmites* invasion supports denitrification by supplying labile organic carbon compounds for oxidation and supporting nitrification through enhanced root zone oxygenation (Toyama et al., 2015; Yacano et al., 2022). Native plant assemblages such as *S. alterniflora* and *J. roemarianus* are unable to match the aggressive above and belowground biomass productivity of *Phragmites* leading to smaller nutrient fluxes from plant litter, root exudates, and trapped particulate organic matter, subsequently lessening the availability of carbonaceous electron donors and inorganic nitrogen species for denitrification thereby lowering overall denitrification capacity (Ehrenfeld, 2010; Ooi et al., 2022; Yacano et al., 2022).

Inputs of biochar from prescribed burn events may stimulate denitrification through a variety of direct and indirect mechanisms that could possibly recover losses in denitrification capacity after *Phragmites* is removed. In controlled incubation and mesocosm studies, biochar has been observed to facilitate denitrification both indirectly by inducing optimal environmental conditions and directly by assisting electron transfer to denitrifying organisms (Cayuela et al., 2013; Weldon et al., 2019).

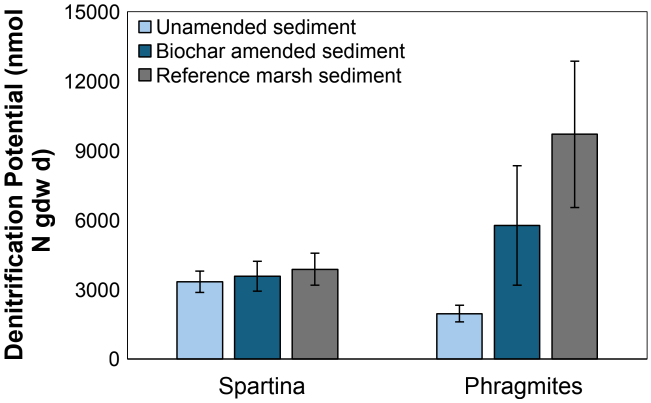


**Figure 6.** Average denitrification potential (n = 9-15) with standard error bars in reference marsh sediment and experimental plots with unamended and biochar amended (10% v/v) sediment applied. There was a significant difference in denitrification potential by treatment but not grass species (ANOVA: p = 0.045, p = 0.249, respectively).

However, *in situ* experiments display contradictory results where some conclude that biochar deposition has minimal effects on denitrification due to losses of the charred material via tidal flushing and wind export, volatilization of key nutrients during the burn process, or ecosystem level variables exerting more control over denitrification than biochar deposition alone (Geatz et al., 2013; Jones et al., 2022). A biochar amended thin layer placement study within a Delaware tidal marsh system found denitrification potentials to take approximately two years to return to pre-placement application with *Phragmites* biochar additions showing no clear denitrification enhancement over sediment additions without biochar (Fig. 6, Leaseburg, 2024). Those results suggest that removing *Phragmites* via burning in favor of native *Spartina* may reduce denitrification ecosystem services. However, further studies are needed to differentiate between the effects of biochar and post restoration vegetation recovery. Thus, the removal of *Phragmites* is thought to have a negative effect on denitrification with moderate confidence, since there is a potential for this process to be enhanced by biochar input from controlled burning.

## Phosphorus Storage

Phosphorus can be a limiting nutrient in salt marshes and adjacent coastal ecosystems (Schafer and Mack, 2018). Nutrient enrichment in marshes has been associated with decreases in belowground production and increases in microbial decomposition yielding destabilized peat and decreased accretion rates (Darby and Turner, 2008; Kutcher et al., 2018), both of which can contribute to marsh loss. Mid-Atlantic coastal plain estuaries are susceptible to eutrophication by residential and agricultural land-use exporting nutrients combined with shallow estuaries with long retention times (Volk et al., 2012), but estuaries can have different responses to nutrient abundances (Sharp et al., 2009). In theory, biochar introduced by prescribed burning of *Phragmites* could immobilize and store phosphorus in soils thereby reducing nutrient enrichment in marsh porewaters and the export of phosphorus to coastal waters. Controlled burning and biochar addition in agricultural, wastewater, and marine sediment applications have been found to increase phosphorus stocks in soil, particularly less mobile phosphorus forms, due to biochar's high surface area and acidic surface functional groups that enhance phosphorus sorption (Bolton et al., 2019; Faridullah et at., 2012; Strømgaard, 1992; Zhang et al., 2019). However, current work investigating phosphorus storage by burning and biochar application in Delaware salt marshes has found little to no association between phosphorus concentration and burn frequency, biochar addition, or black carbon concentration (a proxy for biochar input; Edris, 2024; Fig. 7). The lack of enhanced phosphorus storage likely results from differences in char properties resulting from prescribed burns compared to those for lab-produced chars. Subsequently, the impact of prescribed burning of *Phragmites* on phosphorus storage is assessed as having no effect with moderate confidence. Additional field studies would provide more clarity on the impact and confidence scores.

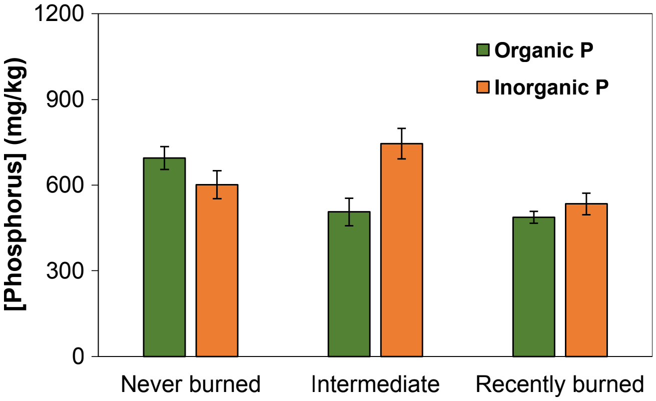


**Figure 7.** Mean organic phosphorus (OP, green) and inorganic phosphorus (IP, orange) concentrations with standard error bars (n = 51-57) in the surface soil of 3 Delaware marshes with different burn histories. The intermediately burned site has more IP than the recently burned site (ANOVA: p = 0.008), and the never burned site has more OP than the other 2 sites (ANOVA: p = 0.0002).

## Pollutant Removal

Heavy metals are accumulated in salt marsh biomass (Duarte et al., 2010) and soils (Teuchies et al., 2013) at high rates, keeping these harmful pollutants from entering estuaries. Biochar introduced by prescribed burning has been found to sorb heavy metals like lead, copper, and cadmium. (Cai et al., 2020; Li et al., 2013; Zheng et al., 2022). Arsenic, cadmium, chromium, lead, zinc, and copper were found to be removed by 53-96% due to the introduction of biochar (Das et al., 2023). Polycyclic aromatic hydrocarbons (PAHs), which are petroleum-derived and risk to human health, can also be remediated via biochar sorption as can polyfluorinated alkyl substances (PFAS; Bianco et al., 2021; Ramos and Ashworth, 2024). Thus, we speculate that prescribed burning of *Phragmites* has a positive impact on pollutant removal due to the introduction of biochar, but this assessment is made with low confidence. The specific properties of the char may determine its sorption effectiveness as was found for phosphorus storage (Edris, 2024). Field and lab studies to understand the effects of biochar derived from burned marshes on pollutant sorption are needed to increase this confidence.

## Greenhouse Gas Reduction

A study in Florida that measured greenhouse gas flux before and after controlled fires found there to be temporary increases in methane ($CH_4$) and nitrous oxide ($N_2O$) three to five days and one day after burning, respectively, and remained elevated for weeks after the fire (Levine et al., 1990). Longer duration of monitoring would be beneficial to quantify the direct impacts of controlled burns on greenhouse gas emissions. Mechanical removal of *Phragmites* by mulching in Rhode Island resulted in greater $CH_4$ emissions and lower carbon dioxide ($CO_2$) uptake than an untrimmed reference plot during one year of an experiment, but did not impact these emissions during another study year (Martin and Moseman-Valtierra, 2017a). Mesocosm experiments examining the influence of climate change conditions (elevated $CO_2$ and temperature) on greenhouse gas emissions in *Phragmites* and native *S. patens* stands found that *Phragmites* had significantly greater $CH_4$ emissions under climate change conditions than *S. patens* (Martin and Moseman-Valtierra, 2017b). However, a field study during a growing season in Massachusetts found there to be similar net fluxes of $CO_2$, $CH_4$, and $N_2O$ between *Phragmites* and *S. alterniflora* (Emery and Fulweiler, 2014). Emery and Fulweiler (2014) also note that unvegetated areas had greater net $CO_2$ emissions than vegetated areas, but the presence of vegetation did not affect $CH_4$ and $N_2O$ fluxes. Overall, *Phragmites* removal by burning or physical means resulted in a short term increase in greenhouse gas emissions while no apparent differences in emissions between grass species are observed, so the impact of burning *Phragmites* on greenhouse gas emissions is assessed to be negative with low confidence. More field studies with longer monitoring periods are needed to understand this relationship.

# Biological

Acting as a transitional zone between terrestrial and aquatic ecosystems, salt marshes provide refuge, feeding grounds, and spawning areas for a wide range of transient organisms, including birds, fish and crustaceans (Fischer et al., 2000). In addition to providing trophic support, salt marshes enhance the survivorship of these species by reducing their mortality rates (Deegan et al., 2000). Salt marsh systems are considered nursery grounds for juvenile forms of many fishes and are thus of great importance to commercial and recreational fishermen (Minello et al., 2003; Whitfield, 2017). Salt marshes serve as crucial areas for nesting, feeding, refuge, and migration for a variety of bird species, including shorebirds, perching birds, wading birds, ducks, gulls, and terns (Craig and Beal, 1992; Darnell and Smith, 2004; Teixeira et al., 2014) that are of interest to birders, photographers, hunters, and other recreational users of salt marshes. Therefore, the impacts of prescribed burning of *Phragmites* to restore native vegetation, invertebrates, fish, and birds are described below, including effects on specific species that may be management targets. As an ecosystem service, biological resources show considerable overlap with recreational ecosystem services.

## Native Vegetation

Understanding the response of native vegetation after controlled burning is vital to determining the success of this restoration strategy. The effects of annual burning on native vegetation in Blackwater National Wildlife Refuge, Maryland have been examined by multiple studies (Bickford et al., 2012; Flores, 2011; Leonard et al., 2010). Flores et al. (2011) examined the influence of burn frequency (none, annual, or three year) on vegetative response and found that live biomass was greatest with annual burning, but litter amounts were similar in the annual and three year burn regimes. It was also found that prescribed burning increased biomass and/or stem density of *Distichlis spicata*, *Spartina patens*, and *S. alterniflora* but not *Schoenplectus* *americanus* (Flores et al., 2011). Leonard et al. (2010) also investigated the impacts of burn frequency on vegetation but monitored longer burn treatments (none, annual, three to five year, and seven to ten year) and found no difference in overall, above-, or belowground biomass between burn regimes. By species, *D. spicata* had greater biomass in the burn sites than the control, but *S. americanus*, *S. cynosuroides*, and *S. patens* stem densities did not differ by burn treatment (Leonard et al., 2010). Bickford et al. (2012) examined burn sites (control or canopy replacement) and unburned sites (control, canopy removal, ash deposition, or canopy removal and ash deposition) to determine whether canopy removal or ash deposition is the mechanism responsible for vegetation recovery after burning. Canopy removal with or without burning increased above- and belowground biomass of sites dominated by sedge, but there was no significant difference in biomass with the same treatments in the grass-dominated sites. Vegetation response to treatment varied by subestuary which was attributed to site environmental conditions and surrounding vegetation more than watershed land use differences (Rohal et al., 2023). A wildfire near the Long Island Sound, NY provided an opportunity to measure the influence of burning on plant communities for three years (Tyo and Andruk, 2022). Plant abundances and species richness were not affected by the wildfire in the salt marsh habitat. Interestingly, *Phragmites* was dominant immediately after the fire, but *S. patens* recovered and became dominant one year after the fire (Tyo and Andruk, 2022). Along the Chesapeake Bay, eight subestuaries with *Phragmites* invasion were subject to three years of herbicide treatment and two years of monitoring which revealed that the cover of *Phragmites* was reduced and native plant communities increased, but the composition of treated sites remained distinct from native reference plots suggesting incomplete restoration during the monitored period (Rohal et al., 2023).

Other work has shown *Phragmites* shoot densities to recover to pre-fire densities within three years of herbicide-paired burns (Ailes, 1993; Boone, 1987; Chambers et al., 1999; Gucker, 2008), and it must be noted that *Phragmites* still has the ability to re-invade areas that have experienced burns or

*Phragmites australis* florets. *Credit: DNREC.*

other management practices (Hazelton, 2018; Tyo and Andruk, 2022). A literature review to examine the causes of variation in vegetation response to *Phragmites* management found that factors influencing the reduction of *Phragmites* and recovery of native vegetation after treatment include the type of treatment, initial area of invasive vegetation, duration of treatment, and site and landscape conditions like hydrology, extent of surrounding healthy vegetation, and the presence of a native seed bank (Rohal et al., 2023).

In summary, removing *Phragmites* by burning and herbicide applications resulted in no difference or an increase in native vegetation with the outcome varying by grass species and site parameters. Native vegetation is therefore assessed to be positively impacted by prescribed burns with moderate confidence. Since restoring native vegetation is a major goal of these management efforts, continuing to monitor the native vegetation response (for greater than five years) to burning and herbicide application is needed to evaluate the success of restoration efforts.

## Invertebrate Habitat

The removal of *Phragmites* via burning and herbicides demonstrated a positive effect on invertebrate populations along the Alloway Creek in Delaware Bay (Gratton and Denno, 2006; Kimball and Able, 2007). Restored sections of marsh, which resembled native vegetation communities within five years of *Phragmites* treatment, exhibited higher catch per unit effort for blue crabs as well as a return to arthropod food web assemblages similar to *Spartina* reference sites (Kimball and Able, 2007).

Some studies conducted along the East Coast of the United States observed positive relationships between the removal of *Phragmites* from disturbed wetlands and the restoration of pre-disturbance arthropod food webs (Fell et al., 2003; Gratton and Denno, 2006). However, there are conflicting reports that observed *Phragmites* stands exhibiting similar species assemblages and acting as invertebrate habitats (Able and Hagan, 2000; Hanson et al., 2002; Kimball and Able, 2007). For example, Able and Hagan (2000) found blue crabs (*Callinectes sapidus*) and ghost shrimp (*Palaemonetes*) to be more abundant in *Spartina* habitats while mud crabs (*Rhithropanopeus harrisii*) are more abundant in *Phragmites* habitat. Hanson et al. (2002) found similar species in *Phragmites*-dominated sites as in *Spartina*-dominated sites along the Hudson River estuary including dagger-blade grass shrimp (*Palaemonetes pugio*), blue crab, and water fiddler crab (*Uca minax*). Rochlin et al. (2012) found restoration efforts to encourage tidal exchange which resulted in a shift from *Phragmites* to native vegetation that was associated with an increase in blue crab abundance. The rare skipper (*Problema bulenta*), a butterfly native to *S. cynosuroides* brackish marshes (Cromartie and Schweitzer, 1993) and considered to be at risk for extinction by NatureServe, may have their overwintering populations eliminated by winter burning of *Phragmites*.

These studies overall indicate that the effectiveness of *Phragmites* removal on invertebrate species abundance is dependent on a number of external factors including hydrology, species life cycle behavior, and size. The balance of the literature suggests *Phragmites* removal positively impacts invertebrate communities, but confidence is moderate with regard to this benefit. Individual species can be negatively affected, and further burn-specific studies are needed to confirm this assessment.

## Fish Habitat

Marshes and adjacent estuarine waters act as critical nursery grounds for commercially, recreationally, and ecologically important fisheries, making it essential to understand how treatment and removal of *Phragmites* may impact this function. Along the Alloway Creek in Delaware Bay, sites restored by a two year treatment period of herbicide application and prescribed burning acted as nurseries for mummichogs similar to native vegetation reference sites within two years of ceasing treatment (Able

Salt marsh at St. Jones Delaware National Estuarine Research Reserve in Dover, DE, in July 2022, where a biochar amendment experiment was conducted.

et al., 2003) which indicated that habitat function was restored after burning. Additional studies conducted along the same creek around the same time period on overall fish assemblages found little to no differences in species composition and abundance among sites differing in vegetation type which was attributed to the greater impacts of site properties like salinity, tidal range, and water depth on fish habitat preferences (Grothues and Able, 2003; Kimball and Able, 2007). There were some vegetative habitat preferences observed for specific species. Several studies reported greater abundances of juvenile fish at undisturbed or restored sites dominated by native vegetation compared to *Phragmites*-dominated sites such as mummichogs (*Fundulus heteroclitus*), spotfin killifish (*Fundulus luciae*), bay anchovy (*Anchoa mitchilli*), Atlantic silverside (*Menidia menidia*), hogchoker (*Trinectes maculatus*), and sheepshead minnow (*Cyprinodon variegatus*), which indicates that native vegetation creates important fish resident and nursery habitat (Able et al. 2003; Able and Hagan, 2000; Grothues and Able, 2003; Rochlin et al., 2012; Weinstein et al. 2019; Weinstein and Balletto, 1999). Sampling along the Mid-Atlantic found increasing stages of *Phragmites* invasion to be associated with a decline in habitat function for young mummichogs, reduction in spotfin killifish populations, and an overall decrease in fish abundance (Hunter et al., 2006). Notably, *Phragmites* has been observed to be a preferable habitat for some nekton including, mummichog, spot (*Leiostomus xanthurus*), Atlantic menhaden (*Brevoortia tyrannus*), and white perch (*Morone americana*; Hanson et al, 2002; Fell et al., 2003; Grothues and Able, 2003). It is important to monitor fish responses to controlled burning for extended time periods because research conducted in the Everglades observed that prescribed burns created a pulsed effect in wetlands with only a short-term increase in fish abundance (Venne et al., 2016). Overall, removing *Phragmites* with prescribed burns has a positive impact on fish populations, though some species preferred *Phragmites* habitats, which results in moderate confidence of controlled burning benefitting fish.

## Bird Habitat

Wetland prescribed burns have a varied effect on bird populations depending on several factors including bird species and season of burn (Mitchell et al., 2006). Burns are often conducted for the creation of better waterfowl habitats by removing certain native species such as *Spartina patens*, *Juncus roemerianus*, and *Distichlis spicata* which are less suitable waterfowl food (Goodwin, 1979). While there is not much scientific literature documenting the success of prescribed burns for waterfowl populations, a New Jersey study found that several duck species (American black duck, green-winged teal, northern shoveler, and northern pintail) did not have different eating habits in different vegetation habitats, but mallards ate more in *Phragmites* and mudflat habitat than in native grass habitat (van Neste et al., 2020). Duck habitat preferences may be due to other environmental factors like open water access and vegetation canopy rather than grass species (Kantrud, 1986).

Prescribed burns conducted to promote waterfowl habitat along the Gulf Coast and in Utah were observed to have both positive impacts on the abundance of non-target species such as blackbirds, sparrows, and wrens but negative impacts on egret and heron nesting habitat (Bray, 1984; Gabrey et al., 1999). Several studies centered around the Chesapeake Bay have found that prescribed burns have positive effects on populations of least bitterns, Virginia rails, saltmarsh sparrows, and seaside sparrows (Kern, 2010; Kern et al., 2012; Kern and Shriver, 2014).

Though these results indicate that there is a net positive impact on bird populations from prescribed burns, more research is needed to assess how the timing and number of burns continue to affect populations especially for larger, nest building species. Further research is also needed on whether burns or other management strategies such as tidal restoration are the driving factor in bird population success (Kern et al., 2012; Rochlin et al., 2012; Rogers et al., 2013; Kern and Shriver, 2014). Burns paired with herbicide applications have the potential to negatively impact bird species, as seen in a preliminary study by Lazaran et al. (2013) where marsh wren nest and territory density declined after aerial herbicide application, but longer term and broader scope studies are needed to determine the impacts of herbicide-burn treatments on avian communities.

The utilization of *Phragmites* stands by various bird species post-restoration has been studied in multiple areas along the Atlantic coast, Gulf coast, and Great Lakes. Some early reporting on the effect of the invasive reed in 40 Connecticut sites found that marsh wren, swamp sparrow, red-winged blackbird, tree swallows, and barn swallows used *Phragmites*-dominated areas while seaside sparrows, saltmarsh sharp-tailed sparrow, willet, wading birds (snowy egret, green heron), water fowl (mallard, American black duck), and shorebirds (willet, least sandpiper, semipalmated sandpipers) did not use *Phragmites* habitat (Beniot and Askins, 1999). Marsh wrens did not nest in *Phragmites* in a study along Lake Erie (Lazaran et al., 2013). *Phragmites* thus appears to benefit a few species but adversely affects already declining species (Benoit and Askins, 1999; Chambers et al, 2012; Whyte et al., 2015). Key tidal marsh species such as great egrets and blue herons were observed to not utilize *Phragmites* stands for nesting and foraging (Parsons, 2003; Trocki and Paton, 2006). The effect of *Phragmites* on avian populations can also be broken down into how certain foraging guilds respond to either invasion or restoration. Guntenspergen and Nordby (2006) found that generalists (birds that nest outside of marshes including wading birds, shorebirds, ducks, and aerial insectivores) were unaffected by the reed invasions, but specialist species (birds that nest in marshes including seaside sparrow, saltmarsh sharp-tailed sparrow, willet) are more likely to be affected. There is increased risk of negative effects on specialist species as *Phragmites* stands grow in size leading to decreased edge habitats utilized by waders. Overall, *Phragmites* appears to benefit generalist species while having a negative impact

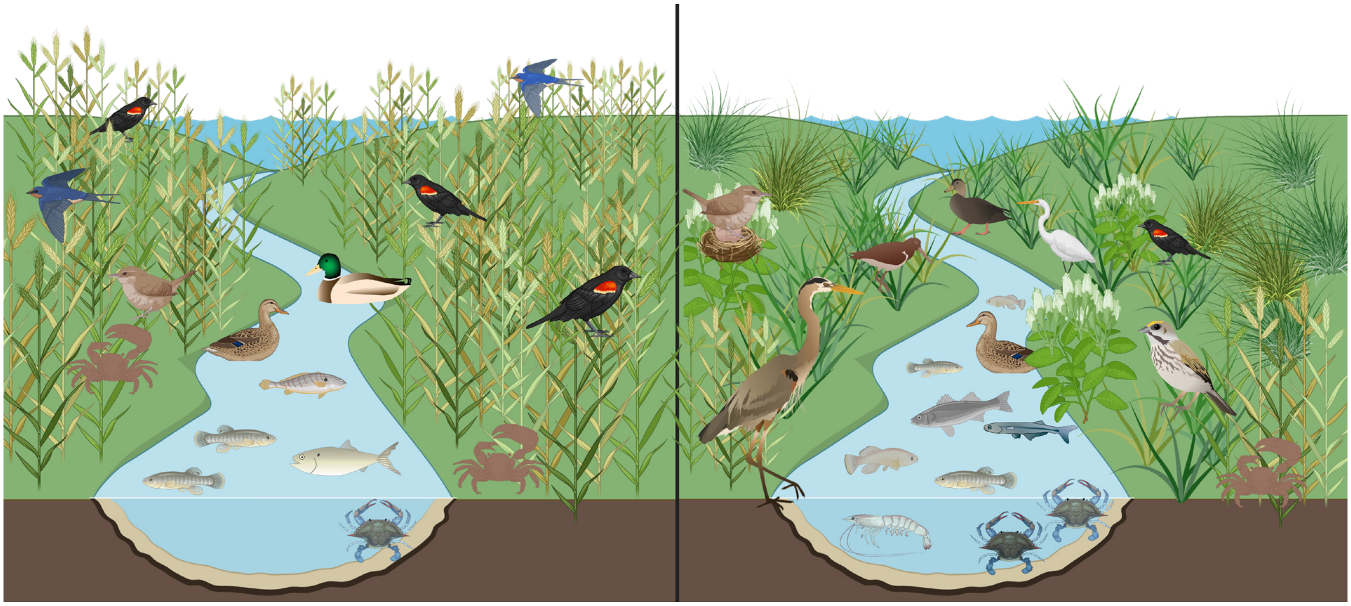


**Figure 8**. A summary of the differences in biological services provided by a *Phragmites* impacted marsh (left) vs an idealized restored marsh (right). In the restored marsh, there is more native vegetation than invasive which facilitates an overall increase in invertebrate, fish, and bird species and abundance. The response of specific species to restoration by burning varies. Made with BioRender.com using some images from Integration and Application Network (ian.umces.edu/media-library).

on the abundance of already declining species with specialist feeding strategies. Restoration practices to enhance tidal exchange increased species richness and abundance in urban wetlands like water birds including sandpipers, killdeer, yellow legs, ducks, and Canada geese as well as many passerine birds in New York and New Jersey marshes likely by restoring habitat heterogeneity (Rochlin et al., 2012; Seigel et al., 2005).

Overall, *Phragmites* management by prescribed burning has a positive impact on salt marsh bird communities with moderate confidence due to varied responses by specific species. Species, burn conditions and timing, and environmental conditions impact the habitat use and population of avian species. Managers should consider the impact of *Phragmites* to the decline of threatened and endangered species, the reported responses of species of interest, and the negative impacts of herbicides on biological ecosystem services in the context of their specific biological management goals and outcomes.

## Physical

Physical ecosystem services such as sedimentation, elevation maintenance, hydrology/tidal flow, and coastal resilience are vital to marsh function and longevity. Collectively, these services determine a marsh's ability to withstand sea level rise, erosion, and marsh loss.

### Sedimentation

Marsh vegetation contributes to sedimentation by trapping mineral sediments from tides and storms and by directly supplying organic material via litter (Cahoon et al., 2010; Chambers et al., 1999; Henton et al., 2013), which maintains marsh area. It has been found that burning in marshes decreases the litter and surface accretion rates in a Mid-Atlantic marsh whose main sediment source is plant litter (Cahoon et al., 2010). Opposingly, a companion study in Texas marshes that had high mineral sediment input from hurricanes found increased surface accretion with burning which could potentially be due to ash deposition (McKee and Grace, 2012). Further direct tests are needed to assess the impacts of burning on sedimentation.

Information on potential burning restoration impacts can be gained by investigating sediment accretion in *Phragmites* versus native grass marshes. *Phragmites* marshes are associated with high sedimentation rates due to high rates of above- and belowground biomass production resulting in higher organic matter accumulation rates, stabilization of surface sediments, and increased sediment trapping from the water column (Chambers et al., 1999). To test this association, Coleman et al. (2023) used a model based on a long term field study comparing the impact of *Phragmites* versus native vegetation on marsh sedimentation rate and found that *S. alterniflora* attenuated incoming waves more efficiently than *Phragmites* due to *S. alterniflora*'s greater stem density. This lowered wave energy would be more favorable for sediment deposition, but the model results may depend on stem density rather than vegetation species and contrast with other observational and modeling work. A study conducted in an eastern shore Chesapeake Bay marsh found no difference in sediment deposition between *S. alterniflora* and *Phragmites* (Leonard et al., 2002). However, in a Deal Island Wildlife Management area marsh further south along the eastern shore of Chesapeake Bay, short term sediment deposition was higher in *Phragmites* areas than *Spartina*, possibly due to the high density of *Phragmites* litter contributing to and trapping additional sediment (Rooth and Stevenson, 2000). In a longer term study in the same area, Rooth et al. (2003) found that a 20-year old *Phragmites* stand had the greatest accretion rate compared to 5-year old *Phragmites* and native grasses (*Typha* spp. and *Panicum virgatum*), a result that was attributed to *Phragmites*' high litter production. This finding was corroborated by a modeling study which examined how vegetation, waves, inundation, and coastal structure influence accretion in New York marshes and found greater accretion of sediment in *Phragmites* marshes compared to *S. alterniflora*; the higher accretion rates were attributed to the greater amounts of slowly degrading litter produced by *Phragmites* enabling enhanced sediment trapping (Sheng et al., 2021).

Overall, the summarized value of the impact of burning *Phragmites* on sedimentation rates is assessed as negative with moderate confidence due to more studies suggesting *Phragmites* to be situationally more favorable for sedimentation and because additional studies of burned marshes are needed. Ultimately, sedimentation is impacted by a variety of factors including sediment source, hydrodynamics, and other disturbances. Removing vegetation generally has a negative impact on sediment accretion, and more studies showed *Phragmites* to be more effective at sediment accumulation than native grasses. There is a need for research into the properties of a marsh that most influence sedimentation rates including field studies regarding 1) how sediment composition on a mineral to organic matter dominated continuum influences sedimentation impacts, and 2) how variations in plant-specific properties (e.g., species, stem density, biomass quantities) determine vegetation's ability to attenuate waves and trap sediment.

## Elevation Maintenance

Beyond surface sediment accretion, marsh elevation gain to keep up with sea level rise also involves root zone subsidence and the shrink-swell of lower sediment horizons (Cahoon et al., 2010). One study found that while burning was associated with a short-term elevation drop (first 3 months post burn), there were no significant differences in long term elevation 2 years after burning (Henton et al., 2013). This was corroborated by another study finding that annual burning did not significantly impact overall vertical development since their lowered surface accretion rates were offset by a decline in root zone subsidence compared to less frequent and unburned sites (Cahoon et al., 2010). However, with a 3-5 year burn regime, burning increased elevation gain compared to not burning, which in this case was attributed to surface accretion from ash deposition (McKee and Grace, 2012). Burn frequency seems to influence the impact of elevation changes with less frequent burns being associated with elevation gain. Since prescribed burning is typically paired with herbicide use, it is important to note that a study from Louisiana found decreased elevation in areas treated with herbicide despite a lack of impact on decomposition rates at sites of varying salinity (Lane et al., 2016). This could be due to herbicide addition reducing root tensile strength and potentially marsh soil stability as was found by Hollis and Turner (2019).

The contrasting results lead to a rating of unknown effect (due to variable observations) with moderate confidence regarding how herbicide-burning treatments of *Phragmites* influence elevation in tidal marshes. The disparate apparent effects suggests that the mechanism of restoration (e.g., burn frequency, herbicide intensity) may influence the impacts. Future work may be able to clarify the potential roles of burn frequency and herbicide additions and provide clarity on the mechanisms driving elevation changes due to burning over long periods of time.

## Tidal Flow

Tidal flow in marshes impacts gas and nutrient exchange between soil and water, microclimate regulation, food quality of suspension feeders, sediment deposition and retention, and export of organic material to estuaries (Leonard et al., 2002). Vegetation impacts flow velocity, direction, and turbulence, which influences sediment transport and wave attenuation in marshes (Tempest et al., 2015). Tidal flow and wave energy rapidly dissipate due to friction with marsh vegetation, but the rate is determined by flow conditions and plant properties like vegetation type and flexibility (Schoutens et al., 2019; Shepard et al., 2011; Tempest et al., 2015). For example, tidal and wave flows decrease with increasing plant biomass, stem density, and height (Tempest et al., 2015).

Our analysis found no studies directly assessing prescribed burn impacts on tidal flow so the differences between *Phragmites* and *S. alterniflora* will be discussed. Leonard et al. (2002) observed greater variation in flow direction in a *S. alterniflora* marsh in Maryland, which indicates a potential difference in tidal flow structure and sedimentation in high water events. Unfortunately, this study did not have a full data set on flow property differences in *Phragmites* and *S. alterniflora* marshes due to low water level during the sampling period (Leonard et al., 2002). As a result, the trends of greater plant biomass, stem density, and height reducing tidal velocity and wave energy described by Tempest et al. (2015) could still suggest that *Phragmites* may be more effective at reducing tidal flow.

Since no published studies investigating the impact of burning to tidal flow were found, the assessed impact of prescribed burns is unknown with low confidence. There is a potential for *Phragmites* to reduce flow more than native grasses, but more comprehensive field studies are needed to confirm this trend.

## Coastal Resilience

Marshes improve coastal resilience by reducing the impacts of flooding and attenuating wave energy, which protects coastal structures and reduces coastal erosion. Elevation maintenance with the pace of sea level rise is an important aspect of coastal resilience that is discussed above. Prescribed burning protects coastal communities by reducing fuel loads (Cahoon et al., 2010; McKee and Grace, 2012), but burning may need to be frequent since dead plant material returns to pre-burn conditions quickly (1-2 years, McKee and Grace, 2012).

Vegetation contributes to wave attenuation by impacting flow as discussed above. A model calibrated with a long-term field study found that *S. alterniflora*'s greater stem density attenuates waves more efficiently than *Phragmites*, especially in late fall which corresponds to more protection from hurricanes (Coleman et al., 2023). This study also noted that at high water storm surge conditions, both grasses were similarly ineffective at reducing wave heights. Notably, the extension of these models to marshes in other locations depends on the stem densities for vegetation at a given marsh.

A New York study using a model that considers vegetation properties, inundation, wave height, and an economic analysis using building and damage report data found no difference in inundation or surface currents between *Phragmites* and native *Typha* grasses (Sheng et al., 2021). During the growing season, there was also no difference between grass type and impact on wave height, however *Phragmites* continued to dissipate waves while *Typha* did not. A study in North Carolina marshes found no impact of the density of *Phragmites* on shoreline stabilization, but this could be due to low aboveground biomass in the studied marshes compared to Mid-Atlantic and northeast US *Phragmites* stands (Theuerkauf et al., 2017). When *Phragmites* are growing behind dunes, any stabilization effect they provide prevents the dunes from naturally migrating landward, so the dunes erode with sea level rise.

It is important to note that for the context of removing *Phragmites*, it is significantly more beneficial to have any vegetation (native or invasive) than an unvegetated tidal flat, so efforts to remove *Phragmites* also need to include the reestablishment of native grasses (Coleman et al., 2023; Leonard et al., 2002; Rooth and Stevenson, 2000; Sheng et al., 2021). Notably, the repeated application of herbicides has been found to convert *Phragmites* to unvegetated soils with reduced ability to withstand erosion that are ultimately converted to open water habitat (Fell et al., 2006, Lane et al., 2016; Hollis and Turner, 2019), an outcome that removes marsh cover and eliminates associated ecosystem services. Specifically, glyphosate application has been observed to reduce elevation compared to untreated areas (Lane et al., 2016), and experimental atrazine addition reduced the tensile root strength of *S. patens* (Hollis and Turner, 2019). Successful planting campaigns may prevent the erosion of soils and conversion to open water. Timing of herbicide application in the growing season or tidal cycle, amount of inundation, and manual application could improve the effectiveness and reduce the negative impacts of herbicide application (Elsey-Quirk and Leck, 2021; Kiviat, 2009; Kleinhenz et al., 2016; Ruggeri, 2014). While damage to coastal structures is influenced by wetland type and size as well as storm characteristics, a vegetated marsh is predicted to reduce loss from storm flooding and waves by $2 million compared to an unvegetated tidal flat (Sheng et al., 2021). *Phragmites* removal should be limited to areas with plant and wildlife diversity goals since its removal could contribute to erosion, particularly in already vulnerable marshes (Rooth and Stevenson, 2000).

In summary, the impact of burning *Phragmites* is assessed to have an unknown impact on coastal resilience (due to variable observations) with low confidence. Burning itself reduces fuel loads, but there are conflicting results of the impact of grass type on wave attenuation and shoreline stability.

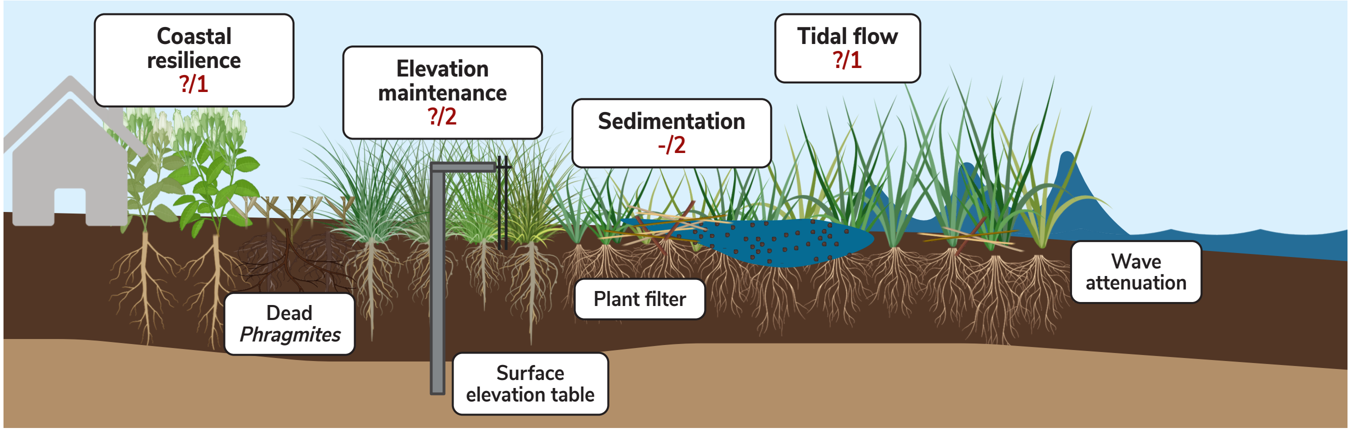


**Figure 9.** A summary of physical services provided by a Mid-Atlantic, USA, *Spartina*-dominated marsh. The impact of *Phragmites* removal by burning is indicated in red text. Sedimentation includes trapping sediment from tidal water and depositing sediment as decomposed plant litter. Elevation maintenance is represented by a surface elevation table which is used to track marsh elevation over time. Wave attenuation describes the reduction in wave energy through the marsh by friction with plants and enhances coastal resilience. *Made with BioRender.com.*

## Recreational

Tidal marshes benefit the public in numerous ways that have been listed throughout this document, but recreation serves as a direct and visible service to most people. These services are of significant interest to policymakers and researchers as they are often how the public interacts with these wetlands. According to Santoni et al. (2017), a survey conducted in 2015 revealed that 68% of Delaware residents interacted recreationally with salt marshes by engaging in activities such as fishing/shellfishing, hiking, birdwatching, kayaking, and hunting, among others.

Within the context of this document's analysis, there are no studies examining how prescribed burns in tidal marshes affect recreational activities. We are also unaware of studies examining how recreational interests are impacted by the presence or absence of *Phragmites* versus native vegetation. Recreation in and around tidal marshes rely on the existence of a marsh and its resources (e.g., vegetation for viewing and habitat; creeks for boating and habitat; birds for hunting, viewing, photographing; fish, crabs, and muskrats for fishing, crabbing, and trapping). To that end, recreational ecosystem services are intimately tied to biological services influencing vegetation and animal presences and abundances as well as physical services that influence the existence of the marsh.

Recreational services provided by marshes are tightly coupled to economic benefits created as people visit these habitats through ecotourism. Santoni et al. (2017) estimated that DE residents spent $38 million on fishing, $15 million on wildlife viewing, and $9 million on hunting annually while utilizing DE salt marshes. In 2006, it was estimated that 23 million United States residents 16 years and older traveled at least 1 mile to observe wildlife, and an estimate of 81.1 million stayed within a mile of home for wildlife viewing (Aiken, 2009; US Fish and Wildlife Service, 2016). These numbers demonstrate the public's interest in and willingness to pay for trips to enjoy various recreational activities (e.g., hunting, fishing, hiking, and wildlife viewing) and justify restoration or preservation practices.

Myers et al. (2010) surveyed visitors to three popular birding locations along the Delaware Bay during the annual horseshoe crab spawning season to gauge how much the average household was willing to pay for day and overnight birding trips. They concluded that the average household was willing to spend $93.55-127.56 for day trips and $283.48-602.39 for overnight visits adjusted for current inflation (CPI Inflation Calculator, US BLS). An investigation into the economic value of wetlands-based recreation around coastal Louisiana dating back to 1990 estimated an annual aggregate value of $145 million (Bergstrom et al., 1990). A more recent study utilizing a nationwide survey estimated households would be willing to pay a one time tax of $909 for restoration along coastal Louisiana, and resource users are willing to pay a substantially higher price (Petrolia et al., 2014). While there are no studies examining the influence of prescribed burning on ecotourism, restoration to improve the experience of marsh visits such as enhancing landscapes and wildlife presence is expected to have a positive impact on ecotourism with low confidence.

The abundance of hunting and fishing species in response to *Phragmites* burning can be predicted based on the reaction of species of interest described in the biological section above. Management objectives of marsh restoration by *Phragmites* removal frequently seek to have a positive impact on hunters and fishers, but there is a lack of information shared. There is a need to study the impacts of prescribed burning on marsh recreational services due to the public and economic importance of these services. While improving these services are often a restoration goal, the success of these measures needs to be monitored and reported.

## Public Perception of Prescribed Burning

Examination of public perceptions of prescribed burns in other systems may inform how they are viewed in wetlands. A study investigating public perception of prescribed burns in ponderosa pine forests near Tucson, AZ found that survey participants were generally pro-burning to improve scenery (Taylor and Daniel, 1984). Miller et al. (2002), conducted surveys around the Greater Chicago Region's tall-grass prairies and oak savannas which revealed that 73% of the respondents were pro-burning in either some or all cases. A more local study focusing on land managers and forest recreationists around Pennsylvania and New Jersey employed intercept surveys and found support for prescribed burns as well as a moderate public understanding of burn practices (Wu et al., 2022).

The results of these studies indicate there is a general trend of acceptance of prescribed burns to accomplish restoration goals, including improving recreational services, which increases when the public are educated about the habitat, understand the ecological impacts of the burn, and if they are current habitat recreationers. This suggests that the public may similarly accept prescribed burns conducted in tidal wetlands, but a survey should be conducted to confirm if these attitudes hold true for both tidal wetlands and Delaware residents. Efforts to educate the public on benefits created by burns on fisheries and bird populations important to local recreation could increase their willingness to pay for burn restoration.

Biochar amendment experiment setup at St. Jones Delaware National Estuarine Research Reserve in Dover, DE, in June 2022.

## Cultural Ecosystem Services

Tidal marshes provide a connection to the land by contributing to art, literature, and music. These pathways are often integral to creating "culture" in the sense of how they aid in the transmission of knowledge and values across generations (Reimold et al., 1980). Reimold et al., (1980) puts forth a litany of artists including John James Audubon and Thomas Eakins that have demonstrated daily life and a connection to nature through the creation of pieces across a variety of geographic areas and artistic styles. Additionally, Sarah Kavage created *Water Spirit*, which includes *Phragmites* in elements of their construction and demonstrates a cultural knowledge of the plant and the local environment that is owed to the many cultural influences in the area. Noted authors including Ralph Waldo Emerson and Walt Whitman have drawn from wetland imagery to compose prose about their importance to life and culture. Books and letters written by famous naturalists such as William Bartram and Rachel Carson have worked to foster a connection between the public and natural environments in ways that created major societal changes. Wetlands of both native and nonnative species thus have cultural significance through our connection to the land.

Apart from art and literature, wetlands and *Phragmites* are an integral part of the cultural identity of indigenous people in North America. *Phragmites* has several documented uses by indigenous tribes including food, musical instruments, shelter construction, clothing, and games (Kiviat and Hamilton, 2001).

The above-described cultural ecosystem services created by tidal wetlands present a challenge separate from the previous categories in this document. It can be a difficult task to define what a cultural service is, and these services are usually removed from the economic plane due to their often intangible nature. Even so, it is evident that our socio-cultural values and "quality of life" can be impacted by wetland management. The degree to which these cultural services impact management decisions is, of course, at a land manager's discretion.

Pamela Edris and Emma Leaseburg adding tidal creek sediment to the field experiment in St. Jones Research reserve in June 2022.

# 4. Summary Scores

The removal of invasive *Phragmites* from tidal marshes and its subsequent success and impact on the environment is a complex issue faced by today's land managers. Historically, *Phragmites* has been viewed in a negative light due to its aggressive growth and transformation of Mid-Atlantic salt marshes. While *Phragmites* efficiently outcompetes and removes native vegetation, altering the natural landscape and environmental conditions, it also enhances certain ecosystem services compared to that provided by the native plant assemblages. In general, biological and recreational ecosystem services related to sustaining native floral and faunal species are most likely to benefit from *Phragmites* removal and native habitat restoration. Conversely, physical and biogeochemical related services appear to have a neutral or positive response to the presence of *Phragmites* due to the invasive reed's unique morphology and its impact on surrounding sediment and environmental conditions compared to native vegetation types. Thus, the removal of *Phragmites* using prescribed burns, even with the subsequent addition of biochar, may not be substantial enough to maintain the elevated ecosystem service provision observed when *Phragmites* is present. Ecosystem services related to recreational activities and the cultural significance of salt marsh systems and the impact of *Phragmites* invasion and removal have not been critically evaluated within the Mid-Atlantic region. At this time, we cannot confidently extrapolate how the removal or persistence of *Phragmites* would impact these services in Mid-Atlantic tidal marshes due to the lack of data available.

Our assessment of how prescribed burning for the removal of *Phragmites* and replacement with native vegetation impacts each tidal marsh ecosystem service affected by *Phragmites* invasion and management is summarized in Table 3. Please refer to Tables 1 and 2 for more information regarding scores. Table 4 distinguishes which impact scores have been determined based on data available for the Mid- Atlantic and specifies future research needs for each service based on the 1.) amount of total available data (e.g., number and completeness of studies), 2.) spatial scales of the available data, 3.) specificity of the available data to prescribed burning and *Phragmites* removal, and 4.) consistency in the conclusions from multiple studies. We recognize that location specific data is critical for properly evaluating and grading the impact of *Phragmites* removal and note where literature evaluating this topic within the Mid- Atlantic region is not available. Furthermore, where data is not available on the concomitant impacts of burning, data is drawn from *Phragmites* management studies to estimate the general impact of *Phragmites* removal on a marsh system (as specified within the text and the Future Research Needs section). As a reminder, the impact and success of any restoration attempt is influenced by a variety of factors, including the condition of the marsh in question. Thus, discretion should be used when interpreting these impact scores and associated confidence levels as they may not be representative of all marsh systems.

A prescribed burn conducted at Woodland Beach Wildlife Area in 2011. *Credit: Jay Davis, DNREC.*

**Table 3:** Impacts of *Phragmites* removal on salt marsh ecosystem service provision, with a focus on prescribed burning.

| Ecosystem Service | | Impact/ Confidence | Citations |
|---|---|---|---|
| **Biogeochemical** | Carbon Storage | +/3 | Gu et al., 2020; Kelly et al., 2023; Wang et al. 2019; Zhao et al., 2012 |
| | Nitrogen Removal | -/2 | Cayuela et al., 2013; Geatz et al., 2013; Jones et al., 2022; Leaseburg, 2024; Weldon et al., 2019; Yacano et al., 2022 |
| | Phosphorus Storage | 0/2 | Bolton et al., 2019; Edris, 2024; Faridullah et at., 2012; Strømgaard, 1992; Zhang et al., 2019 |
| | Pollutant Removal | +/1 | Bianco et al., 2021; Cai et al., 2020; Das et al., 2023; Li et al., 2013; Zheng et al., 2022 |
| | Greenhouse Gas Reduction | -/1 | Emery and Fulweiler, 2014; Levine et al., 1990; Martin and Mosiman-Valtierra, 2017a; Martin and Mosiman-Valtierra, 2017b |
| **Biological** | Native Vegetation | +/2 | Bickford et al., 2012; Flores et al., 2011; Leonard et al., 2010; Rohal et al., 2023, Tyo and Andruk, 2022 |
| | Invertebrate Habitat | +/2 | Able and Hagan, 2000; Fell et al., 2003; Gratton and Denno, 2006; Kimball and Able, 2007 |
| | Fish Habitat | +/2 | Able et al. 2003; Able and Hagan, 2000; Grothues and Able, 2003; Rochlin et al., 2012; Weinstein et al. 2019; Weinstein and Balletto, 1999 |
| | Bird Habitat | +/2 | Beniot and Askins, 1999; Bray, 1984; Chambers et al, 2012; Gabrey et al., 1999; Goodwin, 1979; Kern, 2010; Kern et al., 2012; Kern and Shriver, 2014; Mitchell et al., 2006; Parsons, 2003; Trocki and Paton, 2006; Whyte et al., 2015 |
| **Physical** | Sedimentation | -/2 | Cahoon et al., 2010; Chambers et al., 1999; Coleman et al., 2023; Leonard et al, 2002; McKee and Grace, 2012; Rooth and Stevenson, 2000; Rooth et al. 2003; Sheng et al., 2021 |
| | Elevation Maintenance | ?/2 | Cahoon et al., 2010; Henton et al., 2013; Hollis and Turner, 2019; McKee and Grace, 2012; Lane et al., 2016 |
| | Tidal Flow | ?/1 | Leonard et al., 2002; Tempest et al., 2015 |
| | Coastal Resilience | ?/1 | Cahoon et al., 2010; Coleman et al., 2023; Fell et al., 2006; Hollis and Turner, 2019; McKee and Grace, 2012; Lane et al., 2016; Sheng et al., 2021; Theuerkauf et al., 2017 |
| **Recreational** | Ecotourism | +/1 | Aiken, 2009; Bergstrom et al., 1990; Kauffman et al. 2019; Miller et al., 2002; Myers et al., 2010; Petrolia et al., 2014; Santoni et al., 2017; Taylor and Daniel, 1984; US Fish and Wildlife Service, 2016 |
| | Outreach and Education | ?/1 | Miller et al., 2002; Taylor and Daniel, 1984; Wu et al., 2022 |
| | Hunting and Fishing | +/1 | Able and Hagan, 2000; Fell et al., 2003; Grothues and Able, 2003; Hanson et al, 2002; Kimball and Able, 2007; van Neste et al., 2020; Rochlin et al., 2012; Santoni et al. 2017; Weinstein et al., 2019 |

| Ecosystem Service | | Impact/ Confidence | Citations |
|---|---|---|---|
| **Cultural** | Connection to the Land | ?/1 | Reimold et al., 1980 |
| | Spiritual | ?/1 | Kiviat and Hamilton, 2001 |
| **Economical** | Biogeochemical-Carbon and Nutrient Markets | +/2 | Canning et al., 2021; Heberling et al., 2018; Jenkins et al., 2010; McLeod et al., 2011; Mulvaney et al., 2022; Raffensperger et al., 2017; Salzman et al., 2018 |
| | Biological – Hunting and fishing | +/1 | Able and Hagan, 2000; Fell et al., 2003; Grothues and Able, 2003; Hanson et al, 2002; Kimball and Able, 2007; van Neste et al., 2020; Rochlin et al., 2012; Santoni et al. 2017; Weinstein et al., 2019 |
| | Recreational - Ecotourism | +/1 | Aiken, 2009; Myers et al., 2010; Santoni et al., 2017; US FWS, 2016 |
| | Physical – Coastal resilience | 0/1 | Coleman et al., 2023; Rooth and Stevenson, 2000; Sheng et al., 2021 |

* The ecosystem services listed are a collection of commonly cited and important services within the Mid-Atlantic region. We recognize that this is not an exhaustive list and certain services of importance across larger spatiotemporal scales (those greater than the present Mid-Atlantic region) may not be included.

**The responses of these ecosystem services to *Phragmites* removal are categorized based on the resulting impacts described in the currently available body of published literature and data. The grading scale is described in Tables 1 and 2. We have noted that certain ecosystem services do not have associated literature or data regarding the impact of *Phragmites* removal via prescribed burning. This is highlighted in **Table 4**.

***Color codes **orange** and **blue** are used for Impact Scores/Confidence Levels to denote whether or not prescribed burn specific data is available and was utilized to assess the impact of *Phragmites* removal using prescribed burns on the listed ecosystem services. **Blue denotes burn data is not available**. **Orange denotes burn data is available**.

**Table 4.** Assessment of future research needs on the impacts of prescribed burns on ecosystem services.

| Ecosystem Service Category | Ecosystem Service | Data Available for the Mid-Atlantic Region? | Further Research Needs |
|---|---|---|---|
| **Biogeochemical** | Carbon Storage | Yes | Additional studies helpful, not critical |
| | Nitrogen Removal | Yes | Burn specific data needed |
| | Phosphorus Storage | Yes | Additional studies helpful, not critical |
| | Pollutant Removal | No | Regional and burn specific data needed |
| | Greenhouse Gas Reduction | No | Regional and burn specific data needed |
| **Biological** | Native Vegetation | Yes | Additional studies helpful, not critical |
| | Invertebrate Habitat | Yes | Additional studies helpful, not critical |
| | Fish Habitat | Yes | Additional studies helpful, not critical |
| | Bird Habitat | Yes | Additional studies helpful, not critical |
| **Physical** | Sedimentation | Yes | Additional studies helpful, not critical |
| | Elevation Maintenance | Yes | Additional studies helpful to resolve contradicting results |
| | Tidal Flow | Yes | Additional studies and burn specific data needed |
| | Coastal Resilience | Yes | Regional field studies and burn specific data needed |
| **Recreational** | Ecotourism | No | General data needed regarding the impact of *Phragmites* on this service, regional and burn specific data needed |
| | Outreach and Education | No | General data needed regarding the impact of *Phragmites* on this service, regional and burn specific data needed |
| | Hunting and Fishing | No | General data needed regarding the impact of *Phragmites* on this service, regional and burn specific data needed |
| **Cultural** | Connection to the Land | No | General data needed regarding the impact of *Phragmites* on this service, regional and burn specific data needed |
| | Spiritual | No | General data needed regarding the impact of *Phragmites* on this service, regional and burn specific data needed |
| **Economical** | Biogeochemical-Carbon and Nutrient Markets | No | Regional and burn specific data needed |
| | Biological – Hunting and fishing | No | General data needed regarding the impact of *Phragmites* on this service, burn specific data needed |
| | Recreational - Ecotourism | No | General data needed regarding the impact of *Phragmites* on this service, regional and burn specific data needed |
| | Physical – Coastal resilience | No | General data needed regarding the impact of *Phragmites* on this service, regional and burn specific data needed |

# 5. Recommendations

The above literature review and analysis represents a best assessment of the effects of prescribed burns given the available data for our region. Managers are urged to use the information in this document taking their well-defined marsh/*Phragmites* management goals and ecosystem service priorities into account. The analysis identified several gaps in our understanding of the effects of prescribed burns on ecosystem services. Recognizing that logistical, regulatory, and funding constraints present barriers to further study, we offer the following recommendations for future work:

The impact scores and confidence levels assigned above for each ecosystem service category would be vastly improved with the implementation of pre- and post-intervention monitoring of the concomitant effects of prescribed burn (paired with herbicide applications) and *Phragmites* removal across the critically listed ecosystem service categories. We also suggest extending these monitoring efforts over long time periods (5-10 years) as it takes several years to decades for a system to recover back to a natural state after burning and *Phragmites* removal. Longer monitoring windows will thus allow for a stronger evaluation of the success of the restoration. Monitoring programs vary on a continuum from simple to difficult to implement and can include pictures taken over time at the same locations, vegetation surveys, wildlife surveys, camera installations to monitor wildlife use, landscape analysis using aerial images, and specific biogeochemical and physical measurements. Monitoring efforts that compare burned marshes to reference sites with desired ecosystem service provisioning provide context for evaluating success. To some degree, monitoring data already exist. The management community would benefit greatly from the assembly of these existing (and yet to be collected) monitoring data into a database that can be critically evaluated to better understand the factors that influence positive/negative impacts of burns on a given ecosystem service. Characteristics of marsh systems associated with successful restoration by burning may be elucidated. For example, such an assessment may allow managers to be able to predict whether a marsh will receive an elevation benefit from a burn whereas currently, we assess the impact of burns on marsh elevation as unknown due to variable impacts.

Studies that identify optimal herbicide-burn implementation conditions could be useful for eliminating variations in outcomes as well. It has been suggested that altering the timing of burns to minimize *Phragmites* ability to rebound after a burn can enhance ecosystem service outcomes though definitive studies haven't been attempted to our knowledge. Similarly, studies that evaluate how herbicide timing and composition maximize ecosystem service goals are scant in the literature. Managers' ability to maximize burn and herbicide timing are severely restricted by regulations, staffing, and logistics, and waiting for the optimal time is not likely a feasible option. However, studies of herbicide and burn timing can help a manager understand whether an herbicide-burn opportunity will provide a return on investment.

Finally, the economic justifications for marsh burns need to be further evaluated to maximize stakeholder benefits. Continued education of the public on the biological, biogeochemical, physical, recreational, and cultural ecosystem services provided by tidal marshes are needed to provide these important stakeholders a holistic context for evaluating the values of marshes. Studies examining a willingness to pay to preserve a marsh (with marsh loss being the other outcome) exist and should be updated given new socio-economic and environmental conditions. Further, studies examining willingness to pay to restore native vegetation versus retaining a marsh with *Phragmites* (or allowing continued *Phragmites* expansion) are needed.

## Recommendations

Managers are urged to use the information in this document while taking their well-defined marsh/ *Phragmites* management goals and ecosystem service priorities into account.

**Long term (5-10 years) monitoring efforts** that evaluate how prescribed burns impact ecosystem services should be incorporated into any marsh intervention plan including prescribed burns as marsh properties evolve beyond typical 1-2 year monitoring efforts.

To the extent that regulatory and logistical barriers will allow, **investigations into herbicide applications (timing, herbicide composition, mechanism of application) and prescribed burn implementations** (timing) that assess how they alter ecosystem service outcomes are needed.

A large-scale community effort to **assemble and critically evaluate a database of existing short- and long-term monitoring data** would be valuable for identifying environmental conditions that can predict the success or failure of restoration goals (e.g., *Phragmites* removal and replacement with native vegetation).

**Studying the public and stakeholders' perception of marsh ecosystem services and willingness to pay** for the replacement of *Phragmites* with native vegetation will allow managers to make informed management decisions that maximize stakeholder benefits and can be enhanced by education efforts.

*Left to right:* Emma Leaseburg, Andrew Wozniak, Chris Kelly, and Pamela Edris after setting up a biochar amendment experiment at St. Jones Delaware National Estuarine Research Reserve in Dover, DE, in July 2022.

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