

Carbon Sequestration Potential of Wetland Invasive Species: A Review of *Phragmites australis* in the United States.

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North American wetlands are increasingly affected by *Phragmites australis*, an invasive reed species. As wildlife management continues to use extensive methods to control the plant, *P. australis*' carbon storing potential has raised discussions regarding its eradication. This paper explores the characteristics of *P. australis* in optimizing its carbon sequestration. Additionally, it investigates the impacts of the invasive lineage of *P. australis* on biomass increase, gross primary productivity (GPP), and management under various environmental conditions that contribute to its carbon capture capacity. Using a combination of literature review, case studies, and interviews, I explored the characteristics and impact of *P. australis* in wetlands in the United States while comparing the invasive strand to that of Chinese wetlands. The study reveals that *Phragmites*-invaded wetlands exhibit around 3.1 times higher NPP compared to non-invaded wetlands, indicating the species' ability to efficiently sequester carbon. Moreover, the productivity of the plant is heavily reliant on its invasive properties and is influenced heavily by nutrient availability, specifically to Nitrogen, salinity and CO₂ concentrations. In the case study site in Byfield, Massachusetts, *P. australis* holds a 11.15% coverage, which is higher than the reported coverage at nearby sites under the same watershed, presumably due to nutrient content differences. Thus, this invasive plant's impressive capacity for sequestering blue carbon, driven by its unique properties, presents a compelling opportunity for implementing optimized management strategies that can harness its potential as a natural form of carbon sequestration. However, *P. australis*' invasiveness and impact on native species and biodiversity necessitate careful management. As global mitigation efforts call for less resource intensive solutions to sequester atmospheric carbon, this research highlights the need for comprehensive understanding, effective management strategies, and further ecological research to optimize the balance between natural carbon sequestration potential and the preservation of native wetlands and biodiversity in the context of *P. australis* invasion.

Keywords: Wetland, Marsh, Carbon sequestration, Blue Carbon, Invasive species, *Phragmites australis*

Introduction

In an era marked by increasingly evident consequences of climate change, the imperative for global action to combat rising greenhouse gas emissions has reached a critical juncture. Climate change now impacts all aspects of human life without exception; no country, sector, or people is excluded from its effects¹. As the international community convenes for the 28th Conference of the Parties (COP 28) later this year, the significance of decarbonization takes center stage as a paramount objective to ensure the fulfillment of the Paris Agreement's ambitious target of limiting global warming to 1.5°C by 2050. With the participation of over 70,000 individuals, including heads of state, government officials, and industry leaders, COP 28 will embark on hosting the first Global Stocktake since the adoption of the Paris Agreement. This pivotal event aims to provide a comprehensive assessment of global efforts, paving the way to halve global greenhouse gas emissions that will accelerate decarbonization initiatives and drive transformative

changes for a sustainable future².

Many nations have begun prioritizing the transition to renewable energy sources to encourage decarbonization³. Prior to the conference, EU diplomats have reached a consensus to enhance their efforts in phasing out dependence on fossil fuels⁴. Consequently, the prevalence of new energy technologies is expanding, with solar PV generation alone experiencing a remarkable increase of over 22% in 2021 from the previous year⁵. However, renewable energy alone is insufficient to meet current global decarbonization objectives. In fact, more than a threefold increase in annual solar capacity deployment is necessary to align with the Net Zero Emissions by 2050 scenario⁵. Thus, several countries are now investing in carbon capture technology as a means to offset carbon emissions. The concept of Carbon Capture, Utilization, and Storage (CCUS) has only recently begun widespread implementation with governments investing in this sector to facilitate mass production of this expensive technology⁶. The surge of interest in carbon capture is well-founded, as scientists warn that without

the consideration of CCUS, atmospheric carbon (CO₂) levels could increase by a staggering 140%⁷. Nevertheless, the rate at which this technology is progressing falls short of the necessary benchmarks due to its geographic inaccessibility and costly nature.

Wetlands have emerged as a highly promising and natural approach to carbon sequestration. These coastal blue carbon ecosystems have been recognized by the National Oceanic and Atmospheric Administration (NOAA) as a crucial component of the Paris Agreement, providing a measurable and accountable method for carbon sequestration and storage⁸. Despite occupying only 5-8% of global land area⁹, wetlands represent the largest terrestrial biological carbon pool, with a carbon removal capacity ten times greater than that of tropical rainforests¹⁰. Through the process of photosynthesis, the highly productive plant life in wetlands actively sequesters carbon, while the decomposition of organic matter traps greenhouse gasses within their deep, nutrient-rich peat and soil. Globally, coastal blue carbon ecosystems sequester approximately 100 MMT of CO₂ annually⁸. Furthermore, the significance of wetlands extends beyond their carbon sequestration capabilities, playing a vital role in protecting coastal communities from floods, providing habitat for diverse ecosystems, and supporting livelihoods, culture, food security, water quality, recreation, and tourism¹¹. Recognizing the immense potential of these natural systems, policymakers, researchers, and educators are allocating significant resources towards advancing natural carbon capture and removal projects including \$12 billion dollars under the U.S. Infrastructure Investment and Jobs Act¹⁰. Additionally, wetland carbon sequestration projects, such as the "Bringing Wetlands to Market" project which aims to restore critical wetland zones to secure carbon credits, are gaining traction across the United States¹².

As managers have begun to restore blue carbon sinks, invasive species have caused significant concern, adversely affecting the balance of wetlands. One such invader, *P. australis*, arrived in the Americas in the 1800s from Europe and began spreading rapidly in the late 20th century, establishing itself as one of the most prevalent invasive plant species¹³. This invasion has resulted in reduced plant biodiversity, displacement of native species, habitat disruption for animals, and loss of crucial ecosystem services, raising alarm among American land managers in the Great Lakes Region, Southwest Basin, Gulf Coast, and Atlantic Coast¹⁴. However, the wide distribution of *P. australis* across America, coupled with its ongoing global expansion, has led to the hypothesis that the species could contribute significantly to carbon sequestration at a growth rate comparable to that of native plant life.¹⁵ This invasive species exists globally¹⁶ and exhibits favorable traits, including fast growth¹⁷, rapid reproduction¹⁸, and the ability to adapt to changing global conditions¹⁹, setting it apart from unadaptive native plants. Due to its plasticity, *P. australis* has

the potential to store carbon at an accelerated rate through its rapid photosynthesis and decomposition process. Understanding both its environmental implications and climate mitigation benefits is imperative, given its widespread prevalence.

A comprehensive review of existing literature was conducted to establish a foundation of knowledge regarding invasive species, carbon sequestration dynamics, and management strategies with particular focus on *P. australis*. To provide insights into the spatial distribution and abundance of *P. australis*, drone technology is employed to capture aerial imagery at a wetland site of The Great Salt Marsh in Byfield, Massachusetts, to identify and map invasive species in an area that faces challenges in its management. Moreover, a series of case studies from Chinese marshlands involving plant community dynamics, soil characteristics, and carbon storage capacities was reviewed to compare invasive and native strands. This paper aims to investigate the role of *P. australis* as an invasive species in wetlands highlighting its benefits for carbon sequestration. By doing so, this research includes a review of management strategies in combat *P. australis*, acknowledging its significant implications for wetland restoration and management strategies worldwide. This research provides valuable insights for policymakers, land managers, and conservation practitioners in making informed decisions regarding invasive species management and wetland restoration, while ensuring ecosystem resilience and the long-term sustainability of the carbon sequestration process.

Methodology

To obtain a comprehensive understanding of the characteristics of invasive species and carbon sequestration in wetlands, a systematic literature review and meta-analysis was conducted. The review encompassed research papers and encyclopedic information obtained through search engines such as Google Scholar, as well as databases including GALE, ProQuest, and EBSCO. At the beginning, the search terms used in Google Scholar consisted of general descriptors such as "invasive species in wetlands", "wetland carbon sequestration", "wetland blue carbon", and "*Phragmites australis*" to retrieve background information. Later more specific phrases including "*Phragmites australis* carbon sequestration potential" were employed for the retrieval of niche data where the researcher relied on the relevance of information in the given titles and in the abstracts to find more applicable sources. It is important to note that while many sources were utilized, some were not recent or available in their entirety, resulting in the utilization of specific sections of information. Several results of sources that examined native *P. australis* strands were generalized for the invasive strand thus these findings may not comprehensively reflect subspecies differences. Due to the potential unreliability and bias of articles from unverified

sources, an evaluation of website credibility was undertaken before incorporating information from such sources.

In order to investigate the impact of invasive species on carbon sequestration in wetlands more generally, two case studies were used. To test the productivity of invasive species in general, Chinese wetland studies were utilized as *Spartina alterniflora* represents an invasive species while *P. australis* is native — the opposite from North American marshlands. The explored case study was based on the Beijing Hanshiqiao Wetland Nature Reserve, China.²⁰ Additionally, a variety of raw data from previous studies was acquired through public wetland management websites and academic studies retrieved via Google for meta-analysis.

To identify the prevalence of *P. australis* in a North American site, aerial imagery of the wetland area was captured using a DJI Mavic Air 2 drone to analyze the coverage of *P. australis* in Byfield, Massachusetts. Byfield is particularly significant as it lies within The Great Salt Marsh, the largest marsh in New England, spanning over 20,000 acres²¹. Studying *P. australis* in this salt marsh, rather than a freshwater marsh, holds great relevance due to potential influences from sea level rise on its future growth implications. This area is particularly pertinent to the study as it faces significant challenges in managing invasive species, directly aligning with the research focus. Initially, various sites identified from satellite imagery available on Google Maps, featuring the presence of *P. australis* and located near the Parker River, were visited. The final site (42°45'21.1"N 70°54'02.0"W) was selected due to its remote location, away from roads and infrastructure that could potentially influence the result, as well as its accessibility for on-ground verification of the imagery (Figure 1). Multiple images were captured at varying heights to further confirm the presence of invasive species, aligning with the areas examined for *P. australis*. In the representative sample picture, the areas of *P. australis* were manually delineated in red, then subsequently inputted into an online color ratio calculator to estimate the invasive species' coverage in relation to the total land area. Specific areas of *P. australis* were identified during the site visit in order to validate its presence as identified from the aerial footage.

To understand the management practices employed in wetlands, including those observed in the case study, interviews were conducted with two local wetland management authorities in Massachusetts. The researcher identified potential interviewees through public reserves and management databases provided by NOAA, using platforms such as LinkedIn and general web searches. The interviewees were contacted, and given an overview of the purpose of the study, and a set of questions tailored to their specific locations were posed including:

1. What is the current state of wetland invasive species

(*Phragmites australis*) within their management area?

2. What strategies are/have been employed to manage and control invasive species in their management area, and how effective was the result?
3. Considering the negative and positive effects of invasive species, what impact may it have on management?

The purpose of the interviews was to establish an understanding of current management strategies for invasive species employed in wetlands to inspire discussion on how wetlands might best be managed for invasive species to benefit carbon sequestration and biodiversity.

Results

Characteristics of Invasive Species

Invasive plant species, also referred to as alien, exotic, or non-indigenous species, are plants that have been introduced beyond their native range²². Despite the variety of invasive species, several key characteristics are commonly attributed: (a) high reproductive capacity, (b) rapid growth and sexual maturity, (c) wide range of ecological tolerance, and (d) effective dispersal techniques²³.

Consequently, their presence has escalated into a global concern, ranking among the top five most severe threats to global biodiversity and ecosystem integrity²⁴. By outcompeting native plant species, invasive plants exert adverse impacts on species richness, species diversity, and crucial ecosystem functions²⁵. Invasive species have already contributed to nearly 40% of all animal extinctions since the 17th century²⁶. Meanwhile, the effort to eliminate invasives is taxing, costing an estimated \$19 billion in damage each year in the United States alone²⁷.

The succession of biological invasions is commonly categorized into four primary phases: introduction, establishment, spread, and impact²⁸. During the introduction phase, propagules (e.g. seeds, rhizomes) are transported to novel locations or environments, primarily facilitated by human activity²⁹. Following this, invasive species overcome both biotic and abiotic barriers, enabling them to establish viable and proliferating populations contingent on their inherent biological traits²⁹. The subsequent lag phase plays a pivotal role in determining the success or failure of the species, as it exists at low population levels for a specific period³⁰. Should colonization prove successful, invasive plants employ diverse strategies for rapid dispersal, thereby expanding their geographic range. The invasiveness of a species can be attributed to its remarkable capacity for adaptation primarily facilitated by its inherent plasticity or genetic diversity³¹. Finally, the impact phase encompasses the ecological consequences triggered by



Fig. 1 Aerial drone image of case study site in Byfield, Massachusetts, traced in red

invasive plants, including competition with native species, disruption of ecological functions, habitat degradation, and the broader influence on economic, cultural, and ecological balance³². The ever-increasing interconnectedness of our modern world has facilitated the introduction of species to wider ranges of land than ever before, rendering numerous areas susceptible to invasion³³. Moreover, modern environmental crises including climate change, habitat destruction, and pollution continue to intensify invasive species' impact³⁴.

Characteristics of *Phragmites australis*

P. australis is one of the most aggressive invasive species in North American wetlands with multiple conspecific lineages of the common reed existing across all states in the contiguous United States³⁵. The perennial grass species, belonging to

the Poaceae family, has seven genetic lineages found in North America with *P. australis*, or haplotype M native to Europe, being the most prevalent and threatening strand to native-species richness^{25,31}. The invasive common reed is characterized by a long 2 – 6m green culm with flat, long, dark green leaves tightly adhered to the stem accompanied with a dense inflorescence³⁶ (Figure 2).

P. australis exhibits complex growth patterns influenced by a multitude of factors, including nutrient availability, light exposure²⁵, and CO₂ levels³⁷. When introduced to new habitats, *P. australis* displays a strong response to both CO₂ and nitrogen (N), leading to a significant increase in biomass. The introduced strand of *P. australis* shows a preference for nutrient-rich environments, as evidenced by a biomass increase of 47% with CO₂, 136% with N, and 319% with the combination of CO₂ and N¹⁹. In comparison to *Spartina alterniflora*, a com-



Fig. 2 *Phragmites australis* inflorescence comparison, Source: Yiqiao Wang, inspired by³⁶

peting native wetland species, *P. australis* demonstrates higher rates of nitrogen, urea, and amino acid assimilation³⁸. Additionally, *P. australis* has a pronounced affinity for ammonium (NH_4^+), distinguishing it from other wetland plants²⁵. This adaptability enables *P. australis* to thrive in both nutrient-starved and nutrient-rich environments, including those with high salinity, making salt marshes particularly favorable for its growth.

Phenological variations between native and invasive strand of *P. australis* exemplify the disparity in photosynthetic productivity within the subspecies. The invasive strand exhibits a height increase of 13–20% and a 36–38% greater leaf area per ramet compared to the native variants²⁵. Consequently, the invasive strand achieves a photosynthesis rate that is 12–80% higher per unit leaf area, fixing 112% more carbon²⁵. Moreover, introduced *P. australis* can thrive weeks to months longer than native strands, increasing its Gross Primary Productivity (GPP) significantly³⁹.

P. australis utilizes a unique two-pronged approach for extensive invasion: (a) vegetative propagation in close proximity and (b) seed dispersal covering vast distances⁴⁰. While wind and water predominantly facilitate seed dispersal, human and animal activities also contribute to this process⁴¹. However, the most successful reproduction occurs through stolons or rhizomes, which generate new shoots underground, extending from 25–100 m away from the parent plant⁴⁰. This re-

productive strategy allows *P. australis* to establish itself prolifically. Furthermore, the high genetic diversity observed in common reed populations enables the invasive plant to continually adapt to changing conditions, enhancing its spread⁴⁰.

Blue Carbon Storage Potential

Blue carbon encompasses the carbon that is stored within coastal and marine ecosystems, particularly in the form of plant biomass and soil deposits found in salt marshes, mangroves, and seagrass meadows⁴². These ecosystems support highly productive plant life, which undergoes high rates of photosynthesis, converting CO_2 into organic matter, contributing to the substantial biomass of the ecosystem. As this biomass decomposes over time, the organic carbon becomes sequestered within the soil, remaining there for extended periods, ranging from centuries to millennia⁴². The long-term sequestration potential of blue carbon is commonly attributed to its sedimentary composition with anoxic conditions, slow decomposition rates⁴³, large amounts of mineral particles, and constant flocculation⁴⁴. Notably, wetlands in the contiguous United States store 11.52Pg of carbon (C)⁴³, while globally they sequester 830 TgC/yr⁹.

Carbon Sequestration Potential of *Phragmites australis*

The introduced lineage of *P. australis* demonstrates a remarkable ability to proliferate rapidly, leading to the absorption of substantial amounts of atmospheric CO_2 through photosynthesis. This carbon sequestration potential is reflected in the plant's biomass, with above-ground stem growth reaching an impressive rate of 4 cm/day and dense homogeneous clumps consisting of up to 200 stems/m²⁴⁵. However, a significant portion, approximately two-thirds, of the plant's biomass exists below ground in the form of rhizomes and roots⁴⁵. The invasive common reed reproduces most productively asexually with growing lateral rhizome spread as great as 1–2 m/year to depths of 2 m⁴⁵. As a result, native *P. australis* store 1.17–1.76 kgC/m² with a 2–4 times carbon fixation potential than plants globally⁴⁶.

In the introduced lineage of *P. australis* growing under low soil nitrogen levels and ambient CO_2 conditions, the GPP was measured at 1.66 ± 0.05 kgC/m²/yr within the average plant density of *P. australis*⁴⁷. However, when exposed to elevated levels of CO_2 and N, the reed's biomass increased by a striking 319%¹⁹, resulting in a GPP of 3.24 ± 0.08 kgC/m²/yr, representing a 95% increase⁴⁷. Comparing the distribution of soil nitrogen in the United States with the presence of *P. australis*, a notable correlation can be observed, particularly in the Southwest region⁴⁸. *Phragmites*-invaded wetlands exhibit a significantly higher net primary productivity (NPP) of 3.1 times that of non-invaded wetlands, while also assimilat-

ing carbon at a faster rate than many other temperate ecosystems⁴⁷.

During the decomposition phase, when *P. australis* undergoes senescence, the organic matter is broken down by microbial activity and other decomposers. Due to the crude lignin content of *P. australis*, the overall decomposition of the plant is slow^{49,50}. However, this extended decomposition period enhances the plant's carbon sequestration productivity compared to native species such as *S. patens*, which decompose at a faster rate but store 37–77% less carbon⁵¹. Remarkably, *P. australis* can contribute 0.10–0.46 cm of soil accretion per year solely through its decomposition, while concurrently storing carbon within the soil⁵¹.

Carbon Sequestration of *Phragmites australis*: Comparison to Chinese Wetlands

In Chinese wetlands, a contrasting scenario emerges where *P. australis* serves as the native species, while *S. alterniflora* is deemed invasive⁵². Despite this difference, *S. alterniflora* demonstrates a remarkable carbon sequestration rate of 3.16 MgC/ha/yr within the top 100 cm soil profile, surpassing native plant marshes by a factor of 2.63–8.78⁵². From the carbon sequestration rate comparison of the invasive strands, we can discern a noticeable pattern highlighting the elevated carbon sequestration potential of invasive plant strains when compared to native strands (Table 1). This observation facilitates the theory that heightened phenotypic plasticity increases natural carbon capture and storage. Nevertheless, *P. australis* as a native strand remains a vital species for carbon sequestration and ecosystem services in comparison to other common wetland plants such as *S. alterniflora* with more than triple the capacity²⁰.

In the Hanshiqiao Wetland Nature Reserve, *P. australis* has exhibited a maximum annual carbon sequestration capacity of 2.04 KgC/m²/yr, surpassing the potential of many other wetland plants, which typically range from 0.05–1.35 KgC/m²/yr on average²⁰. In areas with dense *P. australis* populations, such as Baiyangdian, China, carbon storage can reach up to 3.81 KgC/m²/yr⁴⁶. The carbon sequestration potential and prevalence of *P. australis* in Chinese wetlands are significantly influenced by various factors, including soil properties, nutrient availability, hydrology, and management practices. Understanding these factors is crucial for effectively managing carbon sequestration in Chinese wetland ecosystems⁴⁶.

While both the native and the introduced strand of *P. australis* have greater plastic fitness response to resource availability than other flora, the introduced lineage garners 2.5–3.6 times more biomass within any given CO₂ + N treatments (Table 2)¹⁹. Thus, the introduced lineage outcompetes the native strand under elevated CO₂ and N scenarios, exemplary of future environmental conditions. Similarly, due to the in-

roduced lineage's positive response, projected elevated CO₂ scenarios may help it compete against native reeds. Furthermore, the inherently fast growth of the invasive lineage and its greater ability to allocate biomass enables a greater response than native lineages that allocate growth mainly to its stem biomass that is indicative of slow growth rates¹⁹. The invasive strand gains a greater plasticity than the native strand in almost all approaches, labeling it as a “jack-and-master” invader, thus having a higher carbon storage capacity.

However, it is important to acknowledge the divergent methodologies employed by these studies to derive their respective results. While many studies generally undertake long-term fieldwork and sampling, followed by laboratory analyses, the approaches to calculating carbon sequestration rates in plants vary. Some studies have determined sequestration rates based on the observed increase in soil organic carbon (SOC) density within specific soil profiles, while others have relied on the Net Primary Productivity (NPP) measured on a comprehensive scale. Additionally, variations exist in the data collection methods, with some studies heavily reliant on in-field samples for data acquisition, while others have employed sensor data, yielding greater precision. Moreover, the frequency of sampling also varies, with some studies conducting yearly sampling over extended periods, and others performing periodic monthly sampling within a shorter time frame.

Considering these methodological disparities, the comparison of carbon sequestration data may be influenced by the precision and rigor of the studies, thus potentially accounting for observed differences in results. Nevertheless, a consistent pattern emerges, indicating that invasive strains do exhibit enhanced carbon sequestration capabilities when compared to native plants, as evidenced by the substantial differences in their sequestration values.

Case Study Aerial Image Analysis

In order to assess the prevalence of the invasive common reed, *P. australis*, in the study area, an aerial image analysis was conducted (Figure 3). The unique dark coloration of the reed was utilized to identify the study area and determine the presence of *P. australis*. However, the inaccessibility of the site posed a challenge, leading to a lower overall precision of the analysis due to human-tracing errors despite visual verification. Through color data analytics, the ratio of *P. australis* to non-*Phragmites* plants was calculated to be 7.60 : 60.54, respectively (Table 3), which corresponds to a *P. australis* coverage of approximately 11.15%. These results demonstrate a high distribution of *P. australis* in the specific sample area of 11,870 m² along the Parker River, with a recorded presence of 2286 m². Notably, the distribution of the plant within the site exhibited distinctive clumps, positioned roughly 2–3 m away

Table 1 Comparison of the Carbon Sequestration Rate between Native and Invasive Strand of *Spartina alterniflora* and *Phragmites australis*

Plant Species	<i>S. alterniflora</i>		<i>P. australis</i>	
Strand	Native	Invasive	Native	Invasive
Location	United States (Atlantic Coast)	China	China	United States (Atlantic Coast)
Carbon Sequestration Rate (KgC/m2/yr)	0.18 [65]	0.32 [49]	2.04 [19]	3.24 [43]

Table 2 Comparison between Native and Invasive strand of Phragmites

<i>Phragmites</i> status	Invasive	Native
Location	United States	China
Carbon Sequestration Rate (kgC/m2/yr)	3.24	2.04
Stimulated Biomass to elevated CO2	47%	98%
Stimulated Biomass to elevated N	136%	254%
Stimulated Biomass to elevated CO2 + N [18]	319%	510%
Growing Season	July-November [60]	April-August [19]

from the Parker River bank. This pattern can be attributed to the plant’s asexual reproductive capability, resulting in vertical spreading.

Discussion

The research conducted highlights the high productivity of the invasive strain of *P. australis*, which correlates with its significant carbon sequestration potential. These traits can be attributed to the species’ unique r-selected characteristics and the nitrogen-rich composition of wetland soils. Despite the challenges faced by management in controlling the aggressive growth of this common reed, the study underscores the potential benefits associated with its invasive properties. This investigation explores the capacity of *P. australis* to serve as a natural source of carbon sequestration in combating the rising concentration of atmospheric carbon dioxide⁵³. Based on a comprehensive analysis of previous research, *P. australis* exhibits a remarkable capacity for carbon storage in comparison to global plant species⁴⁶. The species demonstrates an ability to store 2-4 times more carbon than the average global plant population, and an impressive 37-77% more carbon than the native species *S. patens*⁵¹. This enhanced carbon sequestration potential can be attributed to the accelerated growth rate of *P. australis*, facilitated by its rhizomatous growth habit and effective seed dispersal mechanisms. As *P. australis* under-

goes decomposition, it effectively sequesters carbon within the soil, a process that occurs gradually but reliably. This slow decomposition rate ensures the long-term stability and longevity of the stored carbon, free from artificial interventions. Thus, *P. australis* emerges as an unexpected yet promising candidate for rapid and efficient carbon sequestration efforts.

Comparing the findings with previous studies on *P. australis* mapping in a different and broader section of the Parker River, it was discovered that the presence of the invasive reed was primarily identified in direct proximity to the river bank, which aligns with the current case study⁵⁴. However, the results obtained in this study were abnormally high. In comparison, the vertical distance of the Byfield case study was 500ft while the East Salisbury Marsh along the same river covered a horizontal distance of over 1.25 miles. In the Îles-de-Boucherville National Park mapping, which employed Airborne Hyperspectral Imagery, *P. australis* covered only 7.26% of the park, much less than the coverage observed in the Byfield case study of 11.15%³⁵. The considerable disparity observed can be attributed to the limited sample size employed in the case study, which may have generated anomalous results. The pronounced abundance of *P. australis* at the site, in contrast to other land plots, accounts for this deviation. Furthermore, it is essential to consider the nutrient content of the Parker river as high levels of N compounds from anthropogenic sources may explain the higher concentrations of *P.*

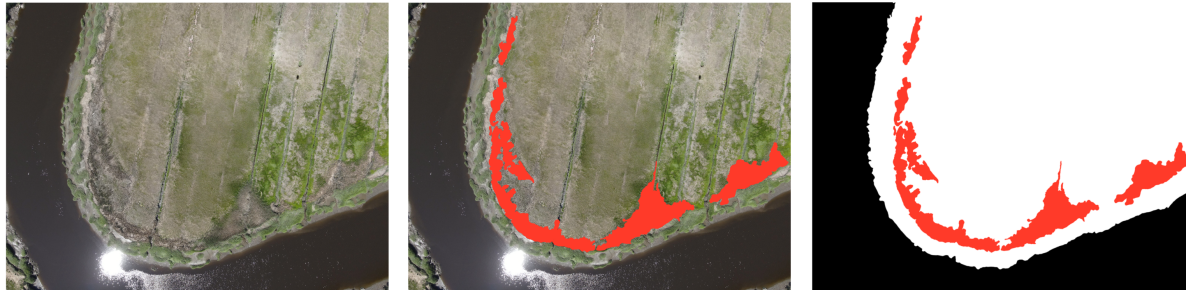


Figure 3. Aerial drone image of case study site in Byfield, Massachusetts, with *Phragmites australis* traced in red and case study area filled in white.

Fig. 3 Aerial drone image of the case study site in Byfield, Massachusetts, with *Phragmites australis* traced in red and the case study area filled in white.

Table 3 Color ratio of the case study site in Byfield, Massachusetts, showing *P. australis* presence in red and research area in white.

Color	Percentage
White	60.54%
Black	31.86%
Red	7.60%

australis. In order to enhance the reliability of data obtained from the Byfield case study, it is recommended that future research endeavors encompass a wider sample area or incorporate multiple sites. This approach will facilitate the identification of data outliers and contribute to the reduction of measurement uncertainties, thus ensuring heightened accuracy and precision in subsequent analyses. Moreover, analyzing the nutrient content of the waterbody and soil of the case study site will prove critical in determining a correlation between nutrient and plant density.

While an increase in the productivity of *P. australis* concurrently augments the carbon sequestration potential of wetland ecosystems, it is important to acknowledge that invasive species continue to pose a significant threat to native plants and overall ecosystem functioning. The presence of *P. australis* jeopardizes species richness³¹, disrupts wildlife habitats⁵¹, and disrupts natural ecological processes. Consequently, extensive and intensive management efforts have been implemented across all 48 affected states to mitigate the aggressive spread⁵⁵. Given its established nature, the man-

agement of *P. australis* primarily focuses on asset-based protection and containment strategies⁵⁶. Based on an institutional economic survey conducted with 285 land managers in the United States, it was revealed that these private and public organizations expend more than US\$4.6 million per year on the suppression of *P. australis*⁵⁷. The predominant control method is the use of herbicides that contribute to 94% of treatment⁵⁷ that includes two broad-spectrum herbicides, glyphosate and imazapyr⁵⁸. Additionally, mechanical methods such as prescribed fires and flooding are utilized in conjunction with chemical means to curb regrowth⁵⁸. However, new discussion posits that the use of broad-spectrum herbicides may be inadvertently damaging native plant populations. Due to *P. australis*' invasive adaptability, it is more likely to persist even in the damaged environment necessitating more herbicidal control causing a positive feedback loop that eliminates native species and diminishes resilience. Since achieving and sustaining total eradication of *P. australis* is challenging due to its plasticity, it raises pertinent questions regarding whether the costs of control outweigh the benefits that *P. australis* may provide⁵⁹.

The refuge manager of Parker River, Thacher Island, Great Bay and Wapack NWRs, corroborated the constant and expensive battle against the management of invasive species including *P. australis* and Perennial Pepperweed. Extensive amounts of herbicidal and mechanical controls have been established in the region for more than 20 years to prevent the spread of invasive species in order to save the rapidly declining salt marsh sparrows⁵⁴. However, the plasticity of *P. australis* has made their management next to impossible, explaining areas overrun by the species. Without replanting of native species, the battle proves futile in regulating the invasive species. In the Byfield case study site, the presence of *P. australis* was first identified in 2006, but due to management, the species did not proliferate through the landscape entirely⁶⁰. The control of invasive species is a top priority for wildlife managers even with its high carbon capture potential. Instead the restoration of

wetland with native flora may contribute more to the ecosystem, prodigy critical services, cultural activity, while restoring carbon at a natural rate.

The research findings indicate that the substitution of native plant species with *P. australis* has the potential to increase the stock of blue carbon. However, this ecological shift comes at the expense of compromising the biodiversity of marsh ecosystems. A concern for management is despite the carbon capture capacity of *P. australis*, many ecological catastrophes can occur. Yet emerging studies suggest that *P. australis* provides similar ecosystem services to native flora, *S. alterniflora*. In fact, the invasive species supports the ecosystem more in terms of flood regulation, nutrient sequestration, and soil formation⁶¹. Moreover, it is one of the little-known plant species whose growth can keep pace with projected sea-level rise which together makes *P. australis* favorable in future scenarios⁶². Thus perhaps its expansion may project greater benefits in the changing environment to tackle both global security concerns and to sequester atmospheric carbon.

In contrast to other carbon capture technologies, natural carbon sequestration through invasive species like *P. australis* offers unique advantages. While CCUS is effective for long-term carbon storage, it demands substantial energy inputs, perpetuating the cycle of anthropogenic carbon emissions if not reliant on renewable sources. Moreover, the high cost of direct air capture, ranging from US\$134-342 per tonne of CO_2 , renders it impractical for struggling communities, while natural approaches entail lower monitoring and expenses⁶³. Invasive species like *P. australis* utilize natural processes such as photosynthesis and decomposition, resulting in less environmental impact and long-term sustainability. Furthermore, *P. australis* provides services beyond carbon sequestration, as it combats sea-level rise, supports ecosystem services, and creates habitats. Given these diverse benefits and the costly and harmful nature of CCUS, an optimized natural approach emerges as a more sustainable solution.

Furthermore, a comprehensive understanding of the nutrient dynamics, salinity levels, and climatic conditions that favor the presence of *P. australis* for effective carbon sequestration is imperative in regards to the process' enhancement. Moreover, eutrophication, caused by the influx of anthropogenic nutrients, may facilitate the accelerated growth of invasive species like *P. australis*, given its positive response to nitrogen. This phenomenon can potentially contribute to the invasive species' expanding dominance within the wetland environment. As such, further research is recommended to empirically test this theory and gain a deeper understanding of the interplay between eutrophication and the proliferation of invasive species in wetlands. Such investigations would advance our knowledge of the ecological dynamics at play and help devise targeted strategies for managing or optimizing the benefits of invasive species in these delicate ecosystems.

As global leaders strive to achieve climate goals, carbon credit and decarbonization systems can derive benefits from wetland areas, particularly those that encompass highly productive regions containing invasive plant species. Nonetheless, the utilization of natural carbon sequestration methods can pose additional challenges to sustainable efforts, notably affecting ecosystem diversity and functioning. Moreover, the artificial introduction of alien species pose significant and potentially unknown threats to ecosystems. While the augmentation of carbon stocks through the presence of *P. australis* can be viewed as a positive contribution to carbon storage, it is vital to carefully assess the trade-offs between increased carbon stocks and potential losses of other crucial ecosystem services. Further research is warranted to evaluate the adverse consequences of unmanaged *P. australis* on ecosystems, thereby determining its overall value for global mitigation efforts. Additionally, a deeper understanding of the interplay between native species and *P. australis* is necessary to hypothesize factors that can facilitate mutualistic relationships or resource partitioning, thereby benefiting the native ecosystem.

Conclusion

Despite the negative association with invasive species, their unique plasticity can optimize efforts in global mitigation. *Phragmites australis*, while viewed as a major threat to biodiversity and ecosystem stability, contrastingly holds great carbon sequestration potential⁶⁴. The plant's reproductive strategies and large biomass facilitate rapid colonization, contributing to its aggressive nature. Its prevalence is pronounced throughout the United States, with an 11.15% coverage on marshland by the Parker River in The Great Salt Marsh in Newbury, Massachusetts. However, as the productivity of the common reed increases, it also leads to a corresponding rise in surface accretion, thereby contributing to carbon storage. The plant's slow decomposition rate is well suited to long-term and stable carbon storage.

Furthermore, *P. australis* demonstrates a positive response to future atmospheric conditions, including elevated nitrogen levels (85-168%), increased salinity (873%), and elevated CO_2 concentrations (193-322%)²⁵. This indicates the species' enhanced ecological fitness under both challenging and resource-rich circumstances. Consequently, *P. australis* not only suggests a more competitive position among wetland plants in future scenarios but also exhibits elevated carbon sequestration potential. In fact, introducing *P. australis* can enhance the overall GPP of an area, thereby bolstering carbon capture efforts. As a result, wetland management should reconsider established control measures for this invasive species to optimize the potential benefits it brings.

With COP 28 paving the way for the introduction of new decarbonization technologies, it is crucial to adopt a holistic per-

spective that includes evaluating existing processes. Instead of the expensive investment to fulfill the ambitious target of the Paris Agreement by 2050, we should also explore optimized natural restoration approaches. In this critical juncture of global efforts, it becomes imperative to review the strategies implemented by public and private entities, while also conducting significant research on other plant species, invasive or native, that may offer similar carbon sequestration benefits as *P. australis*. By doing so, we can maximize the potential of natural systems to contribute to carbon mitigation and help us progress towards a sustainable future.

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