RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

RESEARCH ARTICLE

Restored wetlands show rapid vegetation recovery and substantial surface-water expansion

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Ecological restoration is essential for improving the ecological integrity of degraded ecosystems to enhance ecosystem services and biodiversity. In this study, we assessed the effectiveness of wetland restoration on retired cranberry farms by analyzing vegetation recovery and surface-water dynamics using the enhanced vegetation index (EVI) and normalized difference water index (NDWI) derived from Sentinel-2 satellite imagery. To quantify temporal dynamics of both vegetation recovery and surface-water cover, we identified the spectral distinctions among restored wetland plant communities. Our results indicated the emergence of distinct plant communities upon restoration. Restored wetlands in general showed significant and progressive vegetation recovery and expanding surface-water cover with clear spectral differentiation among plant communities, as indicated by improved EVI and NDWI estimates. Wetlands restored in 2016 showed higher EVI estimates compared to both reference wetlands and those restored in 2020, suggesting more advanced vegetation recovery. Wetlands restored in 2020 displayed greater variability in EVI, particularly for open-water wetlands, with less consistent patterns compared to the 2016 restorations. Reference wetlands consistently exhibited the highest NDWI values, indicating that restored wetlands have not yet achieved full hydrological saturation. Notably, wetlands restored in 2020 had significantly greater surface-water coverage than those restored in 2016. Our study suggests that restored wetlands have gained remarkable progress in vegetation recovery, although they are yet to reach the desired state of hydrological saturation compared to reference wetlands. By providing insights into the ecological trajectories of restored wetlands, our study supports evidence-based management practices for fostering sustainable wetland ecosystems.

Key words: coastal plain ecoregion, spectral index, surface water extent, vegetation recovery, wetland restoration

Implications for Practice

- Computing spectral indices from open-access satellite imagery offers an efficient, scalable, and cost-effective approach for assessing restoration outcomes, reducing dependence on labor-intensive field surveys.
- Distinct recovery trajectories observed among wetland plant communities emphasize the need for tailored restoration strategies that account for site-specific ecological and hydrological conditions.
- While vegetation recovers rapidly, restored wetlands often lag in achieving hydrological equivalence to reference wetlands, underscoring the need for adaptive management approaches that enhance hydrological connectivity to ensure long-term success.
- Variations in vegetation and hydrologic responses underscore the role of time in achieving ecosystem stability, reinforcing the importance of continued monitoring for decision-making.
- Spectral index analysis offers a replicable framework for monitoring restored wetlands and improving restoration outcomes.

Introduction

Despite increasing global investments in wetland restoration, significant challenges persist in assessing the effectiveness of restoration (Mohanty et al. 2024). Restoring degraded wetlands is critical for improving their functional and biodiversity values, yet the high costs of field surveys hinder evaluating restoration outcomes, thereby impeding efforts to guide future strategies and highlighting the need for cost-effective alternatives to assess restoration progress (Zedler 2000; Lake et al. 2007). Wetland restoration initiatives prioritize the establishment and recovery of plant communities due to their ecological uniqueness, rarity, and critical roles in supporting biodiversity and habitat

Author contributions: TDS, KKS conceived and designed the research; TDS performed the fieldwork; TDS, KKS, Y-HC analyzed the data; TDS curated the data; TDS, KKS, acquired funding; TDS, KKS, Y-HC wrote and edited the manuscript.

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doi: 10.1111/rec.70046
Supporting information at:
http://onlinelibrary.wiley.com/doi/10.1111/rec.70046/suppinfo

heterogeneity. Evaluating the success of these efforts requires detailed assessments of plant productivity and growth dynamics, particularly in comparison to natural ecosystems (Zedler 2000; Beheshti et al. 2023). By analyzing recovery trajectories across diverse wetland plant communities, we aim to quantify restoration outcomes and support evidence-based management practices in wetland restoration.

Wetland restoration efforts often focus on reestablishing natural hydrological regimes, including river–floodplain interactions, recurrent flood pulses, and increased soil moisture (Mohanty et al. 2024). Surface-water cover plays a crucial role in shaping habitat complexity, wetland biodiversity, vegetation structure and composition, and ecosystem processes, making these hydrological characteristics essential for maintaining wetland health and ecological integrity (Bobbink et al. 2006). Therefore, monitoring surface hydrology is essential for assessing restoration outcomes. Variations in surface-water extent influence the establishment of distinct wetland plant communities, underscoring the importance of systematic hydrological measurement in evaluating restoration effectiveness and identifying emerging communities. Integrating surface-water monitoring with vegetation assessments provides a more comprehensive framework for the evaluation of restoration success (Reif & Theel 2017; Wilson & Norman 2018).

Conventional wetland monitoring methods rely on labor-intensive field surveys that are costly, logistically demanding, and often constrained by terrain, weather, and safety challenges (Lyon & McCarthy 1995; Beheshti et al. 2023). These limitations restrict geographic reach and delay results, diminishing their effectiveness for timely management and policy decisions. In contrast, novel approaches like remote sensing technologies offer efficient, scalable alternatives for assessing restoration outcomes (Nagendra et al. 2013). Aerial photography and satellite imagery enable large-scale, repetitive, and non-invasive monitoring of vegetation and hydrological changes while offering high-quality, open-access remote sensing data aligned with open science initiatives (Klemas 2013). Remote sensing also offers high temporal and spatial resolution data, facilitating the detection of dynamic ecological changes over time across large geographies while reducing the need for frequent field visits (Reif & Theel 2017; de Almeida et al. 2020). This approach is particularly valuable for tracking hydrological variations, assessing habitat conditions, and identifying emerging new plant communities following restoration (Wilson & Norman 2018; Dronova et al. 2021).

Vegetation and water indices, such as normalized difference vegetation index, enhanced vegetation index (EVI), and normalized difference water index (NDWI), are derived from remotely sensed satellite imagery and play a crucial role in monitoring the growth, health, and productivity of newly established plant communities. These indices leverage unique spectral signatures to provide insights into the restoration progress (Suir et al. 2020). For example, EVI is used to quantify carbon dioxide uptake during photosynthesis in coastal wetlands (Yang et al. 2023), while NDWI accurately captures temporal dynamics of surface water (Ashok et al. 2021). By analyzing EVI and NDWI estimates across different wetland plant communities, we aim to quantify the temporal trends in vegetation recovery and surface-water cover, evaluating whether restored wetlands show significant improvements following restoration. We hypothesize that restored wetland plant communities will demonstrate increased productivity and greater surface-water cover over time. Additionally, we anticipate that the emerging wetland plant communities will exhibit distinct spectral characteristics, allowing for differentiation based on their vegetation structure and hydrological conditions. This study addresses two critical questions: What are the recovery patterns among native plant communities post-restoration, and how do these patterns vary both interannually and intra-annually? What are the interannual recovery patterns in surface-water cover across different wetland communities? By addressing these questions, our research aims to advance the understanding of wetland restoration outcomes and informs evidence-based management practices for achieving sustainable wetland ecosystems.

Methods

Study Area

Our study was conducted in the Northeastern Atlantic Coastal Plains ecoregion, specifically in the Town of Plymouth, southeastern Massachusetts, United States (Fig. 1). The study sites included retired cranberry farms restored into wetlands in two phases. The Tidmarsh Mass Audubon Wildlife Sanctuary, covering 195 ha, was restored during 2015 and 2016 (hereafter 2016) and the 51 ha Foothills Preserve was restored in 2020 (both sites collectively referred to as the Tidmarsh area). Prior to restoration, both sites were commercial cranberry farms originally developed in low-elevation coastal peat bogs (Ballantine et al. 2020). Restoration activities involved removing water-control structures (e.g. dams, dikes, and floodgates) to reconnect streams with floodplains, creating meandering stream channels to increase water residence time, establishing watershed-wide stream continuity, and reintroducing native flora (Ballantine et al. 2020). At Tidmarsh, most of the cranberry bogs were restored to wetlands, while some areas were left unrestored, resulting in a mosaic of terrestrial, wetland, and aquatic plant communities.

Identification of Flagship Plant Communities

We used the Coastal Change Analysis Program (C-CAP) land cover classification scheme to identify flagship wetland plant communities (hereafter, flagship communities)—distinctive vegetation assemblages typical of the ecoregion—at Tidmarsh (Table 1; National Oceanic and Atmospheric Administration & Office for Coastal Management 2024). The C-CAP classification was modified by replacing "cultivated crops" with "cranberry bogs" since cranberries are the sole cultivated crop in the area. Shaped by regional hydrology and recurring in similar abiotic conditions such as saturated soils and hydrophytes, we captured six flagship communities in our modified C-CAP scheme: open-water wetlands, cranberry bogs, scrub-shrub wetlands, palustrine emergent wetlands (hereafter, emergent wetlands), palustrine forested

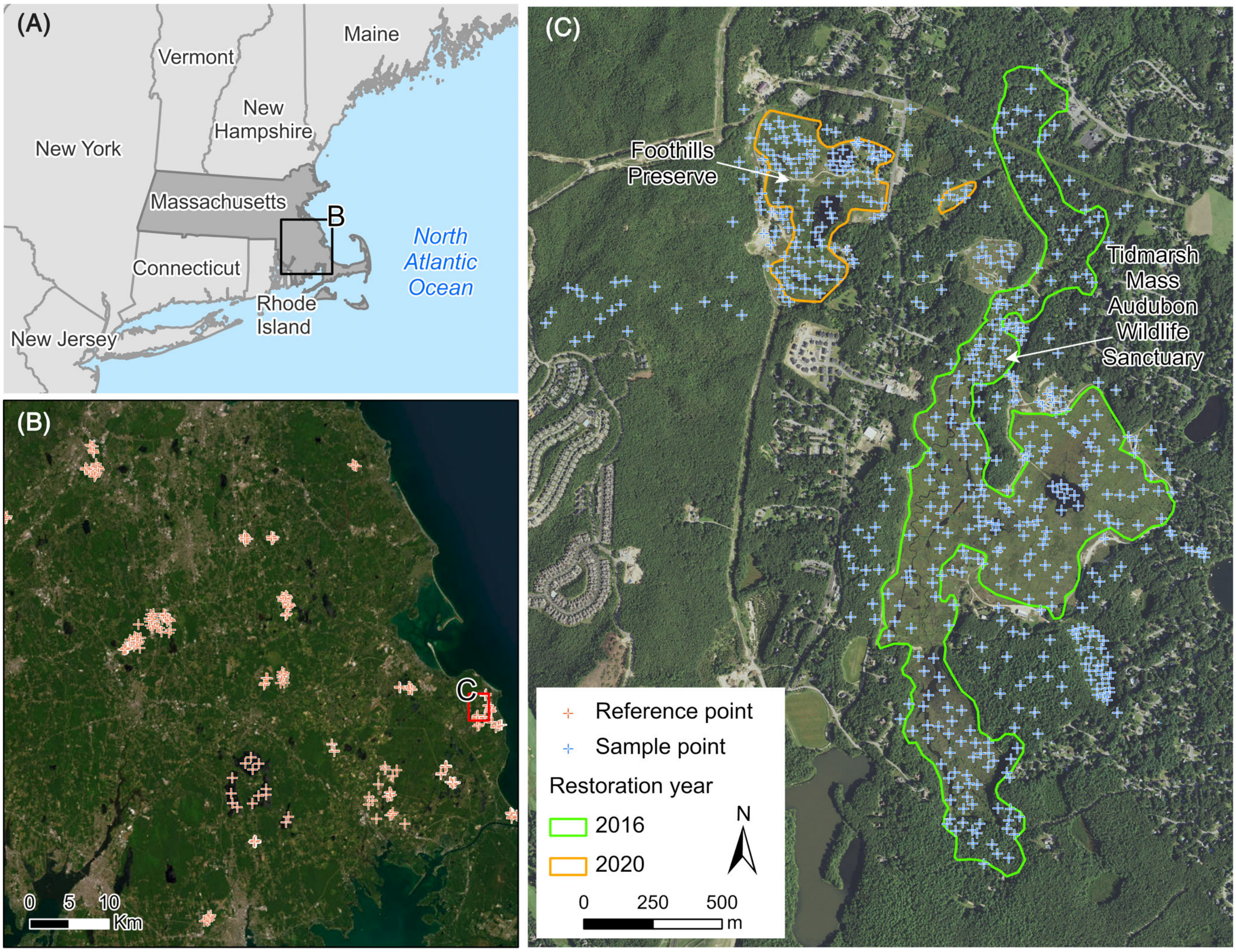

Figure 1. Study area and reference points. (A) The black box represents the geographic location of the study area within Massachusetts, United States. (B) Detailed map showing the locations of reference points (+) and the study area (red rectangle). (C) Detailed view of the Tidmarsh Mass Audubon Wildlife Sanctuary and Foothills Preserve, Plymouth, Massachusetts, United States, highlighting the wetland areas restored in 2016 (orange lines) and 2020 (green lines), along with the locations of field survey points (+).

Table 1. The modified wetland classification scheme with descriptions of flagship wetland plant community types adapted from (National Oceanic and Atmospheric Administration & Office for Coastal Management 2024).

Community type	*Description*
Open-water wetlands	Lakes, and ponds of varied sizes and depths, where warm to cool, moderately oxygenated water is present year-round, and support sparse amounts of submerged, emergent, and floating aquatic vegetation
Cranberry bogs	Historical, commercial scale cranberry farms that are not actively managed. The dominant vegetation includes carberry mats with a variety of herbaceous and/or graminoid species that can tolerate water-logged conditions. These bogs overlay peat and sand layers and remain connected to irrigation ditches
Scrub-shrub wetlands	Shrub-dominated freshwater wetlands containing a patchwork of shrub and herb dominance, with trees generally absent or thinly scattered. Standing water is limited to certain parts of the year
Palustrine emergent wetlands (emergent wetlands)	Dominated by emergent or submergent herbaceous vegetation and associated with flat or shallow basins, trees are absent, although sparsely scattered shrubs often account for less than 25% of the wetland surface. The presence of standing water is relatively longer than in scrub-shrub wetlands
Palustrine forested wetlands (forested wetlands)	A type of wetland dominated by woody vegetation at least 6 m tall with persistent or seasonal standing water. Common tree species include willows, Atlantic white cedars, red maple, and black gum
Palustrine aquatic bed (aquatic bed)	A type of wetland characterized by a predominance of rooted or floating aquatic vegetation, such as algae, submerged plants, or floating-leaved plants. These shallow wetlands are permanently or seasonally flooded

wetlands (hereafter, forested wetlands), and palustrine aquatic beds (hereafter, aquatic beds).

Survey Design for Ground Observations

We used ArcGIS (V 10.6, ESRI, Redding, CA, U.S.A.) to generate 529 random points across both restored and unrestored wetlands within the Tidmarsh area. To compare recovery patterns of Tidmarsh flagship communities with regional natural wetlands, we generated 282 random points as reference locations representing natural wetlands outside the Tidmarsh area. We overlaid these point locations on the National Agricultural Imagery Program images in ArcGIS, aiming to allocate at least 30 point locations per plant community by visually examining the imagery on the computer screen. In May 2019, before the 2020 restoration phase, we conducted in-situ field surveys at each point location to validate our initial image-based plant community identification. To capture the flagship communities emerging from the second restoration phase completed in 2020, we surveyed the wetlands in May 2021 after visually examining the aerial imagery. During these field surveys, we selected point locations within plant-community patches greater than 10 m^2 area to ensure compatibility with the spatial resolution of the remotely sensed imagery. We used a Garmin Montana 650 t to locate each point and visually inspected the vegetation to assign each location to its respective plant community type following the C-CAP classification scheme (Table 2).

Remote Sensing Data Processing

Using the Google Earth Engine platform, we accessed Level-2A atmospherically corrected imagery from the Sentinel-2 sensor, which was launched in 2015 for monitoring Earth's surface and vegetation analysis. We selected Sentinel imagery for its high spatial (10-m) and temporal resolution (15 days), which allowed for a detailed analysis of recovery patterns in flagship communities. The imagery includes bands spanning the visible and near-infrared (NIR) regions of the electromagnetic spectrum. Sentinel-2, a passive sensor, is sensitive to cloud cover and atmospheric conditions, which can impact data quality. To ensure reliable results, we applied cloud probability layers from the Sentinel-2 collection to mask areas with over 35% cloud cover probability. We estimated the EVI and NDWI spectral indices (Equations 1 & 2) to quantify recovery patterns of flagship communities and surface water, respectively. By analyzing temporal changes in these spectral indices and comparing them with reference locations, we identified recovery patterns in both wetland vegetation and surface-water extent in the Tidmarsh area.

$$\mathrm{EVI} = 2.5 \times \left(\frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + 6 \times \mathrm{Red} - 7.5 \times \mathrm{Blue} + 1)} \right) \quad (1)$$

$$\mathrm{NDWI} = \frac{(\mathrm{NIR} - \mathrm{Green})}{(\mathrm{NIR} + \mathrm{Green})} \quad (2)$$

The NIR, Red, Blue, and Green bands in Sentinel-2 Multi-Spectral Instrument (MSI) imagery correspond to bands 8, 4, 2, and 3, respectively. The central wavelengths are 832.8 nm (NIR), 664.6 nm (Red), 492.7 nm (Blue), and 559.0 nm (Green), with bandwidths of 105, 30, 65, and 35 nm, respectively.

The EVI is specifically designed to quantify vegetation greenness and plant productivity by enhancing the reflectance signal of green vegetation while minimizing soil and atmospheric effects, making it ideal for assessing temporal patterns of vegetation recovery following wetland restoration (Huete et al. 1997). Likewise, the NDWI is sensitive to soil moisture and surface water, making it an effective index for monitoring surface water changes in wetlands (Gao 1996). We analyzed time-series spectral indices to detect temporal patterns in flagship communities and surface water, assessing both vegetation recovery and surface-water changes following restoration. Given that the flagship communities in our study are either fully or partially submerged, we calculated both the EVI, for vegetation monitoring, and the NDWI, for detecting standing water, for each wetland community.

We imported all 811 point locations, including reference locations, to estimate EVI values for all available dates from January 2019 to December 2023. For NDWI estimation, we restricted the analysis to the leaf-off months (November–April) to minimize interference from canopy cover and ensure detection of surface water reflectance. Images with snow cover were excluded from the analysis to prevent erroneous reflectance

Table 2. Number of point locations created for each flagship wetland plant community type with subsequent field validations at the Tidmarsh wetland complex using the wetland classification scheme. [a]The same ground-surveyed point locations were used for both before and after 2020 restoration assessments. [b]The row total indicates the number of ground-surveyed point locations across all plant community types, while the values in parentheses show the corresponding numbers recorded after the 2020 restoration phase.

Flagship wetland plant community type	*The number of field-surveyed point locations*					
	Restored in 2016	*Before restoration in 2020*	*After restoration in 2020*	*Unrestored*	*Reference locations*	*Row total*
Open-water wetlands	101	10	17	15	53	179 (186)
Cranberry bogs	123	82	0	5	48	258 (176)
Scrub-shrub wetlands	0	11	0	15	40	66 (55)
Emergent wetlands	98	0	86	10	42	150 (236)
Forested wetland	13	0	0	5	55	73
Aquatic bed	22	0	0	19	44	85
Column total	357	103[a]		69	282	811[b]

values. To derive spectral indices, we initially extracted the band values for each point location from the corresponding Sentinel-2 pixel and then computed the indices (Equations 1 & 2). In total, 418 Sentinel-2 images were processed for spectral index calculations for point locations (Fig. S1). The wider spatial distribution of reference locations compared to point locations in the Tidmarsh area required additional imagery for data retrieval. To address missing values resulting from cloud cover, shadow, and atmospheric conditions, we applied the Savitzky–Golay filter (Savitzky & Golay 1964) using the "savgol_filter" function from the Scipy package (Virtanen et al. 2020). This method, commonly used for smoothing time-series spectral indices (i.e. Shao et al. 2016; Cao et al. 2018), applies a weighted moving average based on a polynomial of specified degree (Chen et al. 2004). We selected a window length of 5 and a polynomial degree of 2 to achieve an optimal balance between noise reduction and data retention.

Statistical Analysis

We implemented non-parametric approaches, free of normality assumptions, to analyze the vegetation recovery patterns, surface-water extent, and the spectral distinctiveness of flagship communities following restoration. All statistical analyses as well as graphic production were performed in the R programming language using the RStudio Integrated Development Environment (R Core Team 2024; RStudio Team 2024).

To determine whether flagship communities emerging after restoration exhibit spectral differences in EVI and NDWI, we performed Kruskal–Wallis tests (KW test), with spectral indices as response variables and flagship communities as predictor variables. This rank-transformed test evaluates significant differences between three or more groups (Tiit 2000). If significant differences were detected, we conducted pairwise comparisons using the Wilcoxon rank-sum test with Bonferroni corrections to identify differences in vegetation productivity and surface-water dynamics. The Wilcoxon rank-sum test, which compares two independent groups, assesses whether their population median differs. To assess intra-annual shifts in vegetation recovery among flagship communities, we applied the KW test with monthly average EVI as the response and month as the predictor. Pairwise comparisons were conducted using the Wilcoxon rank-sum test. To assess interannual recovery of each flagship community, we used the Friedman test, treating annual mean EVI as the response variable and year as the predictor, to detect significant year-to-year changes in vegetation recovery. When significant differences were found, we applied the Wilcoxon signed-rank test with Bonferroni adjustments to identify pairs of years with differing EVI estimates while controlling for Type I errors. The Friedman test detects differences across treatments in randomized block designs with repeated measurements on the same subjects (Tiit 2000), while the Wilcoxon signed-rank test compares two related samples or matched pairs, which assesses whether their population mean ranks differ, making it suitable for analyzing paired data. The Bonferroni method adjusts the significance level by dividing the desired alpha level by the number of comparisons being performed, reducing the likelihood of false positives. We applied the same approach to analyze interannual shifts in NDWI to assess changes in surface-water cover among flagship communities. First, we implemented the Friedman test where the annual average NDWI served as the response variable and the year as the predictor variable, followed by post hoc pairwise comparisons using the Wilcoxon signed-rank test. For data visualization, we constructed box and whisker plots with Yeo-Johnson power transformed spectral indices to illustrate: (1) spectral distinctions among flagship communities and surface water emerging in response to wetland restoration using both EVI and NDWI, (2) interannual trends in post-restoration vegetation and surface water recovery, and (3) the intra-annual variability in monthly average EVI estimates of flagship communities.

Results

EVI-Based Spectral Distinctions Among Flagship Communities

The flagship communities showed significant spectral distinctions in terms of the EVI estimates after restoration activities implemented in 2016, both all years combined (KW test; $H = 695.0$, $p < 0.0001$) and on a year-to-year basis (2019: $H = 138.0$, 2020: $H = 142.0$, 2021: $H = 142.0$, 2022: $H = 155.0$, 2023: $H = 153.0$, all significant at $p < 0.0001$; Fig. 2A–E). A similar pattern was evident among wetlands emerging after restoration in 2020, where flagship communities differed significantly all years combined ($H = 47.6$, $p < 0.0001$; Fig. 2F–J) as well as on a year-to-year basis (2021: $H = 40.80$, 2022: $H = 37.2$, 2023: $H = 41.0$, all significant at $p < 0.0001$) in their EVI estimates. Pairwise comparisons (Wilcoxon signed-rank tests) of EVI estimates between 2016 and 2020 restorations also supported these spectral distinctions, indicating the emergence of distinct flagship communities due to restoration (Table 3). Concerning the 2016 restoration efforts, forested wetlands emerged as the most distinctive plant community and consistently displayed the greatest EVI estimates across all years. This set them apart from other flagship communities. In contrast, open-water wetlands consistently exhibited the greatest variation in the EVI estimates (Fig. 2A–E). Emergent wetlands were the most distinctive among flagship communities resulting from 2020 restoration actions, as evidenced by greater EVI estimates observed across years (Fig. 2F–J).

NDWI-Based Spectral Distinctions among Flagship Communities

The NDWI values differed significantly across different flagship communities throughout the 2019–2023 period for both 2016 (KW test; $H = 258.0$, $p < 0.0001$; Fig. 3A–E) and 2020 ($H = 25.4$, $p < 0.0001$; Fig. 3F–J) restoration phases, indicating spectral distinctions among flagship communities. These distinctions persisted across years for both 2016 (KW test; 2019: $H = 42.2$; 2020: $H = 53.7$; 2021: $H = 53.7$; 2022: $H = 71.3$; 2023: $H = 64.3$, all significant at $p < 0.0001$) and 2020 restoration phases (2021: $H = 3.7830.0$, $p \sim 0.05$; 2022: $H = 37.2$, $p < 0.0001$; 2023: $H = 33.4$, $p < 0.0001$). Additionally, follow-up pairwise analyses (Wilcoxon signed-rank tests)

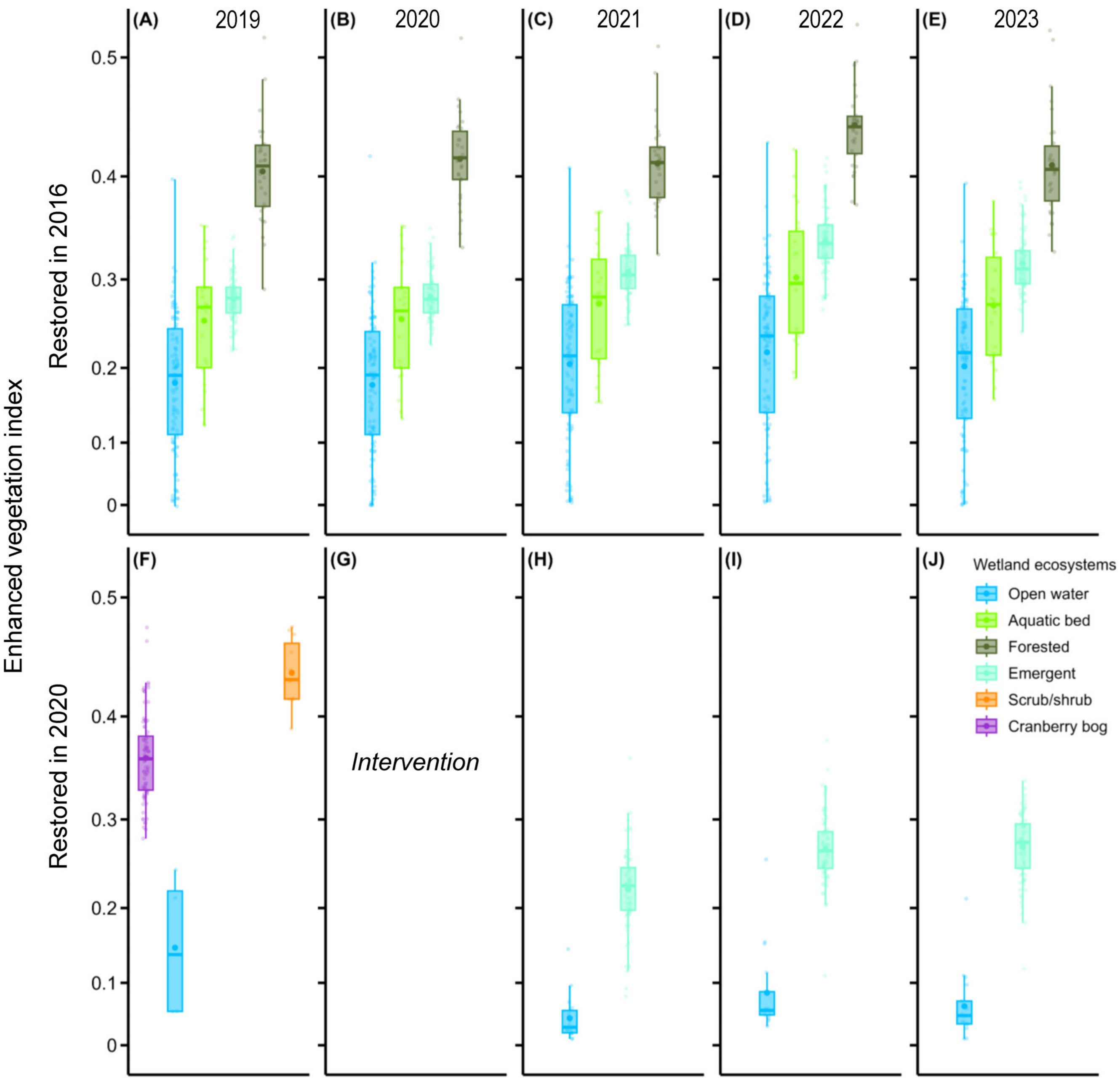

Figure 2. Spectral distinctions among flagship wetland plant communities, estimated using the enhanced vegetation index with Yeo-Johnson power transformation, at Tidmarsh Mass Audubon wildlife sanctuary and Foothill preserve (Tidmarsh wetland complex) in response to wetland restoration actions in 2016 (A–E) and 2020 (F–J).

revealed significant NDWI-based spectral differences between all flagship community types for both restoration phases, except for aquatic beds and emergent wetlands (Table 3). This indicates persistent differences in surface-water cover among flagship communities following the 2016 and 2020 restoration efforts. Open-water wetlands consistently had the highest NDWI estimates across all years and restoration phases, while forested wetlands had the lowest (Fig. 3). Open-water wetlands and emergent wetlands displayed the greatest and least NDWI variation, respectively, for both restoration phases, except for the year 2021 for the 2020 restoration phase (Fig. 3).

Interannual Vegetation Recovery Patterns

The restored flagship communities showed progressive and significant recovery of vegetation following restoration efforts as evident from improving EVI estimates (Fig. 4, Table S1) while vegetation communities emerging from both restoration phases exhibited significant improvements in recovery for all

Table 3. Wilcoxon signed-rank tests for pairwise comparisons of the enhanced vegetation index (EVI) and normalized difference water index (NDWI) among the flagship wetland plant communities at Tidmarsh Mass Audubon wildlife sanctuary and Foothill Preserve (Tidmarsh wetland complex) restored in 2016 and 2020. Asterisks (*) indicates pairwise comparisons that are significant at 95% confidence levels.

		EVI		*NDWI*	
Restoration time frame	*Between-community comparison*	W	p	W	p
2016	Open-water versus aquatic bed	14,500.0	<0.0001*	38,170.0	<0.0001*
	Open-water versus emergent	21,650.0	<0.0001*	153,500.0	<0.0001*
	Open-water versus forested	421.0	<0.0001*	62,700.0	<0.0001*
	Aquatic bed versus emergent	15,505.0	<0.001*	24,323.0	>0.05
	Aquatic bed versus forested	415.0	<0.0001*	11,505.0	<0.0001*
	Emergent versus forested	1467.0	<0.0001*	40,835.0	<0.0001*
2020	Open water versus emergent	5085.0	<0.0001*	15,114.0	<0.0001*

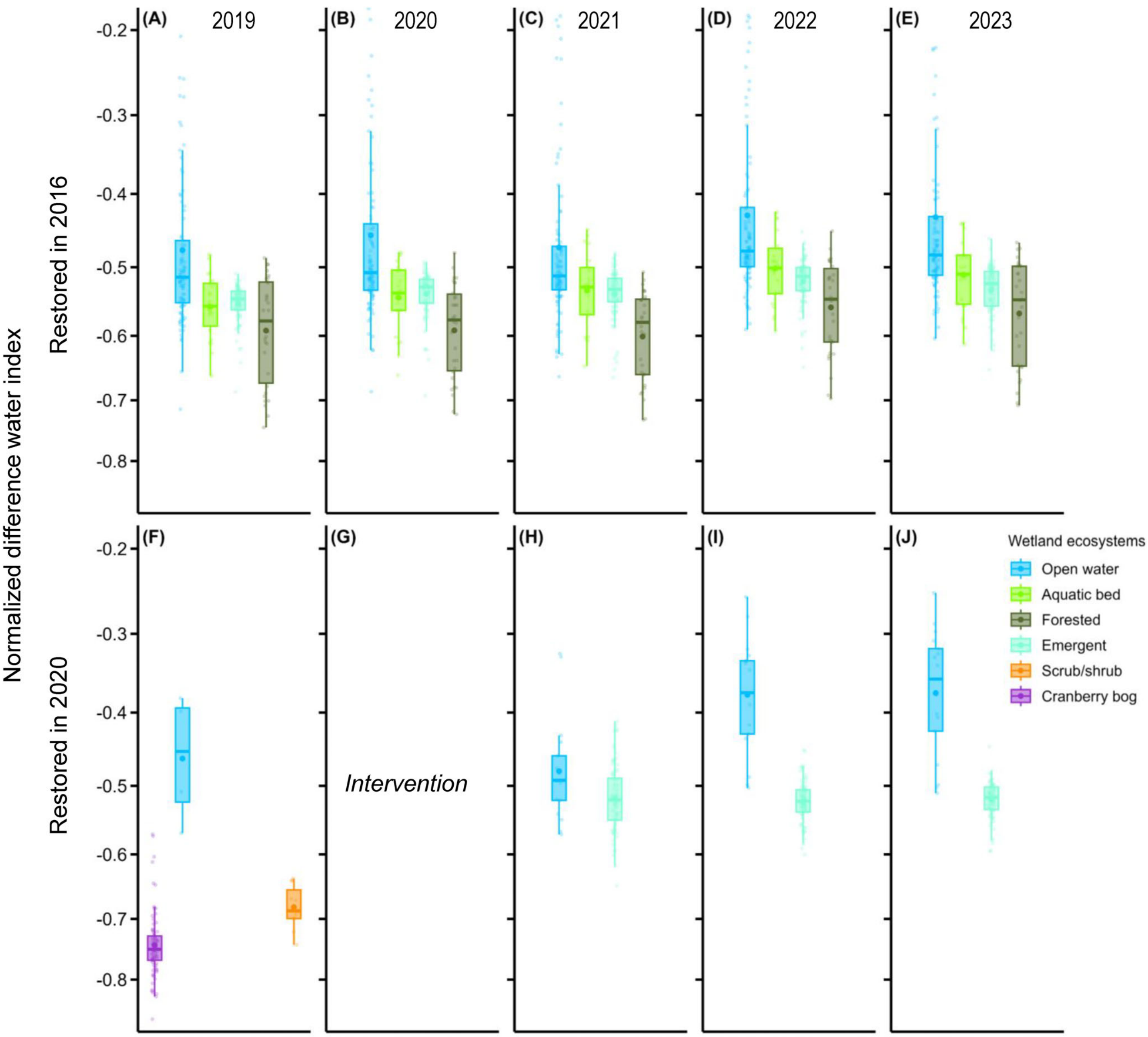

Figure 3. Surface water extent, assessed using the normalized difference water index, with Yeo-Johnson transformation for flagship wetland plant communities at Tidmarsh Mass Audubon wildlife sanctuary and Foothill Preserve (Tidmarsh wetland complex) following restoration in 2016 (A–E) and 2020 (F–J).

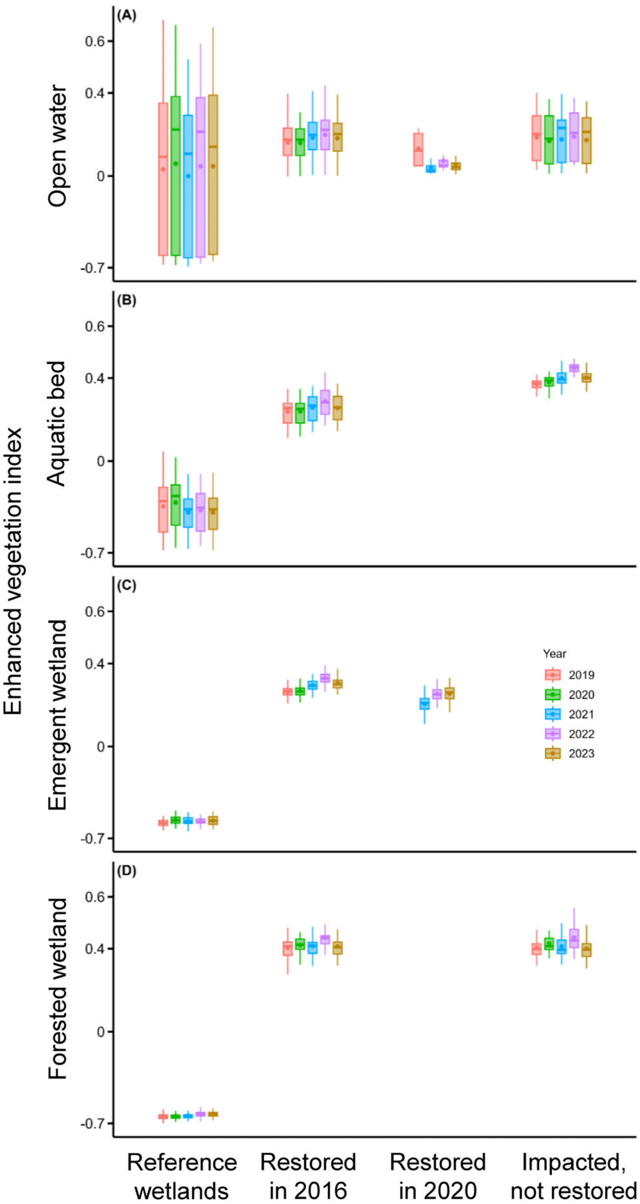

Figure 4. Interannual trends in vegetation recovery of flagship wetland plant communities estimated using enhanced vegetation index (EVI) with Yeo-Johnson power transformation between 2019 and 2023 (A–D) resulting from restoration efforts completed in 2016 and 2020 at Tidmarsh Mass Audubon Wildlife Sanctuary and Foothills Preserve (Tidmarsh wetland complex). Reference and adjacent unrestored wetlands were included for comparison. Box plots show mean EVI values.

between-year comparisons (Table S1). Restored open-water wetlands from both the 2016 and 2020 phases exhibited significant vegetation recovery (2016 phase: $Q = 199.0$, $p < 0.0001$; 2020 phase: $Q = 185.0$, $p < 0.0001$) with EVI estimates increasing from the time of restoration until 2022, followed by a significant decline from 2022 to 2023 ($p < 0.0001$, Table S1). Additionally, open-water wetlands restored in 2016 had significantly higher EVI estimates than both the reference wetlands ($W = 58{,}114.0$, $p < 0.05$) and those restored in 2020 ($W = 13{,}337.0$, $p < 0.0001$), while the latter had lower, though not statistically significant, EVI estimates compared to the reference wetlands ($W = 4{,}493.0$, $p > 0.05$) (Table 4; Fig. 4A). Both aquatic beds ($Q = 59.2$, $p < 0.0001$) and emergent wetlands ($Q = 238.0$, $p < 0.0001$) restored in 2016 showed significant increases in EVI values from 2019 to 2022 and declined significantly in the following year ($p < 0.0001$; Table S1; Fig. 4B & 4C). Nonetheless, both wetland types had significantly greater EVI estimates compared to their reference counterparts (aquatic beds: $W = 1{,}569.0$, $p \le 0.0001$; emergent wetlands: $W = 21{,}546.0$, $p \le 0.0001$) (Table 4; Fig. 4B). The EVI values of emergent wetlands restored in 2020 surpassed those of the reference wetlands ($W = 19{,}066.0$, $p < 0.0001$) but remained significantly lower than those restored in 2016 ($W = 52{,}387.0$, $p < 0.0001$), while showing continuous and consistent improvement in vegetation recovery over time ($Q = 19{,}066.0$, $p < 0.0001$; Table S1; Fig. 4C). Forested wetlands restored in 2016 showed significant shifts in EVI estimates across years ($Q = 63.4$, $p < 0.05$), indicating differences among years, though the between-year differences were subtle and EVI values remained relatively stable except for an increase in 2022 (Table S1; Fig. 4D). These wetlands had significantly greater EVI estimates than the reference wetlands ($W = 5{,}691.0$, $p < 0.0001$; Table 4). Unrestored adjacent wetlands exhibited no consistent EVI patterns, except for aquatic beds where EVI values improved over time (Fig. 4). Restoration efforts in 2020, converting cranberry bogs into either open-water wetlands (Friedman test: $Q = 17.0$, $p < 0.0001$) or emergent wetlands (Friedman test: $Q = 65.0$, $p < 0.0001$), led to a significant decline in EVI estimates (Fig. 5A). This declining trend was also observed in scrub/shrub wetlands converted into emergent wetlands ($Q = 11.0$, $p < 0.0001$; Fig. 5B), whereas reservoirs converted into emergent wetlands resulted in a notable increase in EVI estimates ($Q = 4.0$, $p < 0.001$; Fig. 5C).

Intra-Annual Vegetation Recovery Patterns

Flagship communities restored in both 2016 and 2020 peaked consistently during the June–July period over five consecutive years, aligning with the peak growth season in southeastern Massachusetts (Fig. 6), including reference areas. While the magnitude of the EVI estimates varied among different wetland communities during the June–July period, all flagship communities displayed synchrony in their intra-annual productivity across the observed years (Fig. 6). Forested wetlands and open-water wetlands consistently exhibited the highest and lowest EVI values, respectively, during this period, with variable magnitudes generating statistically significant distinctions in vegetation recovery of various flagship communities (KW test: $H = 538.00$, $p < 0.0001$). Intra-annual EVI trends among various flagship communities were less distinctive but statistically significant during the dormant (December–February) season (KW test: $H = 441.00$, [degrees of freedom] $df = 3$, $p < 0.0001$), indicating stable productivity and turnover patterns across years. These findings provide compelling evidence of the emergence of distinct plant communities because of the restoration interventions. The repetitive patterns observed in intra-annual EVI estimates suggested that these

Table 4. Comparison of the enhanced vegetation index (EVI) and normalized difference water index (NDWI) of flagship wetland plant communities at Tidmarsh Wildlife Sanctuary and Foothills Preserve, restored in 2016 (A) and 2020 (B) against reference wetlands, and (C) between the two restoration phases (2016 and 2020) using pairwise Wilcoxon rank-sum tests. The matrix cell values correspond to test statistics of the Wilcoxon signed-rank test (W). Column headings show Friedman test statistics (Q). Asterisks (*) indicates significant pairwise comparisons at the 95% confidence level.

	EVI			*NDWI*		
Ecosystem types	*Estimate*	W	p	*Estimate*	W	p
(A) Wetlands restored in 2016 versus reference wetlands						
Open water	−0.07	58,114.0	0.0027*	0.57	92,486.0	<0.0001*
Aquatic bed	−0.58	1569.0	<0.0001*	0.37	21,532.0	<0.0001*
Wetland	−0.84	21,546.0	<0.0001*	0.08	80,290.0	<0.0001*
Forested wetland	−1.04	5691.0	<0.0001*	0.07	33,403.0	<0.0001*
(B) Wetlands restored in 2020 versus reference wetlands						
Open water	0.09	4493.0	>0.05	−0.51	2825.0	<0.05*
Emergent wetland	−0.79	19,066.0	<0.0001*	−0.07	3101.0	<0.0001*
(C) Wetlands restored in 2016 versus 2020						
Open water	0.16	13,337.0	<0.0001*	−0.0589	14,089.0	~0.0001*
Emergent wetland	0.07	52,387.0	<0.0001*	−0.0170	61,582.0	<0.05*

plant communities exhibited among-year stability in terms of productivity while undergoing similar patterns of intra-annual turnover in biomass over multiple years. Although wetlands restored in 2020 displayed variability in intra-annual EVI estimates (Fig. 6F–J), when compared to wetlands restored in the 2016 time frame (Fig. 6A–E), these patterns were less conspicuous for open-water wetlands and did not exhibit a consistent repetitive trend across years. Similarly, although the intra-annual EVI trends among distinct flagship communities in wetlands restored in 2020 were significantly different during the growth season (KW test: $H = 814.00$, $p < 0.05$), the outcome of the dormant season did not show significant differences (KW test: $H = 731.00$, $p > 0.05$).

Interannual Trends in Surface-Water Extent

Open-water wetlands restored in 2020 had significantly greater NDWI values as well as greater variability compared to those restored in 2016 (Table 4; Fig. 7A). The NDWI estimates for open-water wetlands restored in both 2016 ($Q = 251.0$, $p < 0.0001$) and 2020 ($Q = 46.1$, $p < 0.0001$) showed significant interannual variations, with distinct, increasing trends evident in those restored in 2020 (Table S2; Fig. 7A). Aquatic beds restored in 2016 also displayed significant interannual variations in NDWI values ($Q = 30.6$, $p < 0.0001$) registering increasing NDWI values until 2022 from the point of restoration but declining in the following year while maintaining an elevated NDWI compared to the 2019–2022 time frame (Table S2; Fig. 7B). Among wetlands restored in 2016, both emergent ($Q = 120.0$, $p < 0.0001$) and forested ($Q = 21.0$, $p < 0.0001$) wetlands exhibited significant interannual shifts (Table S2; Fig. 7C & 7D). The emergent wetlands restored in 2016 evidenced a gradual improvement in surface-water cover from 2019 through 2022 but declined in the following year, whereas those restored in 2020 did not exhibit tangible variations in the surface-water extent (Table S2; Fig. 7C). Forested

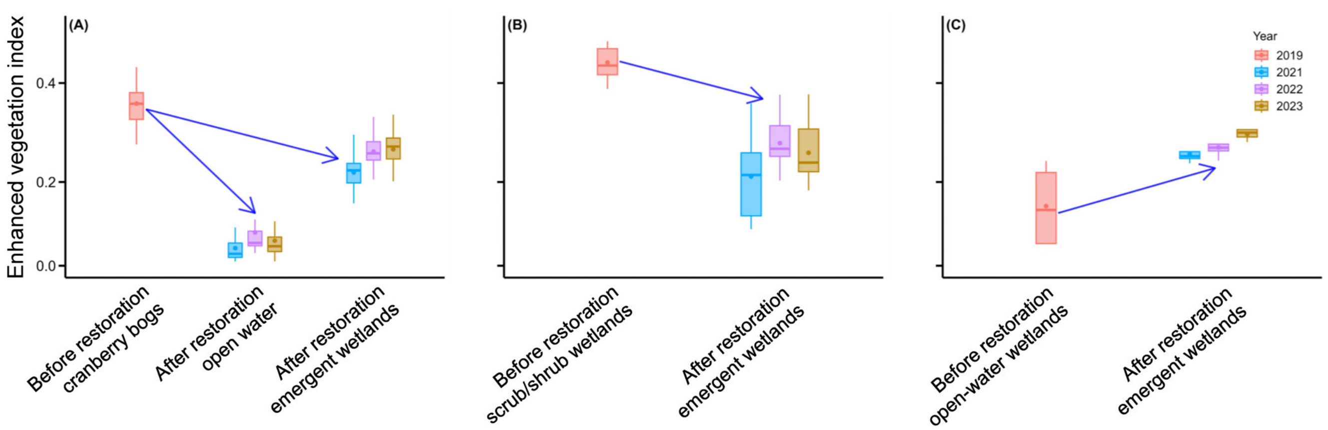

Figure 5. Change in vegetation recovery estimated using the enhanced vegetation index (EVI) with Yeo-Johnson Power Transformation at Foothills Preserve, before (2019) and after restoration (2021, 2022, and 2023) where (A) retired cranberry bogs were converted into either open-water wetlands or palustrine emergent wetlands, (B) palustrine scrub/shrub wetlands were converted into palustrine emergent wetlands, and (C) open-water wetlands were converted into palustrine emergent wetlands.

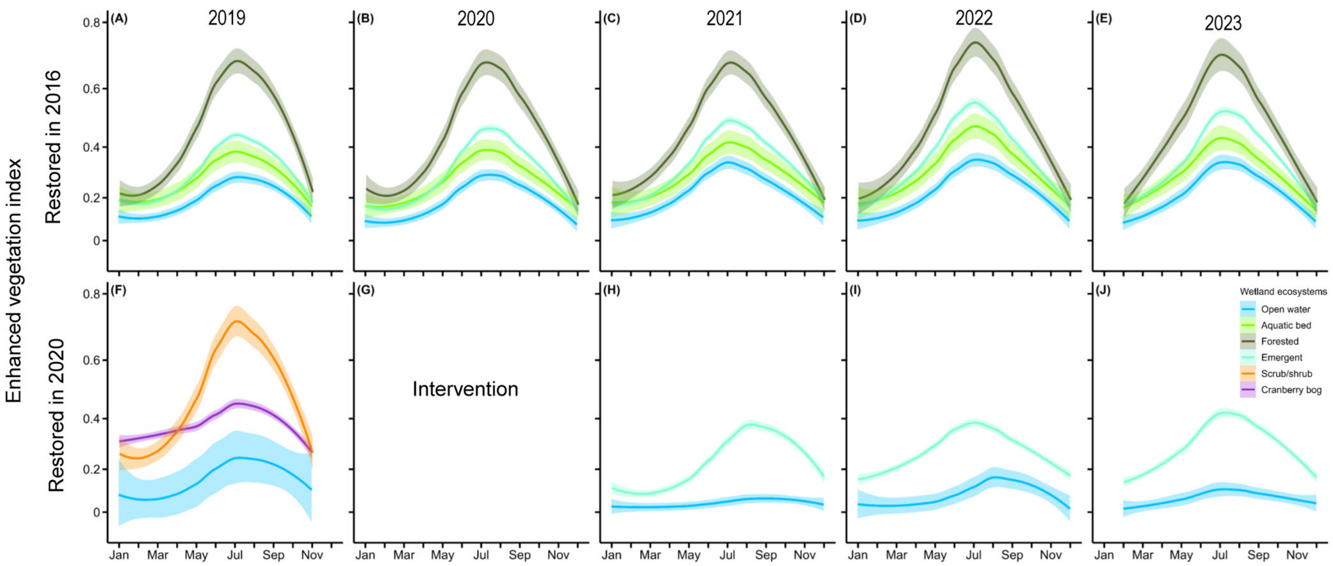

Figure 6. Intra-annual variability of monthly average (± standard error) enhanced vegetation index (EVI, with Yeo-Johnson power transformation) of flagship wetland plant communities at Tidmarsh Mass Audubon Wildlife Sanctuary and Foothill Preserve (Tidmarsh wetland complex) in response to restoration completed in 2016 (A–E) and 2020 (F–J).

wetlands restored in 2016 also evidenced a slow but significant gain in surface-water extent (Fig. 7D).

Reference wetlands consistently exhibited the highest NDWI values, which differed significantly from all the restored wetlands throughout the 2019–2024 period, indicating that restored wetlands have not yet reached the desired state, where soils are fully saturated with water. Open-water wetlands restored in both 2016 ($W = 92{,}486.0$, $p < 0.0001$) and 2020 ($W = 2825.0$, $p < 0.05$) displayed significantly lower NDWI estimates as well as less variability than their reference counterparts, while those restored in 2020 had significantly greater surface water cover ($W = 14{,}089.0$; $p \sim 0.0001$; Table S2; Fig. 7A). Regardless of the restoration phase, emergent wetlands consistently had lower NDWI values compared to reference equivalents (2016: $W = 2{,}825.0$, $p < 0.0001$; 2020: $W = 2{,}825.0$, $p < 0.0001$). Similarly, the EVI of the aquatic beds ($W = 21{,}532.0$, $p < 0.0001$) as well as forested wetlands ($W = 33{,}403.0$, $p < 0.0001$) also remained significantly lower than their reference counterparts (Table 4; Fig. 7B). Compared to reference wetlands, restored aquatic beds showed a narrower variation in NDWI, while the restored forested wetlands sustained a much wider variability of NDWI values compared to their reference equivalents (Table 4; Fig. 7B). However, emergent and forested wetlands from both restoration phases showed NDWI values approaching those of reference wetlands, indicating improved water retention capacity. Unrestored wetlands, on the other hand, generally had the lowest NDWI values, reflecting degraded hydrology and reduced surface-water extent (Fig. 7).

Discussion

Tidmarsh restoration led to significant ecological improvements in wetland vegetation productivity and surface-water dynamics, aligning with our initial hypotheses. As we hypothesized, restored flagship communities exhibited substantial increases in vegetation productivity over time, as reflected in elevated EVI estimates. Both emergent and forested wetlands signaled clear improvements in vegetation recovery and productivity following restoration. Spectral distinctions among flagship communities supported our hypothesis that restoration fosters the development of distinct wetland ecosystems. Over time, pairwise differences became more pronounced, indicating that restoration-driven changes intensified as ecosystems matured. This supports the emergence of diverse wetland ecosystems and the generation of habitat heterogeneity across previously uniform farmed bogs. Notably, significant differences between ecosystems were evident even in the early stages of restoration. Notable interannual and intra-annual patterns in vegetation productivity, particularly among emergent wetlands, forested wetlands, and aquatic beds, highlighted the progressive establishment of restored wetland ecosystems. Similarly, temporal trends in surface-water extent reflected ecological improvements. However, open-water wetlands and aquatic beds exhibited the greatest variability in both vegetation productivity and surface-water extent, suggesting that hydrological recovery in these ecosystems is more complex. While restored wetlands have matched or even surpassed vegetation growth in reference wetlands, they still lag in surface-water cover. Nevertheless, improved water retention indicates progress in ecosystem recovery. Our results demonstrate that hydrological and vegetation responses to restoration have produced positive ecological outcomes, albeit at differing rates, underscoring distinct recovery trajectories.

Using remote sensing time-series imagery proved to be an effective method for evaluating post-restoration plant

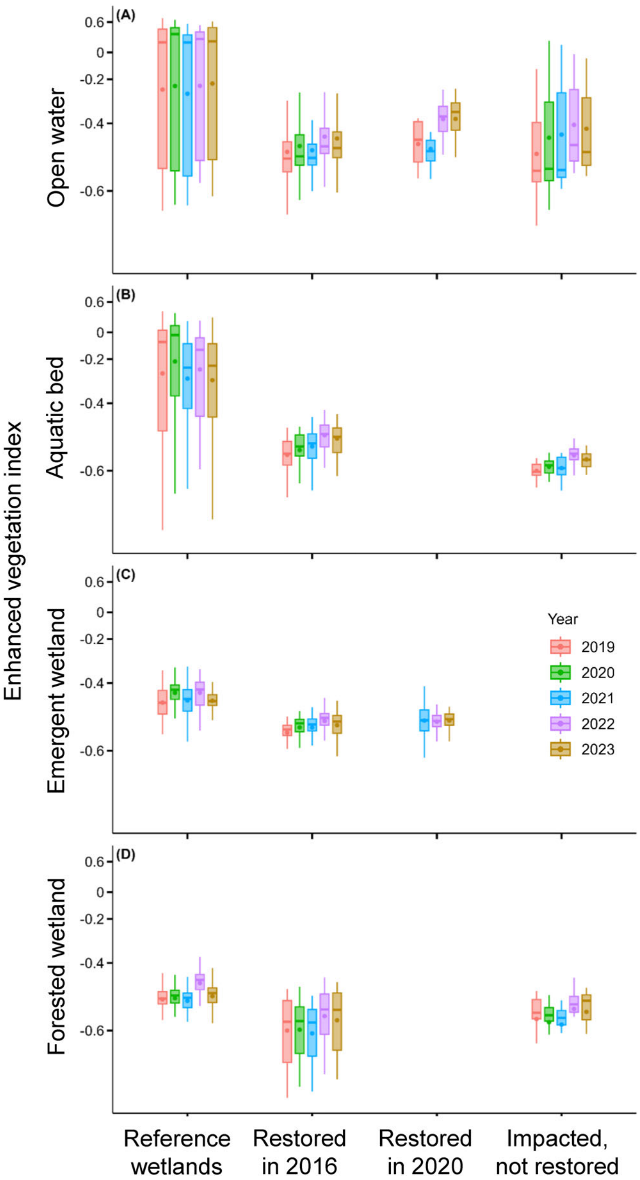

Figure 7. Temporal trends (2019–2023) in surface water, assessed by the normalized difference water index (NDWI), with Yeo-Johnson transformation for flagship wetland plant communities restored in 2016 and 2020 at Tidmarsh Mass Audubon Wildlife Sanctuary and Foothills Preserve. Reference and adjacent unrestored wetlands were included for comparison. Box plots show mean EVI values.

community growth, providing a robust assessment of restoration effectiveness. Our approach aligns with previous research advocating for high-resolution multispectral satellite imagery to capture the spatial and temporal patterns of post-restoration monitoring (Jones et al. 2009; Taddeo & Dronova 2018). Likewise, a combination of spectral indices (e.g. NDWI, normalized difference vegetation index, soil adjusted vegetation index) has been successfully used to discriminate wetlands in Canada (Amani et al. 2018). Singh et al. (2018) and Singh and Gray (2020) suggest that selecting remote sensing imagery during peak phenological differences enhances the detection and mapping of invasive plants and forest types. If such imagery is unavailable or phenological differences are unknown, using temporal signatures from all available images is a viable alternative. Remote sensing excels in capturing large-scale, frequent, and consistent observations while enabling the detection of subtle ecological shifts that often go unnoticed with traditional field methods (Dronova et al. 2015). Our study supports the use of remotely sensed data to track post-restoration ecological responses in small, heterogeneous wetland areas (<500 acres) with environmental complexity. Previous research has relied on specialized equipment and sensors (e.g. field spectroradiometers, commercial satellite imagery, hyperspectral sensors) to differentiate plant communities based on functional traits or taxonomic identity (Mishra 2020). Our findings highlight the effectiveness of vegetation indices for spectral discrimination and wetland ecosystem mapping. This approach offers a valuable tool for assessing restoration outcomes at broader ecological scales. Spectral indices derived from satellite imagery, such as EVI and NDWI, serve as reliable proxies for vegetation growth, productivity, biomass accumulation, and water surface dynamics—key indicators of restoration success (Adam et al. 2010; Ashok et al. 2021).

Our use of Sentinel-2 imagery to derive spectral indices aligns with national-scale studies that demonstrated the responsiveness of vegetation indices to field-based metrics of vegetation structure and composition (Taddeo & Dronova 2018). The spatial and temporal resolution of Sentinel-2 effectively captured spectral variations in flagship communities, making it well-suited for analyzing complex wetland ecosystems and providing detailed insights into both short-term seasonal growth and long-term ecosystem succession (del Río-Mena et al. 2020). The inter- and intra-annual phenology patterns observed at Tidmarsh post-restoration revealed distinct spectral signatures among plant communities. These patterns highlight the emergence of diverse ecosystem types within just 3–7 years post-restoration, providing early evidence of developing complex and varied wetland ecosystems. This early evidence of wetland ecosystem development aligns with Ioana-Toroimac et al. (2022), who used Landsat-derived NDWI to track wetland restoration (1984–2020) and observed increased surface-water area following restoration. This aligns with our findings of improved surface water dynamics and plant communities. We found that NDWI values significantly differed among plant communities during the 2019–2023 period across both restoration phases, confirming clear spectral distinctions that persisted over time. These findings also align with Jackson et al. (2004) demonstrating that NDWI effectively captures surface-water changes. While spectral indices can reflect ecological differences among plant communities, their accuracy can be affected by measurement uncertainties, atmospheric conditions, seasonal variations, and moisture levels (Gao 1996). Although sensitive to foliage water content, restricting NDWI calculations to the dormant period improved surface water extent estimation.

Vegetation and water indices revealed variations in productivity and surface-water extent across different phases of restoration. Older restorations exhibited greater productivity, while newer restorations remained in the early stage of vegetation establishment and growth. Similar observations were made elsewhere. For example, Benayas et al. (2009) demonstrated that as restoration age increases, forested wetlands exhibited enhanced ecosystem functions, including carbon sequestration. Restored delta wetlands at intermediate recovery stages exhibited increased vegetation productivity and significant biomass accumulation. Wetlands in early-stage post-restoration recovery exhibited lower but steadily increasing vegetation growth, reflecting the gradual establishment of plant communities and increasing productivity (Taddeo & Dronova 2020). The EVI variations across restoration phases in our study emphasize the critical role of temporal factors in wetland recovery. Similarly, in restored freshwater-tidal wetlands in coastal California, vegetation responses varied by restoration age—rapid growth in newly restored sites (<5 years), a non-linear decline in intermediate sites (10–15 years), and slower changes in older sites (>15 years) (Taddeo & Dronova 2020). These findings emphasize the necessity of continued monitoring to evaluate long-term restoration success and to implement adaptive management strategies.

In our study, open-water wetlands, in general, exhibited the highest NDWI values and the greatest variation, likely due to fluctuating water levels and seasonal dynamics. In contrast, forested wetlands had the lowest NDWI values, as high evapotranspiration reduced the surface water cover. Our findings indicate significant recovery of plant communities post-restoration, particularly in open-water wetlands restored in 2016, where rising EVI values reflect enhanced vegetation productivity, algal growth, and hydrophytes establishment. Our findings align with Bentley et al. (2022), who demonstrated substantial improvements in the ecological health and biophysical properties of riparian wetlands restored on degraded farmlands. Forested wetlands also showed stable and elevated EVI values post-restoration, consistent with the slower maturation process of woody vegetation. As Meli et al. (2014) suggested, the success of wetland restoration in enhancing biodiversity and ecosystem services hinges on a multi-faceted evaluation of degradation causes, restoration strategies, experimental designs, and ecosystem types, underscoring the need for tailored restoration approaches for different habitats.

The 2020 restoration efforts led to a decline in the EVI values among open-water wetlands and only modest EVI improvements in emergent wetlands. This can be attributed to the initial disturbance caused by restoration activities, which can temporarily reduce aquatic vegetation cover. Prior to the 2020 restoration, the retired cranberry farm was dominated by dense cranberry mats, a legacy effect of the commercial cultivation known for high EVI values (Hoekstra et al. 2020). Therefore, the initial drop in EVI following the conversion of these bogs to wetlands reflects a transition from high-productivity agriculture to early-stage wetland succession. Similarly, Moore et al. (1999) observed declines in both open water and water depth in newly created emergent wetlands in Connecticut, United States, contrasting with the more stable conditions found in reference sites during the same period. However, the conversion of pre-restoration reservoirs into emergent wetlands led to increased EVI values, likely driven by enhanced hydrophyte growth boosting vegetation productivity. These variations underscore the importance of restoration strategies tailored to the ecological characteristics of each wetland type. The variability we observed among flagship communities in the strength, direction, and magnitude of vegetation growth and surface-water retention following restoration underscores the complexity of wetland recovery. This highlights that long-term ecological responses can vary across different wetland ecosystem types. Our findings emphasize the importance of incorporating ecosystem-specific dynamics into restoration design, implementation, and post-restoration management to optimize ecological outcomes.

The between-year EVI differences remained mostly significant across all the flagship wetland plant community types, even between successive years. Such rapid improvements in the median EVI provide credence for enhanced productivity among restored wetlands. In 2022, palustrine forested wetlands showed the highest median EVI, a significant increase from previous years. This wetland plant community type showed the lowest EVI in 2019, reflecting the slow growth and maturation of woody vegetation. Among all wetlands that emerged in response to restoration, as the dominant vegetation in palustrine forested wetlands is woody trees, this type takes the longest to reach maturity in terms of growth and productivity. The median EVI for 2020 and 2021 also differed significantly from 2019 for palustrine forested wetlands, while the increase in median EVI for early years was relatively minor.

Wetlands restored in 2016 demonstrated stable intra-annual growth patterns, characterized by a peak in productivity during June–July and a decline in the dormant season. These seasonal fluctuations align with findings from previous studies on restored wetlands (Zedler & Kercher 2005). This may be attributed to either slow recovery or the fact that post-disturbance systems have transitioned to alternative states that differ from the reference conditions (Moreno-Mateos et al. 2012). Among the restored wetland types, forested wetlands exhibited the highest EVI, reflecting their capacity for substantial photosynthetic activity and biomass accumulation. This is likely due to the presence of woody vegetation that promotes prolonged growth periods and an increase in basal area over time since restoration (Bryzek et al. 2023). In contrast, open-water wetlands recorded the lowest EVI, suggesting lower productivity due to challenges in sustaining plant growth in these habitats. In comparison, wetlands restored in 2020 displayed less consistent growth patterns, with significant EVI differences during the growing season but not the dormant season. This variability may indicate reduced stability in productivity and turnover patterns compared to the more established 2016 restorations. These fluctuations may stem from initial restoration disturbances, which often disrupt existing vegetation and hydrology (Sonnier et al. 2018). Interestingly, the NDWI values consistently showed that restored wetlands have not yet reached desired saturation levels, indicating ongoing hydrological challenges. Open-water wetlands restored in 2020 exhibited higher NDWI values and greater variability compared to the 2016 restorations, likely due to fluctuating water levels and sedimentation that may affect water retention (Steinman et al. 2014). Conversely, aquatic beds and palustrine wetlands exhibited lower NDWI values, possibly reflecting their slower recovery rates. Forested wetlands showed stable but gradually increasing NDWI values, suggesting improving water retention as vegetation matures (Keddy 2010). Overall, these findings underscore the importance of considering interannual growth patterns and hydrological indicators to assess the ecological recovery of restored wetlands. They highlight the necessity of tailored restoration strategies that address the unique ecological characteristics and challenges of each wetland type to enhance ecosystem stability and resilience. Further research should focus on identifying the factors influencing the observed differences in productivity and hydrology across restoration years to optimize future wetland restoration efforts.

Our study demonstrated that the restoration of retired cranberry farms into wetlands successfully fosters the establishment of flagship wetland plant communities. Both remotely sensed spectral indices—EVI and NDWI—revealed clear patterns of vegetation recovery and hydrological response across plant communities. Specifically, restored flagship communities showed marked increases in EVI over time, reflecting enhanced vegetation growth and productivity, particularly in older restoration sites compared to those established more recently. These findings indicate that restoration efforts have effectively facilitated the development of wetland ecosystems resembling the region's native wetland, characterized by increased habitat heterogeneity. The distinct spectral signatures observed among wetland plant communities further support that restoration promotes not only ecological establishment and recovery but also contributes to the development of unique ecosystem types typical to the region within a relatively shorter time frame. Our monitoring approach, leveraging open remote sensing data, provided a robust framework for assessing restoration outcomes. Therefore, we advocate for the use of multispectral satellite imagery in assessing wetland restoration success, as EVI and NDWI offer reliable and comprehensive insights into vegetation productivity and hydrological changes. While our findings illustrate significant improvements in vegetation productivity, they also highlight the complex nature of hydrological recovery, particularly in increasing surface-water extent. The observed variability in NDWI values suggests ongoing hydrological challenges, warranting tailored restoration strategies to address ecosystem-specific needs and promote resilience. Overall, our study advances the understanding of wetland restoration outcomes and supports evidence-based management practices aimed at achieving sustainable wetland ecosystems. Continued monitoring using remote sensing methods and adaptive management will be essential for optimizing future restoration strategies and ensuring the long-term success of these vital ecosystems.

Acknowledgments

We acknowledge the support of Tidmarsh Living Observatory, Mass Audubon, the Town of Plymouth, and the Massachusetts Division of Ecological Restoration for their collaboration and logistical assistance. We express our gratitude for the financial support provided by the National Fish and Wildlife Foundation (Grant No. 1301.20.067179). We also thank the staff of AidData at William & Mary for their contributions, as well as the Bridgewater State University Office of Undergraduate Research for its support in this work. The spectral data used for this project is available from: https://doi.org/10.7910/DVN/MSQBX8.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Acquire date and percentage of valid data for Sentinel-2A images applied to retrieve sample point (a) and reference point (b) in this study.
Table S1. Inter-annual trends in the enhanced vegetation index (EVI) of flagship wetland plant communities restored in 2016 and 2020 at Tidmarsh Wildlife Sanctuary and Foothills Preserve.
Table S2. Inter-annual trends in normalized difference water index (NDWI) for flagship wetland plant communities restored in 2016 and 2020 at Tidmarsh Wildlife Sanctuary and Foothills Preserve.

Coordinating Editor: Loretta Battaglia

Received: 27 November, 2024; First decision: 20 February, 2025; Revised: 12 March, 2025; Accepted: 12 March, 2025