



Condition and Trends of Estuarine Water Quality and Seagrass in Fire Island National Seashore

Northeast Coastal and Barrier Network, 2003–2022



Aerial image of the northern section of Great South Bay estuary at Fire Island National Seashore, New York, USA (ESRI 2025).

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Condition and trends of estuarine water quality and seagrass in Fire Island National Seashore: Northeast Coastal and Barrier Network, 2003–2022

Science Report NPS/SR—2025/294

Jessica L. Nagel ¹, Holly K. Plaisted ², Christopher P. Peck³, and Paul Duffy³

¹ Bryantown, Maryland 20617

² National Park Service
Northeast Coastal and Barrier Network
University of Rhode Island
Coastal Institute in Kingston
Kingston, RI 02881

³ Neptune and Company, Inc.
1435 Garrison Street, Suite 201
Lakewood, CO 80215

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Abstract

This report summarizes conditions and trends in routine long-term water quality monitoring and seagrass data collected at Fire Island National Seashore in New York from 2003 through 2022 as part of the NPS NCBN Vital Signs Estuarine Nutrient Enrichment monitoring program. This comprehensive program incorporates spatial surveys, repeated monitoring at trend stations, and continuous monitoring at a fixed logging station in an effort to establish overall water quality condition of the estuary as well as to identify potential trends or changes in condition over time. All monitoring was conducted during a four-week summer index period. Monitored variables included dissolved oxygen concentration, chlorophyll-a concentration, attenuation of downwelling photosynthetically available radiation (PAR), salinity, temperature, turbidity, and pH. In addition, long-term monitoring of seagrass condition was conducted at permanently established transects. Water quality condition and trends were generally consistent between the spatial station surveys, the trend stations, and continuous logging station. Although the majority of the monitored area was generally classified as being in fair to good condition for most years sampled, there were several years when more than 50% of the park estuary was classified as being in poor condition with respect to chlorophyll-a concentrations and water clarity, as measured by PAR attenuation. Bottom dissolved oxygen concentrations were consistently classified as being in good condition throughout the majority of the estuary. While there was no statistical evidence of significantly increasing water temperature over time, summertime temperatures at the logging station, most trend stations, and in a large percentage of the estuary exceeded 25°C in several years. The formation of the new inlet following Hurricane Sandy in 2012 resulted in significant increases in salinity throughout the system and significant declines in temperature at the trend station closest to the inlet. Trends in seagrass condition in the park's reference bed varied by species with eelgrass experiencing precipitous declines followed by its complete disappearance and widgeon grass persisting despite significant declines over the monitoring timeframe. The identification of status and trends may help managers to make better informed decisions, develop effective mitigation measures, reduce management costs, and provide a means of measuring progress towards goals.

Acronyms and Abbreviations

edf: Effective degrees of freedom

ENE: Estuarine nutrient enrichment

FIIS: Fire Island National Seashore

GAM: Generalized additive model

GLMM: General linear mixed model

MCT: Multiple comparison test

n: Number of observations

NCBN: Northeast Coastal and Barrier Network

NOAA: National Oceanic and Atmospheric Administration

NPS: National Park Service

NTU: Nephelometric turbidity units

PAR: Photosynthetically active radiation

psu: Practical salinity units

SAV: Submerged aquatic vegetation

SD: Standard deviation

SE: Standard error

TPRS: Thin plate regression spline

USEPA: United States Environmental Protection Agency

Acknowledgments

This report is the culmination of efforts by many people who contributed to the National Park Service Northeast Coastal and Barrier Network (NCBN) estuarine Vital Signs monitoring at Fire Island National Seashore from 2003 through 2022. We are grateful to the many scientists and technicians who served on field crews (FC) and the technical steering committee (TSC) or facilitated data management and analysis (DMA) and reporting (R), including: Kelly Medeiros (TSC), Sophia Fox (TSC), James Caldwell (DMA, R), Blaine Kopp (DMA, R), Dennis Skidds (DMA), Scott Rasmussen (DMA), Robin Baranowski (DMA), Bradley Peterson (FC, TSC), Stephen Heck (FC), Ken Moore (TSC), Betty Neikirk (TSC), and Erin Shields (TSC). Their dedication to the program and their attention to quality assurance during data collection and data management is paramount and provides the foundation for this report. We are particularly grateful to Hilary Neckles for her effusive enthusiasm and leadership on all aspects of this program. We greatly appreciate the support and leadership provided by Sara Stevens, NCBN Program Manager, throughout this project. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Introduction

Six parks within the National Park Service (NPS) Northeast Coastal and Barrier Network (NCBN) contain critical estuarine habitat (Figure 1). Roman et al. (2000) identified nutrient enrichment as the primary threat to the ecological integrity of estuaries within this region, and threats to coastal water quality are one of the highest priority issues identified by park managers (Stevens et al. 2005). As part of the NCBN Vital Signs Monitoring Program, NCBN partnered with USGS scientists to develop a protocol (Kopp and Neckles 2009) for monitoring estuarine nutrient enrichment (ENE) in NCBN parks that was fully implemented beginning in 2007. The vital signs selected for monitoring include: estuarine water chemistry, estuarine water quality, estuarine water clarity, seagrass distribution, and seagrass condition. Previous reports summarized water quality condition and trends in NCBN parks during 2003–2006 (Kopp et al. 2009) and 2006–2011 (Caldwell et al 2015). The current report summarizes conditions and trends for both water quality and seagrass condition data collected in Fire Island National Seashore from 2003 through 2022.

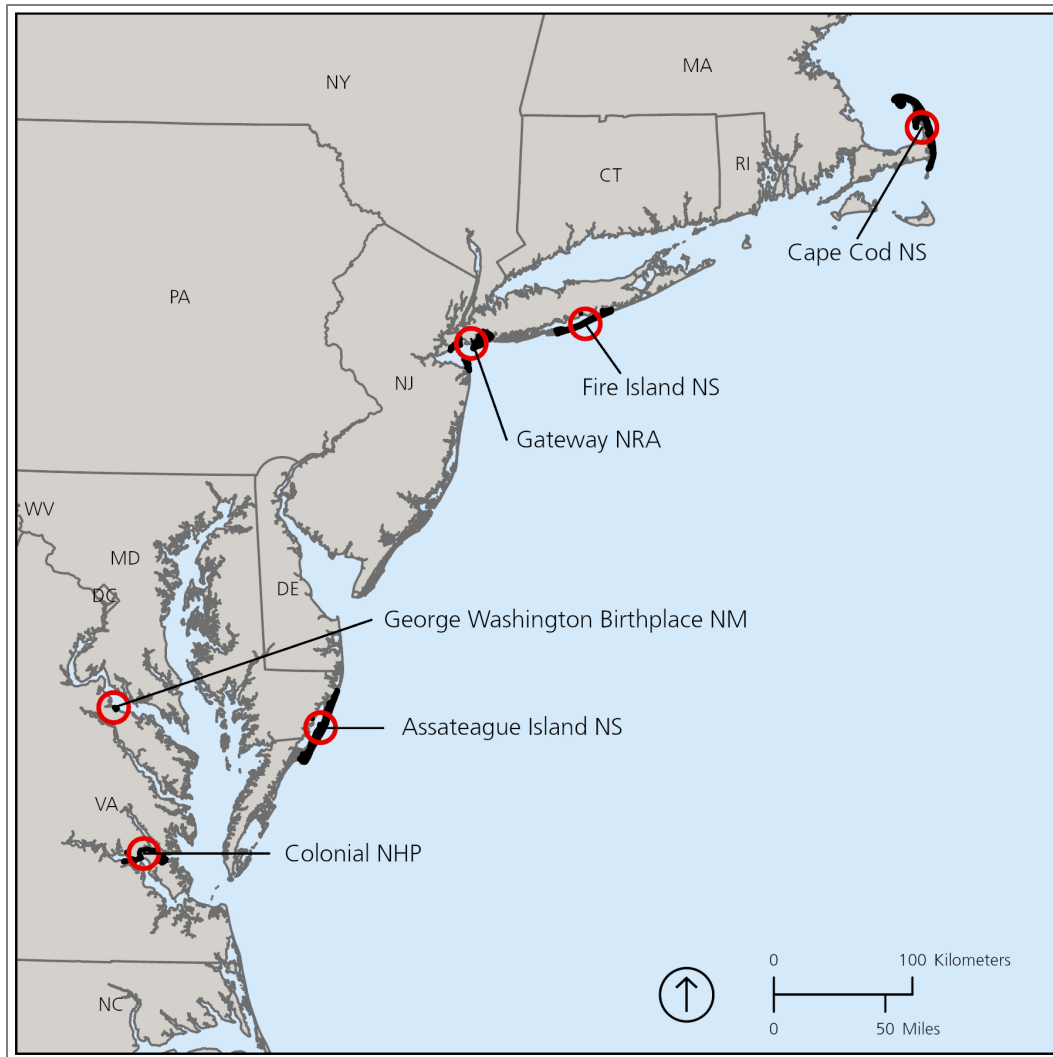


Figure 1. Locations of Northeast Coastal and Barrier Inventory & Monitoring (I&M) Network parks monitored for estuarine nutrient enrichment. NS: National Seashore; NRA: National Recreation Area; NM: National Monument; NHP: National Historical Park.

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Vital Signs Monitoring

The NPS Vital Signs Monitoring Program is designed to help address the major challenges facing NPS in preserving natural resources and develop strategic approaches to resolving them. The program incorporates 270 parks into 32 biogeographic networks that share funding, staff, and similar geographic and natural resource characteristics to improve efficiency and reduce costs while still using customized and relevant monitoring approaches. All networks in the program share the following five goals:

- Determine the status of and trends in selected indicators of the condition of park ecosystems to allow managers to make better informed decisions and to work more effectively with other agencies and individuals for the benefit of park resources.

- Provide early warning of abnormal conditions of selected resources to help develop effective mitigation measures and reduce costs of management.
- Provide data to better understand the dynamic nature and condition of park ecosystems and to provide reference points for comparisons with other altered environments.
- Provide data to meet certain legal and Congressional mandates related to natural resource protection and visitor enjoyment.
- Provide a means of measuring progress towards performance goals.

Goals of NCBN Monitoring

The NCBN coastal parks are highly dependent on good water quality conditions to sustain the complex estuarine and nearshore ecosystems within them. While parks in the NCBN represent a wide range of sizes (33 ha to almost 20,000 ha), latitudes (more than 540 km of latitude), watershed geology (shallow soils overlying granite bedrock to thick sandy glacial deposits), tidal range (microtidal to more than 3 m), and freshwater sources (surface water versus ground water), estuaries within these parks share fundamental temperate zone characteristics and the threat of nutrient enrichment as a primary management concern (Roman et al. 2000). Consequently, the estuarine Vital Signs monitoring protocol for NCBN parks relates to the stressor with the greatest potential impact: nutrient enrichment (Kopp and Neckles 2009).

The goal of estuarine monitoring in coastal parks of the NCBN is to assess how estuarine natural resources are affected by changing nutrient inputs. This goal is addressed by the ENE monitoring protocol, which tracks indicators of estuarine response to nutrient enrichment (Kopp and Neckles 2009).

The data presented in this report result from ENE monitoring of water chemistry, water quality, water clarity, and seagrass condition. Monitored variables for estuarine water chemistry include: temperature, which affects biological and chemical processes; salinity, which affects osmoregulation and species distribution; and pH and dissolved oxygen, which provide indirect information on nutrient loading and direct information on threats to estuarine fauna. Chlorophyll-*a* concentration, a direct indicator of phytoplankton biomass and indirect indicator of nutrient loading, was used as a measure of estuarine water quality. Estuarine water clarity, which is known to directly influence seagrass distribution and productivity, was monitored using photosynthetically available radiation (PAR, light between 400–700 nm) and turbidity. Measurements of seagrass condition, such as density, biomass, percent cover, and canopy height, were included to serve as indicators of seagrass bed integrity. For detailed information about the rationale for variable selection, see Kopp and Neckles (2009).

Conceptual Monitoring Approach

The ENE monitoring protocol incorporates both spatial and temporal sampling designs to address questions at a hierarchy of scales (Kopp and Neckles 2009). Characteristics that address the Vital Signs of water quality, water clarity, and water chemistry are all sampled using a probability design within park estuaries during a late-summer index period. This statistical approach allows the

condition of unsampled locations to be inferred from the distribution of data from a set of randomly positioned “probability”, or spatial, stations. A subset of sampling stations is sampled repeatedly during the index period and is not re-randomized in subsequent years. These “trend stations” allow us to examine temporal variability within the index period, and to improve the sensitivity of the monitoring protocol to detecting change through time. Additionally, one site considered to be representative of water quality conditions within each park stratum is equipped for continuous monitoring throughout the index period. Thus, the protocol includes elements of probabilistic and targeted spatial sampling, and the temporal intensity ranges from snapshot assessments to continuous monitoring. This mixture of sampling approaches and intensities was adopted to allow for overall condition assessment while enhancing the ability to detect change in response to nutrient enrichment. The result is a geographically broad program that tracks conditions in almost 500 km² of estuarine habitat. It is statistically rigorous and is designed to integrate with marine monitoring programs of the USEPA and NOAA.

A reference seagrass bed that was considered to be representative of seagrass growth conditions in the park was selected for seagrass condition monitoring (Kopp and Neckles 2009). The sampling design incorporated a cluster design with three transects stratified by depth zone: shallow, mid-depth, and deep. These transects were sampled at least annually during the period of peak biomass to allow for comparison of trends in seagrass characteristics across different depths.

Methods

Study Area

Fire Island National Seashore is a 7,810-ha park located on a barrier island bordering the south shore of Long Island, New York and the Atlantic Ocean (Figure 2). The park boundary extends from Fire Island Inlet on the west to Moriches Inlet on the east and encompasses parts of Great South Bay and Moriches Bay. Approximately 46 percent of this area is shallow, submerged estuarine habitat with limited exchange with the open ocean. During Hurricane Sandy in 2012, a new inlet was formed west of Smith Point, which resulted in direct exchange and increased flushing with the Atlantic Ocean. This new inlet remained open through 2022 but has since closed. The spatial design for ENE monitoring includes approximately 4,532 ha of estuarine area, which comprises 100 percent of the NPS estuarine resources at this park. While much of the land within the park boundary is predominantly forested, wetlands or open space (e.g., beach, dune, etc.), the larger surrounding watershed is subject to nutrient inputs from suburban and urban sources and is also under pressure for further development.

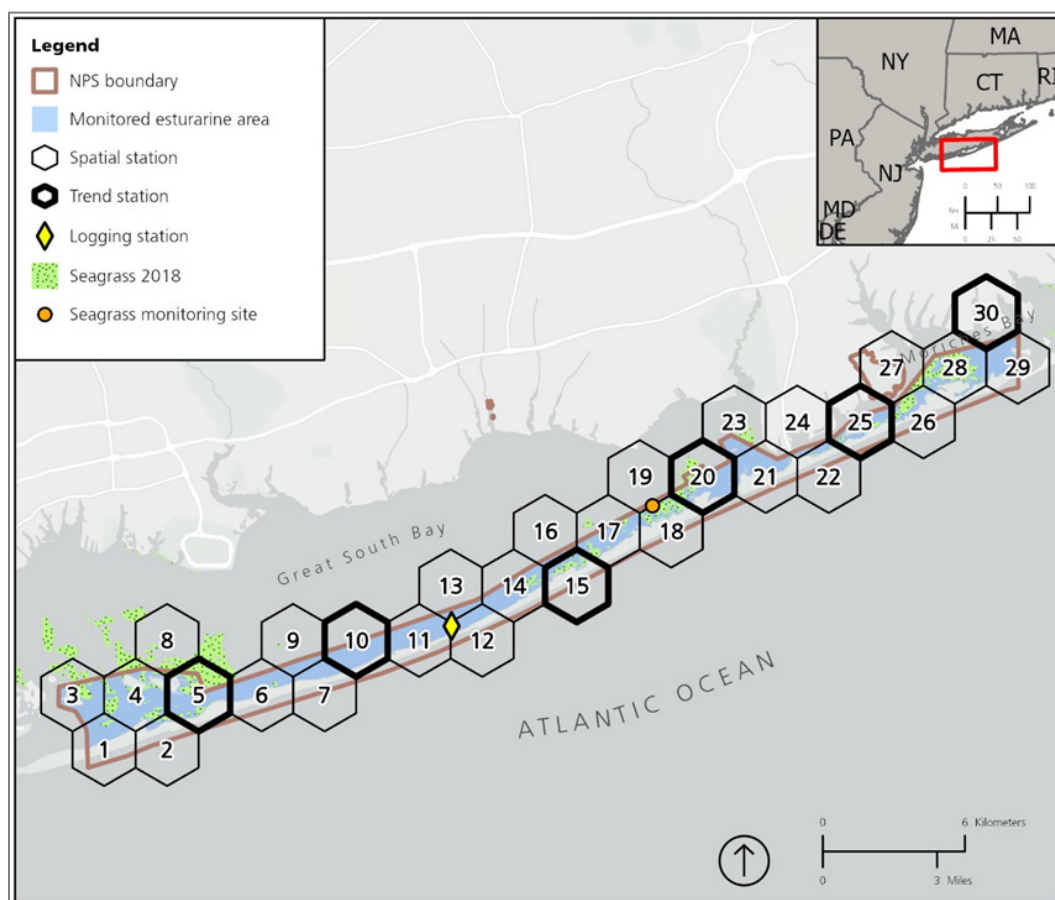


Figure 2. Spatial domain and sampling design for estuarine monitoring at Fire Island National Seashore, New York. Sampling hexagons with a bold outline represent those assigned with trend stations.

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Seagrass beds are a dominant feature within the shallow waters within and adjacent to FIIS. However, human activities such as nutrient pollution in the region have led to significant declines in both seagrass abundance and distribution. Beginning in 2007, seagrass condition was monitored at a well-established seagrass bed in Great South Bay that contained a mix of eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*) (Figure 3). The precipitous decline in eelgrass within the bed since 2011 prompted the establishment of a second reference bed in Moriches Bay in 2021. Due to the relatively limited amount of data available to this point for the Moriches Bay seagrass bed, trend analyses were not performed for this site. Only analyses for the Great South Bay reference bed are reported here.

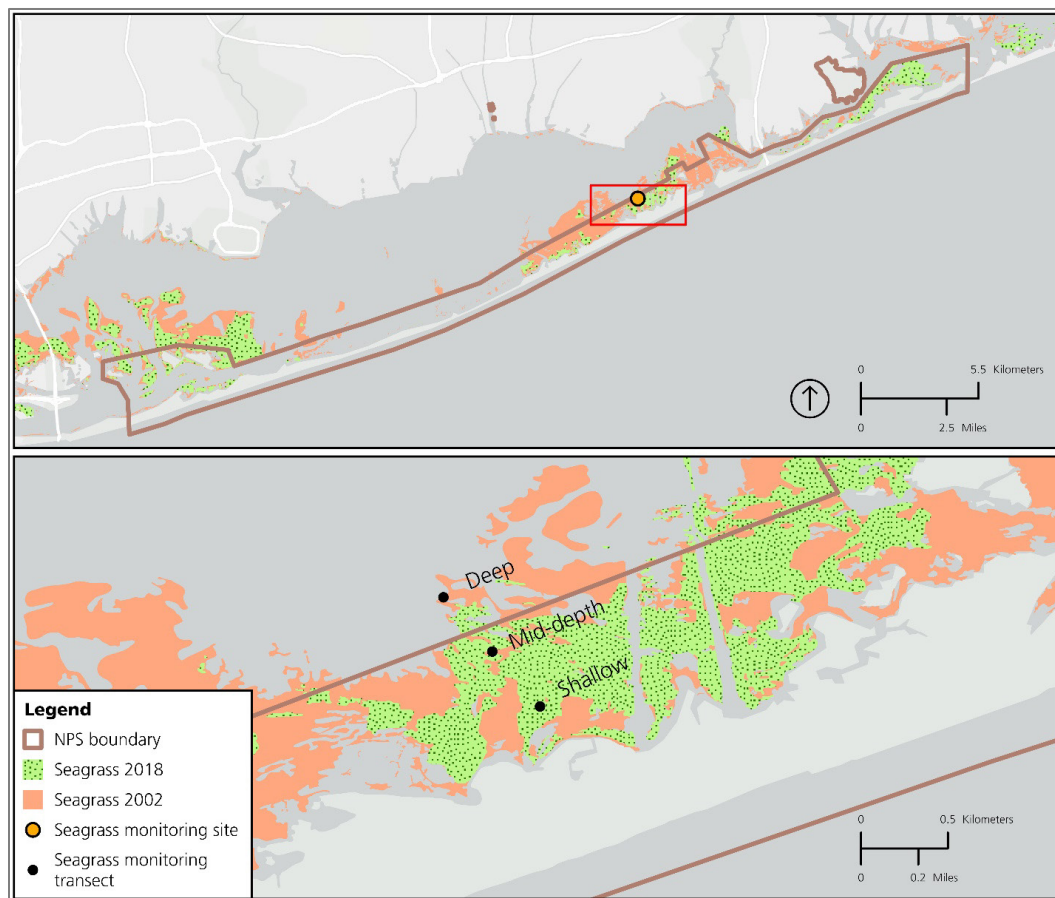


Figure 3. Location of seagrass sampling transects at Great South Bay reference bed, Fire Island National Seashore. Seagrass coverage in 2002 and 2018 is shown for reference.

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Sampling Designs

The methods and procedures for the monitoring of water quality and seagrass condition are described in detail in the NCBN ENE protocol (Kopp and Neckles 2009). A brief summary of the sampling design can be found in the subsections below. Water quality monitoring was conducted in 2003, 2009, 2011, 2013, 2014, 2015, 2016, 2017, 2019, and 2021. Seagrass monitoring was conducted annually between 2007 and 2022 except for 2021.

Spatial Station Water Quality

The spatial sampling survey design adopted for NCBN estuaries treats each park estuary as a continuous resource and uses a randomized-tessellation stratified design as the basis for sample site selection (Stevens 1997; Stevens and Olsen 2003). The spatial domain was overlaid with a grid of tessellated hexagons with one random site selected for monitoring within each hexagon (Figure 2). This approach results in a set of samples that is balanced spatially over the entire estuary of interest with the statistical advantages of random sampling. In addition, this sampling design is comparable to that used by the USEPA National Coastal Assessment Program (USEPA 2001a) thus allowing for data from NCBN estuaries to be evaluated within the context of other estuaries in the region and also contribute toward overall regional condition assessments.

Spatial stations were sampled during a 4-week summer index period each sampling year following the standardized monitoring protocol (Kopp and Neckles 2009). In most years, a minimum of 30 stations were sampled. Temperature, salinity, turbidity, dissolved oxygen, and pH (beginning in 2019) were measured at three depths (i.e., surface, mid-depth, and near bottom) within the water column at each station using a multi-parameter water-quality instrument (sonde). Grab samples for chlorophyll-*a* concentrations were collected from a depth of 20–30 cm beneath the water surface in amber polyethelene bottles for subsequent extractive fluorometric analysis (Arar and Collins 1997). The attenuation coefficient, K_d (m^{-1}), of downwelling PAR was quantified from depth profiles of PAR obtained using LI-COR quantum sensors within 3 hours of local solar noon (i.e., the time when the sun crosses the local meridian). Sampling start and end dates for each index period are provided in Table 1.

Table 1. Sampling start and end dates for each index period within Fire Island National Seashore.

Year	Start	End
2003	2003–07–28	2003–08–19
2009	2009–07–15	2009–08–05
2011	2011–07–05	2011–07–19
2013	2013–07–03	2013–07–22
2014	2014–07–01	2014–07–22
2015	2015–07–06	2015–07–27
2016	2016–07–08	2016–07–27
2017	2017–07–05	2017–07–26
2019	2019–07–01	2019–07–22
2021	2021–07–07	2021–07–27

Trend Station Water Quality

While monitoring for overall estuary condition is best accomplished by obtaining the greatest overall number of random sampling locations, monitoring for trends is best accomplished by revisiting one set of sampling locations through time (Urquhart et al. 1998). For the water quality parameters reported here, 20 percent of the hexagons in each park were selected as “trend” stations. To the

extent possible, hexagons identified for trend stations were distributed systematically throughout the spatial domain (Figure 2).

Six trend stations were selected for monitoring changes in water quality over time. Trend stations were sampled once a week for four consecutive weeks during each summer index period between 2003 and 2021. Sampling start and end dates for each index period are provided in Table 1. Parameters measured included water column PAR attenuation (K_d), as well as surface chlorophyll-*a*, dissolved oxygen, salinity, temperature, and turbidity using the same protocols as for spatial surveys.

Continuous Logging Station Water Quality

Continuous monitoring data are used to identify temporal variability in estuarine Vital Signs that is not captured by weekly trend monitoring. While continuous stations do not contribute statistically to assessments of average estuarine condition, these high-resolution trend stations provide information that assists spatial data interpretation. Continuous monitoring stations were established in areas expected to represent typical conditions for the estuarine environment and avoid obvious sources of bias to water quality.

Continuous in situ measurements of water quality parameters were collected at a permanently established logging station during each summer index period from 2003 through 2021 following the standardized monitoring protocol outlined in Kopp and Neckles (2009) (Figure 2). Sampling start and end dates for each index period are provided in Table 1. Parameters measured included chlorophyll-*a*, dissolved oxygen, PAR attenuation (K_d), salinity, temperature, turbidity, pH, and depth. Measurements of in situ PAR were collected at 15-min intervals using two LI-192 underwater quantum sensors positioned 0.5 m vertically apart below the water surface. Measurements of all the other parameters were collected at 15-min intervals using a multiparameter data logger that was mounted to a pier, piling, or other structure a fixed distance from the estuary bottom, so that the water depth of the data logger is tidally varying.

Seagrass Condition

High-resolution seagrass monitoring data were collected annually in most years between 2007 and 2022 (excluding 2021) from a permanently established site (Figure 2) following the standardized monitoring protocol outlined in Kopp and Neckles (2009) and Short et al. (2004). The monitoring site at Great South Bay contains a mix of both eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*) and consists of three permanent 50-m transects that run parallel to shore across an increasing depth gradient. Data for both species were collected at twelve 0.25 m² quadrats located at fixed random locations along each transect. Seagrass attributes measured included percent cover, canopy height, and shoot density in 0.25-m² quadrats and above- and belowground biomass in 0.0035-m² cores. In addition to seagrass data, sediment samples for percentage of fine-grain (i.e., silt and clay) sediment and organic material were also collected from each transect.

Continuous measurements of in situ water temperature within seagrass beds were collected using a data logger positioned at or near the sediment surface adjacent to the shallow (A) and deep (C)

transects. Data were recorded year-round at 15- to 30-min intervals in most years from 2019 through 2022.

Spatial Station Water Quality Data

Data Analysis

Area-weighted Condition

Area-weighted water quality is reported in two ways: the mean condition and the percent of the estuarine area exceeding threshold values for selected parameters. In both cases, parameter values are weighted by the estuarine area within the hexagon from which each sample is collected (Cochran 1977, Stevens and Olsen 2003). The area-weighted mean ($\bar{y}$) was computed for each measured depth, as applicable, as:

$$\bar{y} = \sum_{i=1}^n w_i \cdot y_i,$$

where y_i represents the measurement within the i^{th} hexagon and w_i is the percent of the total estuarine area contained within the hexagon.

Condition was also characterized by the percent of estuarine area within quality categories for a subset of parameters. Thresholds for chlorophyll-*a*, dissolved oxygen, and water clarity were defined in Kopp and Neckles (2009) (Table 2) and are consistent with thresholds used by the USEPA and NOAA (Bricker et al. 1999; USEPA 2001b; USEPA 2004). Temperature thresholds were based on eelgrass (Shields et al. 2019) and blue crab (*Callinectes sapidus*) (Bauer and Miller 2010a, 2010b) tolerance (Table 2). The proportion of estuarine area in each quality category j (p_j) was computed as:

$$p_j = \sum_{i=1}^n w_i \cdot 1_{ij}$$

where 1_{ij} is an indicator for whether the measurement within the i^{th} hexagon falls within the category j values and w_i is the percent of the total estuarine area contained within the hexagon. For NPS reporting on these indicators, the proportion of the resource area that falls into each of four quality categories (good, fair, poor, or missing) is calculated for each park. The fourth (“missing”) category includes spatial elements that were not sampled or data that were excluded during quality control procedures. All computations were carried out using the R Statistical Computing Environment (R Core Team 2022).

Table 2. Threshold values associated with each parameter quality category as defined in Kopp and Neckles (2009).

Parameter	Quality Category ^A		
	Good	Fair	Poor
Chlorophyll- <i>a</i> (near surface)	< 5 µg/L	5–20 µg/L	> 20 µg/L
Dissolved oxygen (near bottom)	> 5 mg/L	2–5 mg/L	< 2 mg/L

^A Good/Fair/Poor is not applicable to surface water temperature.

Table 2 (continued). Threshold values associated with each parameter quality category as defined in Kopp and Neckles (2009).

Parameter	Quality Category ^A		
	Good	Fair	Poor
PAR attenuation K_d (SAV standard)	< 0.92 m ⁻¹	0.92–1.61 m ⁻¹	> 1.61 m ⁻¹
Water temperature (near surface)	< 28°C	28–33°C	> 33°C

^A Good/Fair/Poor is not applicable to surface water temperature.

General Linear Mixed Model (GLMM)

Consistent with the previous report by Caldwell et al. (2015), a general linear mixed model was used to determine whether there are differences in water quality parameters among index periods. Year was treated as a categorical fixed effect and individual hexagons are included as random intercepts. The fitted model was used to test the hypothesis: H_0 : the mean parameter value was the same across years versus H_1 : at least one of the year's means was different. If the null hypothesis was rejected at the 5% significance level (i.e., p -value < 0.05), then a multiple comparison test (MCT) was performed to determine which pairs of years have statistically different means based on Tukey-adjusted p -values (i.e., $H_0: \mu_1 = \mu_2$ versus $H_1: \mu_1 \neq \mu_2$).

Residual analysis indicated that the homogeneity of variance assumption was oftentimes violated. Therefore, each parameter was log-transformed prior to fitting the model and the results of the MCT are presented on the log scale. Analyses were carried out using the R Statistical Computing Environment (R Core Team 2022). The nlme package (Pinheiro et al. 2020) was used to fit the models and multiple comparison tests are carried out using the emmeans package (Lenth 2020).

Generalized Additive Model (GAM)

Based on initial exploratory analyses, several parameters display potential nonlinear trends over time. Generalized additive models (GAMs; Wood 2017) are used to estimate trends in water quality parameters as smooth functions over time. Each water quality parameter was modeled using a gamma distribution with log link function. This is a commonly used distribution when data are non-negative, continuous, and potentially right-skewed. A major benefit of this model over applying a log transformation to data is the ability to model the mean of the parameter on the response scale, rather than the transformed scale. This in turn simplifies interpretation of the estimated model parameters and plots of the GAM smooths represent the mean response. Additionally, the log link has the added benefit of ensuring that simulated values used in power simulations will be non-negative.

For each parameter, we modeled the mean of response as a function of both time and location within the estuary. Mathematically, the model can be written as:

$$\begin{aligned} \text{response}_i &\sim \text{Gamma}(\mu_i, \phi) \\ \log(\mu_i) &= \beta_0 + f_1(\text{year}_i) + f_2(\text{longitude}_i, \text{latitude}_i), \end{aligned}$$

where μ_i is a vector of response values, year and hexagon location (longitude, latitude) are covariate vectors, β_0 is the intercept, f_1 and f_2 are non-linear smoothing functions, and $i = 1, \dots, n$ indexes the

respective year or hexagon within the estuary. Thin plate regression splines (TPRS; rank of basis expansion equal to number of years of data) and Gaussian process splines (rank 50 basis expansion) were utilized for the year and location smooths, respectively. The spatial dependence of observations was modeled in the mean structure (i.e., first-order model specification; Hefley et al. 2017) through the inclusion of the interaction smooth between longitude and latitude. Attempts to model temporal autocorrelation in a majority of cases resulted in unidentifiable models. Factors likely contributing to this include: (1) the relatively short time series, (2) irregular intervals of data collection, and (3) insufficient information in the data to uniquely distinguish between the wiggly trend and autocorrelation since they can both be used to describe similar patterns in the data (Simpson 2018). Therefore, for consistency across all models, temporal autocorrelation was not modeled. Residual analysis indicated a lack of temporal autocorrelation in a majority of parameters. For parameters that did exhibit significant temporal autocorrelation, the lag-1 autocorrelation was generally less than 0.4.

The first derivative was approximated along the length of the year smooth using the finite difference method. Periods of significant temporal change were identified as intervals of time wherein the 95% confidence interval of the first derivative (i.e., slope of tangent line) did not contain the value of zero.

Analyses were carried out using the R Statistical Computing Environment (R Core Team 2022). Each model was fit using the mgcv package (Wood 2011). Results were summarized and visualized using the gratia package (Simpson 2020).

Multivariate Mann-Kendall Trend Analysis

Despite several parameters exhibiting non-linear trends over time, it is still of interest to quantify whether parameters are increasing/decreasing over time. The multivariate Mann-Kendall test (trend R package; Pohlert 2020) was used to determine whether there exists a monotonically increasing or decreasing trend in values for all sites within the estuary over time (Libiseller and Grimvall 2002). Positive values of the test statistic Z_{MK} indicate that measurements tend to increase with time, whereas negative values indicate a decrease.

Area-Weighted Condition Results

Chlorophyll-a (Near Surface)

Area-weighted average near surface chlorophyll-*a* concentrations ranged from 1.07 to 24.30 $\mu\text{g/L}$ and were classified as being in good (i.e., $< 5 \mu\text{g/L}$) or fair condition (i.e., $5\text{--}20 \mu\text{g/L}$) for the majority of the index periods (Table 3). Poor area-weighted average conditions (i.e., $> 20 \mu\text{g/L}$) were observed in both 2009 and 2013. More than 50% of the estuary was in poor condition during 2009 and 2015 (Table 4).

Table 3. Area-weighted average water quality condition estimated from spatial station surveys at Fire Island National Seashore during the index periods of 2003–2021. [NA = not available].

Parameter	Depth(s)	Sampling Year									
		2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
Chlorophyll-a ($\mu\text{g/L}$)	Surface	1.07	24.30	7.65	20.26	6.98	19.47	11.57	16.80	5.70	4.29
Dissolved oxygen (% saturation)	Surface	137.90	114.89	109.28	109.48	105.11	103.25	108.60	112.53	96.96	105.81
Dissolved oxygen (% saturation)	Mid-Depth	120.31	113.39	103.86	108.70	94.51	105.29	103.52	98.18	94.06	104.14
Dissolved oxygen (% saturation)	Bottom	135.98	114.65	107.88	107.10	105.10	102.06	107.65	111.49	99.20	104.48
Dissolved oxygen (mg/L)	Surface	9.89	8.35	7.71	7.63	7.48	7.18	7.50	7.83	6.90	7.57
Dissolved oxygen (mg/L)	Mid-Depth	8.80	8.33	7.34	7.53	6.69	7.37	7.21	6.88	6.74	7.32
Dissolved oxygen (mg/L)	Bottom	9.77	8.37	7.61	7.50	7.47	7.12	7.44	7.79	7.10	7.34
PAR attenuation (K_d (m^{-1}))	Water Column	1.45	1.70	1.28	1.94	1.00	1.48	1.07	2.02	1.13	1.10
pH	Surface	NA	NA	NA	NA	NA	NA	NA	NA	7.84	7.82
pH	Mid-Depth	NA	NA	NA	NA	NA	NA	NA	NA	7.88	7.86
pH	Bottom	NA	NA	NA	NA	NA	NA	NA	NA	7.87	7.86
Salinity (psu)	Surface	23.43	25.16	26.99	28.96	29.76	30.12	30.63	29.69	27.67	27.92
Salinity (psu)	Mid-Depth	26.68	25.48	27.64	28.90	29.74	30.00	30.58	29.53	28.07	28.09
Salinity (psu)	Bottom	23.55	25.38	26.99	29.04	29.79	30.16	30.64	29.74	27.88	28.06
Temperature ($^{\circ}\text{C}$)	Surface	25.39	24.12	25.28	25.47	23.85	25.11	25.33	25.06	25.23	25.19
Temperature ($^{\circ}\text{C}$)	Mid-Depth	23.22	23.49	24.93	25.85	24.18	24.71	24.98	24.91	25.10	25.16
Temperature ($^{\circ}\text{C}$)	Bottom	25.25	23.84	25.27	25.21	23.83	24.93	25.25	24.85	25.20	25.15
Turbidity (NTU)	Surface	7.46	3.58	2.41	5.15	2.07	4.65	2.98	5.07	2.70	2.49
Turbidity (NTU)	Mid-Depth	4.72	3.85	2.90	5.11	1.99	5.47	3.51	5.94	2.50	2.60
Turbidity (NTU)	Bottom	18.58	3.91	2.43	5.35	2.24	4.67	3.26	5.68	4.03	4.08

Table 4. Proportion of monitored estuarine resources falling into each quality category at Fire Island National Seashore during the index periods of 2003–2021. Estuarine quality category thresholds as defined in Kopp and Neckles (2009) can be found in Table 2.

Parameter	Condition	Sampling Year									
		2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
Bottom dissolved oxygen (mg/L)	Good	97.7	100.0	100.0	91.0	100.0	100.0	97.7	100.0	100.0	100.0
Bottom dissolved oxygen (mg/L)	Fair	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bottom dissolved oxygen (mg/L)	Poor	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bottom dissolved oxygen (mg/L)	Missing	2.3	0.0	0.0	9.0	0.0	0.0	2.3	0.0	0.0	0.0
Chlorophyll- <i>a</i> (µg/L)	Good	94.8	2.7	31.6	8.4	26.2	7.3	16.0	6.7	58.5	73.2
Chlorophyll- <i>a</i> (µg/L)	Fair	0.0	23.4	68.4	43.9	66.0	38.3	81.8	59.0	37.1	26.8
Chlorophyll- <i>a</i> (µg/L)	Poor	0.0	71.8	0.0	47.6	7.8	54.3	0.0	34.3	4.4	0.0
Chlorophyll- <i>a</i> (µg/L)	Missing	5.2	2.1	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Good	22.0	12.4	27.2	6.5	50.8	16.3	28.6	7.6	16.5	24.8
PAR attenuation (K_d (m ⁻¹))	Fair	33.5	30.4	56.4	18.1	39.7	33.5	58.1	27.3	68.3	66.6
PAR attenuation (K_d (m ⁻¹))	Poor	22.9	38.3	12.6	75.4	9.5	47.5	11.0	65.1	9.6	2.9
PAR attenuation (K_d (m ⁻¹))	Missing	21.6	18.9	3.8	0.0	0.0	2.7	2.3	0.0	5.7	5.7
Surface Temperature (°C)	<28	97.7	100.0	93.9	90.4	100.0	100.0	94.0	94.4	81.5	100.0
Surface Temperature (°C)	28–33	0.0	0.0	6.1	9.6	0.0	0.0	3.8	5.6	18.5	0.0
Surface Temperature (°C)	>33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature (°C)	Missing	2.3	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0

Dissolved Oxygen (Near Bottom)

Area-weighted average near bottom dissolved oxygen concentration was classified as being in good condition (i.e., > 5 mg/L) for every index period and ranged from 7.10 to 9.77 mg/L (Table 3). Although there were several years with a small percentage of missing data, the entirety of area within the estuary for which data were available was characterized as being in good condition for all years (Table 4).

PAR Attenuation K_d (SAV Standard)

Area-weighted average PAR attenuation ranged from 1.00 to 2.01 m^{-1} and was classified as being in fair condition (i.e., 0.92–1.61 m^{-1}) for most index periods (Table 3). Poor area-weighted average conditions (i.e., > 1.61 m^{-1}) were observed in 2009, 2013, and 2017. The majority of the estuary generally was characterized as being either in fair or good condition, with the exception of 2013 and 2017 when the majority was classified as being in poor condition (Table 4).

pH

Area-weighted average pH ranged from 7.84 to 7.88 (Table 3). Measurements of pH began in 2019.

Salinity

Area-weighted average salinity ranged from 23.43 (surface depth in 2003) to 30.64 psu (bottom depth in 2016) (Table 3).

Temperature (Near Surface)

Area-weighted average near surface water temperature ranged from 23.85 to 25.47°C and exceeded 25°C during 8 of the 10 years sampled (Table 3). Temperatures in the 28–33°C range were observed in approximately 10–18.5% of the estuary in 2013 and 2019 (Table 4).

Turbidity

Area-weighted average turbidity ranged from 1.99 (mid-depth in 2014) to 18.58 NTU (bottom depth in 2003) (Table 3).

GLMM Results

For each parameter, the analysis of variance based on the fitted GLMM indicates that there was at least one year that was statistically different from the others, assuming a significance level equal to 0.05 (Table 5).

Notable observations from the multiple comparison tests (MCT) for each parameter are addressed below, and a detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Table 5. Analysis of variance for the general linear mixed model fit to log-transformed spatial station water quality measurements collected within Fire Island National Seashore. Each respective F -statistic and p -value corresponds to the test of the hypotheses: H_0 : the mean of the log-transformed parameter values are the same in each year versus H_1 : at least one of the year's means is different. [D.F. = degrees of freedom.]

Parameter	Depth(s)	D.F.	F -value	p -value
Chlorophyll- a ($\mu\text{g/L}$)	Surface	(9, 256)	80.48	< 0.005
Dissolved oxygen (mg/L)	Bottom	(9, 256)	16.27	< 0.005
PAR attenuation (K_d (m^{-1}))	Water Column	(9, 242)	10.25	< 0.005
Salinity (psu)	Surface	(9, 259)	76.05	< 0.005
Temperature ($^{\circ}\text{C}$)	Surface	(9, 259)	3.12	< 0.005
Turbidity (NTU)	Surface	(9, 259)	10.34	< 0.005

Chlorophyll- a (Near Surface)

The MCT results indicate that mean log near surface chlorophyll- a concentrations in 2009, 2013, and 2015 were significantly higher than most other years (Figure 4). In addition, concentrations in 2003 were significantly lower than all other years sampled.

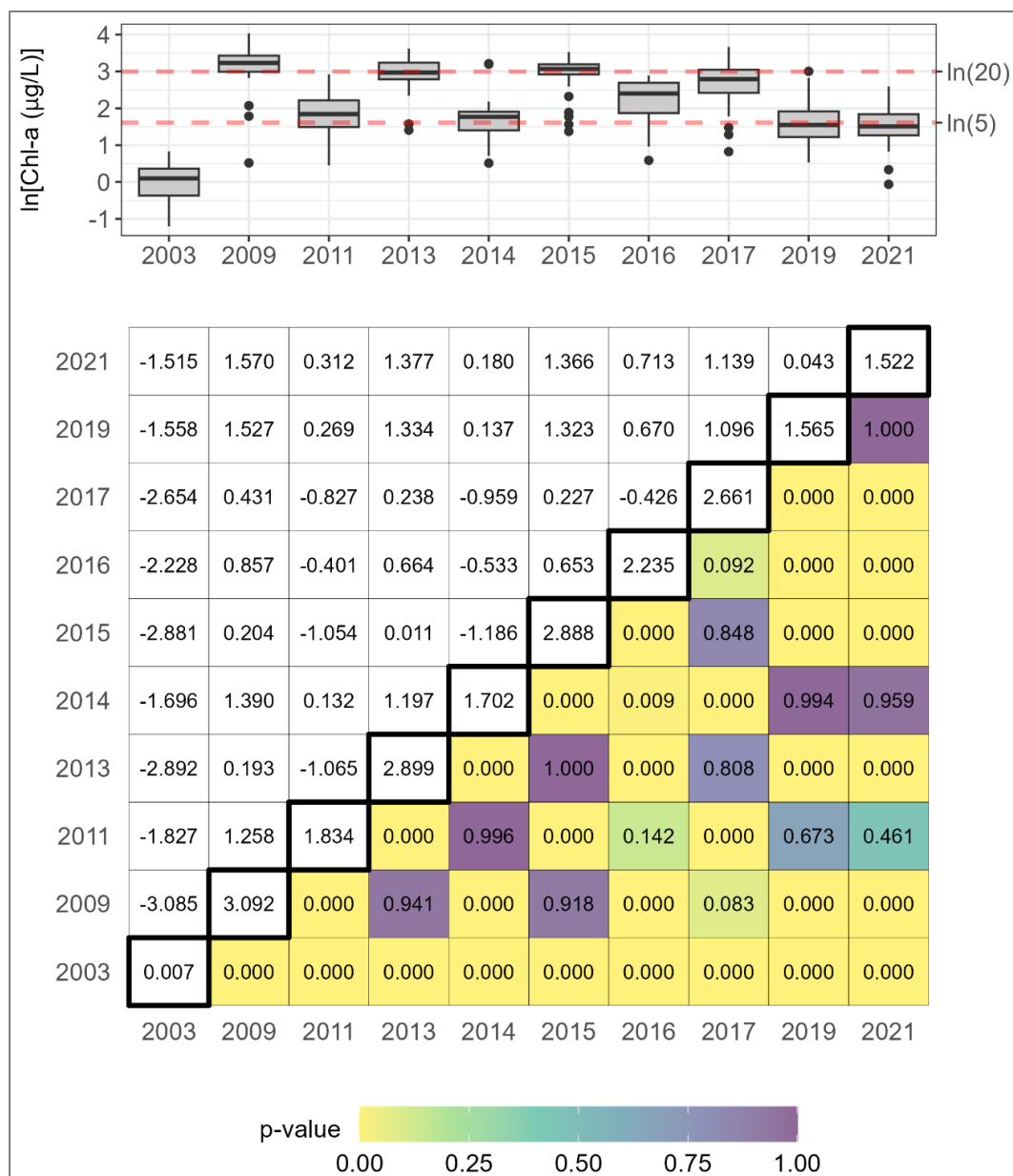


Figure 4. (Top): Boxplot of log surface chlorophyll-a concentration by year within Fire Island National Seashore. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface chlorophyll-a concentration within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus later). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A. Tabular information displayed in this image is provided in [Table 22 of Appendix B](#).

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Dissolved Oxygen (Near Bottom)

The MCT results indicate that mean log bottom dissolved oxygen concentrations in 2003 were significantly higher than all other years (Figure 5). Additionally, mean log bottom dissolved oxygen

in 2009 was significantly higher than 2019. There was no strong evidence of statistical differences between the other index period pairs.



Figure 5. (Top): Boxplot of log bottom dissolved oxygen concentration by year within Fire Island National Seashore. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log bottom dissolved oxygen concentration within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus later). Lower diagonals contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A. Tabular information displayed in this image is provided in [Table 23 of Appendix B](#).

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PAR Attenuation K_d (SAV Standard)

The MCT results indicate that after 2014, mean log PAR attenuation started exhibiting a cyclical pattern which resulted in several statistically different pairs of years (Figure 6).

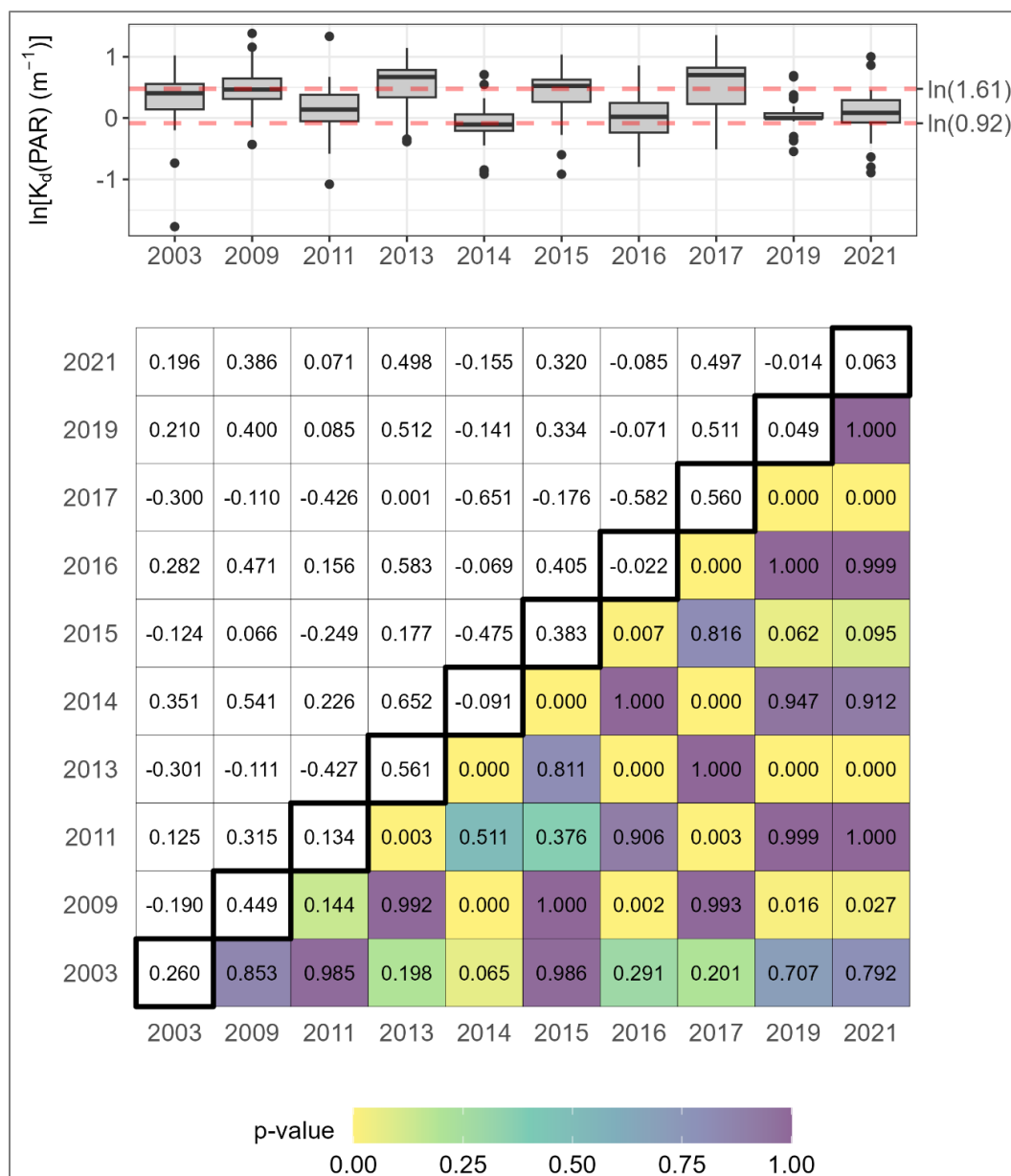


Figure 6. (Top): Boxplot of log PAR attenuation by year within Fire Island National Seashore. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log PAR attenuation within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus later). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A. Tabular information displayed in this image is provided in [Table 24 of Appendix B](#).

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Salinity (Near Surface)

MCT results indicate that mean log surface salinity in 2003, 2009, 2011, 2019, and 2021 was significantly lower than most other years (Figure 7). The box plots indicate that within-year variability decreased after 2013.

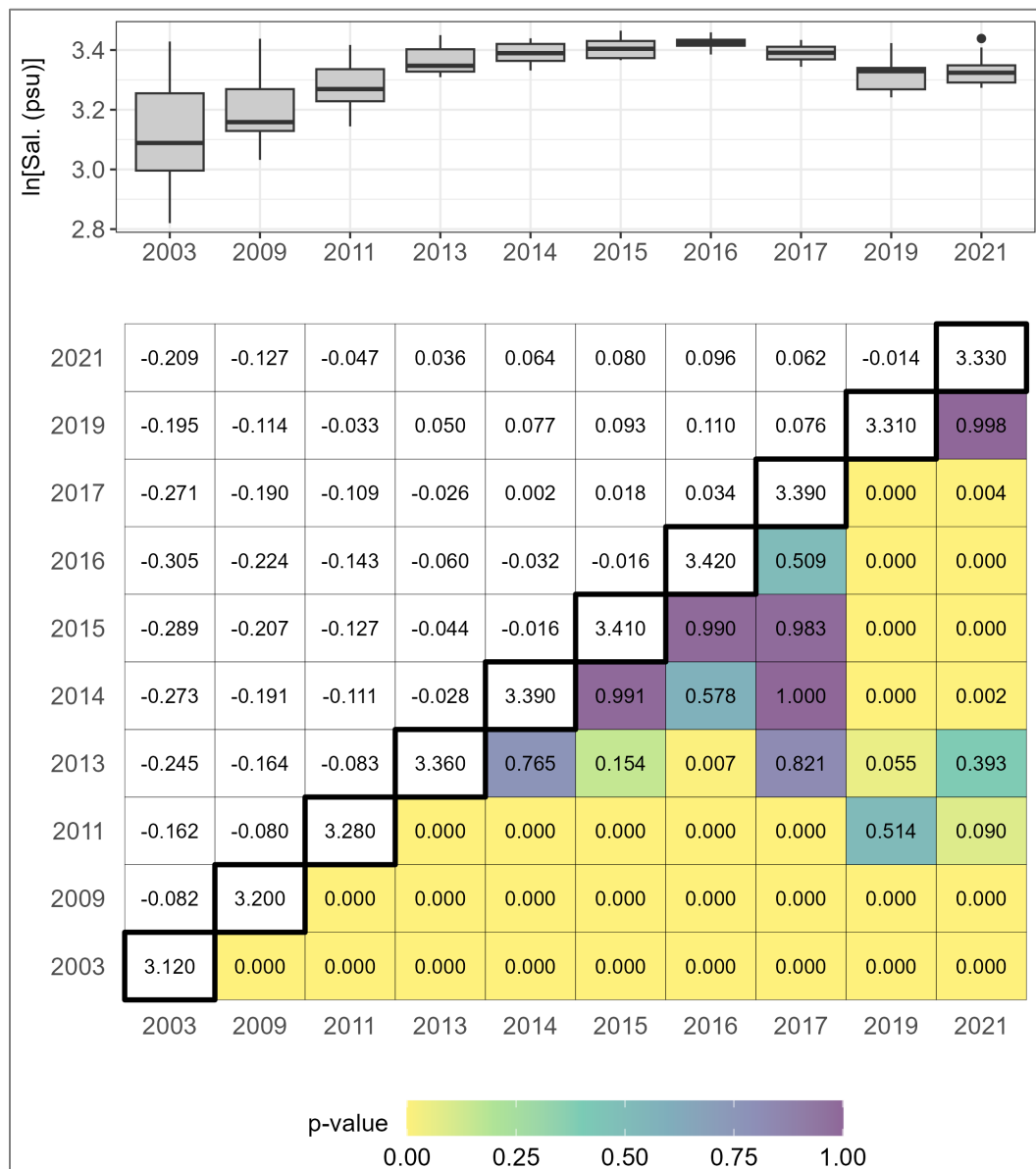


Figure 7. (Top): Boxplot of log surface salinity by year within Fire Island National Seashore. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface salinity within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus later). Lower diagonals contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A. Tabular information displayed in this image is provided in [Table 25 of Appendix B](#).

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Temperature (Near Surface)

The MCT results indicate that mean log surface water temperature in 2014 was significantly lower than most other index periods (Figure 8). There was no strong evidence of statistical differences between the other index period pairs.

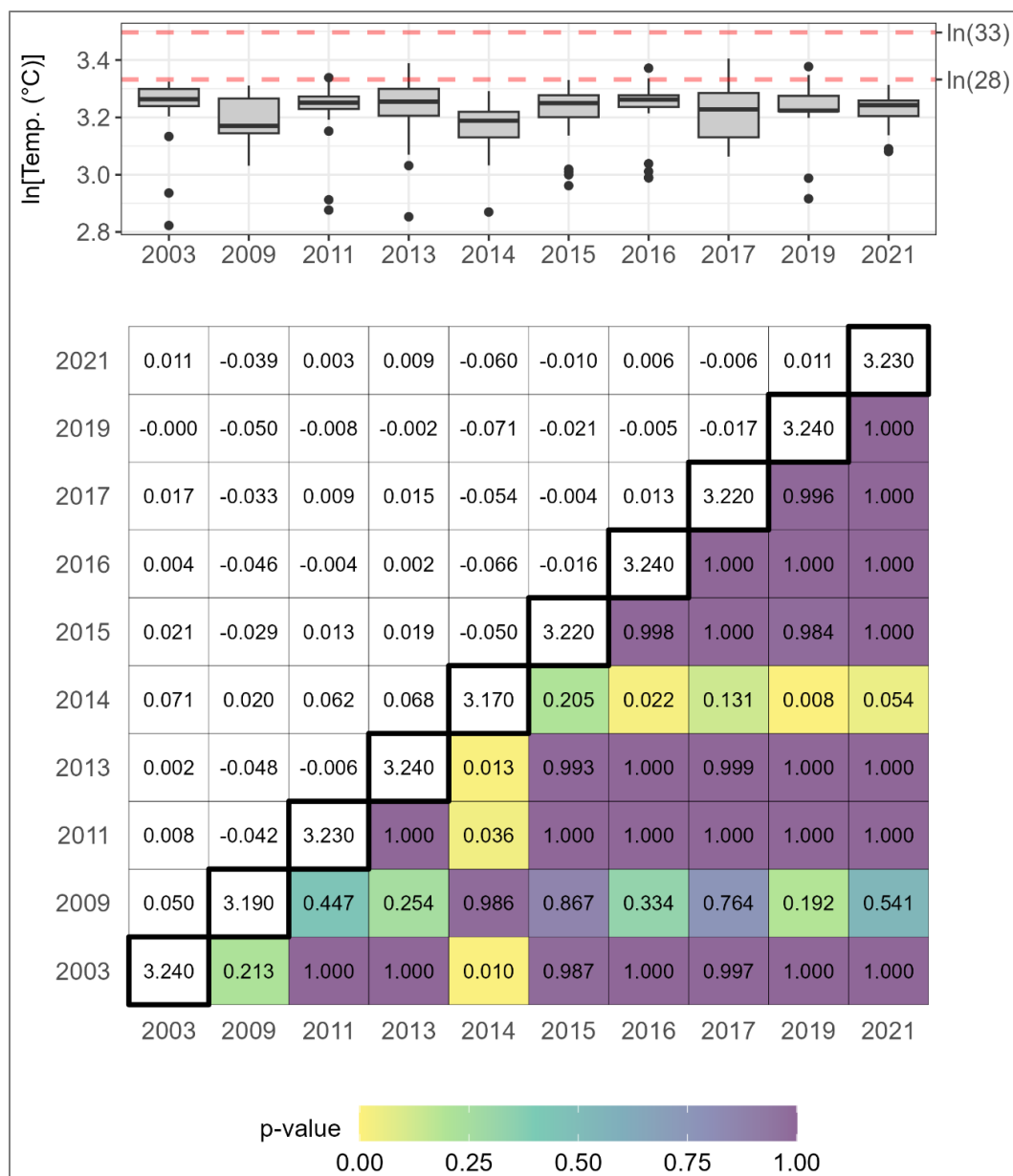


Figure 8. (Top): Boxplot of log surface temperature by year within Fire Island National Seashore. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface temperature within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus later). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A. Tabular information displayed in this image is provided in [Table 26 of Appendix B](#).

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Turbidity (Near Surface)

The MCT results indicate that mean log surface turbidity was statistically different for several pairs of years due to an apparent cyclical pattern (Figure 9).

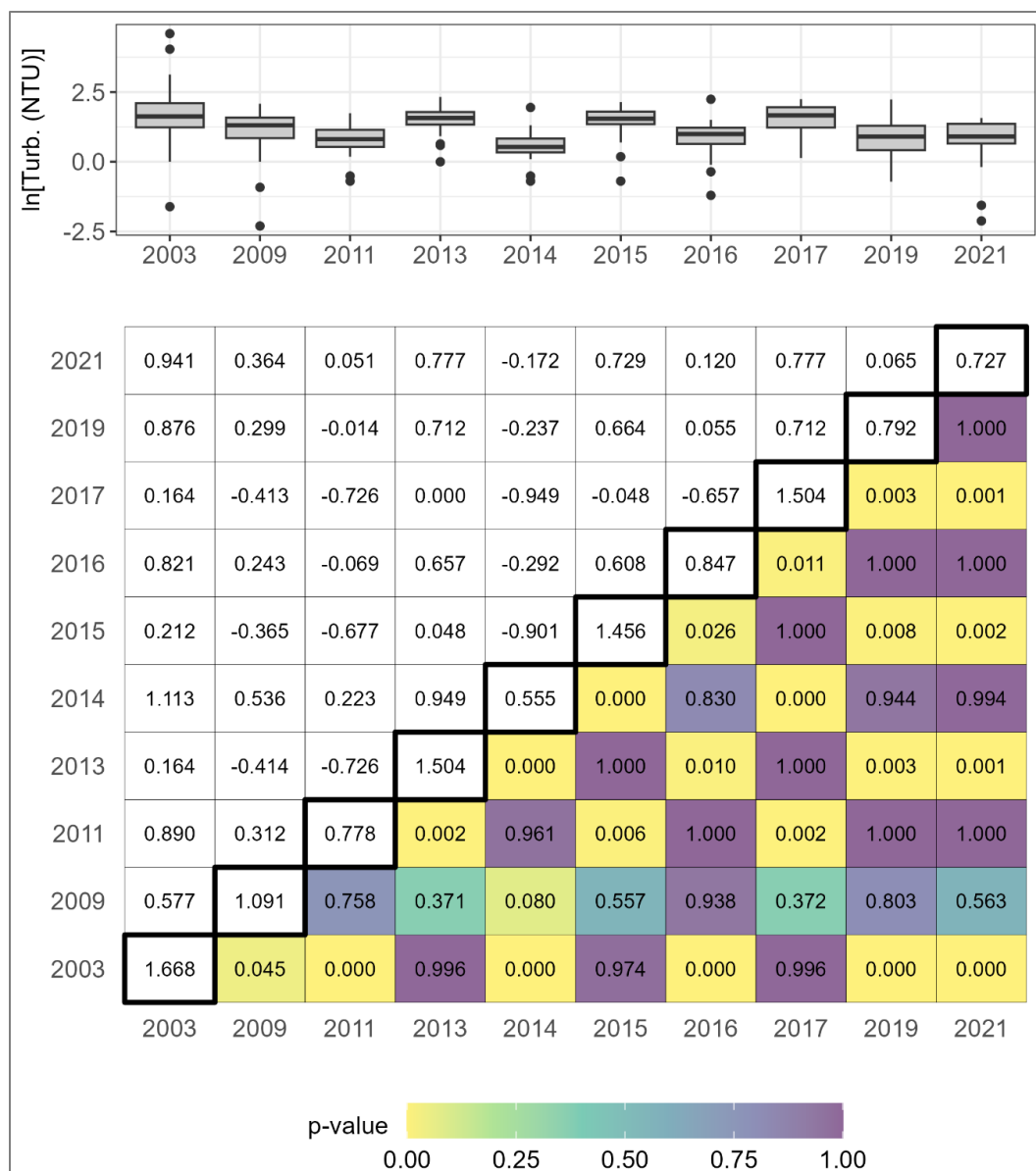


Figure 9. (Top): Boxplot of log surface turbidity by year within Fire Island National Seashore. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface turbidity within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus later). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A. Tabular information displayed in this image is provided in [Table 27 of Appendix B](#).

JESSICA NAGEL

GAM Results

The generalized additive model summaries indicate that there were statistically significant (assuming a 0.05 significance level) spatial and temporal trends in all water quality parameters except surface temperature, which only had a significant spatial trend (Table 6).

Table 6. Approximate significance of the generalized additive model smooth terms for each spatial station water quality parameter model. Each respective F -statistic and p -value corresponds to the test of the hypotheses: $H_0: f(x) = 0$ versus $H_1: f(x) \neq 0$. Note: p -values are computed without considering uncertainty in the smoothing parameter estimates and may need to be interpreted with caution when near the α level. [edf = effective degrees of freedom; long = longitude; lat = latitude].

Parameter	Depth	Model Term	edf	F -value	p -value
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(year)	5.68	84.03	< 0.001
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(long, lat)	6.14	0.80	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	3.26	13.52	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	1.00	0.35	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	8.70	10.69	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	2.88	0.44	< 0.001
Salinity (psu)	Surface	s(year)	5.73	76.91	< 0.001
Salinity (psu)	Surface	s(long, lat)	6.01	2.95	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	1.16	0.25	0.135
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	13.23	3.94	< 0.001
Turbidity (NTU)	Surface	s(year)	7.69	14.22	< 0.001
Turbidity (NTU)	Surface	s(long, lat)	5.08	0.45	< 0.001

Chlorophyll-*a* (Near Surface)

Chlorophyll-*a* concentrations exhibited a highly non-linear temporal trend with several periods of statistically significant change (Figure 10). The most notable changes include a large, significant increase of more than 20 $\mu\text{g/L}$ between 2003 and 2009 and a significant decline to concentrations less than 5 $\mu\text{g/L}$ between 2017 and 2021. Higher concentrations of chlorophyll-*a* were spatially concentrated around Smith Point and Mastic Beach and around the southwestern end of Great South Bay (Figure 11). Based on the fitted model, both time and location account for 55.4% of the variability in chlorophyll-*a* concentrations.

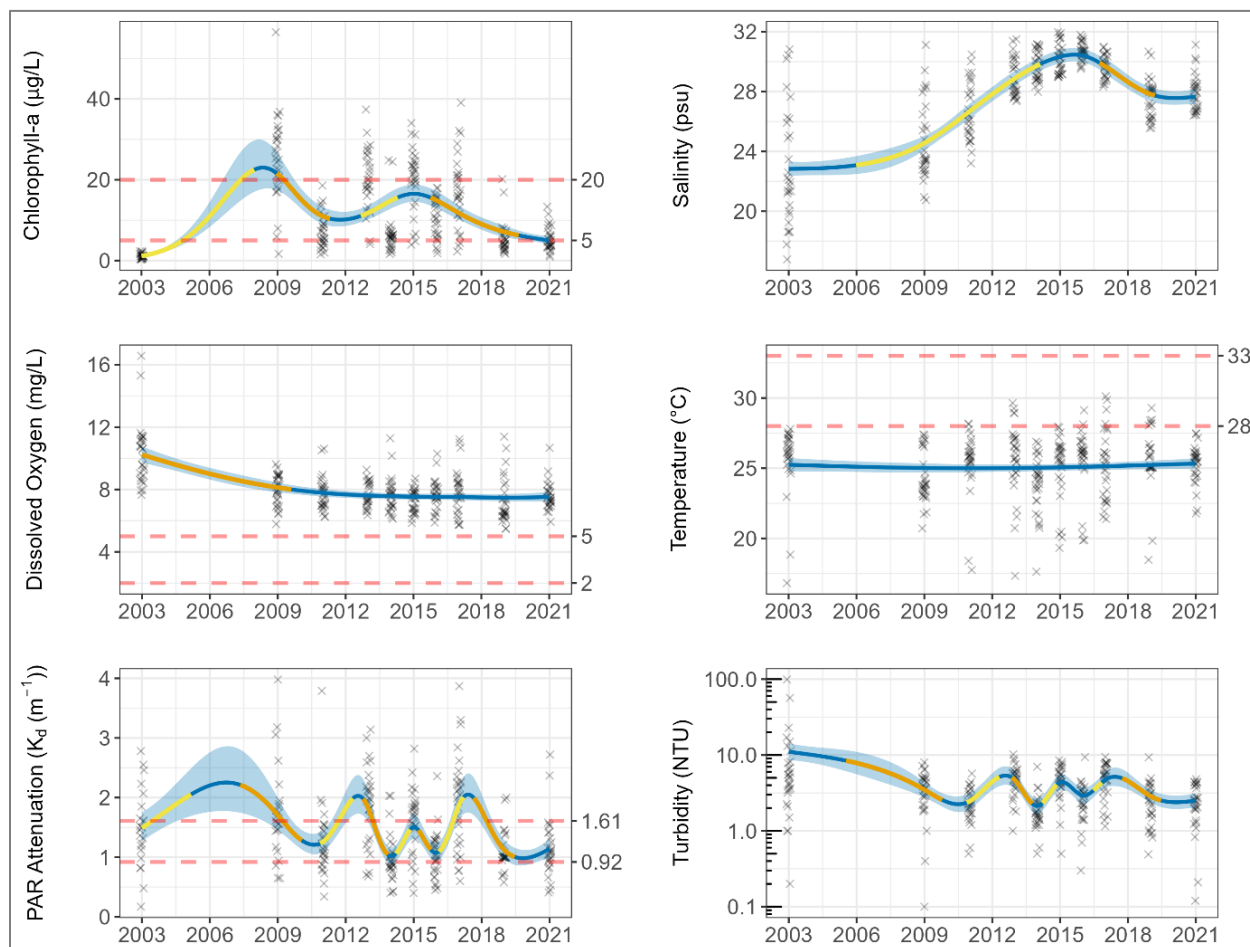


Figure 10. Trends in Fire Island National Seashore spatial station water quality parameters based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: (1) in some instances, the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend; (2) observations that were excluded from model fitting are plotted in red.

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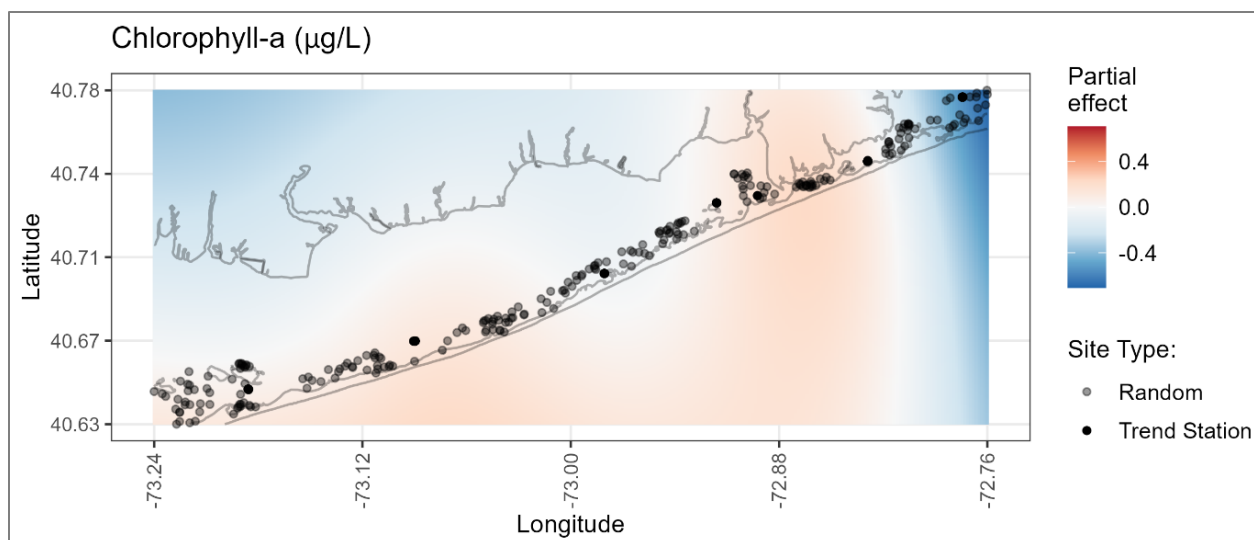


Figure 11. Mean surface for the generalized additive model latitude/longitude smooth of surface chlorophyll-a concentration within Fire Island National Seashore during 2003–2021.

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Dissolved Oxygen (Near Bottom)

Bottom dissolved oxygen concentrations exhibited a statistically significant decrease during the period of 2003 to 2009 but remained relatively constant between 2009 and 2021 (Figure 10). There was a significant spatial trend with lower concentrations occurring in the southwestern end of the estuary and higher concentrations in the northeastern end (Figure 12). Based on the fitted model, both time and location account for only 35.7% of the variability in bottom dissolved oxygen concentrations.

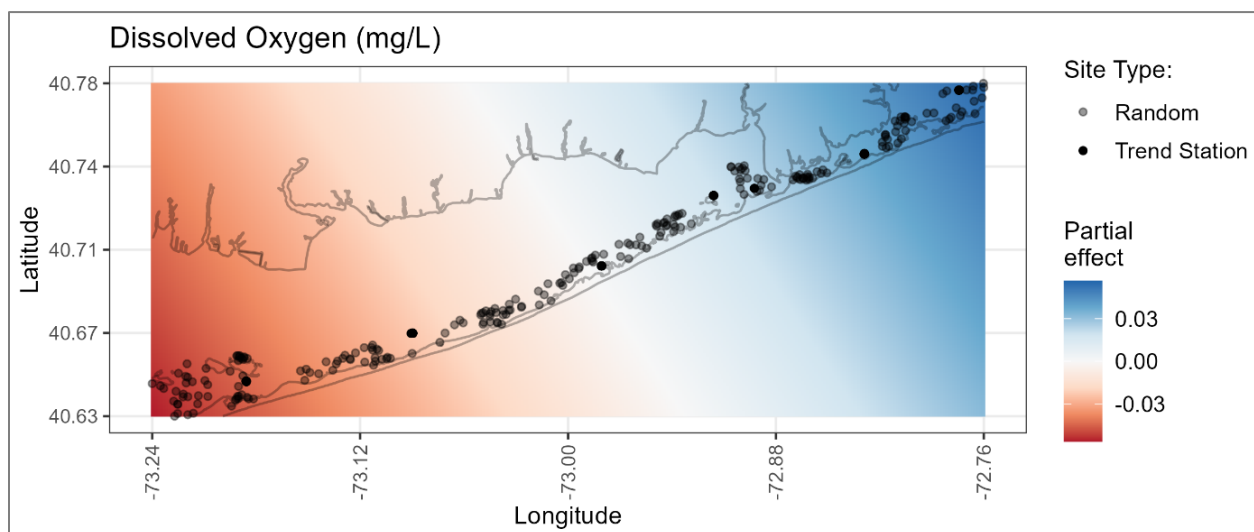


Figure 12. Mean surface for the generalized additive model latitude/longitude smooth of bottom dissolved oxygen concentration within Fire Island National Seashore during 2003–2021.

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PAR Attenuation K_d (SAV Standard)

The temporal trend in PAR attenuation was highly non-linear and cyclic in nature with several periods of statistically significant change (Figure 10). Spatially, PAR attenuation tended to be higher south of Ridge Island and lowest east of Smith Point (Figure 13). Based on the fitted model, both time and location account for only 32.3% of the variability in PAR attenuation.

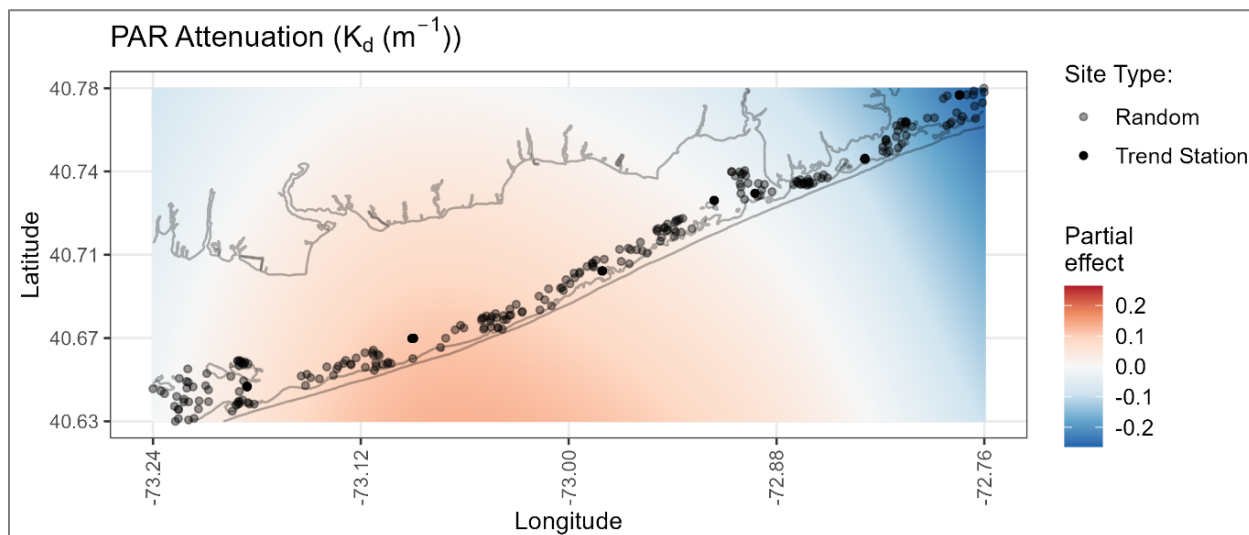


Figure 13. Mean surface for the generalized additive model latitude/longitude smooth of PAR attenuation within Fire Island National Seashore during 2003–2021.

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Salinity (Near Surface)

Surface salinity exhibited a statistically significant increase of nearly 5 psu during the period from 2009 to 2014 and a decrease during 2017 to 2019 (Figure 10). Spatially, salinity was highest in the southwestern and northeastern ends of the estuary (Figure 14). The fitted GAM had the best fit amongst the parameters, with time and location accounting for 73.7% of the variation in salinity.

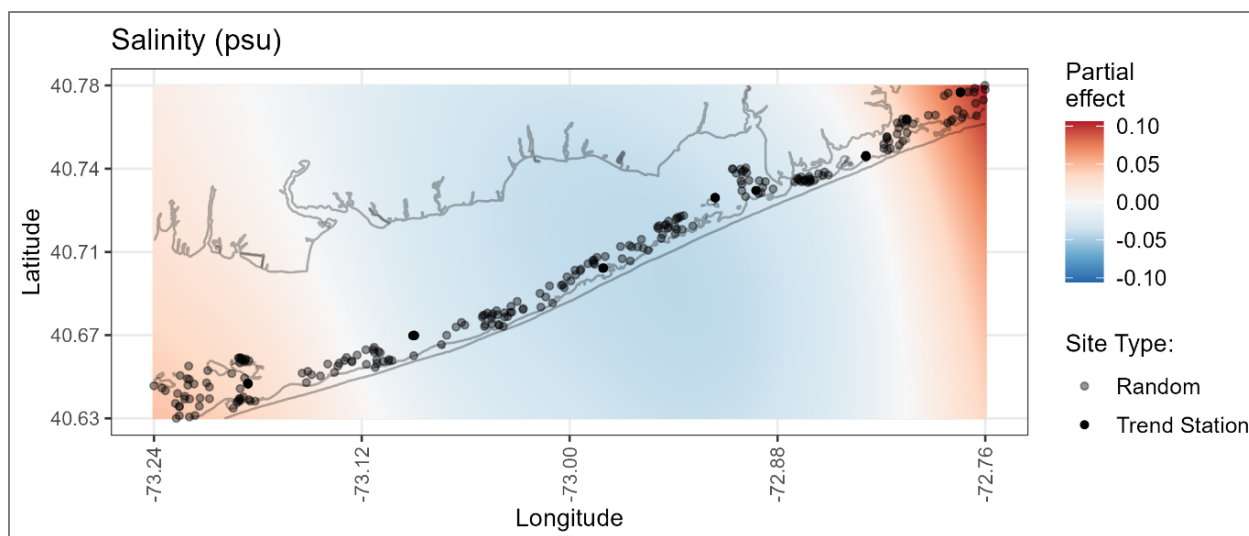


Figure 14. Mean surface for the generalized additive model latitude/longitude smooth of surface salinity within Fire Island National Seashore during 2003–2021.

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Temperature (Near Surface)

Surface water temperature exhibited no statistically significant periods of change and was relatively constant for the period of 2003 to 2021 (Figure 10). Spatially, surface temperatures were warmest in the middle of the estuary and around Mastic Beach and were coolest around the new inlet and in Moriches Bay (Figure 15). Based on the fitted model, both time and location account for only 41.1% of the variability in water temperature.

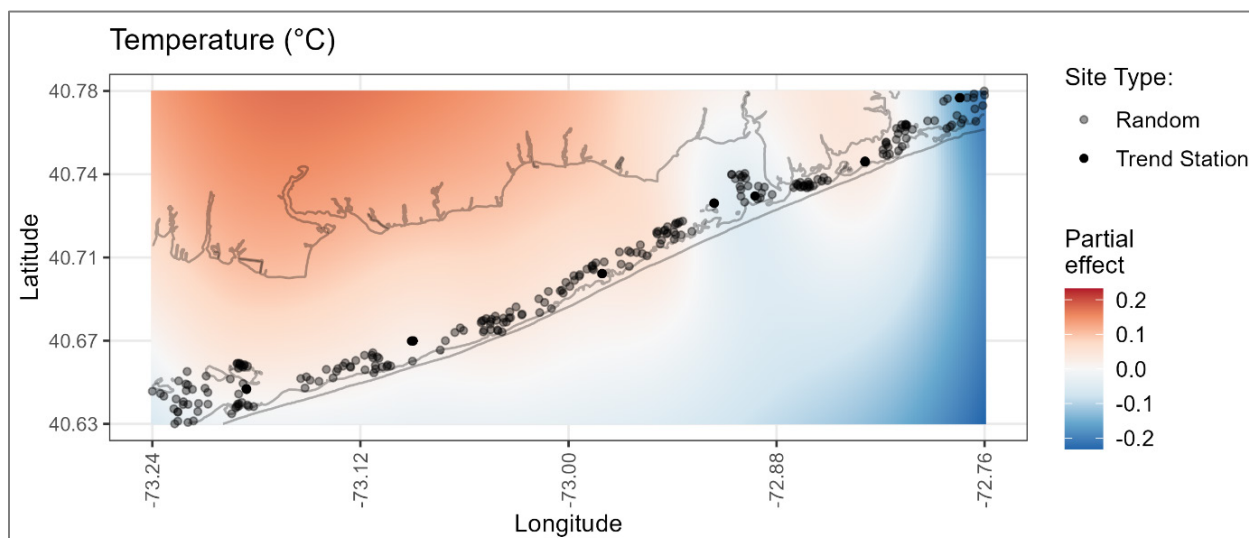


Figure 15. Mean surface for the generalized additive model latitude/longitude smooth of surface temperature within Fire Island National Seashore during 2003–2021.

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Turbidity (Near Surface)

The temporal trend in surface turbidity also was highly non-linear and cyclic in nature with several periods of statistically significant change (Figure 10). Spatially, turbidity was highest in the middle portion of the estuary and lowest at the southwestern and northeastern extremes of the estuary (Figure 16). Time and location account for 43.3% of the variation in turbidity.

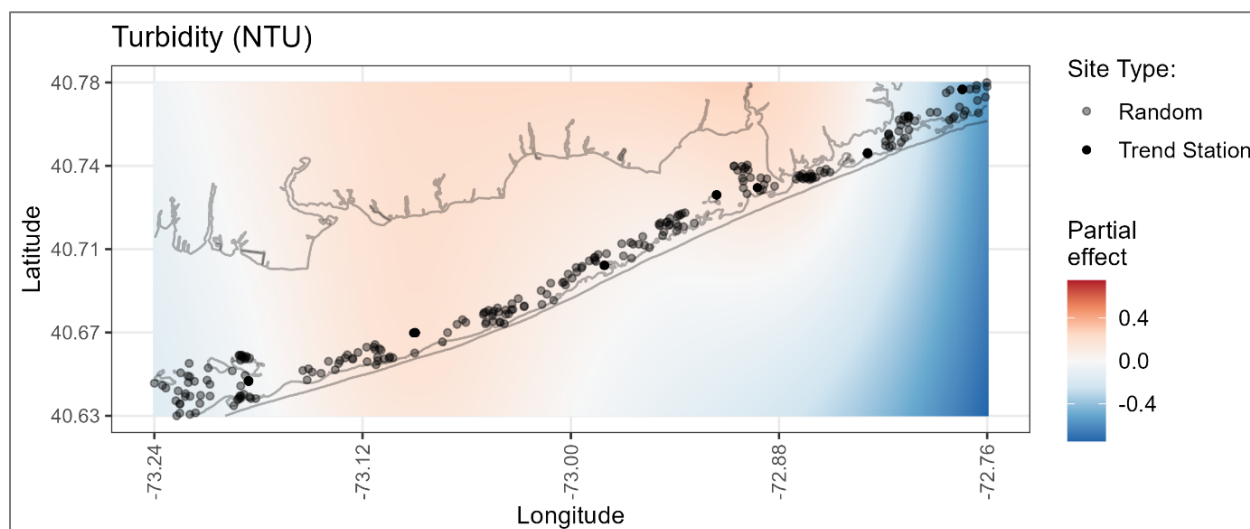


Figure 16. Mean surface for the generalized additive model latitude/longitude smooth of surface turbidity within Fire Island National Seashore during 2003–2021.

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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there was marginal evidence of a statistically significant ($\alpha = 0.05$) decreasing monotonic trend in bottom dissolved oxygen (p -value = 0.054) during the index periods of 2003 to 2021 (Table 7).

Table 7. Summary of multivariate Mann-Kendall test for monotonic trend for each spatial station water quality parameter: H_0 : no monotonic trend versus H_1 : monotonic trend is present. A positive (negative) value of the Mann-Kendall test statistic (Z_{MK}) indicates that measurements tend to increase (decrease) with time.

Parameter	Depth(s)	Z_{MK}	p -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	-0.12	0.904
Dissolved oxygen (mg/L)	Bottom	-1.93	0.054
PAR attenuation (K_d (m^{-1}))	Water Column	-0.56	0.577
Salinity (psu)	Surface	1.60	0.110
Temperature ($^{\circ}\text{C}$)	Surface	0.82	0.413
Turbidity (NTU)	Surface	-0.66	0.512

Trend Station Water Quality Data

Data Analysis

Generalized Additive Model (GAM)

Generalized additive models (GAMs) are used to estimate trends in water quality parameters for each trend station within an estuary. For each parameter, we model the mean response as a function of time. Mathematically, the model can be written as:

$$\begin{aligned} \text{response}_i &\sim \text{Gamma}(\mu_i, \phi) \\ \log(\mu_i) &= \beta_0 + f_{\text{station}_i}(\text{year}_i), \end{aligned}$$

where μ_i is a vector of response values, β_0 is the intercept, and $f_{\text{station}_i}(\text{year})$ is the TRPS smooth of year for the i th trend station. The year smoother is known as a factor-smoother and assumes that all factors (i.e., trend stations) have the same smoothness, but may differ in shape over time. The rank of the basis expansion was set equal to the number of years of data. The relatively short time series within each trend station precluded any modeling of temporal autocorrelation.

The first derivative is approximated along the length of the year smooth using the finite difference method. Periods of significant temporal change are identified as intervals of time wherein the 95% simultaneous confidence interval of the first derivative (i.e., slope of tangent line) does not contain the value of zero.

Analyses were carried out using the R Statistical Computing Environment (R Core Team 2022). Each model is fit using the mgcv package (Wood 2011) and results were summarized/visualized using the gratia package (Simpson 2020).

Multivariate Mann-Kendall Trend Analysis

The multivariate Mann-Kendall test (trend R package; Pohlert 2020) was used to determine whether there exists a monotonically increasing or decreasing trend in values for all trend station sites within the estuary over time (Libiseller and Grimvall 2002). Positive values of the test statistic Z_{MK} indicates that measurements tend to increase with time, whereas negative values indicate a decrease.

GAM Results

The generalized additive model summaries indicate that there were statistically significant temporal trends (assuming a significance level of 0.05) at the trend stations in all water quality parameters (Table 8). Yearly summary statistics for each parameter and trend station can be found in Appendix C.

Table 8. Approximate significance of the generalized additive model smooth terms for each trend station water quality parameter model. Each respective F -statistic and p -value corresponds to the test of the hypotheses: $H_0: f(x) = 0$ versus $H_1: f(x) \neq 0$. Note: p -values are computed without considering uncertainty in the smoothing parameter estimates and may need to be interpreted with caution when near the α level. [edf = effective degrees of freedom; df_{ref} = reference degrees of freedom]

Parameter	Depth(s)	Model Term	edf (df_{ref})	F -value	p -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	s(year, hexagon)	26.02 (59)	6.36	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year, hexagon)	19.84 (59)	3.78	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year, hexagon)	9.92 (59)	0.53	< 0.001
Salinity (psu)	Surface	s(year, hexagon)	35.35 (59)	27.88	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year, hexagon)	9.91 (59)	3.86	< 0.001
Turbidity (NTU)	Surface	s(year, hexagon)	17.53 (59)	1.35	< 0.001

Chlorophyll-a (Near Surface)

Temporal trends in chlorophyll-a indicate a statistically significant increase occurred from 2003 to 2009 across all trend stations (Figure 17). After 2009, chlorophyll-a concentrations generally declined with high year-to-year variation. Although mean concentrations were typically classified as being in fair or good condition, five of the six stations experienced poor conditions (i.e., $>20 \mu\text{g/L}$) in several years over the entire monitoring timeframe. Concentrations were highest at hexagons 5 and 10 in the southwestern end of the estuary.

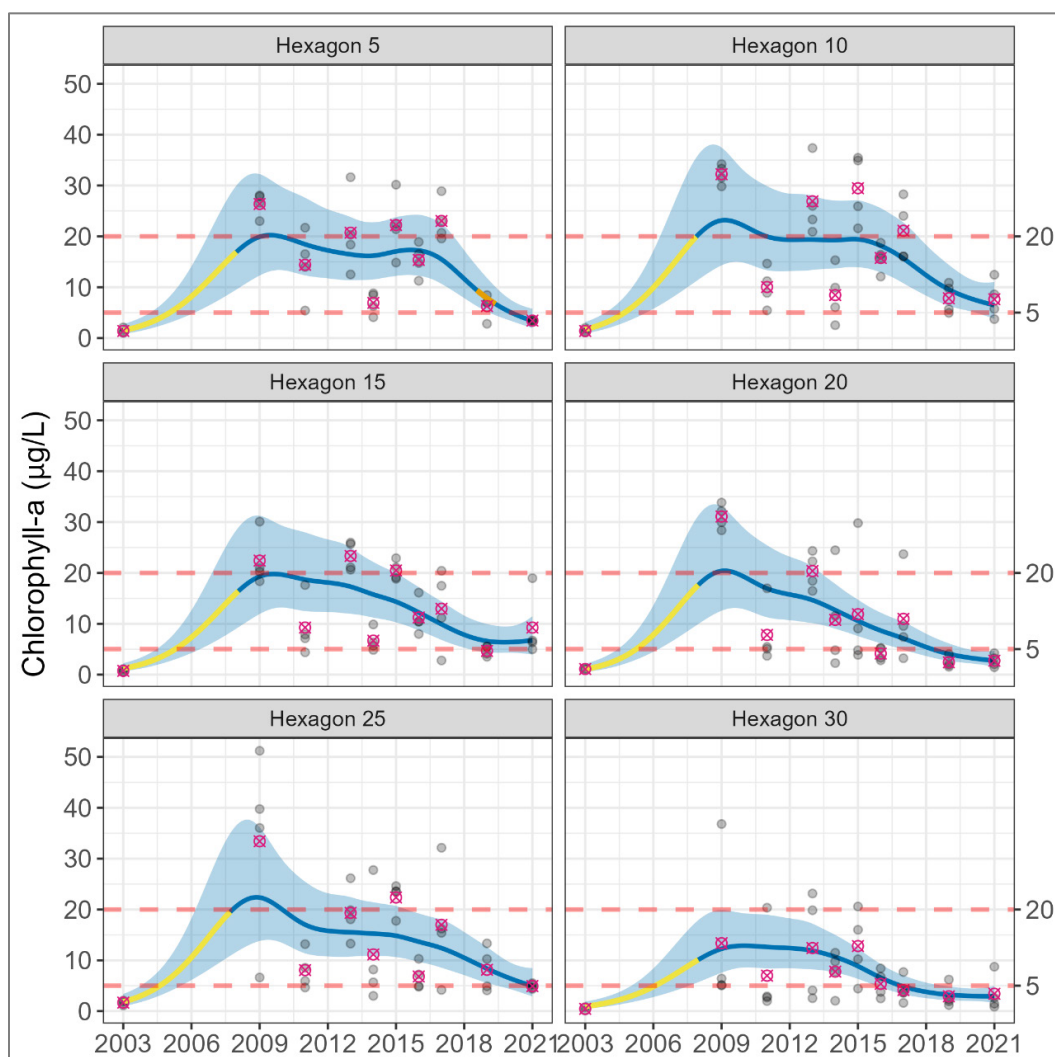


Figure 17. Mean surface chlorophyll-a concentration trend at each Fire Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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Dissolved Oxygen (Near Bottom)

Bottom dissolved oxygen concentrations declined at all stations between 2003 and 2009 with significant declines observed at hexagons 5, 10, and 15 (Figure 18). After 2009, concentrations remained relatively stable and yearly average concentrations were above 5 mg/L (i.e., good quality category) for all years sampled.

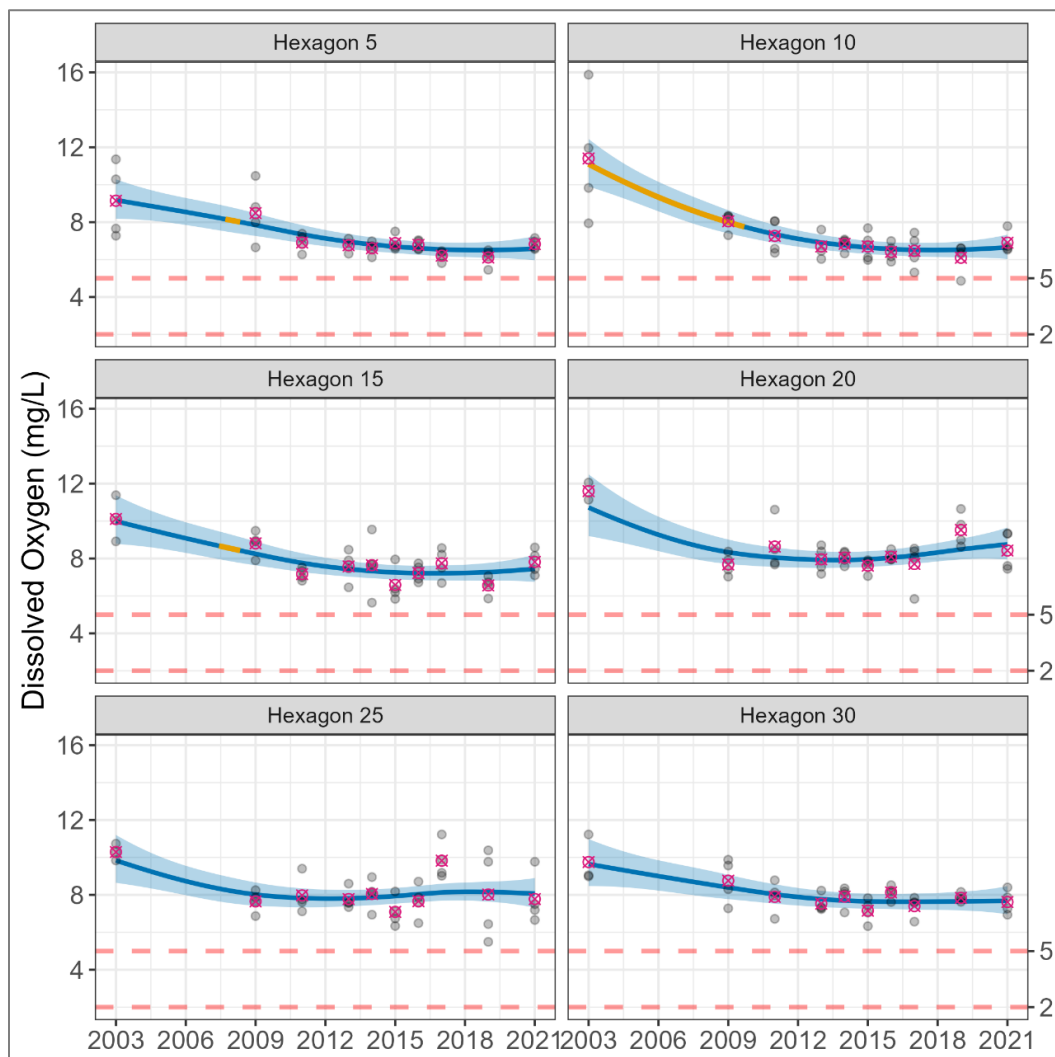


Figure 18. Mean bottom dissolved oxygen concentration trend at each Fire Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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PAR Attenuation K_d (SAV Standard)

There were no periods of significant temporal change in mean PAR attenuation identified at any of the trend stations (Figure 19). Additionally, there was relatively high within year variability with some year-to-year cyclical patterns present. Mean values were typically classified as being in fair or good condition; however, all stations experienced poor condition (i.e., $>1.61 \text{ m}^{-1}$) in several years. Conditions appeared to improve at hexagon 20 near the new inlet, but this trend was not significant.

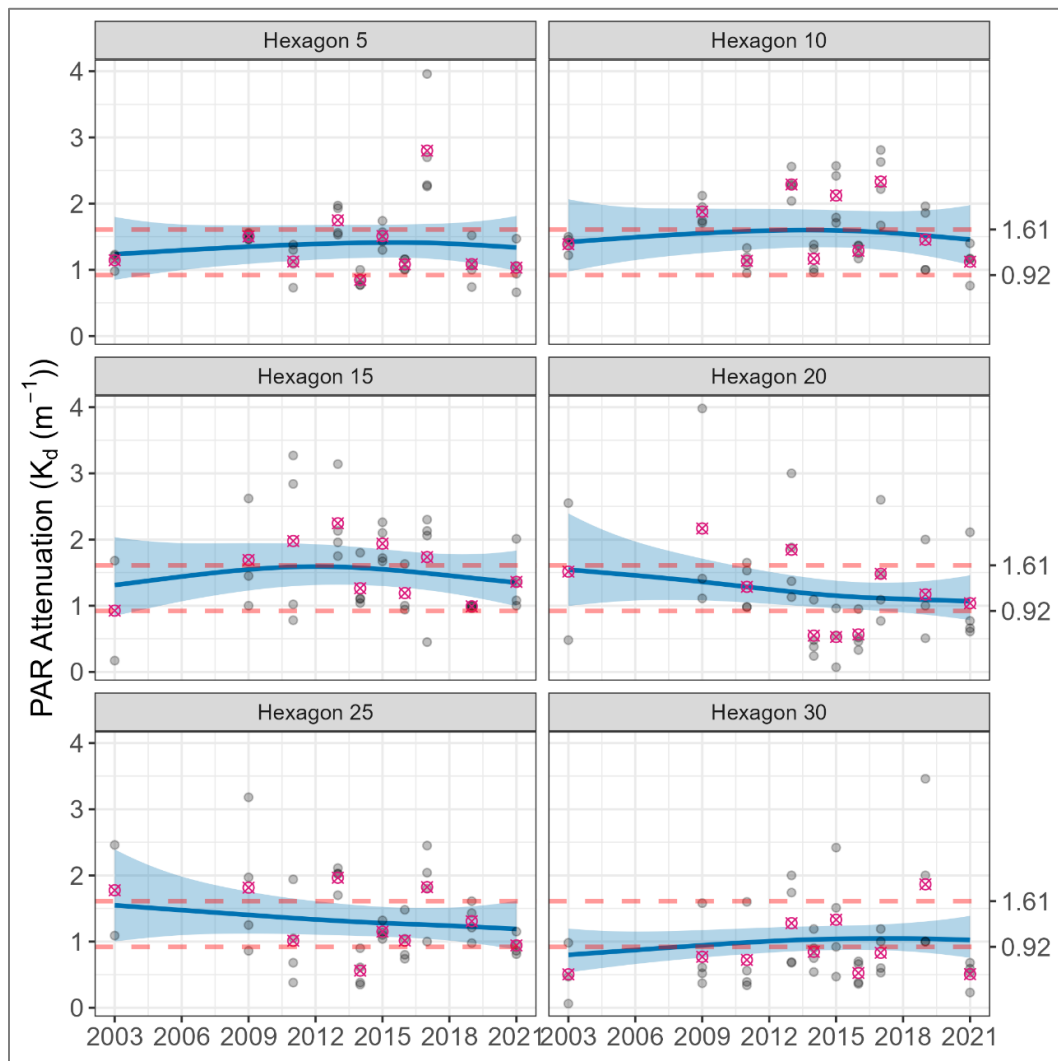


Figure 19. Mean PAR attenuation trend at each Fire Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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Salinity (Near Surface)

Temporal trends for stations within hexagons 10, 15, 20, and 25 indicate a statistically significant increase in salinity during 2009 to around 2013 (Figure 20). Hexagons 10 and 15 exhibited a statistically significant decrease between 2017 and 2019. Hexagon 30 remained relatively constant from 2003 to 2021.

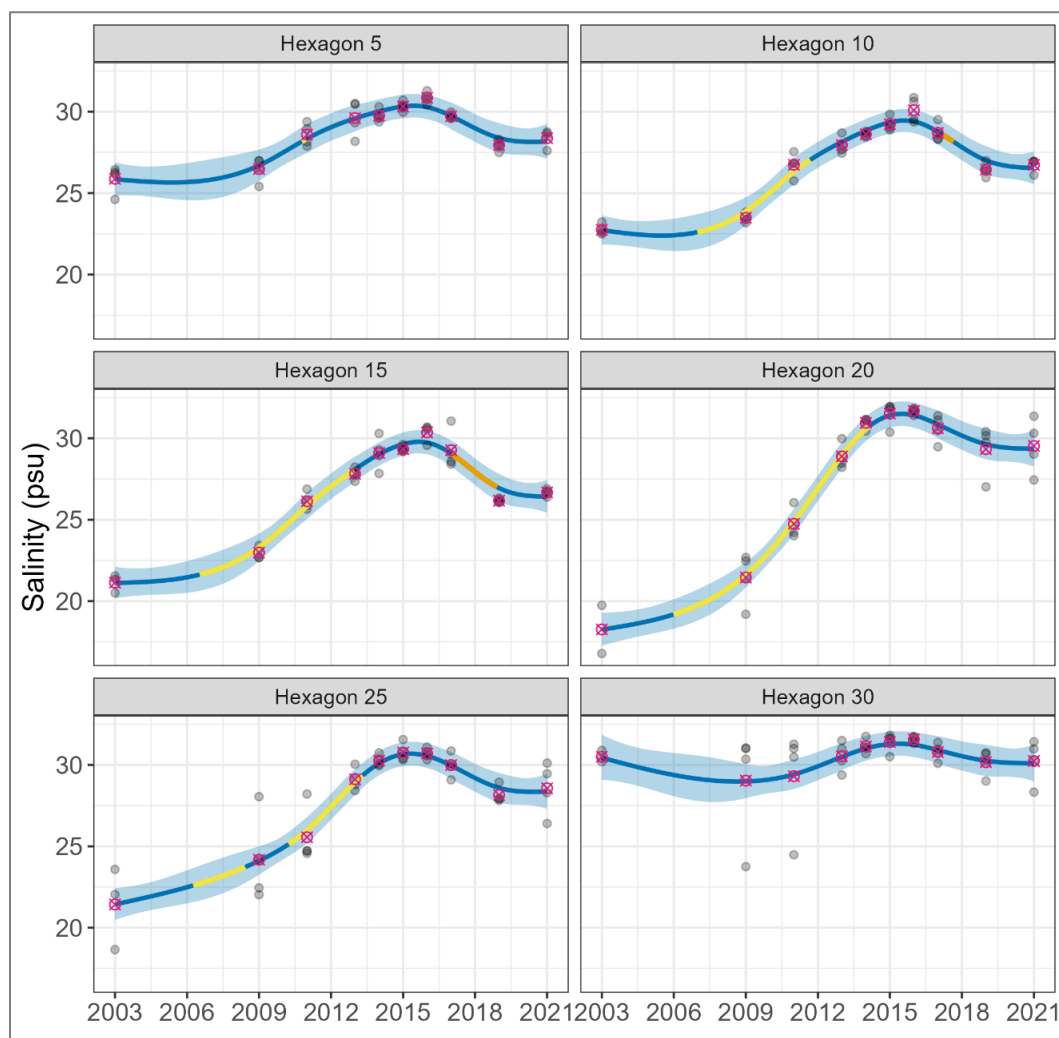


Figure 20. Mean surface salinity trend at each Fire Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively.

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Temperature (Near Surface)

Surface temperature remained relatively constant at all trend stations except hexagon 20, which is closest to the new inlet and exhibited a statistically significant decrease for the period of 2003 to

2021 (Figure 21). Mean temperatures were consistently below 28°C at all stations but were typically greater than 25°C at trend stations 5, 10, 15, and 25.

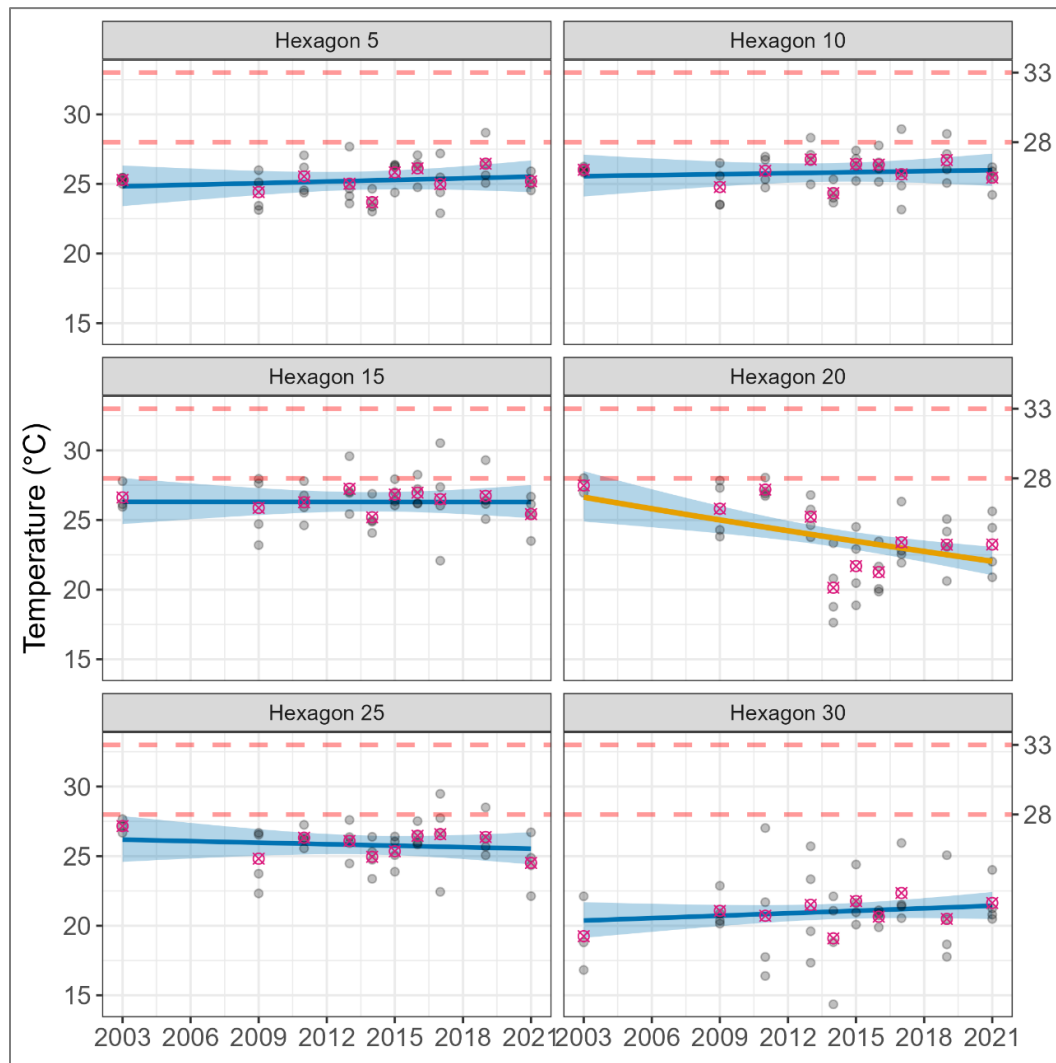


Figure 21. Mean surface temperature trend at each Fire Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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Turbidity (Near Surface)

Surface turbidity was generally constant at most trend stations with some year-to-year cyclical patterns observed. A statistically significant decrease in surface turbidity occurred within hexagon 25 from 2003 to 2009 (Figure 22).

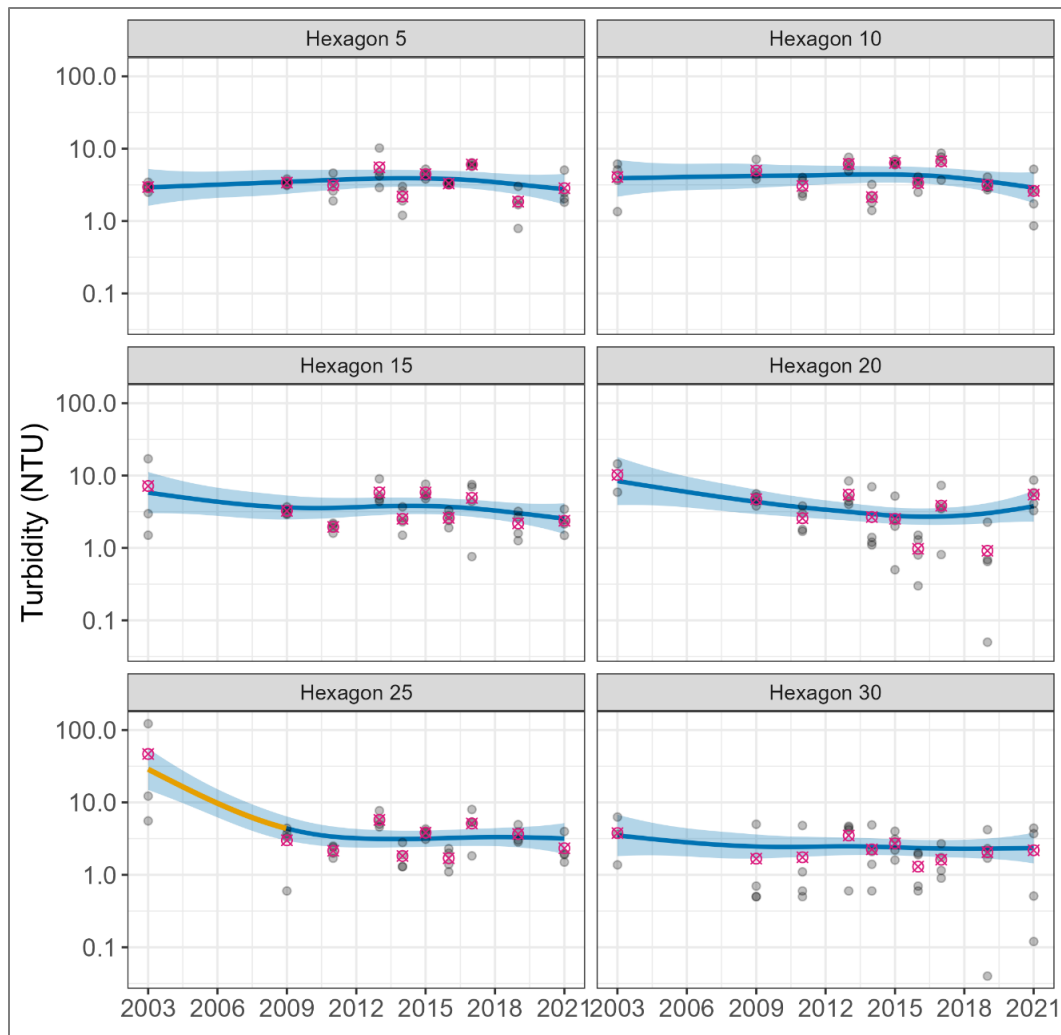


Figure 22. Mean surface turbidity trend at each Fire Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Note: the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend.

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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there was statistical evidence (assuming a significance level of 0.05) of an increasing monotonic trend in surface salinity (p -value = 0.035) measured at the trend stations during the index periods of 2003 to 2021 (Table 9).

Table 9. Summary of multivariate Mann-Kendall test for monotonic trend in each trend station water quality parameter: H_0 : no monotonic trend versus H_1 : monotonic trend is present. A positive (negative) value of the Mann-Kendall test statistic (Z_{MK}) indicates that measurements tend to increase (decrease) with time.

Parameter	Depth(s)	Z_{MK}	p -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	-0.10	0.922
Dissolved oxygen (mg/L)	Bottom	-0.97	0.331
PAR attenuation (K_d (m^{-1}))	Water Column	0.38	0.705
Salinity (psu)	Surface	2.11	0.035
Temperature ($^{\circ}\text{C}$)	Surface	1.04	0.297
Turbidity (NTU)	Surface	-0.20	0.842

Logging Station Continuous Water Quality Data

Data Analysis

Generalized Additive Model (GAM)

Generalized additive models (GAMs) are used to characterize intra-annual trends in continuous logging station data. For each water quality parameter, we modeled the mean response as a function of the day of year (doy) and the hour of day. Mathematically, the model can be written as:

$$\begin{aligned} \text{response}_i &\sim \text{Gamma}(\mu_i, \phi) \\ \log(\mu_i) &= \beta_0 + f_{\text{year}_i}(\text{doy}_i) + f(\text{hour}_i), \end{aligned}$$

where μ_i is a vector of response values, β_0 is the intercept, $f_{\text{year}_i}(\text{doy})$ is a rank 20 TRPS smooth of doys for the i th year, and $f(\text{hour})$ is a rank 24 cyclic cubic spline. The doys smoother is known as a factor-smoother and assumes that all factors (i.e., years) have the same smoothness, but may differ in shape over time. The smooth for hour is included to account for intra-day trends since many of the parameters exhibit diel patterns (e.g., dissolved oxygen). Temporal autocorrelation was not modeled due to the high computational cost of doing so with the large number of observations ($> 15,000$) and the inability to model such structure with the `bam()` function in the `mgcv` R package. However, we do not believe the inability to model such structure impacts the fitted smooths. Each model was fit using the `mgcv` package (Wood 2011) and results were summarized/visualized using the `gratia` package (Simpson 2020).

Additional Data Summaries

In addition to utilizing GAMs to visualize intra-annual trends, the following additional data summaries for each year's index period are included: (1) frequency distribution, and (2) number of hours per day parameter was observed within each estuarine quality category.

Results

An example time series plot of dissolved oxygen measurements over the course of the instrument deployment is provided in Figure 23. Yearly summary statistics for each parameter can be found in Table 10.

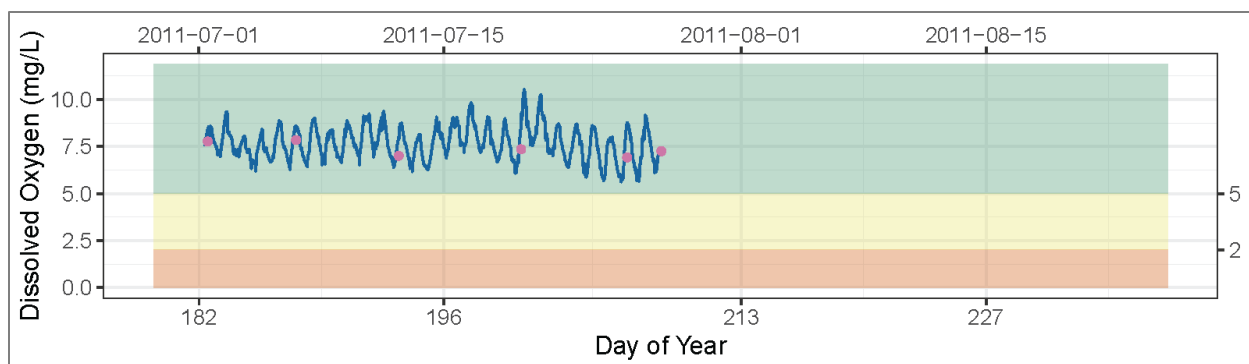


Figure 23. Example continuous dissolved oxygen readings from a data logger deployed at Fire Island National Seashore logging station in 2011. Magenta points represent discrete grab samples collected every week for quality assurance. Estuarine quality category thresholds (Table 2) are delineated by the background color (green = good condition; yellow = fair; orange = poor).

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Table 10. Yearly summary statistics for water quality parameters collected at the Fire Island National Seashore logging station. [SD = standard deviation; n = number of observations; NA = not available]

Parameter	Statistic	Sampling Year									
		2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
Chlorophyll- <i>a</i> (µg/L)	Mean	1.38	NA	9.51	29.85	5.83	40.92	13.77	34.62	10.92	6.18
Chlorophyll- <i>a</i> (µg/L)	SD	0.31	NA	3.85	10.88	8.85	13.73	5.37	19.58	6.34	3.16
Chlorophyll- <i>a</i> (µg/L)	n	2594	0	2488	1838	671	2686	2992	3091	3142	2780
Dissolved oxygen (mg/L)	Mean	7.67	NA	7.69	7.36	6.34	7.71	7.40	7.30	7.19	6.92
Dissolved oxygen (mg/L)	SD	1.23	NA	0.88	1.11	0.92	0.99	1.05	1.36	1.24	1.24
Dissolved oxygen (mg/L)	n	2594	0	2493	1838	671	2686	2484	3091	3169	2780
Depth (m)	Mean	0.78	0.41	0.84	0.72	1.31	0.70	0.84	0.70	1.09	0.77
Depth (m)	SD	0.12	0.13	0.14	0.14	0.12	0.14	0.14	0.14	0.14	0.14
Depth (m)	n	2594	3253	2493	1838	671	2686	2992	3091	3169	2780
PAR attenuation (K_d (m ⁻¹))	Mean	1.30	NA	0.79	1.32	NA	1.14	1.25	0.97	1.00	1.02
PAR attenuation (K_d (m ⁻¹))	SD	0.23	NA	0.28	0.38	NA	0.27	0.55	0.61	0.32	0.44
PAR attenuation (K_d (m ⁻¹))	n	677	0	640	394	0	614	781	619	156	580
pH	Mean	NA	NA	NA	NA	NA	NA	NA	8.21	8.01	7.93
pH	SD	NA	NA	NA	NA	NA	NA	NA	0.10	0.13	0.11
pH	n	0	0	0	0	0	0	0	3089	3169	2780
Salinity (psu)	Mean	22.12	22.51	25.56	27.24	28.08	28.80	30.56	28.60	26.16	26.55
Salinity (psu)	SD	0.43	0.49	0.56	0.39	1.52	0.30	0.51	0.57	0.31	0.41
Salinity (psu)	n	2594	2903	2470	1838	671	2686	2992	3091	3169	2780
Temperature (°C)	Mean	25.68	25.04	26.59	27.09	25.19	25.32	26.39	25.13	27.25	25.58
Temperature (°C)	SD	1.29	1.53	1.37	1.75	2.11	1.30	1.48	2.05	1.24	1.61
Temperature (°C)	n	2594	3253	2493	1838	671	2686	2992	3091	3169	2780
Turbidity (NTU)	Mean	3.94	5.51	2.25	9.23	7.31	6.91	2.55	6.44	2.47	3.52
Turbidity (NTU)	SD	1.87	1.33	1.33	3.24	9.46	1.90	1.27	2.31	1.00	1.01
Turbidity (NTU)	n	2580	2781	2477	1499	619	2625	2978	3088	3164	2770

Chlorophyll-*a*

Mean chlorophyll-*a* concentrations ranged from 1.83 to 40.92 µg/L and were classified as being in poor condition (i.e., > 20 µg/L) in 2013, 2015, and 2017 (Table 10). Intra-annual mean trends in chlorophyll-*a* concentration were highly non-linear for most years (Figure 24), and the associated distribution of measurements tended to be highly skewed in 2014, 2016, 2017, and 2021 (Figure 25). There were several years (e.g., 2013, 2015, and 2017) where chlorophyll-*a* condition was poor for the majority of the hours in each day (Figure 26).

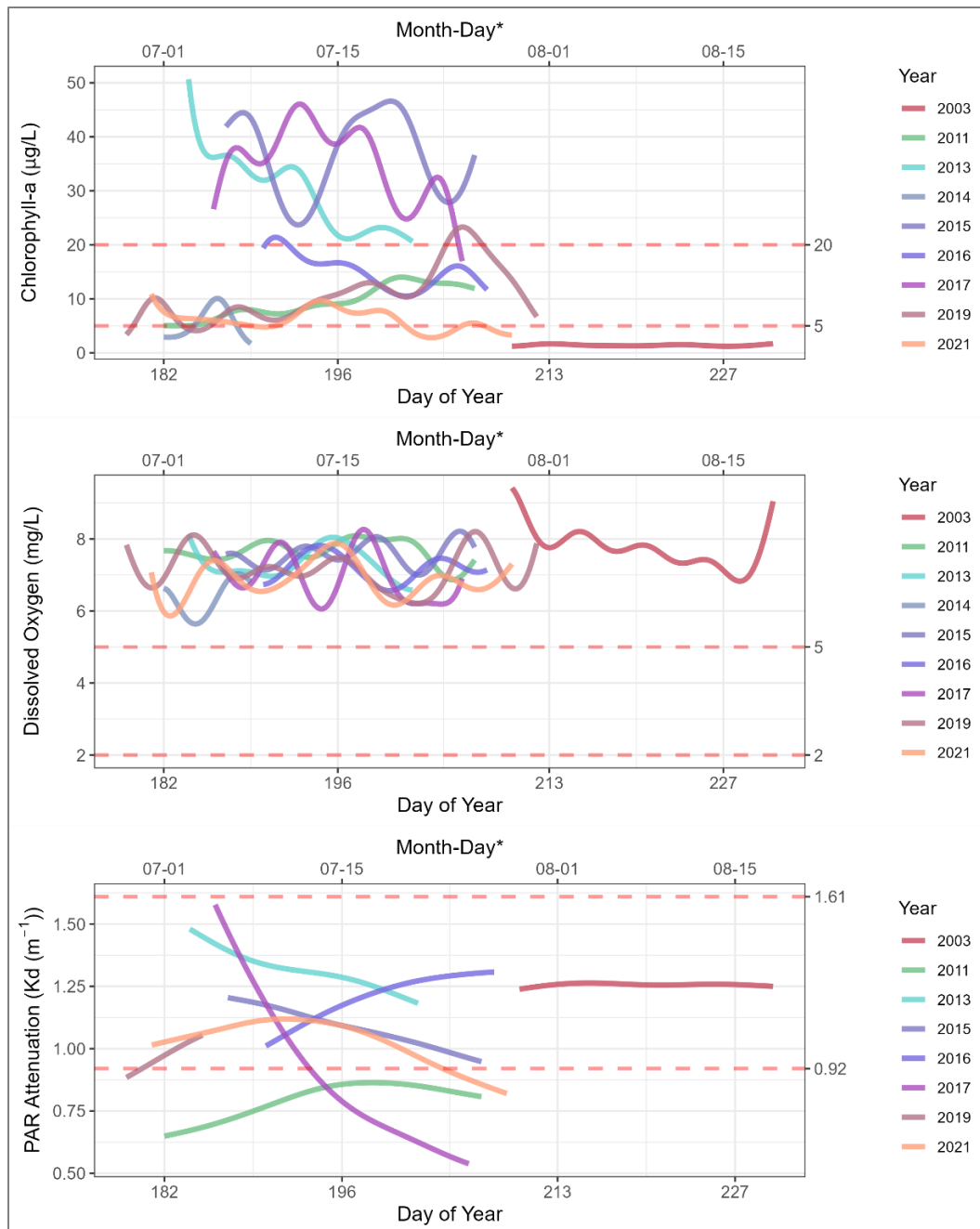


Figure 24. Intra-annual trends in surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Fire Island National Seashore logging station based on generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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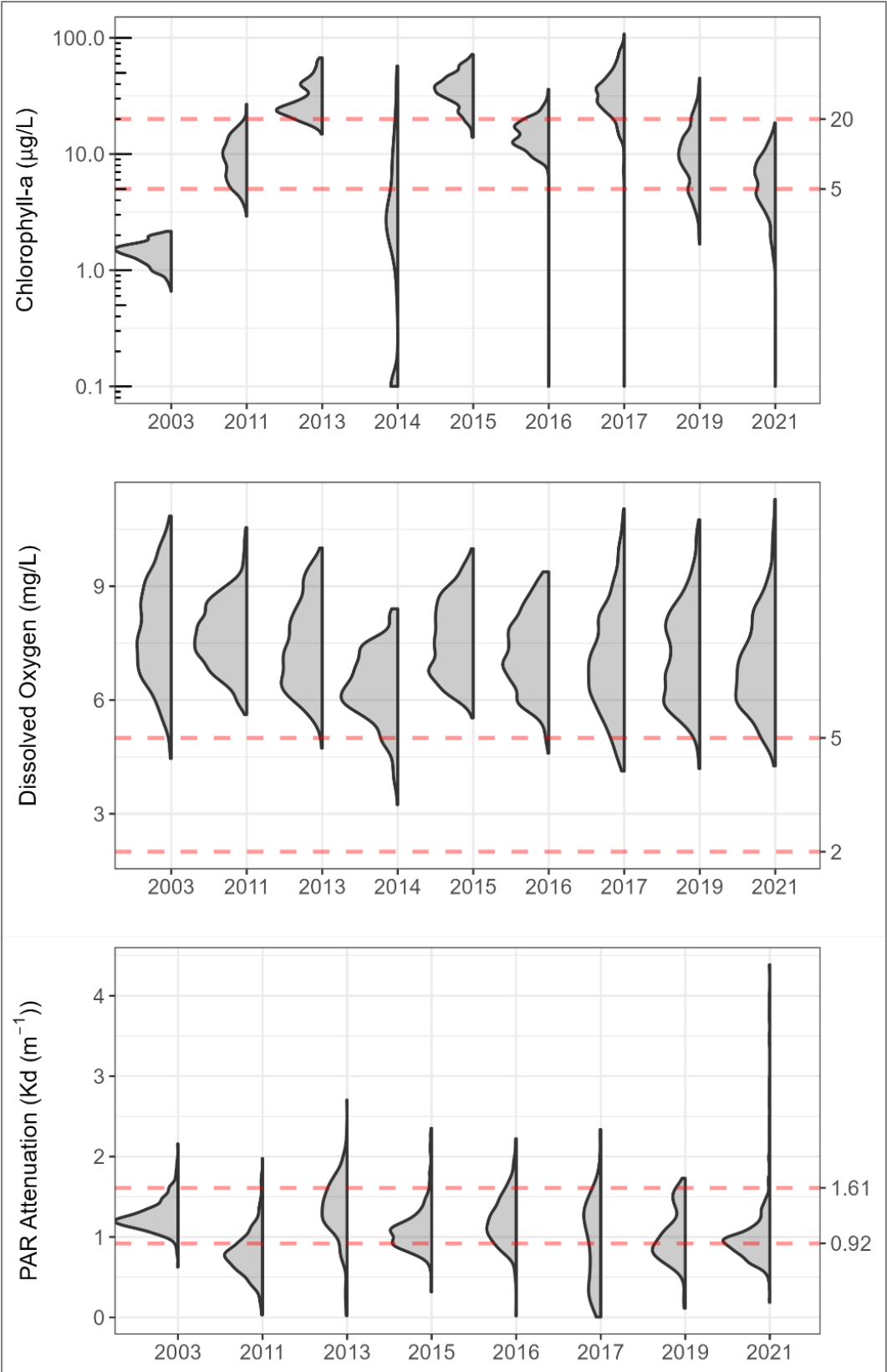


Figure 25. Distribution of index period time series values for surface chlorophyll-*a* concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Fire Island National Seashore logging station. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: the surface chlorophyll-*a* concentration y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated distributions.

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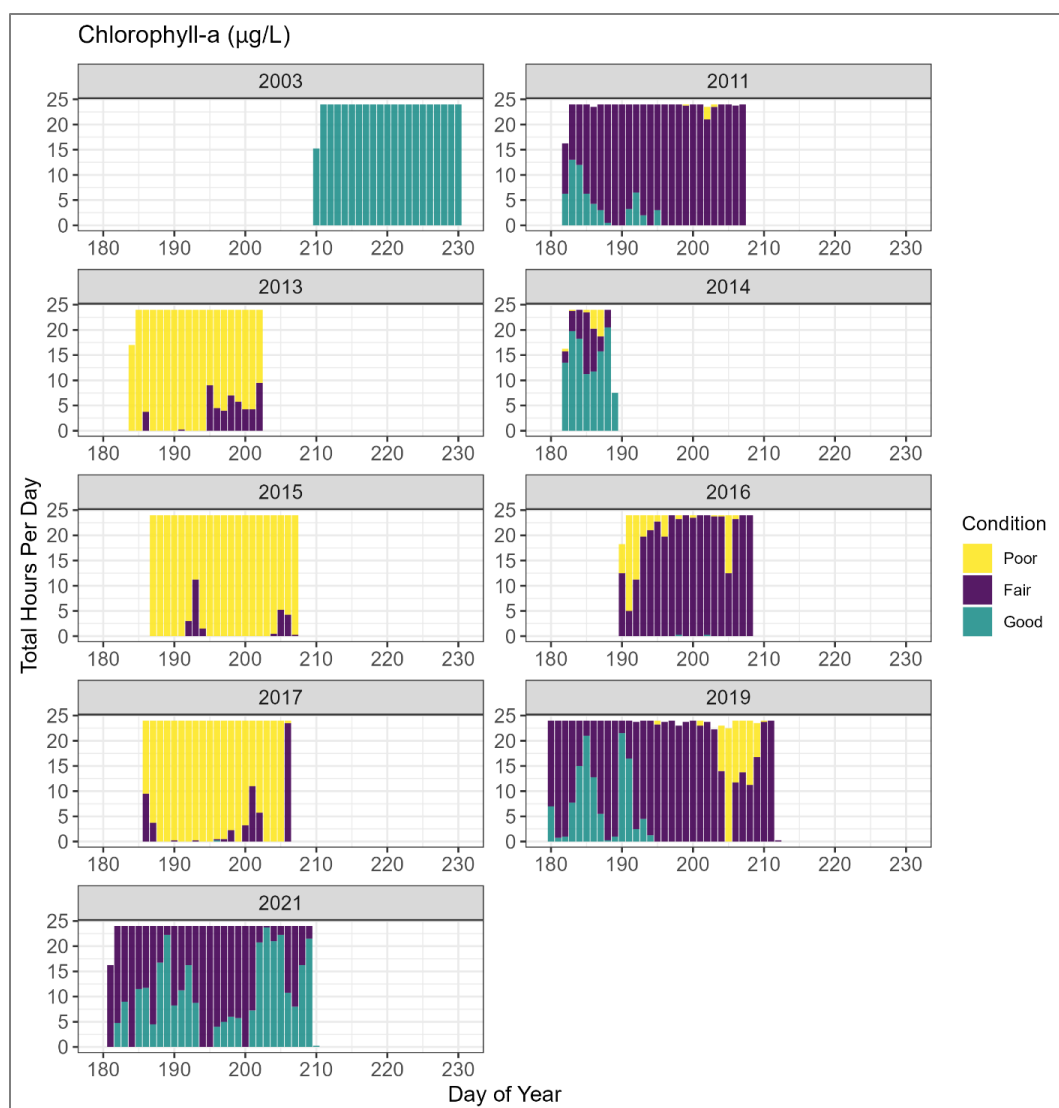


Figure 26. Total hours per day that surface chlorophyll-*a* concentration was observed within each condition category at the Fire Island National Seashore logging station.

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Dissolved Oxygen

Mean dissolved oxygen concentrations ranged from 6.34 to 7.71 mg/L indicating good conditions overall (Table 10). Intra-annual mean trends in dissolved oxygen were highly non-linear at this temporal scale and the cyclic nature was consistent across years (Figure 24). The distribution of measurements was long-tailed in many years sampled with concentrations dropping below 5 mg/L (i.e., fair condition) in most years (Figure 25). Dissolved oxygen conditions were generally good across all years with some days experiencing fair conditions for part of the day (Figure 27).

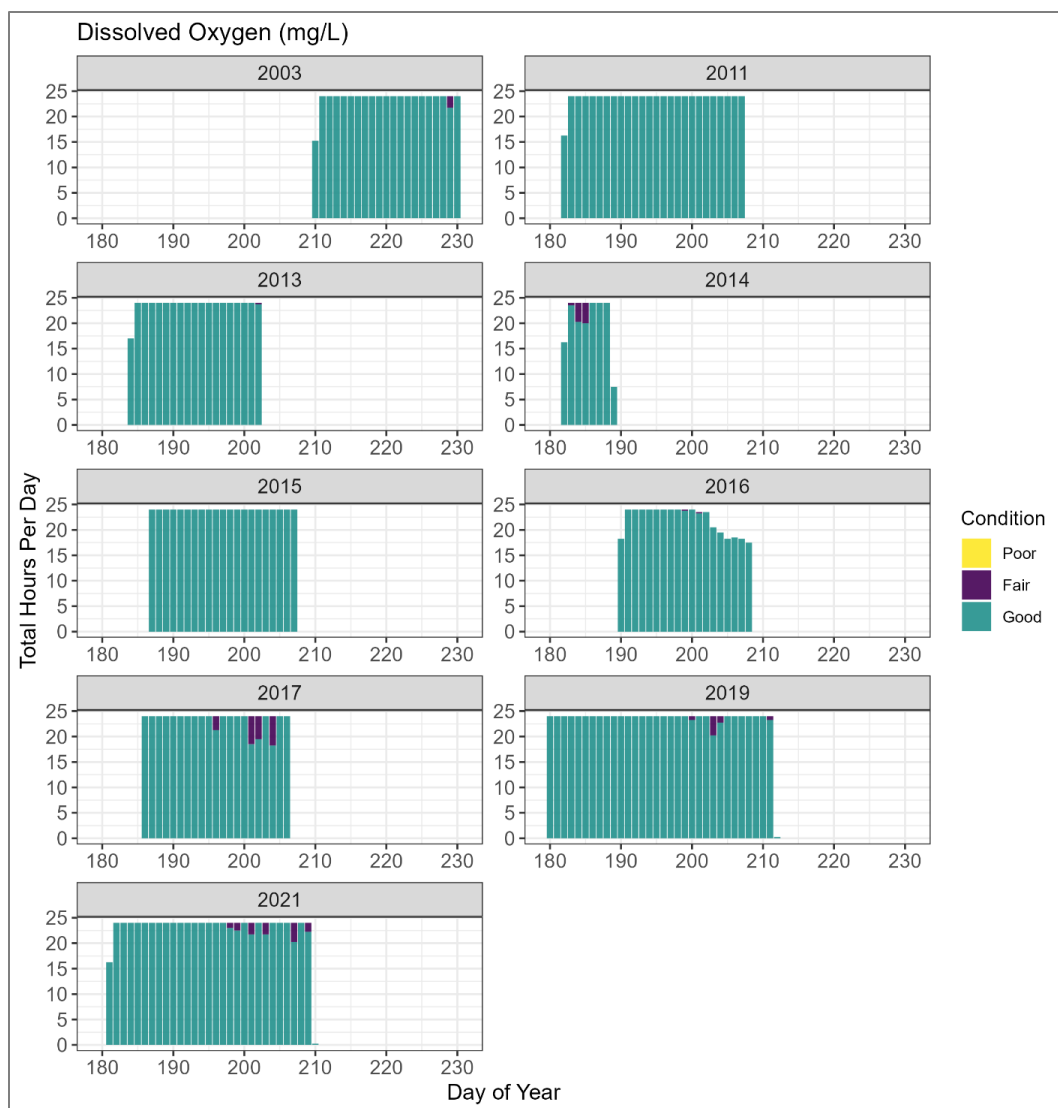


Figure 27. Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the Fire Island National Seashore logging station.

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PAR Attenuation K_d

The lowest mean PAR attenuation (0.79 m^{-1}) was observed in 2011 with the highest observed (1.32 m^{-1}) in 2013 (Table 10). Intra-annual mean trends were typically smooth but often non-linear (Figure 24). The distribution of measurements in 2021 was highly skewed compared to other years (Figure 25). For most years, the majority of daytime hours during which PAR attenuation could be measured were spent in fair to good condition with some short periods of poor conditions observed (Figure 28).

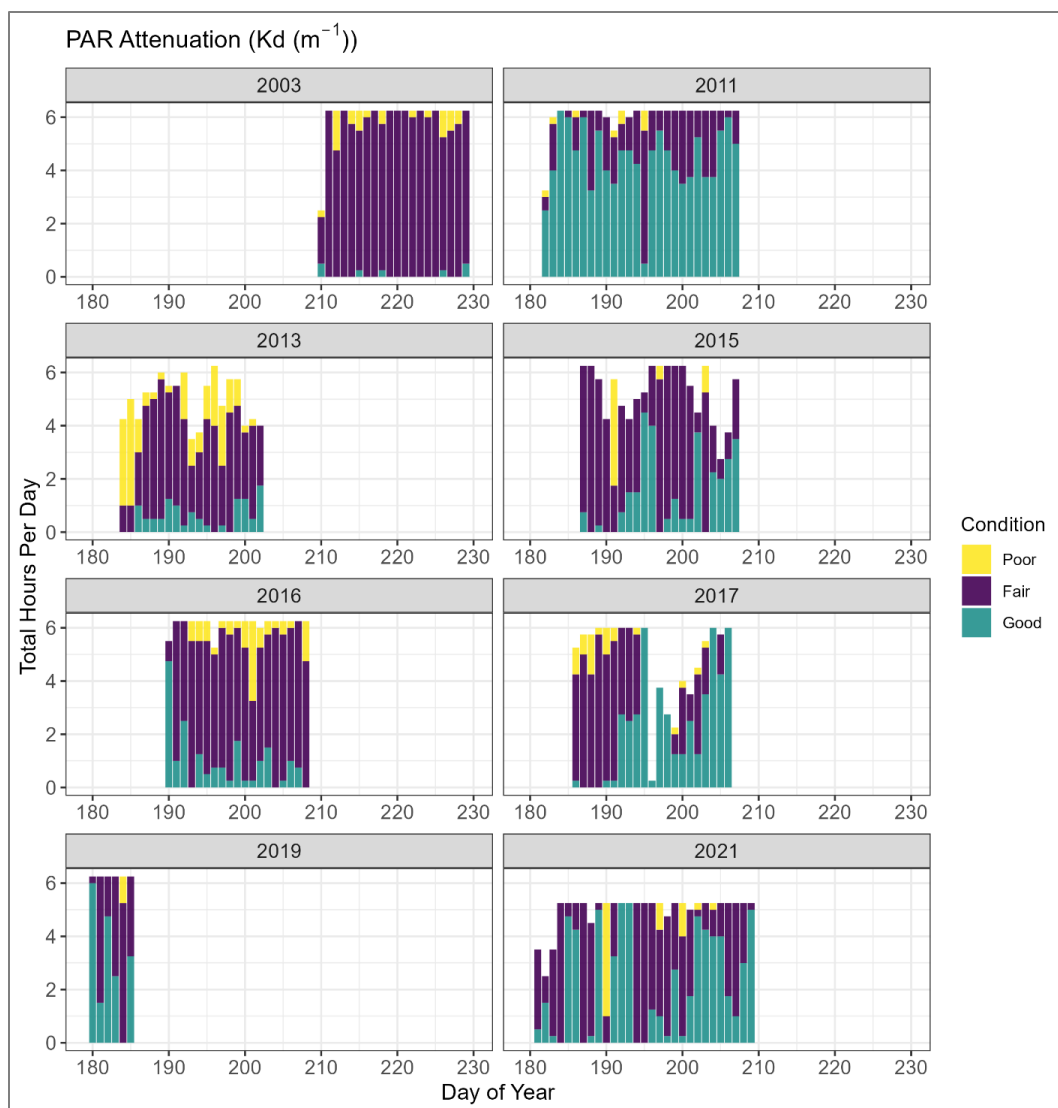


Figure 28. Total hours per day that PAR attenuation was observed within each condition category at the Fire Island National Seashore logging station.

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Salinity

Mean salinity ranged from 22.12 to 30.56 psu and was lowest in 2003 and 2009 (Table 10). Intra-annual mean trends in salinity were non-linear (Figure 29). For most years, salinity measurements within each summer index period typically spanned approximately 2–4 psu, and the distributions in 2014 and 2019 were atypical compared to other years (Figure 30).

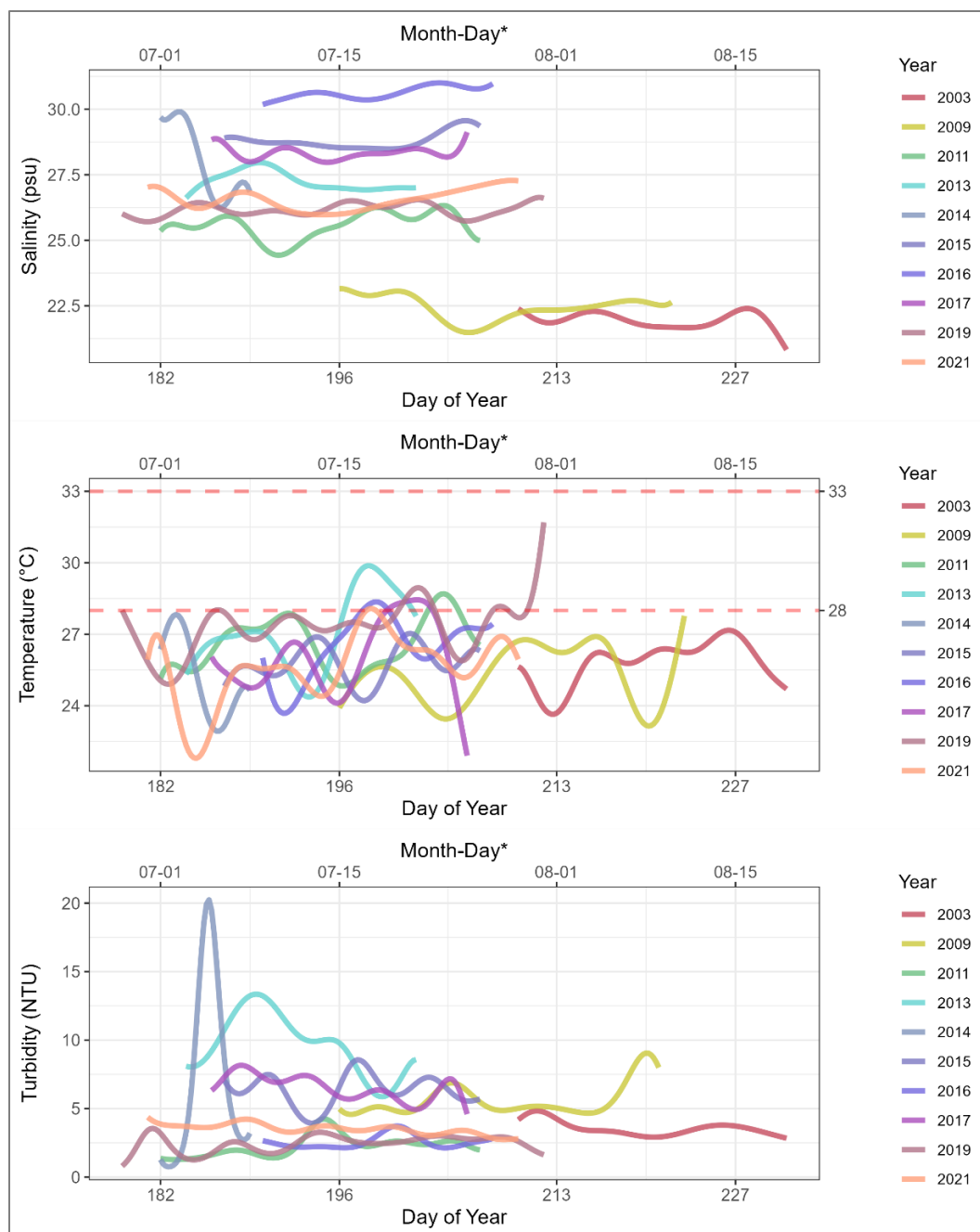


Figure 29. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Fire Island National Seashore logging station based on generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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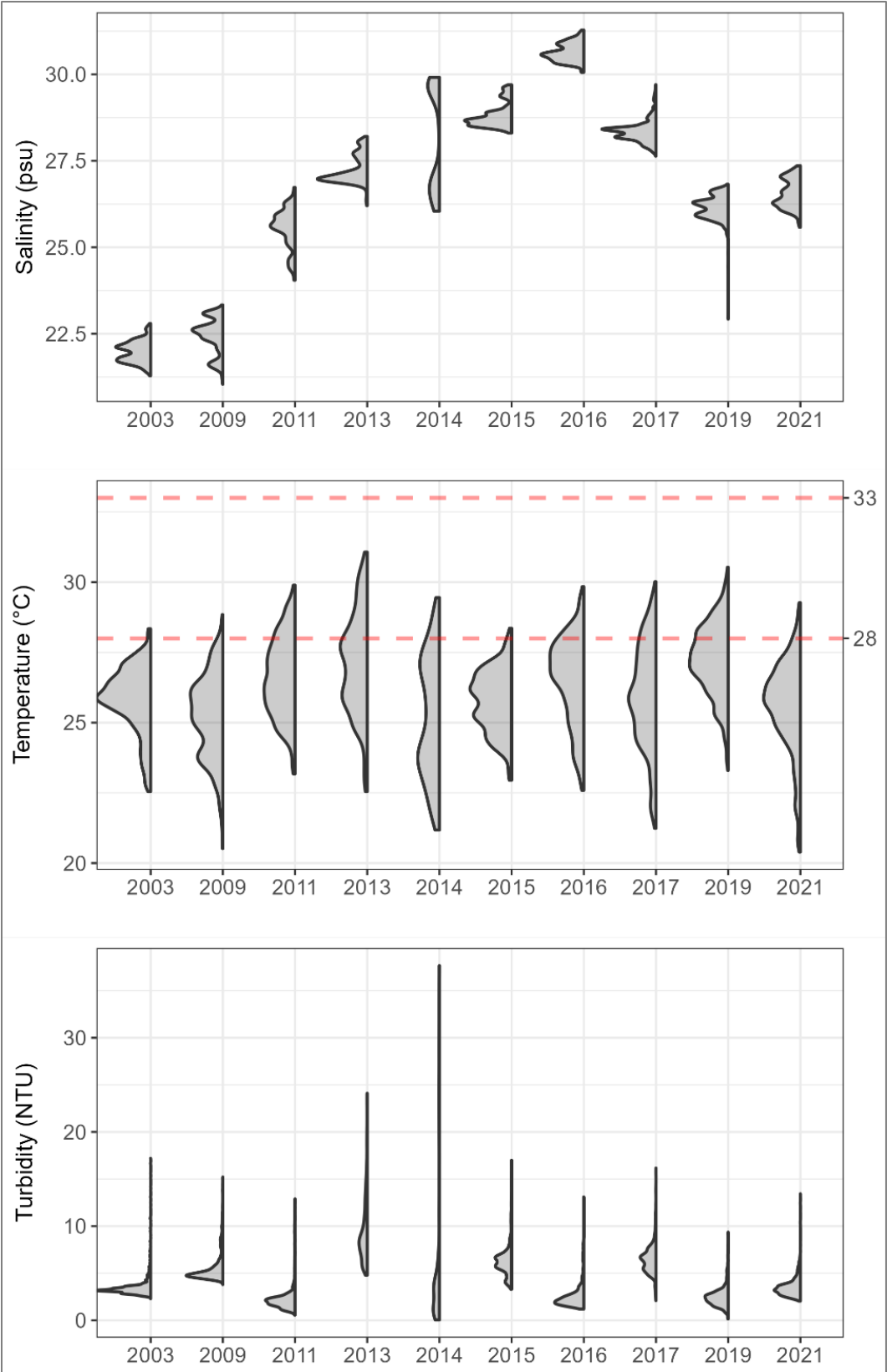


Figure 30. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Fire Island National Seashore logging station. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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Temperature

Intra-annual mean trends in water temperature were highly non-linear with an overall increasing trend from July to August (Figure 29). Water temperature measurements within each summer index period typically spanned approximately 5–8°C, and temperatures exceeded 28°C at some point during the deployment in every year (Figure 30).

Turbidity

Mean turbidity ranged from 2.47 to 9.23 NTU, with the highest values observed in 2013 (Table 10). Intra-annual mean trends in turbidity were generally non-linear and were highly non-linear in 2009, 2013, 2014, 2015, and 2017 (Figure 29). Turbidity measurements were often highly skewed especially in 2013 and 2014 (Figure 30).

pH

Measurements of pH began in 2017 and mean values ranged from 7.93 to 8.21 (Table 10). All years exhibited a non-linear intra-annual mean trend (Figure 31). The distributions of pH measurements suggest that pH was higher overall in 2017 (Figure 32).

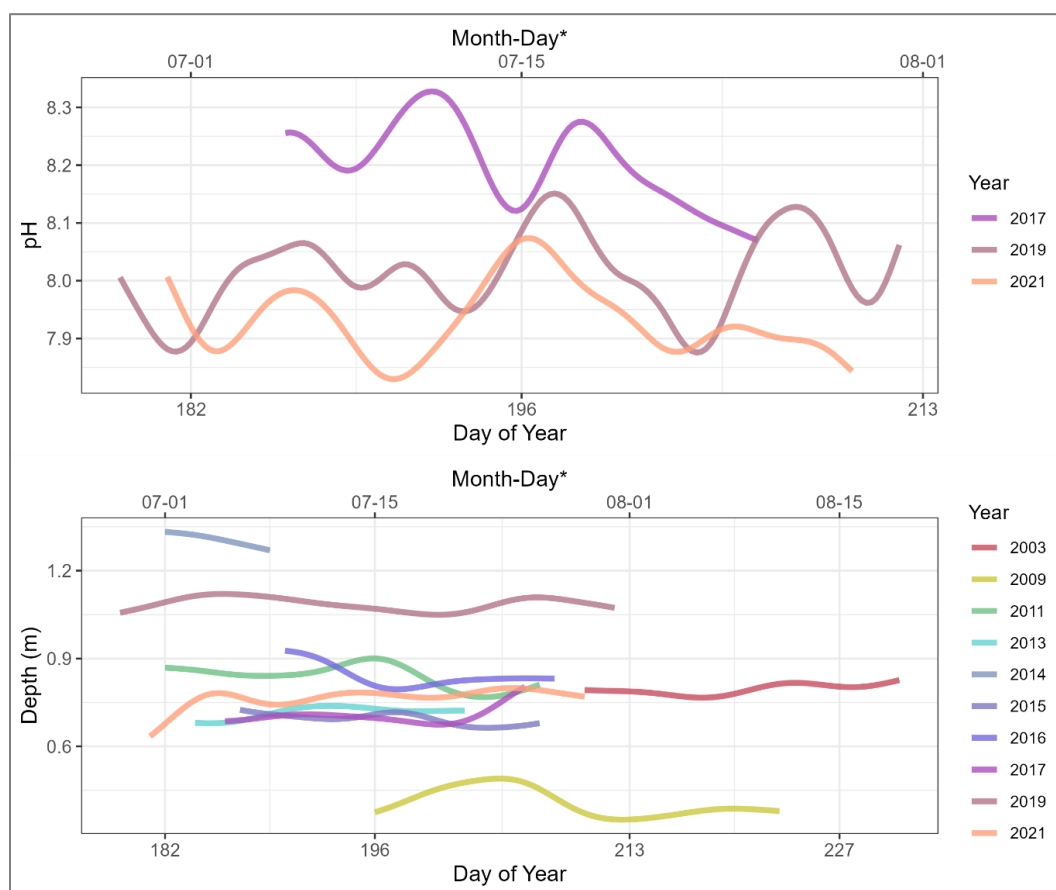


Figure 31. Intra-annual trends in pH (top) and depth (bottom) at the Fire Island National Seashore logging station based on generalized additive model smooths.

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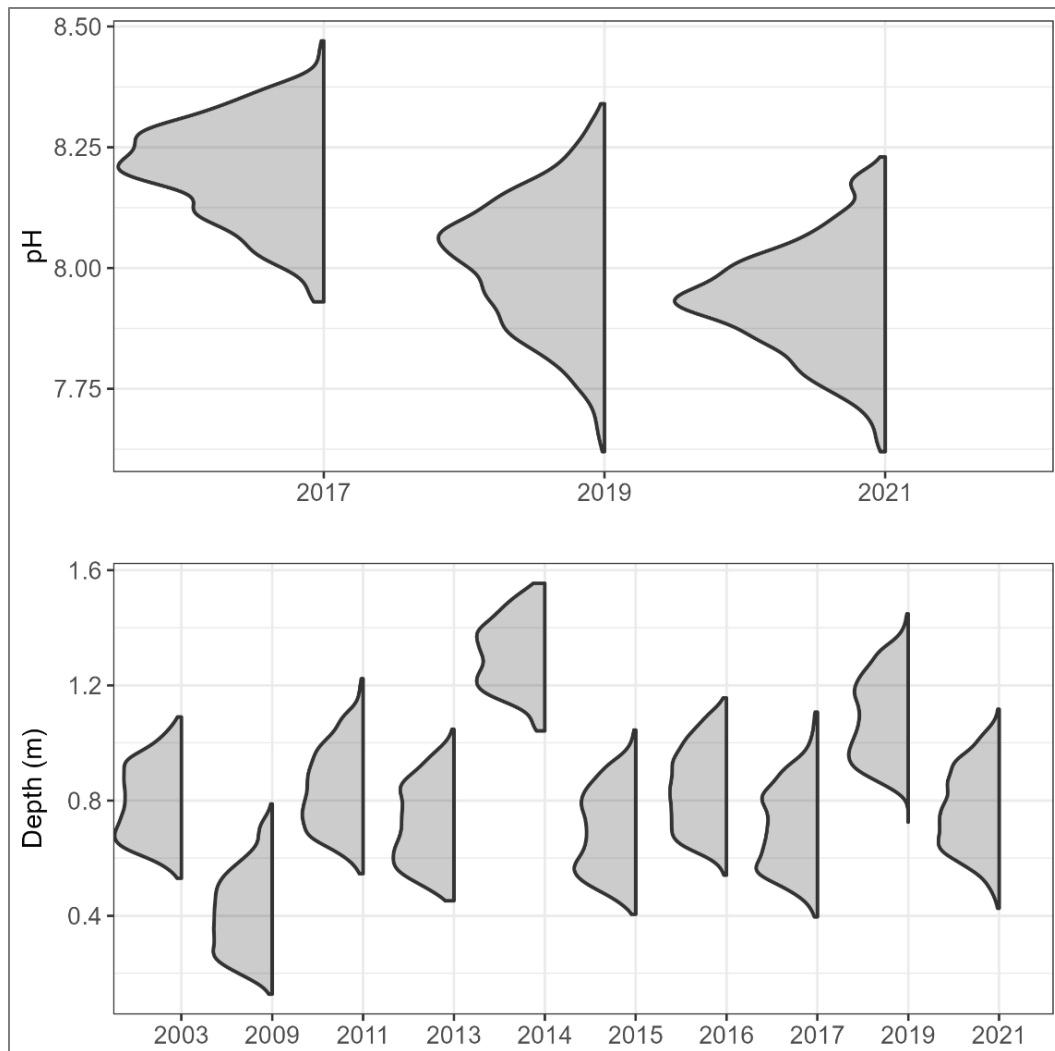


Figure 32. Distribution of index period time series values for pH (top) and depth (bottom) at the Fire Island National Seashore logging station.

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Depth

Mean depth typically ranged from 0.40 to 0.85 m except for in 2014 and 2019 when it exceeded 1 m (Table 10). All years exhibited a relatively smooth intra-annual mean trend (Figure 31). Within a given year, the depth range was generally between 0.5 and 0.6 m (Figure 32).

Seagrass Condition

Data Analysis

Variable Derivations

While most seagrass parameters were direct measurements, total biomass and the ratio of above- to belowground biomass were derived from direct measurements. For eelgrass, total biomass was derived using the formula given in the ENE monitoring protocol (Table 23 in Kopp and Neckles 2009):

$$\text{total biomass} = \left(\frac{\text{total mass (g)}}{1 \text{ shoot}} \right) \times \left(\frac{\text{total shoots}}{\text{m}^2} \right),$$

where total mass per shoot is calculated as the total mass per core divided by the number of meristems per core. For widgeon grass, because shoots were too small to be reliably counted underwater in the field, total biomass was instead estimated based on the formula:

$$\text{total biomass} = \left(\frac{\text{total mass (g)}}{1 \text{ core}} \right) \times \left(\frac{1 \text{ core}}{0.0035 \text{ m}^2} \right),$$

where 0.0035 m² is the area of a 6.7-cm diameter corer. The ratio of above- to belowground biomass for both species was computed as the total weight (g) of leaves and sheaths combined divided by the total weight (g) of the roots and rhizomes combined:

$$\text{ratio of above- to belowground biomass} = \left(\frac{\text{leaf + sheath (g)}}{1 \text{ core}} \right) \div \left(\frac{\text{root + rhizome (g)}}{1 \text{ core}} \right),$$

Generalized Additive Model (GAM)

Generalized additive models (GAMs) were used to estimate trends in seagrass parameters at different water depths at each monitoring site. For each species' response parameter, we model response as a function of both year and transect (i.e., depth). Mathematically, the model can be written as:

$$\begin{aligned} \text{response}_i &\sim \text{Distribution}(\mu_i, \phi) \\ g(\mu_i) &= \beta_0 + f_{\text{transect}_i}(\text{year}_i) \end{aligned}$$

where f_{transect_i} is a TRPS smooth of year for the i th transect (rank equal to the number of years of data), $g(\cdot)$ is a link function, and ϕ is the distribution's variance/precision parameter. The year smoother is known as a factor-smoother and assumes that all factors (i.e., transects) have the same smoothness, but may differ in shape over time. Because the type of data differs depending on the parameter, several different distributions were utilized (Table 11).

Table 11. Summary of the distribution, link function, and offset used to model each seagrass parameter.
[– = not applicable]

Parameter	Distribution	Link Function	Offset
Shoot density	negative binomial	log	log(area)
Percent Cover	beta	logit	–
Canopy height	gamma	log	–
Total biomass	Tweedie	log	–
Above- to belowground biomass	gamma	log	–
Percent fine sediment	beta	logit	–
Percent organic material	beta	logit	–

A summary of the model fit to each parameter is as follows:

- Shoot density—direct counts of seagrass shoots per 0.25 m² or 0.0625 m² subplot within a quadrat. A negative binomial distribution was used instead of a Poisson to allow for overdispersion (i.e., when data based on direct counts exhibit extra variation that is greater than the mean). The negative binomial is more flexible than the Poisson in this respect since it has an additional parameter that adjusts the variance independent of the mean. Additionally, because shoot density is a rate (i.e., density per area), an offset for area was included in the model specification.
- Percent cover—beta distribution used to model proportions data when binomial distribution is not appropriate.
- Canopy height—all-positive data with positive skew modeled with gamma distribution.
- Total biomass—non-negative continuous data with potential point mass at zero (i.e., excess of zeros) is modeled with a Tweedie distribution, which is a flexible probability distribution capable of handling continuous data with probability mass at zero (Bonat and Kokonendji 2017; Dunstan et al. 2013).
- Ratio of above- to belowground biomass—all-positive data with positive skew modeled with gamma distribution.
- Percent fine sediment—defined as sum of percent clay and percent silt in sediment sample. Beta distribution used to model proportions data when binomial distribution is not appropriate.
- Percent organic material—beta distribution used to model proportions data when binomial distribution is not appropriate.

Analyses were carried out using the R Statistical Computing Environment (R Core Team 2022). Each model was fit using the mgcv package (Wood 2011). Results were summarized and visualized using the gratia package (Simpson 2020).

Multivariate Mann-Kendall Trend Analysis

The multivariate Mann-Kendall test (trend R package; Pohlert 2020) was used to determine whether there exists a monotonically increasing or decreasing trend in values for each transect within the seagrass reference bed over time (Libiseller and Grimvall 2002). Positive values of the test statistic Z_{MK} indicates that measurements tend to increase with time, whereas negative values indicate a decrease.

GAM Results

Summary statistics for each month/year combination are provided in Appendix D for both *Zostera marina* and *Ruppia maritima* (where applicable) for the following: shoot density, percent cover, canopy height, total biomass, and ratio of above- to belowground biomass.

The generalized additive model summaries indicate that there were statistically significant temporal trends within transects for all *Ruppia maritima* parameters (Table 12) and ancillary sediments (Table 13). Because *Zostera marina* presence in all transects was nonexistent from 2011 to 2022 after experiencing sharp declines from 2007 to 2010, GAMs were not fit to *Zostera marina* due to a lack of data.

Table 12. Approximate significance of the generalized additive model smooth terms for each Fire Island National Seashore *Ruppia maritima* parameter model. Each respective p -value corresponds to the test of the hypotheses: $H_0: f(x) = 0$ versus $H_1: f(x) \neq 0$. Note: p -values are computed without considering uncertainty in the smoothing parameter estimates and may need to be interpreted with caution when near the α level. [edf = effective degrees of freedom; – = not applicable]

Parameter	Model Term	edf	p -value
Shoot density	–	–	–
Percent cover	s(year, transect)	20.69	< 0.001
Canopy height	s(year, transect)	7.19	< 0.001
Total biomass	s(year, transect)	23.19	< 0.001
Above- to belowground biomass	s(year, transect)	7.05	< 0.001

Table 13. Approximate significance of the generalized additive model smooth terms for each Fire Island National Seashore ancillary sediment model. Each respective p -value corresponds to the test of the hypotheses: $H_0: f(x) = 0$ versus $H_1: f(x) \neq 0$. Note: p -values are computed without considering uncertainty in the smoothing parameter estimates and may need to be interpreted with caution when near the α level. [edf = effective degrees of freedom]

Parameter	Model Term	edf	p -value
Percent fine sediment	s(year, transect)	10.07	< 0.001
Percent organic material	s(year, transect)	6.31	0.001

Shoot Density

Prior to its decline in 2011, *Zostera marina* shoot density was highest within the deep transect (Figure 33). Highest shoot densities were observed in 2007 with densities in the deep transect exceeding 200 shoots m^{-2} .

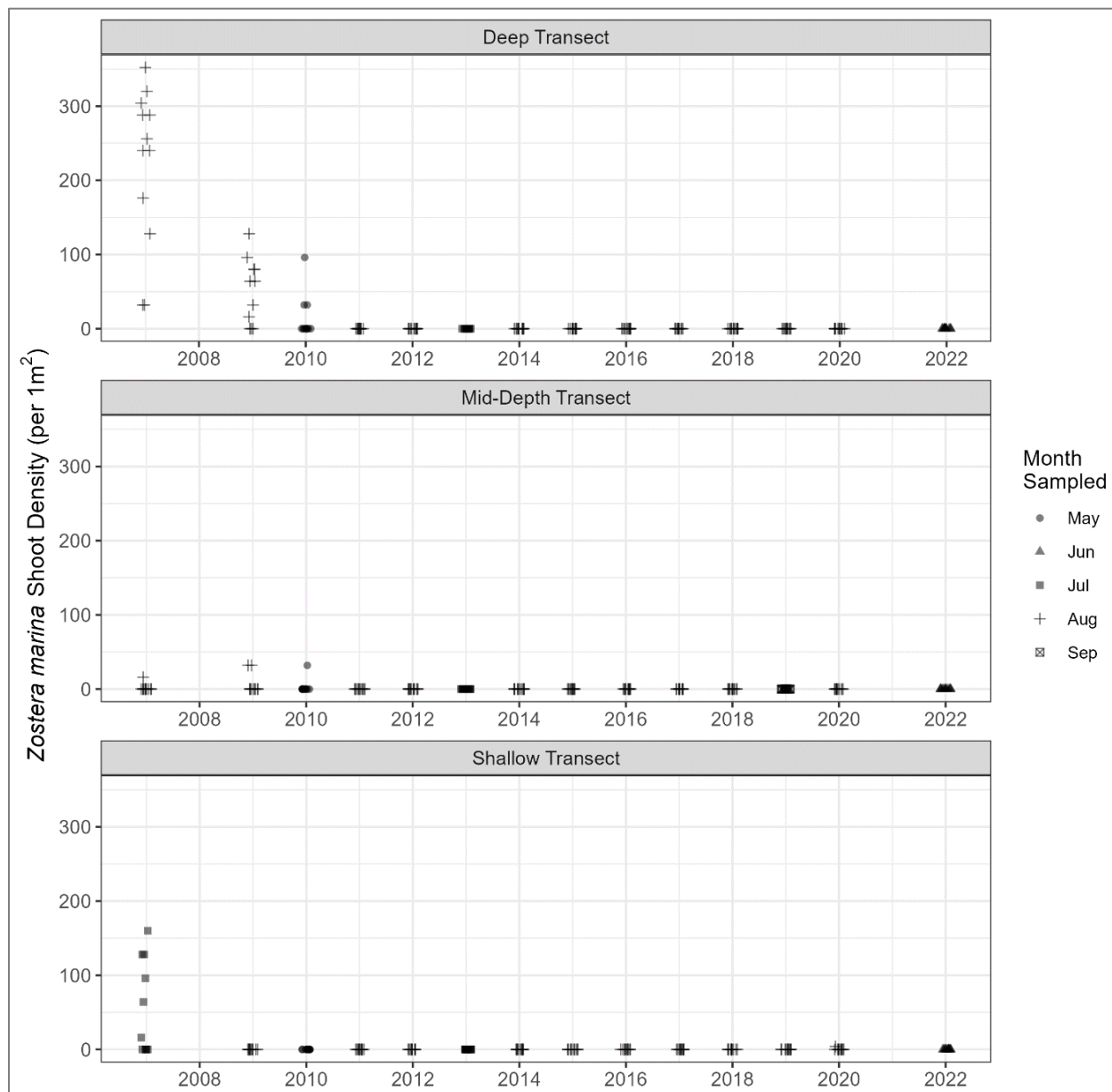


Figure 33. Observed *Zostera marina* shoot density (per 1 m^2) by transect at the Fire Island National Seashore reference seagrass bed. Note: trends were not quantified due to a majority of observations equaling zero.

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Percent Cover

Zostera marina percent cover was highest within the deep transect before its absence from 2011 on (Figure 34). Percent cover of *Ruppia maritima* was generally highest within the shallow transect and lowest in the deep transect where none was observed from 2014 to 2022 (Figure 35). In the mid-depth transect, percent cover was more variable with several years of very low to no cover.

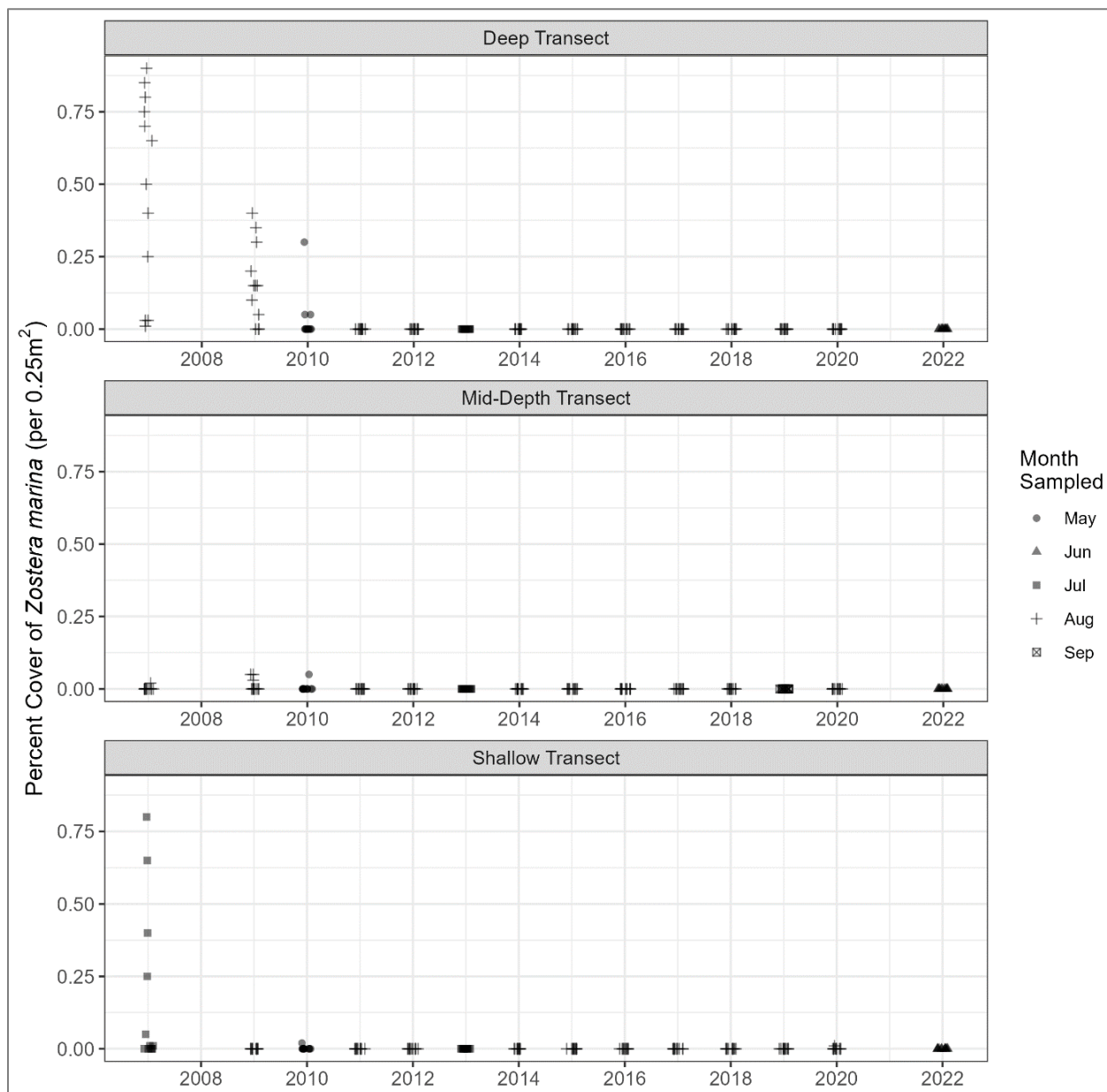


Figure 34. Observed percent cover of *Zostera marina* (per 0.25 m²) by transect at the Fire Island National Seashore reference seagrass bed. Note: trends were not quantified due to a majority of observations equaling zero.

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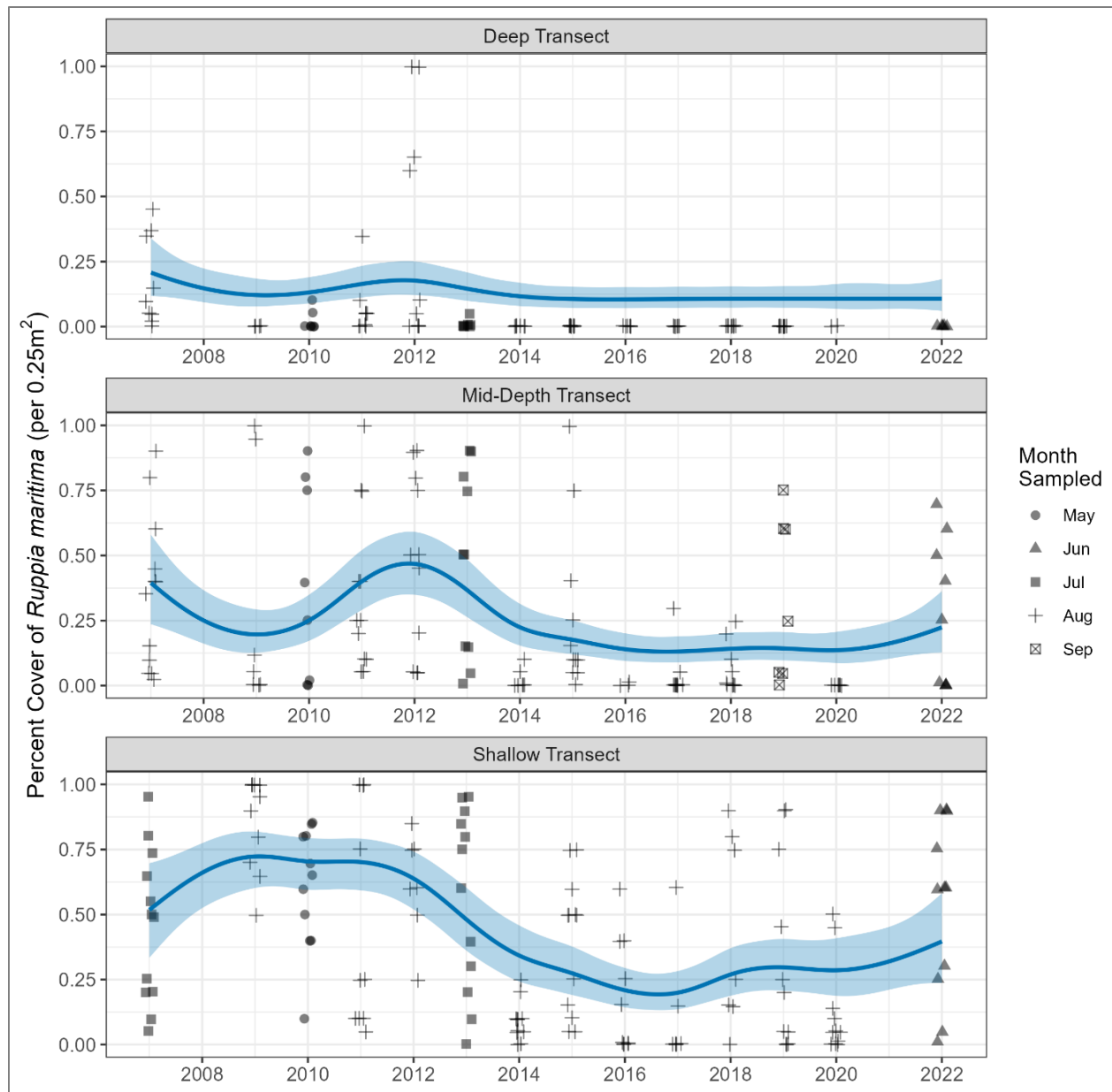


Figure 35. Trend in percent cover of *Ruppia maritima* (per 0.25 m²) by transect at the Fire Island National Seashore reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Canopy Height

Zostera marina canopy height was highest within the deep transect prior to its total disappearance from all transects in 2011 (Figure 36). There was a lack of trend for *Ruppia maritima* canopy height. Canopy heights in the shallow transect were particularly low during 2010 and 2014, and highest in 2013 (Figure 37).

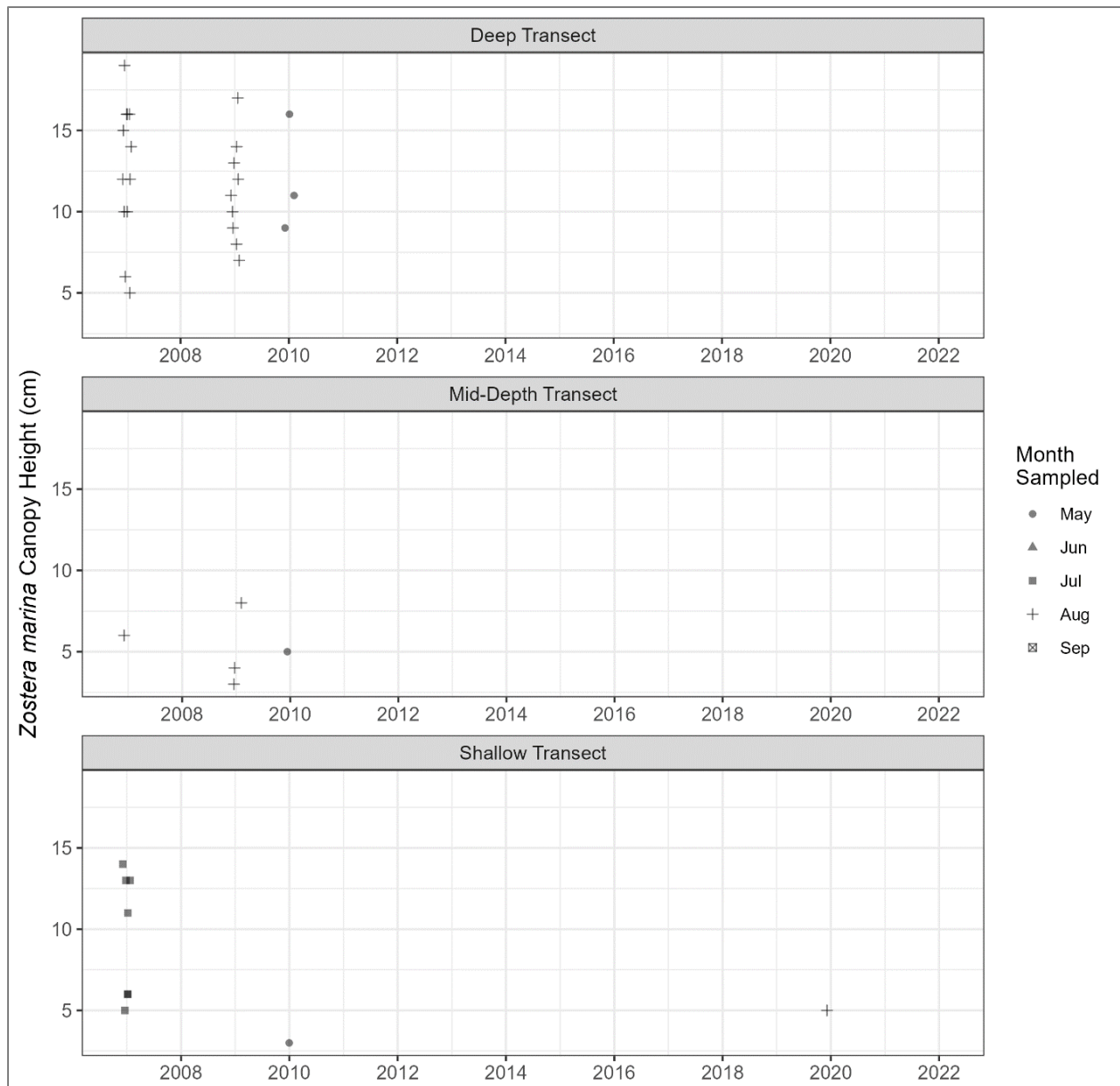


Figure 36. Observed *Zostera marina* canopy height by transect at the Fire Island National Seashore reference seagrass bed. Note: trends were not quantified due to a limited amount of data.

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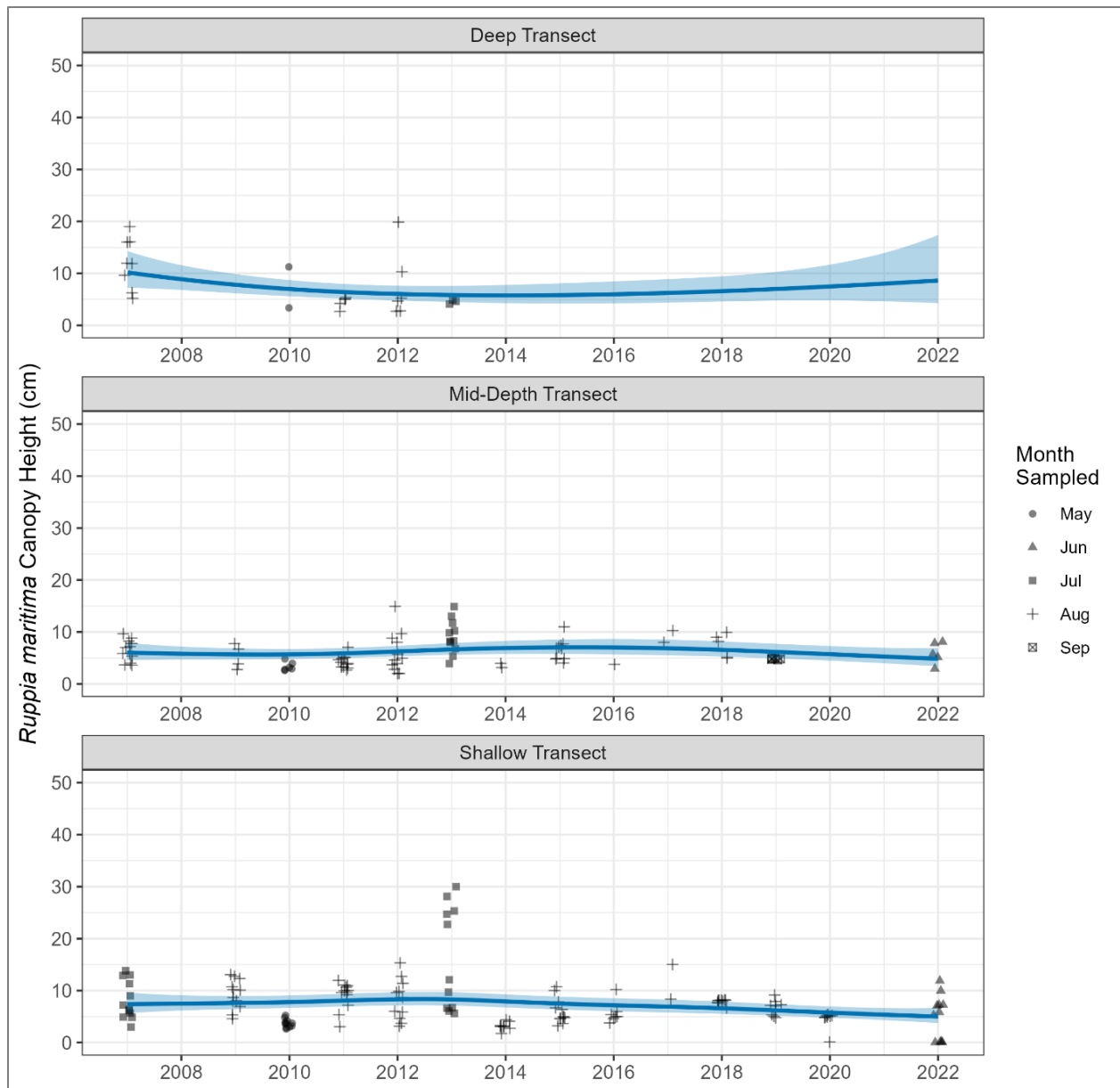


Figure 37. Trend in *Ruppia maritima* canopy height by transect at the Fire Island National Seashore reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Total Biomass

Before its decline in 2011, *Zostera marina* total biomass was highest within the deep transect where values exceeded 40 g m^{-2} (Figure 38). Total biomass of *Ruppia maritima* was generally highest within the shallow transect where values exceeded 100 g m^{-2} in some years and the trend was cyclical in nature (Figure 39). Biomass increased within all transects during the period of 2012–2013, but no *Ruppia maritima* was observed in the deep transect after 2014.

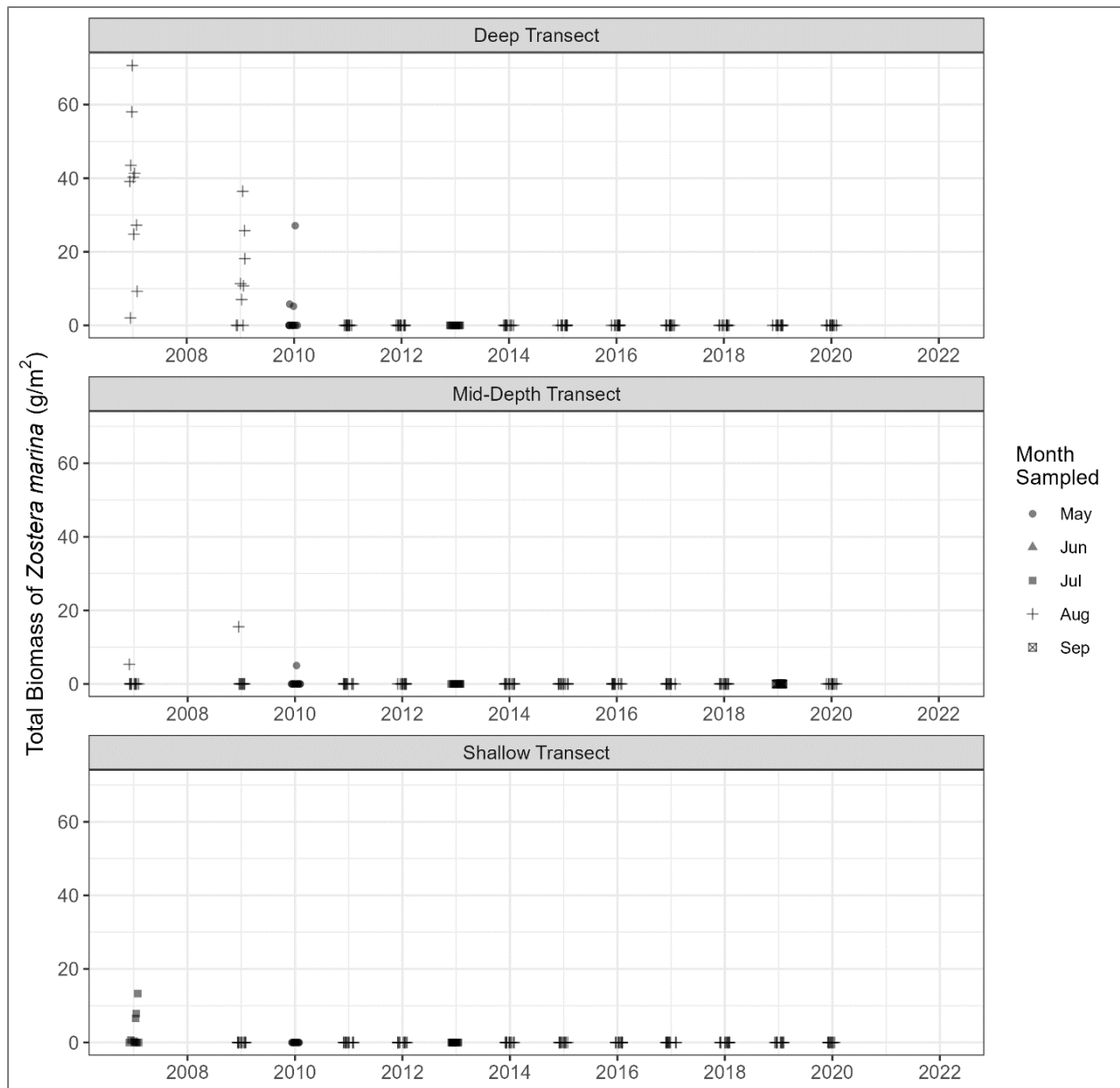


Figure 38. Observed *Zostera marina* total biomass (g/m²) by transect at the Fire Island National Seashore reference seagrass bed. Note: trends were not quantified due to the majority of observations equaling zero

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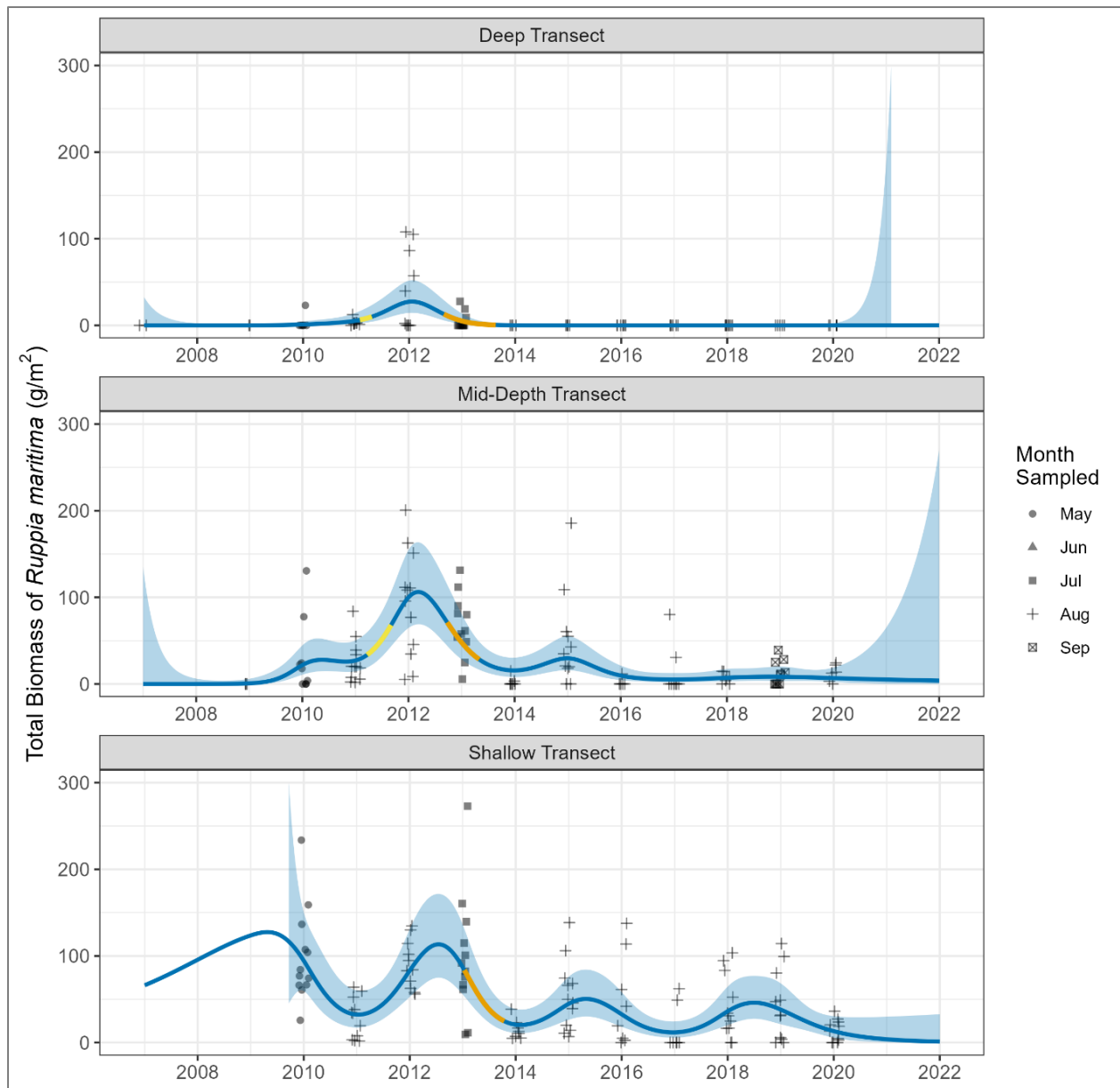


Figure 39. Trend in *Ruppia maritima* total biomass (g/m²) by transect at the Fire Island National Seashore reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Above- to Belowground Biomass Ratio

Zostera marina above- to belowground biomass ratio was generally highest within the deep transect (Figure 40). The above- to belowground biomass ratio for *Ruppia maritima* was relatively constant within the mid-depth and deep transects. The shallow transect trend suggests a possible increase over time to around 1, although it was not statistically significant (Figure 41).

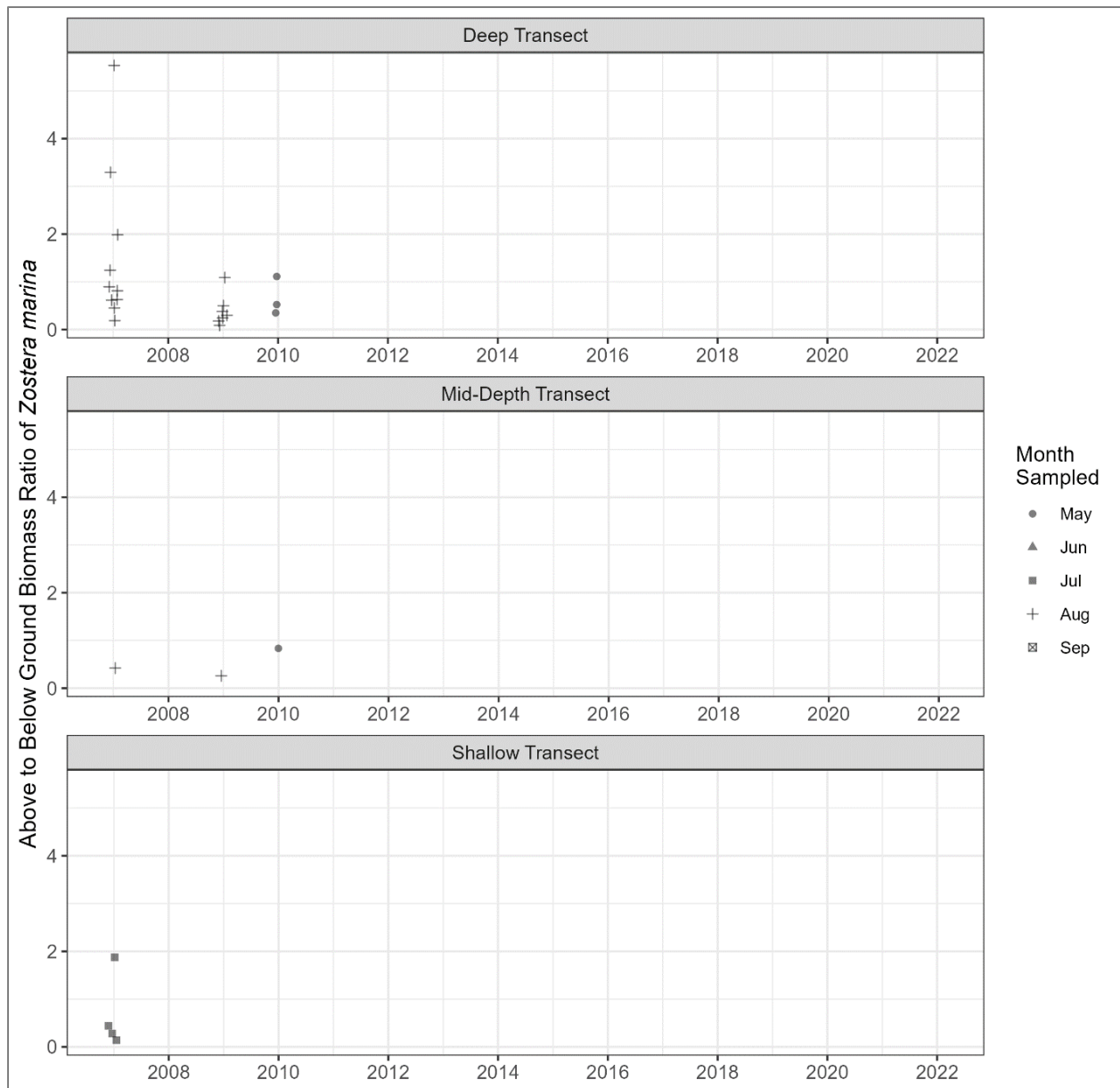


Figure 40. Observed above- to belowground biomass ratio of *Zostera marina* by transect at the Fire Island National Seashore reference seagrass bed. Note: trends were not quantified due to a lack of data.
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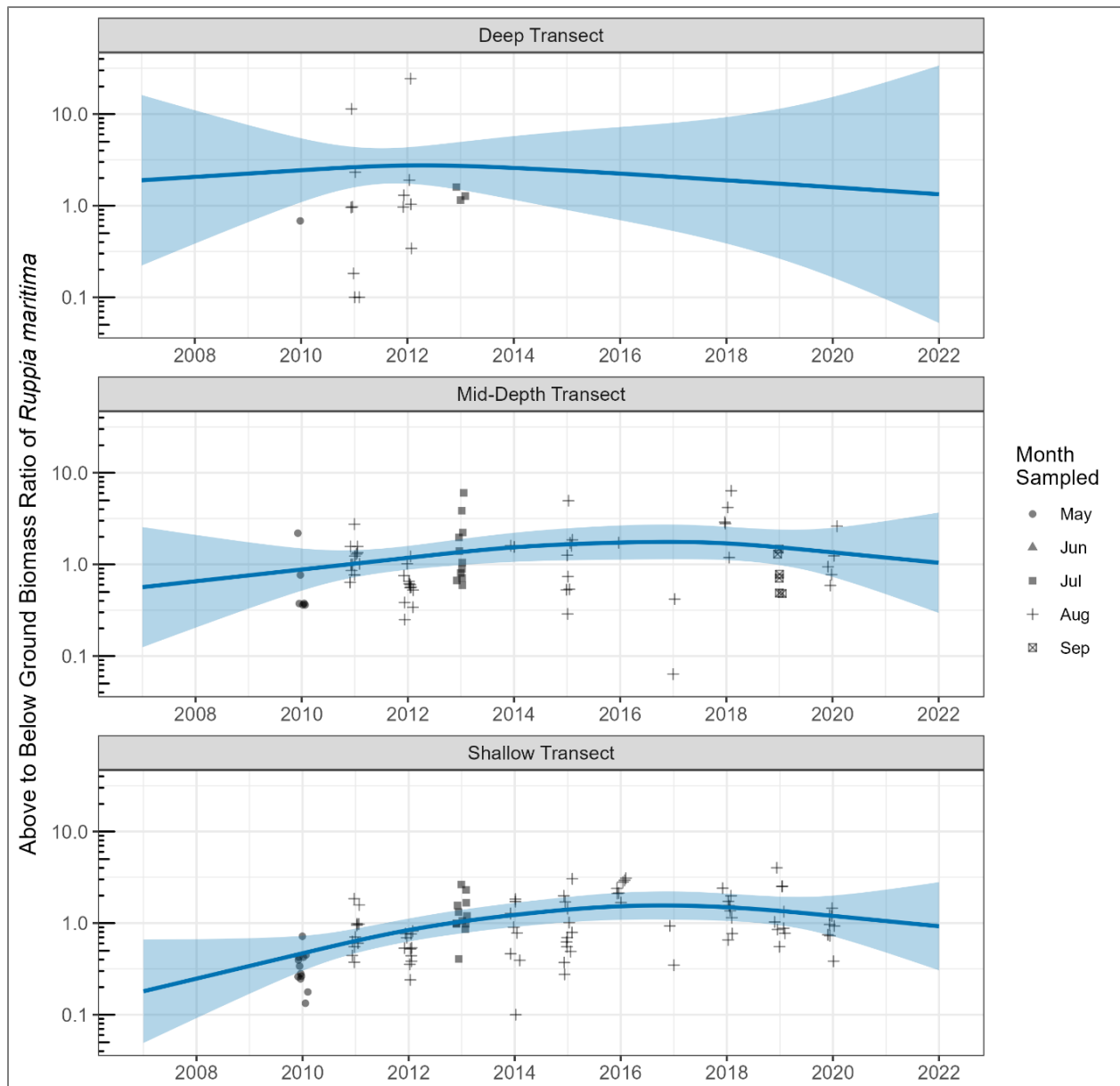


Figure 41. Trend in above- to belowground biomass ratio of *Ruppia maritima* by transect at the Fire Island National Seashore reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: y-axes are transformed to the $\log_{10}$ scale to better visualize the estimated trends.

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Percent Fine Sediment

Percent fine sediment within the transects was typically less than 6%. Temporal trends indicated a significant increase in all three transects between 2020 and 2022 (Figure 42).

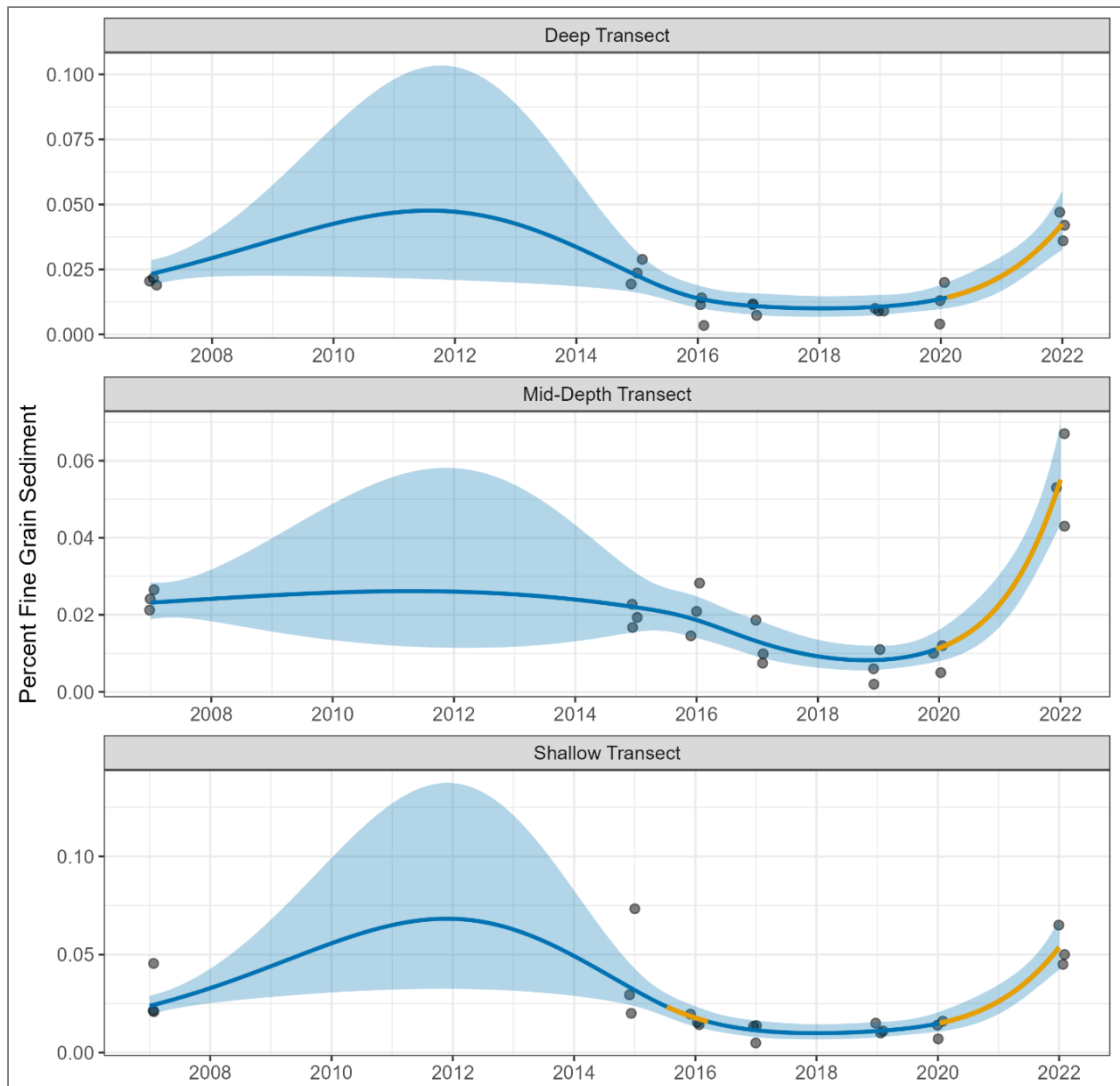


Figure 42. Trend in percent fine sediment (i.e., clay and silt) by transect at the Fire Island National Seashore reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Percent Organic Material

Percent organic material within the transects was very low and generally less than 1%. Temporal trends suggest that there was an increase in percentage of organic material between 2020 and 2022; however, this change was only significant in the shallow transect (Figure 43).

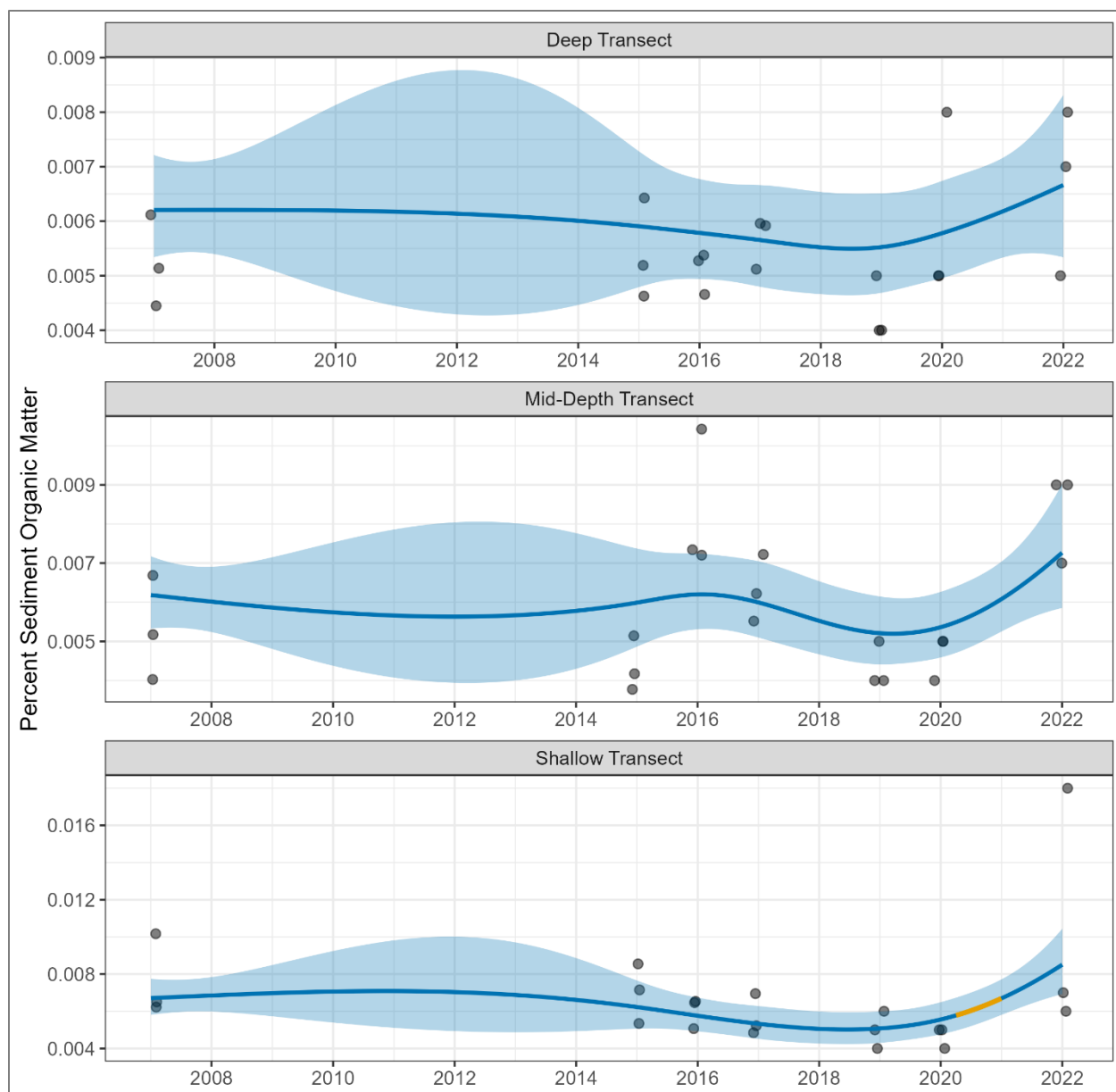


Figure 43. Trend in percent sediment organic material by transect at the Fire Island National Seashore reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there is statistical evidence (assuming a significance level of 0.05) of a decreasing monotonic trend in *Ruppia maritima* canopy height (deep transect), total biomass (shallow transect), and percent cover (shallow and deep transects) (Table 14). There was also evidence of an increasing monotonic trend in the above- to belowground biomass ratio in the shallow transect.

Table 14. Summary of multivariate Mann-Kendall tests for monotonic trend in each *Ruppia maritima* parameter by transect: H_0 : no monotonic trend versus H_1 : monotonic trend is present. A positive (negative) value of the Mann-Kendall test statistic (Z_{MK}) indicates that measurements tend to increase (decrease) with time. [- = not applicable]

Parameter	Transect	Z_{MK}	p -value
Canopy Height (cm)	Shallow	-1.51	0.131
Canopy Height (cm)	Mid-Depth	-0.91	0.362
Canopy Height (cm)	Deep	-3.10	0.002
Total Biomass (g/m ²)	Shallow	-2.85	0.004
Total Biomass (g/m ²)	Mid-Depth	-1.05	0.294
Total Biomass (g/m ²)	Deep	-1.35	0.176
Above- to Belowground Biomass Ratio	Shallow	2.84	0.005
Above- to Belowground Biomass Ratio	Mid-Depth	1.74	0.081
Above- to Belowground Biomass Ratio	Deep	1.81	0.070
Percent Cover (per 0.25 m ²)	Shallow	-1.92	0.054
Percent Cover (per 0.25 m ²)	Mid-Depth	-1.67	0.094
Percent Cover (per 0.25 m ²)	Deep	-2.36	0.018
Shoot Density (per 1 m ²)	Shallow	–	–
Shoot Density (per 1 m ²)	Mid-Depth	–	–
Shoot Density (per 1 m ²)	Deep	–	–

Water Temperature Summaries

Mean water temperatures within transect A (shallow) were comparable to those in transect C (deep) but had slightly higher range overall (Figure 44). Temperatures were highest in July and August, and summer temperatures exceeded 28°C in every year monitored, with some years reaching as high as 30°C (Figure 45). Days wherein the daily average temperature exceeded 28°C occurred between the months of June to September, with more days observed in the shallow transect (Table 15).

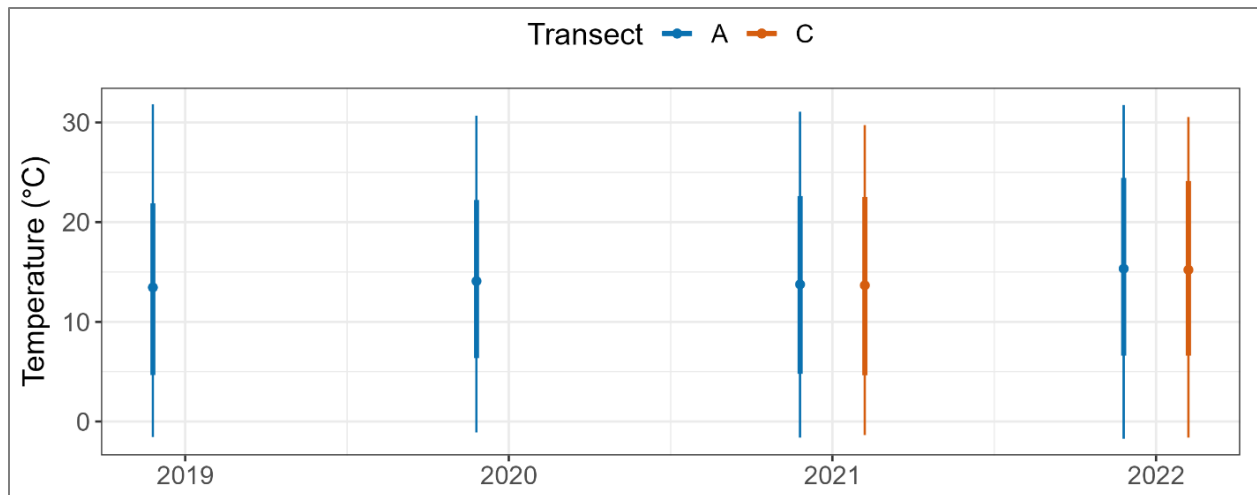


Figure 44. Dot and whisker plots depicting the mean (dot), range (thin line) and middle 50% of observed water temperatures (°C) (thick line) within the shallow (A) and deep (C) transects at the Fire Island National Seashore reference seagrass bed. Only years in which complete data records were available are included here.

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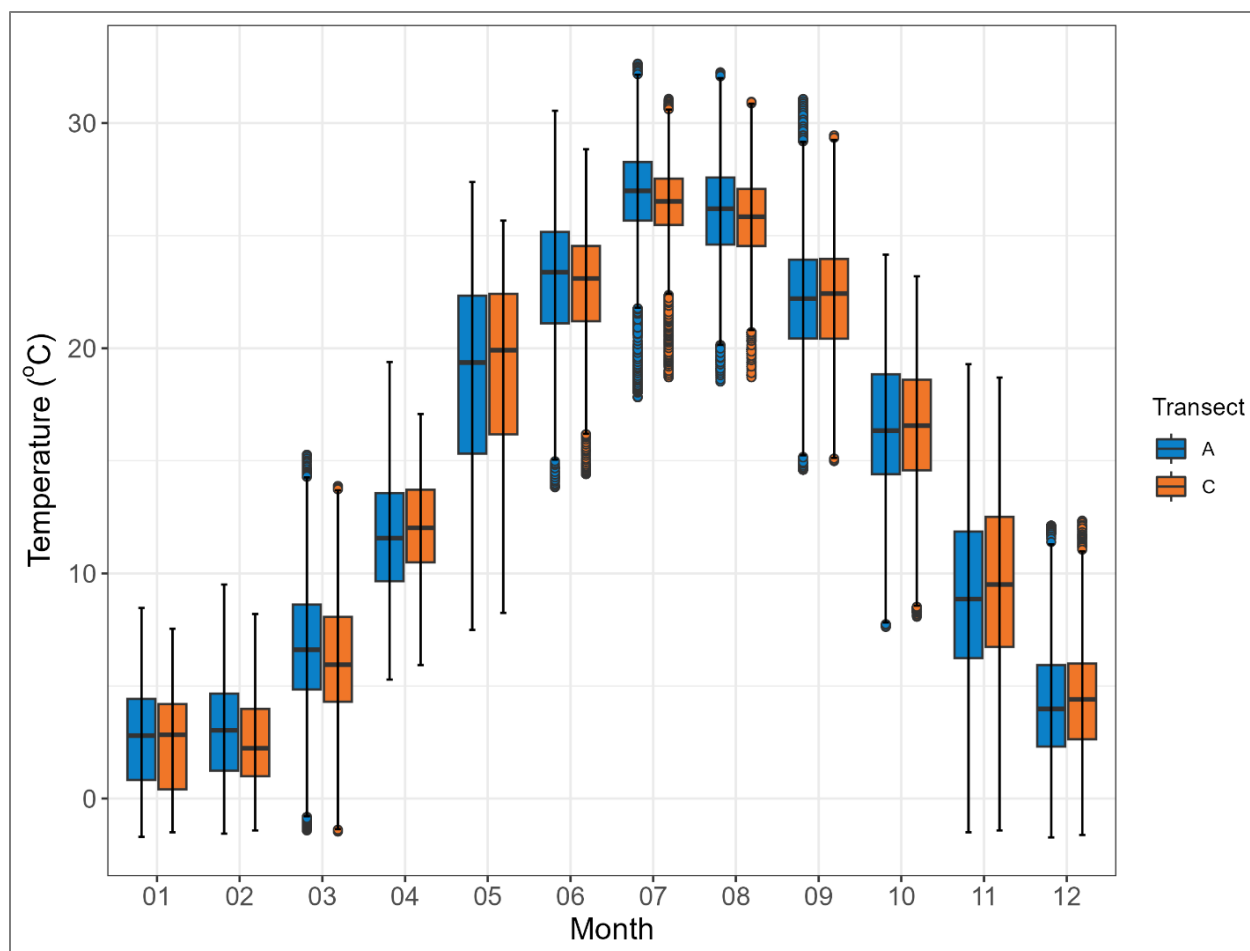


Figure 45. Box plots of mean temperature by month for the shallow (A) and deep (C) transects at the Fire Island National Seashore reference seagrass bed from 2019 to 2022. Circles indicate outliers.

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Table 15. Number of days per month wherein average daily water temperature exceeded 28°C for the shallow (A) and deep (C) transects at the Fire Island National Seashore Great South Bay reference seagrass bed. A basic range of colors from yellow to purple are associated with the range of number of days exceeding 25°C with yellow representing zero days, light green to teal representing 1 to 11 days, and blue to purple representing 12 to 18 days. [NA = not available]

Transect	Year	Number of Days per Month Daily Average Temperature > 28°C											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Shallow (A)	2022	0	NA	0	0	0	0	6	8	0	0	0	0
	2021	0	NA	0	0	0	0	3	4	0	0	0	0
	2020	0	0	0	0	0	0	10	4	0	0	0	0
	2019	0	NA	0	0	0	1	10	2	0	0	0	0
	2018	NA	NA	NA	NA	NA	NA	6	9	3	0	0	0
	2017	NA	NA	NA	NA	NA	NA	NA	NA	0	0	NA	NA
Deep (C)	2022	0	NA	0	0	0	0	3	5	0	0	0	0
	2021	0	NA	0	0	0	0	2	2	0	0	0	0
	2020	NA	NA	NA	NA	NA	NA	NA	NA	0	0	0	0
	2019	0	NA	0	0	0	NA	5	NA	NA	NA	NA	NA
	2018	NA	NA	NA	NA	NA	NA	3	7	1	0	0	0
	2017	NA	NA	NA	NA	NA	NA	NA	NA	0	0	NA	NA

Discussion

Routine long-term water quality monitoring was conducted at Fire Island National Seashore during summer months from 2003 through 2022 as part of the NPS NCBN Vital Signs ENE monitoring program. This comprehensive program incorporates monitoring at various spatial and temporal scales in an effort to establish overall condition of the estuary as well as to identify potential trends or changes in condition over time. Analysis of the monitoring data revealed several patterns and trends with respect to water quality condition, and condition and trends at both the trend stations and logging station were generally consistent with those of the spatial stations.

The entirety of the park estuaries was consistently classified as being in good condition with respect to bottom dissolved oxygen concentrations in every year sampled. A significant decline in concentrations occurred between 2003 and 2009; however, concentrations remained above 5 mg/L (i.e., good condition) over the entire monitoring timeframe. Spatially, concentrations were lowest in the southwestern portion of Great South Bay. Similarly, bottom dissolved oxygen concentrations at the trend stations were generally good with significant declines observed between 2003 and 2009 at stations located in the southwestern end of Great South Bay. For all years, the majority of each day at the logging station was spent in good condition, and no periods of poor conditions were observed. Overall, these results are consistent with other recent studies in the region (Gobler et al. 2019; Methratta et al. 2017) and indicate that dissolved oxygen concentrations within the park estuaries are sufficient to protect critical living estuarine resources.

For most years, the majority of the park estuary was classified as being in fair to good condition with respect to chlorophyll-*a* concentrations. Conditions declined significantly between 2003 and 2009, and there were several years when more than 50% of the estuary was classified as being in poor condition. Chlorophyll-*a* concentrations at the trend stations were also generally characterized as being in fair condition, with some stations experiencing poor conditions in several years. Continuous monitoring at the logging station showed that in 6 of the 9 years monitored there were consecutive days in which chlorophyll-*a* conditions were poor for the majority of hours each day. Spatially, both the spatial station and trend station data indicate that conditions were worse along the southwestern portion of Great South Bay and around Smith Point. Other studies also reported fair conditions in the region in recent years and attributed the higher concentrations in Great South Bay to higher residence times (i.e., reduced flushing) and around Smith Point to higher nutrient loading compared to the rest of the monitored area (Gobler et al. 2019; Methratta et al. 2017).

Water clarity, as measured by PAR attenuation, was typically fair to good throughout the majority of the monitored area in most years sampled with no significant changes observed. There were, however, several years when the majority of the estuary was classified as being in poor condition. Water clarity at the trend stations also was generally fair with some years of poor conditions observed over the entire monitoring timeframe. Continuous monitoring at the logging station revealed that in most years sampled there were often consecutive days when poor conditions were observed during daylight hours in which PAR attenuation could be monitored each day. Degraded water clarity may be attributed to the high phytoplankton abundance associated with nutrient over-

enrichment as well as the limited flushing and wind-driven sediment resuspension typical in this shallow, coastal lagoon (Hinrichs et al. 2018; Gobler et al. 2019).

While there was no statistical evidence of significantly increasing water temperature over time, summertime temperatures at the logging station, most trend stations, and in a large percentage of the estuary exceeded 25°C in most years. Temperatures above 25°C have been shown to be detrimental to the survival of eelgrass (Moore et al. 2014; Shields et al. 2019), blue crab (Bauer and Miller 2010a, 2010b), and hard clam populations (Weiss et al. 2007), and rising temperatures may have significant impacts on marine life by leading to changes in population dynamics, species composition and diversity, and timing of ecosystem-level events and processes (Doney et al. 2012). In addition, higher temperatures have been shown to offset improvements in bottom dissolved oxygen concentrations following reductions in nutrient loading to Chesapeake Bay (Ni et al. 2020). Considering that regional temperatures are projected to rise in the coming decades (IPCC 2022) and that increasing temperatures may negatively influence estuarine water quality and key resources, continued monitoring of temperature and water quality parameters will be extremely valuable for supporting future management efforts in this system.

The formation of the new inlet in 2012 had significant impacts on the park estuaries. Salinity increased significantly throughout the system and temperature declined significantly at the trend station closest to the new inlet. In addition, there was some evidence of declining chlorophyll-*a* concentrations and improving water clarity at the trend station near the inlet, although these changes were not significant. Other studies documented similar changes in salinity and temperature as well as significant improvements in water quality and clarity, eelgrass growth, and hard clam and mussel production following the creation of the new inlet (LaFrance Bartley et al. 2022; Gobler et al. 2019; Methratta et al. 2017). However, aside from increased salinity and decreased water residence times system-wide (Hinrichs et al. 2018), these changes primarily were limited to within 10 km of the inlet. With the closing of the inlet after 2022, continued water quality monitoring will be crucial for determining whether the restorative effects of the inlet are temporary or will benefit the system in the long-term.

Trends in seagrass condition within the park's reference bed varied by species. The reference bed contained a healthy mix of eelgrass and widgeon grass when monitoring began in 2007. During the next four years, eelgrass experienced a precipitous decline and vanished from all three transects with no signs of recovery between 2011 and 2022. In contrast, widgeon grass persisted in the shallow and mid-depth transects. However, despite relatively high interannual variability, there were significant declines in widgeon grass biomass and percent cover since monitoring began in 2007. Other recent studies have also reported declines in seagrass distribution and abundance in this region (LaFrance Bartley et al. 2022; Methratta et al. 2017). Possible causes of eelgrass decline in the park may be related to chronically poor water clarity from algal blooms limiting growth at depth and heat stress from prolonged exposure to summertime temperatures greater than 25°C limiting growth in shallow areas. Unusually warm temperatures have been shown to contribute to eelgrass loss across the northeastern US (Plaisted et al. 2022), and even short-term exposure to excessive temperatures can lead to significant die-off events (Moore et al. 2014; Shields et al. 2019). The persistence of widgeon

grass in the shallow and mid-depth transects following eelgrass decline is not surprising as it has been shown to have a higher heat tolerance (Evans et al. 1986) and a better ability to rapidly recolonize areas after dieback events (Shields et al. 2019). While widgeon grass may provide valuable ecosystem services, widgeon grass-dominated beds are characterized by higher seasonal and interannual variability as well as lower biomass and productivity compared to eelgrass beds, which ultimately may affect local food webs (Cho et al. 2009). Management efforts to prevent further loss of eelgrass in this system should focus on improvements in water clarity and possibly reseeded or transplanting with more heat-tolerant genotypes.

Conclusions

Although most aspects of water quality were typically classified as being in fair to good condition, there were several years in which more than 50% of the monitored area was in poor condition with respect to chlorophyll-*a* concentrations and water clarity at Fire Island National Seashore over the timeframe of 2003 to 2021. Conditions were generally worse in the southwestern portion of Great South Bay. The disappearance of eelgrass from the park's reference seagrass bed since 2007 suggests that conditions are becoming less conducive for supporting eelgrass growth. The continued monitoring of estuarine nutrient enrichment vital signs and seagrass condition will be essential for managers to make informed decisions, develop effective mitigation measures, reduce management costs, and provide a means of measuring progress towards goals.

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Appendix A: Spatial Station Water Quality Data

This appendix contains summaries of the multiple comparison test results for all possible yearly contrasts for each spatial station water quality parameter (Table 16–21).

Table 16. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-*a* concentration within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{256}	<i>p</i> -value	95% CI
2003–2009	-3.085	0.147	-20.957	0.000	(-3.556, -2.615)
2003–2011	-1.827	0.146	-12.505	0.000	(-2.294, -1.360)
2003–2013	-2.892	0.146	-19.792	0.000	(-3.359, -2.425)
2003–2014	-1.696	0.146	-11.604	0.000	(-2.163, -1.229)
2003–2015	-2.881	0.146	-19.717	0.000	(-3.348, -2.414)
2003–2016	-2.228	0.147	-15.135	0.000	(-2.699, -1.758)
2003–2017	-2.654	0.146	-18.164	0.000	(-3.121, -2.187)
2003–2019	-1.558	0.146	-10.665	0.000	(-2.025, -1.091)
2003–2021	-1.515	0.146	-10.369	0.000	(-1.982, -1.048)
2009–2011	1.258	0.143	8.781	0.000	(0.800, 1.716)
2009–2013	0.193	0.143	1.349	0.941	(-0.265, 0.651)
2009–2014	1.390	0.143	9.700	0.000	(0.932, 1.848)
2009–2015	0.204	0.143	1.425	0.918	(-0.254, 0.662)
2009–2016	0.857	0.145	5.928	0.000	(0.395, 1.319)
2009–2017	0.431	0.143	3.010	0.083	(-0.027, 0.889)
2009–2019	1.527	0.143	10.658	0.000	(1.069, 1.985)
2009–2021	1.570	0.143	10.959	0.000	(1.112, 2.028)
2011–2013	-1.065	0.142	-7.501	0.000	(-1.519, -0.611)
2011–2014	0.132	0.142	0.927	0.995	(-0.322, 0.585)
2011–2015	-1.054	0.142	-7.423	0.000	(-1.508, -0.600)
2011–2016	-0.401	0.143	-2.799	0.142	(-0.859, 0.057)
2011–2017	-0.827	0.142	-5.825	0.000	(-1.281, -0.373)
2011–2019	0.269	0.142	1.894	0.674	(-0.185, 0.723)
2011–2021	0.312	0.142	2.198	0.460	(-0.142, 0.766)
2013–2014	1.197	0.142	8.428	0.000	(0.743, 1.650)
2013–2015	0.011	0.142	0.077	1.000	(-0.443, 0.465)
2013–2016	0.664	0.143	4.633	0.000	(0.206, 1.122)
2013–2017	0.238	0.142	1.676	0.808	(-0.216, 0.692)
2013–2019	1.334	0.142	9.394	0.000	(0.880, 1.787)
2013–2021	1.377	0.142	9.699	0.000	(0.923, 1.831)

Table 16 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-*a* concentration within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{256}	<i>p</i> -value	95% CI
2014–2015	-1.186	0.142	-8.351	0.000	(-1.639, -0.732)
2014–2016	-0.533	0.143	-3.718	0.009	(-0.991, -0.075)
2014–2017	-0.959	0.142	-6.752	0.000	(-1.412, -0.505)
2014–2019	0.137	0.142	0.966	0.994	(-0.316, 0.591)
2014–2021	0.180	0.142	1.271	0.959	(-0.273, 0.634)
2015–2016	0.653	0.143	4.556	0.000	(0.195, 1.111)
2015–2017	0.227	0.142	1.599	0.848	(-0.227, 0.681)
2015–2019	1.323	0.142	9.317	0.000	(0.869, 1.776)
2015–2021	1.366	0.142	9.621	0.000	(0.912, 1.820)
2016–2017	-0.426	0.143	-2.972	0.092	(-0.884, 0.032)
2016–2019	0.670	0.143	4.676	0.000	(0.212, 1.128)
2016–2021	0.713	0.143	4.977	0.000	(0.255, 1.171)
2017–2019	1.096	0.142	7.718	0.000	(0.642, 1.549)
2017–2021	1.139	0.142	8.023	0.000	(0.685, 1.593)
2019–2021	0.043	0.142	0.304	1.000	(-0.410, 0.497)

Table 17. Summary of the multiple comparison test results for all possible yearly contrasts of mean log bottom dissolved oxygen concentration within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{256}	<i>p</i> -value	95% CI
2003–2009	0.248	0.034	7.186	0.000	(0.138, 0.357)
2003–2011	0.282	0.034	8.194	0.000	(0.172, 0.392)
2003–2013	0.285	0.035	8.053	0.000	(0.172, 0.398)
2003–2014	0.294	0.034	8.523	0.000	(0.184, 0.404)
2003–2015	0.339	0.034	9.850	0.000	(0.229, 0.449)
2003–2016	0.290	0.035	8.360	0.000	(0.180, 0.401)
2003–2017	0.276	0.034	8.003	0.000	(0.166, 0.386)
2003–2019	0.356	0.034	10.328	0.000	(0.246, 0.466)
2003–2021	0.301	0.034	8.751	0.000	(0.192, 0.411)
2009–2011	0.035	0.034	1.018	0.991	(-0.074, 0.144)
2009–2013	0.038	0.035	1.077	0.987	(-0.074, 0.150)
2009–2014	0.046	0.034	1.350	0.941	(-0.063, 0.155)
2009–2015	0.092	0.034	2.689	0.184	(-0.017, 0.201)

Table 17 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log bottom dissolved oxygen concentration within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{256}	p -value	95% CI
2009–2016	0.043	0.034	1.241	0.965	(-0.067, 0.153)
2009–2017	0.028	0.034	0.825	0.998	(-0.081, 0.137)
2009–2019	0.108	0.034	3.172	0.053	(-0.001, 0.217)
2009–2021	0.054	0.034	1.580	0.857	(-0.055, 0.163)
2011–2013	0.003	0.035	0.087	1.000	(-0.109, 0.115)
2011–2014	0.011	0.034	0.332	1.000	(-0.098, 0.120)
2011–2015	0.057	0.034	1.671	0.811	(-0.052, 0.166)
2011–2016	0.008	0.034	0.232	1.000	(-0.102, 0.118)
2011–2017	-0.007	0.034	-0.193	1.000	(-0.116, 0.102)
2011–2019	0.074	0.034	2.153	0.492	(-0.035, 0.182)
2011–2021	0.019	0.034	0.562	1.000	(-0.090, 0.128)
2013–2014	0.008	0.035	0.235	1.000	(-0.104, 0.120)
2013–2015	0.054	0.035	1.536	0.876	(-0.058, 0.166)
2013–2016	0.005	0.035	0.139	1.000	(-0.108, 0.118)
2013–2017	-0.010	0.035	-0.275	1.000	(-0.122, 0.102)
2013–2019	0.070	0.035	2.005	0.596	(-0.042, 0.183)
2013–2021	0.016	0.035	0.458	1.000	(-0.096, 0.128)
2014–2015	0.046	0.034	1.339	0.944	(-0.063, 0.155)
2014–2016	-0.003	0.034	-0.097	1.000	(-0.113, 0.107)
2014–2017	-0.018	0.034	-0.525	1.000	(-0.127, 0.091)
2014–2019	0.062	0.034	1.821	0.721	(-0.047, 0.171)
2014–2021	0.008	0.034	0.230	1.000	(-0.101, 0.117)
2015–2016	-0.049	0.034	-1.424	0.919	(-0.159, 0.061)
2015–2017	-0.064	0.034	-1.864	0.693	(-0.173, 0.045)
2015–2019	0.016	0.034	0.482	1.000	(-0.092, 0.125)
2015–2021	-0.038	0.034	-1.109	0.983	(-0.147, 0.071)
2016–2017	-0.015	0.034	-0.423	1.000	(-0.125, 0.095)
2016–2019	0.066	0.034	1.902	0.667	(-0.044, 0.175)
2016–2021	0.011	0.034	0.325	1.000	(-0.099, 0.121)
2017–2019	0.080	0.034	2.347	0.363	(-0.029, 0.189)
2017–2021	0.026	0.034	0.755	0.999	(-0.083, 0.135)
2019–2021	-0.054	0.034	-1.592	0.851	(-0.163, 0.055)

Table 18. Summary of the multiple comparison test results for all possible yearly contrasts of mean log PAR attenuation within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{242}	p -value	95% CI
2003–2009	-0.190	0.120	-1.587	0.853	(-0.571, 0.192)
2003–2011	0.125	0.114	1.098	0.985	(-0.239, 0.490)
2003–2013	-0.301	0.113	-2.656	0.198	(-0.663, 0.061)
2003–2014	0.351	0.113	3.098	0.065	(-0.011, 0.713)
2003–2015	-0.124	0.114	-1.083	0.986	(-0.489, 0.241)
2003–2016	0.282	0.114	2.467	0.291	(-0.083, 0.646)
2003–2017	-0.300	0.113	-2.648	0.202	(-0.662, 0.062)
2003–2019	0.210	0.114	1.842	0.707	(-0.154, 0.575)
2003–2021	0.196	0.115	1.705	0.792	(-0.171, 0.564)
2009–2011	0.315	0.113	2.795	0.144	(-0.045, 0.675)
2009–2013	-0.111	0.112	-0.995	0.992	(-0.469, 0.246)
2009–2014	0.541	0.112	4.831	0.000	(0.183, 0.898)
2009–2015	0.066	0.113	0.585	1.000	(-0.294, 0.426)
2009–2016	0.471	0.113	4.176	0.002	(0.111, 0.832)
2009–2017	-0.110	0.112	-0.986	0.993	(-0.468, 0.247)
2009–2019	0.400	0.113	3.545	0.017	(0.040, 0.760)
2009–2021	0.386	0.114	3.399	0.026	(0.023, 0.749)
2011–2013	-0.427	0.106	-4.018	0.003	(-0.765, -0.088)
2011–2014	0.226	0.106	2.126	0.511	(-0.113, 0.565)
2011–2015	-0.249	0.107	-2.326	0.376	(-0.591, 0.093)
2011–2016	0.156	0.107	1.458	0.907	(-0.186, 0.498)
2011–2017	-0.426	0.106	-4.008	0.003	(-0.764, -0.087)
2011–2019	0.085	0.107	0.794	0.999	(-0.257, 0.427)
2011–2021	0.071	0.108	0.657	1.000	(-0.274, 0.416)
2013–2014	0.652	0.105	6.199	0.000	(0.316, 0.988)
2013–2015	0.177	0.106	1.670	0.811	(-0.162, 0.516)
2013–2016	0.583	0.106	5.489	0.000	(0.244, 0.922)
2013–2017	0.001	0.105	0.009	1.000	(-0.335, 0.337)
2013–2019	0.512	0.106	4.818	0.000	(0.173, 0.850)
2013–2021	0.498	0.107	4.642	0.000	(0.155, 0.840)
2014–2015	-0.475	0.106	-4.473	0.001	(-0.814, -0.136)
2014–2016	-0.069	0.106	-0.654	1.000	(-0.408, 0.269)
2014–2017	-0.651	0.105	-6.190	0.000	(-0.987, -0.315)
2014–2019	-0.141	0.106	-1.325	0.947	(-0.480, 0.198)
2014–2021	-0.155	0.107	-1.443	0.912	(-0.497, 0.188)

Table 18 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log PAR attenuation within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{242}	p -value	95% CI
2015–2016	0.405	0.107	3.785	0.007	(0.063, 0.747)
2015–2017	-0.176	0.106	-1.661	0.816	(-0.515, 0.163)
2015–2019	0.334	0.107	3.120	0.061	(-0.008, 0.676)
2015–2021	0.320	0.108	2.961	0.095	(-0.025, 0.665)
2016–2017	-0.582	0.106	-5.480	0.000	(-0.921, -0.243)
2016–2019	-0.071	0.107	-0.665	1.000	(-0.413, 0.271)
2016–2021	-0.085	0.108	-0.788	0.999	(-0.430, 0.260)
2017–2019	0.511	0.106	4.809	0.000	(0.172, 0.849)
2017–2021	0.497	0.107	4.633	0.000	(0.154, 0.839)
2019–2021	-0.014	0.108	-0.129	1.000	(-0.359, 0.331)

Table 19. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface salinity within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{259}	p -value	95% CI
2003–2009	-0.082	0.016	-5.133	0.000	(-0.133, -0.031)
2003–2011	-0.162	0.016	-10.179	0.000	(-0.213, -0.111)
2003–2013	-0.245	0.016	-15.410	0.000	(-0.296, -0.194)
2003–2014	-0.273	0.016	-17.144	0.000	(-0.324, -0.222)
2003–2015	-0.289	0.016	-18.148	0.000	(-0.340, -0.238)
2003–2016	-0.305	0.016	-19.030	0.000	(-0.356, -0.254)
2003–2017	-0.271	0.016	-17.046	0.000	(-0.322, -0.221)
2003–2019	-0.195	0.016	-12.281	0.000	(-0.246, -0.145)
2003–2021	-0.209	0.016	-13.132	0.000	(-0.260, -0.158)
2009–2011	-0.080	0.016	-5.093	0.000	(-0.131, -0.030)
2009–2013	-0.164	0.016	-10.373	0.000	(-0.214, -0.113)
2009–2014	-0.191	0.016	-12.123	0.000	(-0.242, -0.141)
2009–2015	-0.207	0.016	-13.137	0.000	(-0.258, -0.157)
2009–2016	-0.224	0.016	-14.042	0.000	(-0.274, -0.173)
2009–2017	-0.190	0.016	-12.025	0.000	(-0.240, -0.139)
2009–2019	-0.114	0.016	-7.215	0.000	(-0.164, -0.063)
2009–2021	-0.127	0.016	-8.074	0.000	(-0.178, -0.077)
2011–2013	-0.083	0.016	-5.280	0.000	(-0.134, -0.033)
2011–2014	-0.111	0.016	-7.030	0.000	(-0.161, -0.061)

Table 19 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface salinity within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{259}	p -value	95% CI
2011–2015	-0.127	0.016	-8.044	0.000	(-0.177, -0.077)
2011–2016	-0.143	0.016	-8.996	0.000	(-0.194, -0.092)
2011–2017	-0.109	0.016	-6.932	0.000	(-0.160, -0.059)
2011–2019	-0.033	0.016	-2.122	0.514	(-0.084, 0.017)
2011–2021	-0.047	0.016	-2.981	0.090	(-0.097, 0.003)
2013–2014	-0.028	0.016	-1.750	0.765	(-0.078, 0.023)
2013–2015	-0.044	0.016	-2.764	0.155	(-0.094, 0.007)
2013–2016	-0.060	0.016	-3.765	0.008	(-0.111, -0.009)
2013–2017	-0.026	0.016	-1.652	0.821	(-0.076, 0.024)
2013–2019	0.050	0.016	3.158	0.055	(-0.001, 0.100)
2013–2021	0.036	0.016	2.300	0.393	(-0.014, 0.087)
2014–2015	-0.016	0.016	-1.014	0.991	(-0.066, 0.034)
2014–2016	-0.032	0.016	-2.032	0.577	(-0.083, 0.018)
2014–2017	0.002	0.016	0.098	1.000	(-0.049, 0.052)
2014–2019	0.077	0.016	4.908	0.000	(0.027, 0.128)
2014–2021	0.064	0.016	4.049	0.003	(0.014, 0.114)
2015–2016	-0.016	0.016	-1.027	0.990	(-0.067, 0.034)
2015–2017	0.018	0.016	1.112	0.983	(-0.033, 0.068)
2015–2019	0.093	0.016	5.922	0.000	(0.043, 0.144)
2015–2021	0.080	0.016	5.063	0.000	(0.030, 0.130)
2016–2017	0.034	0.016	2.129	0.509	(-0.017, 0.085)
2016–2019	0.110	0.016	6.894	0.000	(0.059, 0.161)
2016–2021	0.096	0.016	6.043	0.000	(0.045, 0.147)
2017–2019	0.076	0.016	4.810	0.000	(0.026, 0.126)
2017–2021	0.062	0.016	3.951	0.004	(0.012, 0.113)
2019–2021	-0.014	0.016	-0.859	0.997	(-0.064, 0.037)

Table 20. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{259}	p -value	95% CI
2003–2009	0.050	0.019	2.620	0.214	(-0.011, 0.111)
2003–2011	0.008	0.019	0.422	1.000	(-0.053, 0.069)
2003–2013	0.002	0.019	0.106	1.000	(-0.059, 0.063)

Table 20 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{259}	p -value	95% CI
2003–2014	0.071	0.019	3.691	0.010	(0.010, 0.131)
2003–2015	0.021	0.019	1.076	0.987	(-0.040, 0.082)
2003–2016	0.004	0.019	0.225	1.000	(-0.057, 0.066)
2003–2017	0.017	0.019	0.884	0.997	(-0.044, 0.078)
2003–2019	-0.000	0.019	-0.022	1.000	(-0.061, 0.061)
2003–2021	0.011	0.019	0.556	1.000	(-0.050, 0.072)
2009–2011	-0.042	0.019	-2.219	0.447	(-0.102, 0.018)
2009–2013	-0.048	0.019	-2.538	0.253	(-0.108, 0.012)
2009–2014	0.020	0.019	1.081	0.986	(-0.040, 0.081)
2009–2015	-0.029	0.019	-1.558	0.867	(-0.090, 0.031)
2009–2016	-0.046	0.019	-2.393	0.334	(-0.107, 0.015)
2009–2017	-0.033	0.019	-1.752	0.764	(-0.094, 0.027)
2009–2019	-0.050	0.019	-2.667	0.193	(-0.111, 0.010)
2009–2021	-0.039	0.019	-2.084	0.541	(-0.100, 0.021)
2011–2013	-0.006	0.019	-0.319	1.000	(-0.066, 0.054)
2011–2014	0.062	0.019	3.300	0.036	(0.002, 0.123)
2011–2015	0.013	0.019	0.661	1.000	(-0.048, 0.073)
2011–2016	-0.004	0.019	-0.195	1.000	(-0.065, 0.057)
2011–2017	0.009	0.019	0.467	1.000	(-0.052, 0.069)
2011–2019	-0.008	0.019	-0.448	1.000	(-0.069, 0.052)
2011–2021	0.003	0.019	0.135	1.000	(-0.058, 0.063)
2013–2014	0.068	0.019	3.619	0.013	(0.008, 0.129)
2013–2015	0.019	0.019	0.980	0.993	(-0.042, 0.079)
2013–2016	0.002	0.019	0.121	1.000	(-0.059, 0.063)
2013–2017	0.015	0.019	0.785	0.999	(-0.046, 0.075)
2013–2019	-0.002	0.019	-0.129	1.000	(-0.063, 0.058)
2013–2021	0.009	0.019	0.454	1.000	(-0.052, 0.069)
2014–2015	-0.050	0.019	-2.640	0.205	(-0.110, 0.010)
2014–2016	-0.066	0.019	-3.464	0.021	(-0.127, -0.005)
2014–2017	-0.054	0.019	-2.834	0.131	(-0.114, 0.007)
2014–2019	-0.071	0.019	-3.748	0.008	(-0.131, -0.011)
2014–2021	-0.060	0.019	-3.165	0.054	(-0.120, 0.000)
2015–2016	-0.016	0.019	-0.849	0.998	(-0.077, 0.045)
2015–2017	-0.004	0.019	-0.194	1.000	(-0.064, 0.057)
2015–2019	-0.021	0.019	-1.109	0.984	(-0.081, 0.039)

Table 20 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{259}	p -value	95% CI
2015–2021	-0.010	0.019	-0.526	1.000	(-0.070, 0.050)
2016–2017	0.013	0.019	0.657	1.000	(-0.048, 0.074)
2016–2019	-0.005	0.019	-0.249	1.000	(-0.066, 0.056)
2016–2021	0.006	0.019	0.329	1.000	(-0.055, 0.067)
2017–2019	-0.017	0.019	-0.915	0.996	(-0.078, 0.043)
2017–2021	-0.006	0.019	-0.331	1.000	(-0.067, 0.054)
2019–2021	0.011	0.019	0.583	1.000	(-0.049, 0.071)

Table 21. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface turbidity within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{259}	p -value	95% CI
2003–2009	0.577	0.179	3.229	0.045	(0.006, 1.148)
2003–2011	0.890	0.179	4.976	0.000	(0.318, 1.461)
2003–2013	0.164	0.179	0.916	0.996	(-0.407, 0.735)
2003–2014	1.113	0.179	6.225	0.000	(0.542, 1.684)
2003–2015	0.212	0.179	1.187	0.974	(-0.359, 0.783)
2003–2016	0.821	0.180	4.554	0.000	(0.245, 1.396)
2003–2017	0.164	0.179	0.918	0.996	(-0.407, 0.735)
2003–2019	0.876	0.179	4.899	0.000	(0.305, 1.447)
2003–2021	0.941	0.179	5.263	0.000	(0.370, 1.512)
2009–2011	0.312	0.177	1.763	0.757	(-0.254, 0.878)
2009–2013	-0.413	0.177	-2.334	0.371	(-0.980, 0.153)
2009–2014	0.536	0.177	3.024	0.079	(-0.030, 1.102)
2009–2015	-0.365	0.177	-2.060	0.558	(-0.931, 0.201)
2009–2016	0.243	0.179	1.361	0.938	(-0.328, 0.815)
2009–2017	-0.413	0.177	-2.332	0.373	(-0.979, 0.153)
2009–2019	0.299	0.177	1.686	0.803	(-0.267, 0.865)
2009–2021	0.364	0.177	2.053	0.563	(-0.202, 0.930)
2011–2013	-0.726	0.177	-4.097	0.002	(-1.292, -0.160)
2011–2014	0.223	0.177	1.261	0.961	(-0.343, 0.789)
2011–2015	-0.677	0.177	-3.823	0.006	(-1.243, -0.111)
2011–2016	-0.069	0.179	-0.386	1.000	(-0.640, 0.502)
2011–2017	-0.726	0.177	-4.095	0.002	(-1.292, -0.159)

Table 21 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface turbidity within Fire Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

Contrast	Estimate	SE	t_{259}	p -value	95% CI
2011–2019	-0.014	0.177	-0.077	1.000	(-0.580, 0.552)
2011–2021	0.051	0.177	0.290	1.000	(-0.515, 0.617)
2013–2014	0.949	0.177	5.358	0.000	(0.383, 1.515)
2013–2015	0.048	0.177	0.274	1.000	(-0.518, 0.615)
2013–2016	0.657	0.179	3.674	0.011	(0.086, 1.228)
2013–2017	0.000	0.177	0.002	1.000	(-0.566, 0.566)
2013–2019	0.712	0.177	4.020	0.003	(0.146, 1.278)
2013–2021	0.777	0.177	4.387	0.001	(0.211, 1.343)
2014–2015	-0.901	0.177	-5.084	0.000	(-1.467, -0.335)
2014–2016	-0.292	0.179	-1.635	0.830	(-0.864, 0.279)
2014–2017	-0.949	0.177	-5.356	0.000	(-1.515, -0.383)
2014–2019	-0.237	0.177	-1.338	0.944	(-0.803, 0.329)
2014–2021	-0.172	0.177	-0.971	0.994	(-0.738, 0.394)
2015–2016	0.608	0.179	3.403	0.027	(0.037, 1.180)
2015–2017	-0.048	0.177	-0.272	1.000	(-0.614, 0.518)
2015–2019	0.664	0.177	3.746	0.008	(0.098, 1.230)
2015–2021	0.729	0.177	4.113	0.002	(0.163, 1.295)
2016–2017	-0.657	0.179	-3.672	0.011	(-1.228, -0.085)
2016–2019	0.055	0.179	0.309	1.000	(-0.516, 0.627)
2016–2021	0.120	0.179	0.673	1.000	(-0.451, 0.691)
2017–2019	0.712	0.177	4.018	0.003	(0.146, 1.278)
2017–2021	0.777	0.177	4.385	0.001	(0.211, 1.343)
2019–2021	0.065	0.177	0.367	1.000	(-0.501, 0.631)

Appendix B: Spatial Station Water Quality Data Summaries of Multiple Comparison Test Results

This appendix contains the tabular information displayed in the multiple comparison test results in Figures 4–9 (Tables 22–27).

Table 22. Shows an accessible version of the grid values displayed in [Figure 4](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface chlorophyll-a concentration by year within Fire Island National Seashore is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
2021	-1.515	1.570	0.312	1.377	0.180	1.366	0.713	1.139	0.043	1.522
2019	-1.558	1.527	0.269	1.334	0.137	1.323	0.670	1.096	1.565	1.000
2017	-2.654	0.431	-0.827	0.238	-0.959	0.227	-0.426	2.661	0.000	0.000
2016	-2.228	0.857	-0.401	0.664	-0.533	0.653	2.235	0.092	0.000	0.000
2015	-2.881	0.204	-1.054	0.011	-1.186	2.888	0.000	0.848	0.000	0.000
2014	-1.696	1.390	0.132	1.197	1.702	0.000	0.009	0.000	0.994	0.959
2013	-2.892	0.193	-1.065	2.899	0.000	1.000	0.000	0.808	0.000	0.000
2011	-1.827	1.258	1.834	0.000	0.996	0.000	0.142	0.000	0.673	0.461
2009	-3.085	3.092	0.000	0.941	0.000	0.918	0.000	0.083	0.000	0.000
2003	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 23. Shows an accessible version of the grid values displayed in [Figure 5](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The log bottom dissolved oxygen concentration by year within Fire Island National Seashore is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
2021	0.301	0.054	0.019	0.016	0.008	-0.038	0.011	0.026	-0.054	2.020
2019	0.356	0.108	0.074	0.070	0.062	0.016	0.066	0.080	1.960	0.851
2017	0.276	0.028	-0.007	-0.010	-0.018	-0.064	-0.015	2.040	0.363	0.999
2016	0.290	0.043	0.008	0.005	-0.003	-0.049	2.030	1.000	0.668	1.000
2015	0.339	0.092	0.057	0.054	0.046	1.980	0.919	0.693	1.000	0.983
2014	0.294	0.046	0.011	0.008	2.030	0.944	1.000	1.000	0.721	1.000
2013	0.285	0.038	0.003	2.030	1.000	0.876	1.000	1.000	0.596	1.000
2011	0.282	0.035	2.040	1.000	1.000	0.811	1.000	1.000	0.492	1.000
2009	0.248	2.070	0.991	0.987	0.941	0.184	0.965	0.998	0.053	0.857
2003	2.320	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 24. Shows an accessible version of the grid values displayed in [Figure 6](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log PAR attenuation by year within Fire Island National Seashore is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
2021	0.196	0.386	0.071	0.498	-0.155	0.320	-0.085	0.497	-0.014	0.063
2019	0.210	0.400	0.085	0.512	-0.141	0.334	-0.071	0.511	0.049	1.000
2017	-0.300	-0.110	-0.426	0.001	-0.651	-0.176	-0.582	0.560	0.000	0.000
2016	0.282	0.471	0.156	0.583	-0.069	0.405	-0.022	0.000	1.000	0.999
2015	-0.124	0.066	-0.249	0.177	-0.475	0.383	0.007	0.816	0.062	0.095

Table 24 (continued). Shows an accessible version of the grid values displayed in [Figure 6](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log PAR attenuation by year within Fire Island National Seashore is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
2014	0.351	0.541	0.226	0.652	-0.091	0.000	1.000	0.000	0.947	0.912
2013	-0.301	-0.111	-0.427	0.561	0.000	0.811	0.000	1.000	0.000	0.000
2011	0.125	0.315	0.134	0.003	0.511	0.376	0.906	0.003	0.999	1.000
2009	-0.190	0.449	0.144	0.992	0.000	1.000	0.002	0.993	0.016	0.027
2003	0.260	0.853	0.980	0.198	0.065	0.986	0.291	0.201	0.707	0.792

Table 25. Shows an accessible version of the grid values displayed in [Figure 7](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface salinity by year within Fire Island National Seashore is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
2021	-0.209	-0.127	-0.047	0.036	0.064	0.080	0.096	0.062	-0.014	3.330
2019	-0.195	-0.114	-0.033	0.050	0.077	0.093	0.110	0.076	3.310	0.998
2017	-0.271	-0.190	-0.109	-0.026	0.002	0.018	0.034	3.390	0.000	0.004
2016	-0.305	-0.224	-0.143	-0.060	-0.032	-0.016	3.420	0.509	0.000	0.000
2015	-0.289	-0.207	-0.127	-0.044	-0.016	3.410	0.990	0.983	0.000	0.000
2014	-0.273	-0.191	-0.111	-0.028	3.390	0.991	0.578	1.000	0.000	0.002
2013	-0.245	-0.164	-0.083	3.360	0.765	0.154	0.007	0.821	0.055	0.393
2011	-0.162	-0.080	3.280	0.000	0.000	0.000	0.000	0.000	0.514	0.090
2009	-0.082	3.200	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2003	3.120	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 26. Shows an accessible version of the grid values displayed in [Figure 8](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface temperature by year within Fire Island National Seashore is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
2021	0.011	-0.039	0.003	0.009	-0.060	-0.010	0.006	-0.006	0.011	3.230
2019	0.000	-0.050	-0.008	-0.002	-0.071	-0.021	-0.005	-0.017	3.240	1.000
2017	0.017	-0.033	0.009	0.015	-0.054	-0.004	0.013	3.220	0.996	1.000
2016	0.004	-0.046	-0.004	0.002	-0.066	-0.016	3.240	1.000	1.000	1.000
2015	0.021	-0.029	0.013	0.019	-0.050	3.220	0.998	1.000	0.984	1.000
2014	0.071	0.020	0.062	0.068	3.170	0.205	0.022	0.131	0.008	0.054
2013	0.002	-0.048	-0.006	3.240	0.013	0.993	1.000	0.999	1.000	1.000
2011	0.008	-0.042	3.230	1.000	0.036	1.000	1.000	1.000	1.000	1.000
2009	0.050	3.190	0.447	0.254	0.986	0.867	0.334	0.764	0.192	0.541
2003	3.240	0.213	1.000	1.000	0.010	0.987	1.000	0.997	1.000	1.000

Table 27. Shows an accessible version of the grid values displayed in [Figure 9](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface turbidity by year within Fire Island National Seashore is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
2021	0.941	0.364	0.051	0.777	-0.172	0.729	0.120	0.777	0.065	0.727
2019	0.876	0.299	-0.014	0.712	-0.237	0.664	0.055	0.712	0.792	1.000
2017	0.164	-0.413	-0.726	0.000	-0.949	-0.048	-0.657	1.504	0.003	0.001
2016	0.821	0.243	-0.069	0.657	-0.292	0.608	0.847	0.011	1.000	1.000

Table 27 (continued). Shows an accessible version of the grid values displayed in [Figure 9](#). Upper diagonal cells, where the year displayed in the top row is lower than in the first column, contain the difference between the means of the years indicated by the row and column names (earlier minus later). The mean log surface turbidity by year within Fire Island National Seashore is found in cells where the year values displayed in the top row and first column are equal. Lower diagonal cells, where the year displayed in the top row is higher than in the first column, contain the Tukey-adjusted p-value from a two-sided test. A more detailed summary of the test statistics and confidence intervals is provided in Appendix A.

Year	2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
2015	0.212	-0.365	-0.677	0.048	-0.901	1.456	0.026	1.000	0.008	0.002
2014	1.113	0.536	0.223	0.949	0.555	0.000	0.830	0.000	0.944	0.994
2013	0.164	-0.414	-0.726	1.504	0.000	1.000	0.010	1.000	0.003	0.001
2011	0.890	0.312	0.778	0.002	0.961	0.006	1.000	0.002	1.000	1.000
2009	0.577	1.091	0.758	0.371	0.080	0.557	0.938	0.372	0.803	0.563
2003	1.668	0.045	0.000	0.996	0.000	0.974	0.000	0.996	0.000	0.000

Appendix C: Trend Station Water Quality Data Summaries

This appendix contains yearly summary statistics for water quality parameters for each trend station within Fire Island National Seashore (Tables 28–33).

Table 28. Yearly summary statistics for surface chlorophyll-*a* concentration ($\mu\text{g/L}$) at Fire Island National Seashore trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year									
		2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
5	Mean	1.40	26.38	14.40	20.72	6.91	22.22	15.37	23.04	6.29	3.42
5	SD	0.61	2.34	6.80	8.00	2.19	6.28	3.22	4.16	2.43	0.20
5	n	3	4	4	4	4	4	4	4	4	4
10	Mean	1.40	32.23	10.04	26.91	8.46	29.47	15.74	21.11	7.82	7.63
10	SD	0.52	1.95	3.88	7.29	5.47	6.84	2.76	6.08	2.95	3.79
10	n	3	4	4	4	4	4	4	4	4	4
15	Mean	0.73	22.42	9.25	23.34	6.68	20.48	11.23	12.95	4.65	9.24
15	SD	0.32	5.23	5.77	2.88	2.21	1.90	3.46	7.81	1.02	6.53
15	n	3	4	4	4	4	4	4	4	4	4
20	Mean	1.10	31.09	7.80	20.38	10.76	11.88	4.13	10.97	2.41	2.73
20	SD	0.14	2.41	6.16	3.58	9.94	12.16	1.26	8.89	1.12	1.24
20	n	2	4	4	4	4	4	4	4	4	4
25	Mean	1.67	33.41	8.07	19.33	11.15	22.36	6.81	16.98	8.13	4.92
25	SD	0.51	18.99	3.77	5.32	11.27	3.11	2.57	11.50	4.41	0.53
25	n	3	4	4	4	4	4	4	4	4	4
30	Mean	0.45	13.35	6.97	12.40	7.77	12.80	5.36	4.14	2.90	3.42
30	SD	0.49	15.65	8.92	10.60	4.11	7.01	2.71	2.55	2.25	3.62
30	n	2	4	4	4	4	4	4	4	4	4

Table 29. Yearly summary statistics for bottom dissolved oxygen concentration (mg/L) at Fire Island National Seashore trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year									
		2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
5	Mean	9.14	8.48	6.91	6.76	6.61	6.88	6.78	6.20	6.11	6.82
5	SD	1.99	1.60	0.49	0.41	0.36	0.42	0.26	0.29	0.46	0.28
5	n	4	4	4	3	4	4	4	4	4	4
10	Mean	11.40	8.04	7.26	6.70	6.84	6.70	6.41	6.46	6.10	6.90
10	SD	3.41	0.50	0.92	0.81	0.35	0.80	0.49	0.95	0.84	0.60
10	n	4	4	4	3	4	4	4	4	4	4
15	Mean	10.11	8.81	7.17	7.58	7.64	6.59	7.23	7.74	6.56	7.82
15	SD	1.24	0.66	0.32	0.85	1.60	0.93	0.49	0.83	0.51	0.68
15	n	3	4	4	4	4	4	4	4	4	4
20	Mean	11.60	7.68	8.64	7.96	8.05	7.62	8.10	7.71	9.53	8.43
20	SD	0.65	0.59	1.36	0.71	0.37	0.38	0.27	1.26	0.89	1.04
20	n	2	4	4	4	4	4	4	4	4	4
25	Mean	10.29	7.66	7.97	7.78	8.05	7.09	7.66	9.83	8.02	7.78
25	SD	0.45	0.58	0.99	0.56	0.83	0.79	0.92	1.01	2.42	1.37
25	n	3	4	4	4	4	4	4	4	4	4
30	Mean	9.75	8.76	7.90	7.53	7.91	7.16	8.13	7.40	7.84	7.62
30	SD	1.28	1.20	0.86	0.47	0.58	0.64	0.37	0.57	0.23	0.65
30	n	3	4	4	4	4	4	4	4	4	4

Table 30. Yearly summary statistics for PAR attenuation (K_d (m^{-1})) at Fire Island National Seashore trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year									
		2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
5	Mean	1.15	1.50	1.12	1.75	0.85	1.51	1.08	2.80	1.08	1.03
5	SD	0.11	0.05	0.29	0.23	0.11	0.19	0.09	0.80	0.32	0.34
5	n	4	4	4	4	4	4	4	4	4	4
10	Mean	1.39	1.88	1.14	2.29	1.17	2.12	1.29	2.33	1.46	1.12
10	SD	0.12	0.19	0.16	0.21	0.21	0.44	0.10	0.51	0.53	0.27
10	n	4	4	4	4	4	4	4	4	4	4
15	Mean	0.92	1.69	1.98	2.24	1.26	1.94	1.19	1.73	0.99	1.36
15	SD	1.07	0.84	1.26	0.62	0.36	0.29	0.38	0.86	0.02	0.46
15	n	2	3	4	4	4	4	3	4	4	4
20	Mean	1.51	2.17	1.28	1.84	0.55	0.53	0.56	1.48	1.17	1.04
20	SD	1.46	1.58	0.36	0.83	0.37	0.45	0.27	0.80	0.76	0.72
20	n	2	3	4	4	4	3	4	4	3	4
25	Mean	1.77	1.81	1.01	1.96	0.56	1.15	1.02	1.82	1.31	0.94
25	SD	0.97	1.02	0.68	0.18	0.25	0.12	0.34	0.61	0.27	0.15
25	n	2	4	4	4	4	4	4	4	4	4
30	Mean	0.50	0.77	0.72	1.28	0.84	1.33	0.52	0.83	1.86	0.51
30	SD	0.46	0.55	0.59	0.69	0.27	0.84	0.18	0.32	1.16	0.20
30	n	3	4	4	4	4	4	4	4	4	4

Table 31. Yearly summary statistics for surface salinity (psu) at Fire Island National Seashore trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year									
		2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
5	Mean	25.88	26.48	28.59	29.62	29.76	30.32	30.86	29.72	27.95	28.38
5	SD	0.85	0.75	0.70	1.10	0.39	0.30	0.36	0.18	0.33	0.52
5	n	4	4	4	4	4	4	4	4	4	4
10	Mean	22.75	23.48	26.74	27.95	28.62	29.24	30.10	28.70	26.44	26.73
10	SD	0.32	0.27	0.74	0.55	0.17	0.43	0.76	0.56	0.43	0.42
10	n	4	4	4	4	4	4	4	4	4	4
15	Mean	21.13	22.98	26.13	27.82	29.09	29.34	30.36	29.27	26.16	26.67
15	SD	0.55	0.37	0.54	0.36	1.02	0.20	0.53	1.22	0.12	0.21
15	n	3	4	4	4	4	4	4	4	4	4
20	Mean	18.26	21.45	24.75	28.89	30.95	31.52	31.68	30.62	29.34	29.53
20	SD	2.10	1.60	0.91	0.78	0.34	0.76	0.19	0.85	1.57	1.69
20	n	2	4	4	4	4	4	4	4	4	4
25	Mean	21.43	24.18	25.56	29.12	30.26	30.76	30.70	29.98	28.15	28.56
25	SD	2.52	2.74	1.77	0.70	0.35	0.57	0.33	0.73	0.53	1.63
25	n	3	4	4	4	4	4	4	4	4	4
30	Mean	30.50	29.04	29.31	30.54	31.14	31.40	31.56	30.80	30.17	30.24
30	SD	0.36	3.54	3.24	0.92	0.44	0.60	0.20	0.53	0.81	1.36
30	n	3	4	4	4	4	4	4	4	4	4

Table 32. Yearly summary statistics for surface temperature (°C) at Fire Island National Seashore trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year									
		2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
5	Mean	25.29	24.41	25.54	25.02	23.70	25.83	26.12	24.99	26.45	25.19
5	SD	0.22	1.36	1.30	1.83	0.70	0.97	0.98	1.81	1.59	0.58
5	n	4	4	4	4	4	4	4	4	4	4
10	Mean	26.02	24.78	25.94	26.76	24.34	26.43	26.39	25.69	26.72	25.45
10	SD	0.19	1.51	1.08	1.39	0.72	0.93	1.09	2.43	1.52	0.88
10	n	4	4	4	4	4	4	4	4	4	4
15	Mean	26.63	25.88	26.27	27.25	25.20	26.84	26.97	26.50	26.73	25.42
15	SD	1.02	2.31	1.35	1.72	1.20	0.84	0.99	3.50	1.81	1.39
15	n	3	4	4	4	4	4	4	4	4	4
20	Mean	27.49	25.81	27.19	25.24	20.13	21.69	21.26	23.40	23.23	23.25
20	SD	0.75	2.06	0.59	1.32	2.51	2.51	1.68	1.99	1.93	2.18
20	n	2	4	4	4	4	4	4	4	4	4
25	Mean	27.16	24.82	26.32	26.09	24.95	25.35	26.46	26.58	26.38	24.52
25	SD	0.50	2.14	0.70	1.29	1.26	1.13	0.76	2.99	1.50	1.89
25	n	3	4	4	4	4	4	4	4	4	4
30	Mean	19.25	21.06	20.71	21.50	19.09	21.77	20.65	22.35	20.49	21.63
30	SD	2.68	1.24	4.77	3.74	3.45	1.87	0.53	2.44	3.25	1.61
30	n	3	4	4	4	4	4	4	4	4	4

Table 33. Yearly summary statistics for surface turbidity (NTU) at Fire Island National Seashore trend stations. [SD = standard deviation; n = number of observations]

Station	Statistic	Sampling Year									
		2003	2009	2011	2013	2014	2015	2016	2017	2019	2021
5	Mean	2.95	3.40	3.12	5.52	2.17	4.45	3.30	6.04	1.86	2.84
5	SD	0.38	0.32	1.16	3.22	0.79	0.58	0.12	0.36	0.91	1.50
5	n	4	4	4	4	4	4	4	4	4	4
10	Mean	4.06	4.97	3.05	6.15	2.15	6.35	3.35	6.69	3.15	2.61
10	SD	2.07	1.46	0.89	1.14	0.77	0.51	0.66	2.15	0.62	1.87
10	n	4	4	4	4	4	4	4	4	4	4
15	Mean	7.18	3.25	1.95	5.85	2.52	5.85	2.60	4.92	2.18	2.38
15	SD	8.59	0.37	0.26	2.13	0.91	1.22	0.59	3.09	0.91	0.81
15	n	3	4	4	4	4	4	4	4	4	4
20	Mean	10.19	4.72	2.58	5.45	2.67	2.52	0.98	3.84	0.92	5.46
20	SD	6.09	0.79	1.01	2.01	2.89	1.96	0.54	2.67	0.95	2.37
20	n	2	4	4	4	4	4	4	4	4	4
25	Mean	46.68	3.00	2.15	5.75	1.82	3.83	1.70	5.13	3.67	2.33
25	SD	65.52	1.66	0.37	1.38	0.71	0.51	0.55	2.53	0.96	1.11
25	n	3	4	4	4	4	4	4	4	4	4
30	Mean	3.77	1.68	1.75	3.50	2.25	2.72	1.30	1.62	2.06	2.19
30	SD	2.47	2.22	2.05	1.94	1.87	1.05	0.75	0.80	1.72	2.19
30	n	3	4	4	4	4	4	4	4	4	4

Appendix D: Seagrass Data Summaries

This appendix contains seasonal summary statistics for measured parameters by seagrass species (where available) from 2007 through 2022 (Tables 34–42).

Table 34. Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* shoot density (per 1 m²) at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2007–07	53.8	63.3	11	NA	NA	NA	NA	NA	NA
2007–08	NA	NA	NA	1.3	4.6	12	221.3	107.4	12
2009–08	0.0	0.0	12	5.8	12.9	11	50.9	44.0	11
2010–05	0.0	0.0	11	2.7	9.2	12	13.3	28.8	12
2011–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2012–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2013–07	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2014–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2015–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2016–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2017–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2018–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2019–08	0.0	0.0	12	NA	NA	NA	0.0	0.0	12
2019–09	NA	NA	NA	0.0	0.0	12	NA	NA	NA
2020–08	0.3	1.2	12	0.0	0.0	12	0.0	0.0	12
2022–06	0.0	1.2	12	0.0	0.0	12	0.0	0.0	12

Table 35. Yearly (monthly within year, if applicable) summary statistics for percent cover (per 0.25 m²) of *Ruppia maritima* at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2007–07	45.7	29.5	12	NA	NA	NA	NA	NA	NA
2007–08	NA	NA	NA	35.6	29.7	12	12.8	16.6	12
2009–08	87.5	17.3	12	17.7	37.5	12	0.0	0.0	12
2010–05	55.4	28.5	12	26.0	36.0	12	1.2	3.1	12
2011–08	55.0	43.6	12	35.8	31.5	12	5.1	10.0	12
2012–08	69.2	32.2	12	51.2	35.9	12	28.3	40.8	12

Table 35 (continued). Yearly (monthly within year, if applicable) summary statistics for percent cover (per 0.25 m²) of *Ruppia maritima* at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2013-07	56.7	35.0	12	47.6	38.8	12	0.6	1.4	12
2014-08	8.3	7.8	12	1.2	3.1	12	0.0	0.0	12
2015-08	39.2	26.0	12	24.6	31.9	12	0.0	0.0	12
2016-08	15.2	21.1	12	0.1	0.3	12	0.0	0.0	12
2017-08	6.2	17.5	12	2.9	8.6	12	0.0	0.0	12
2018-08	50.0	43.9	12	5.1	8.7	12	0.0	0.0	12
2019-08	37.9	40.1	12	NA	NA	NA	0.0	0.0	12
2019-09	NA	NA	NA	19.2	28.7	12	NA	NA	NA
2020-08	11.2	17.5	12	0.0	0.0	12	0.0	0.0	12
2022-06	48.8	35.2	12	28.8	34.7	12	0.0	0.0	12

Table 36. Yearly (monthly within year, if applicable) summary statistics for percent cover (per 0.25 m²) of *Zostera marina* at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2007-07	18.1	28.5	12	NA	NA	NA	NA	NA	NA
2007-08	NA	NA	NA	0.2	0.6	12	48.9	33.7	12
2009-08	0.0	0.0	12	1.1	2.0	12	15.4	13.7	12
2010-05	0.2	0.6	12	0.4	1.4	12	3.3	8.6	12
2011-08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2012-08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2013-07	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2014-08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2015-08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2016-08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2017-08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2018-08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2019-08	0.0	0.0	12	NA	NA	NA	0.0	0.0	12
2019-09	NA	NA	NA	0.0	0.0	12	NA	NA	NA
2020-08	0.1	0.3	12	0.0	0.0	12	0.0	0.0	12
2022-06	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12

Table 37. Yearly (monthly within year, if applicable) summary statistics for *Ruppia maritima* canopy height (cm) at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available; – = not applicable]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2007–07	8.2	3.7	12	NA	NA	NA	NA	NA	NA
2007–08	NA	NA	NA	6.5	2.0	12	12.0	4.9	8
2009–08	9.2	2.8	12	5.5	2.4	4	–	–	0
2010–05	3.8	0.8	11	3.5	0.8	6	7.0	5.7	2
2011–08	9.1	2.7	12	4.2	1.2	12	4.4	0.9	5
2012–08	8.4	3.9	11	6.1	3.8	12	7.7	6.6	6
2013–07	16.3	9.8	11	9.1	3.3	11	4.7	0.6	3
2014–08	3.1	0.6	9	3.5	0.7	2	–	–	0
2015–08	6.2	2.4	12	6.6	2.0	10	–	–	0
2016–08	5.7	2.0	7	4.0	–	1	–	–	0
2017–08	11.5	4.9	2	9.0	1.4	2	–	–	0
2018–08	7.9	0.3	9	7.4	2.3	5	–	–	0
2019–08	6.6	1.4	9	NA	NA	NA	–	–	0
2019–09	NA	NA	NA	5.0	0.0	6	NA	NA	NA
2020–08	4.4	1.8	8	–	–	0	–	–	0
2022–06	4.9	4.3	11	4.3	3.4	7	–	–	0

Table 38. Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* canopy height (cm) at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available; – = not applicable]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2007–07	9.7	3.9	7	NA	NA	NA	NA	NA	NA
2007–08	NA	NA	NA	6.0	–	1	12.6	4.3	12
2009–08	–	–	0	5.0	2.6	3	11.2	3.2	9
2010–05	3.0	–	1	5.0	–	1	12.0	3.6	3
2011–08	–	–	0	–	–	0	–	–	0
2012–08	–	–	0	–	–	0	–	–	0
2013–07	–	–	0	–	–	0	–	–	0
2014–08	–	–	0	–	–	0	–	–	0
2015–08	–	–	0	–	–	0	–	–	0
2016–08	–	–	0	–	–	0	–	–	0
2017–08	–	–	0	–	–	0	–	–	0

Table 38 (continued). Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* canopy height (cm) at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available; – = not applicable]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2018–08	–	–	0	–	–	0	–	–	0
2019–08	–	–	0	NA	NA	NA	–	–	0
2019–09	NA	NA	NA	–	–	0	NA	NA	NA
2020–08	5.0	–	1	–	–	0	–	–	0
2022–06	–	–	0	–	–	0	–	–	0

Table 39. Yearly (monthly within year, if applicable) summary statistics for total biomass (g/m²) of *Ruppia maritima* at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available; – = not applicable]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2007–07	–	–	0	NA	NA	NA	NA	NA	NA
2007–08	NA	NA	NA	–	–	0	0.0	0.0	4
2009–08	–	–	0	0.0	0.0	8	0.0	0.0	12
2010–05	99.6	55.2	12	25.1	41.9	11	2.1	7.0	11
2011–08	28.8	23.4	11	25.7	24.2	12	2.3	3.6	11
2012–08	82.5	37.1	12	92.7	61.4	12	33.2	44.5	12
2013–07	99.0	70.7	12	62.2	39.8	12	4.7	9.3	12
2014–08	10.8	11.8	11	1.5	4.3	12	0.0	0.0	12
2015–08	53.3	40.2	12	49.7	54.8	11	0.0	0.0	12
2016–08	31.8	48.3	12	1.0	3.4	12	0.0	0.0	12
2017–08	9.3	21.8	12	9.2	24.0	12	0.0	0.0	12
2018–08	38.0	37.2	12	4.1	5.8	12	0.0	0.0	12
2019–08	38.5	40.7	12	NA	NA	NA	0.0	0.0	12
2019–09	NA	NA	NA	10.6	13.5	12	NA	NA	NA
2020–08	12.2	12.7	12	6.3	9.3	12	0.0	0.0	12
2022–06	–	–	0	–	–	0	–	–	0

Table 40. Yearly (monthly within year, if applicable) summary statistics for total biomass (g/m²) of *Zostera marina* at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available; – = not applicable]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2007–07	2.9	4.7	10	NA	NA	NA	NA	NA	NA
2007–08	NA	NA	NA	0.4	1.5	12	35.6	20.7	10
2009–08	0.0	0.0	12	1.6	4.9	10	12.2	12.7	9
2010–05	0.0	0.0	11	0.4	1.4	12	3.2	7.8	12
2011–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2012–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2013–07	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2014–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2015–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2016–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2017–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2018–08	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2019–08	0.0	0.0	12	NA	NA	NA	0.0	0.0	12
2019–09	NA	NA	NA	0.0	0.0	12	NA	NA	NA
2020–08	0.0	0.0	11	0.0	0.0	12	0.0	0.0	12
2022–06	–	–	0	–	–	0	–	–	0

Table 41. Yearly (monthly within year, if applicable) summary statistics for ratio of above- to belowground biomass of *Ruppia maritima* at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available; – = not applicable]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2007–07	–	–	0	NA	NA	NA	NA	NA	NA
2007–08	NA	NA	NA	–	–	0	–	–	0
2009–08	–	–	0	–	–	0	–	–	0
2010–05	0.3	0.2	12	0.7	0.7	6	0.7	–	1
2011–08	0.9	0.5	11	1.3	0.6	12	2.3	4.1	7
2012–08	0.6	0.2	11	0.6	0.3	12	5.0	9.5	6
2013–07	1.3	0.6	12	1.8	1.7	11	1.3	0.2	3
2014–08	0.9	0.6	8	1.6	0.0	2	–	–	0
2015–08	1.1	0.8	12	1.5	1.4	9	–	–	0
2016–08	2.4	0.5	7	1.7	–	1	–	–	0
2017–08	0.6	0.4	2	0.2	0.3	2	–	–	0

Table 41 (continued). Yearly (monthly within year, if applicable) summary statistics for ratio of above- to belowground biomass of *Ruppia maritima* at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available; – = not applicable]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2018–08	1.5	0.6	9	3.5	1.9	5	–	–	0
2019–08	1.6	1.2	9	NA	NA	NA	–	–	0
2019–09	NA	NA	NA	0.9	0.4	6	NA	NA	NA
2020–08	1.0	0.3	8	1.2	0.8	5	–	–	0
2022–06	–	–	0	–	–	0	–	–	0

Table 42. Yearly (monthly within year, if applicable) summary statistics for ratio of above- to belowground biomass of *Zostera marina* at Fire Island National Seashore. [SD = standard deviation; n = number of observations; NA = not available; – = not applicable]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	N
2007–07	0.7	0.8	4	NA	NA	NA	NA	NA	NA
2007–08	NA	NA	NA	0.4	–	1	1.6	1.7	10
2009–08	–	–	0	0.3	–	1	0.4	0.3	7
2010–05	–	–	0	0.8	–	1	0.7	0.4	3
2011–08	–	–	0	–	–	0	–	–	0
2012–08	–	–	0	–	–	0	–	–	0
2013–07	–	–	0	–	–	0	–	–	0
2014–08	–	–	0	–	–	0	–	–	0
2015–08	–	–	0	–	–	0	–	–	0
2016–08	–	–	0	–	–	0	–	–	0
2017–08	–	–	0	–	–	0	–	–	0
2018–08	–	–	0	–	–	0	–	–	0
2019–08	–	–	0	NA	NA	NA	–	–	0
2019–09	NA	NA	NA	–	–	0	NA	NA	NA
2020–08	–	–	0	–	–	0	–	–	0
2022–06	–	–	0	–	–	0	–	–	0

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1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525