



Condition and Trends of Estuarine Water Quality and Seagrass in Cape Cod National Seashore

Northeast Coastal and Barrier Network, 2003–2022



Aerial image of part of the Pleasant Bay estuary at Cape Cod National Seashore, Massachusetts, USA (ESRI 2025).

NPS

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

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Abstract

This report summarizes conditions and trends in routine long-term water quality monitoring and seagrass data collected at Cape Cod National Seashore in Massachusetts 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. The monitored area included three units or strata, and 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 in two reference beds. Water quality condition and trends were generally consistent between the spatial station surveys, the trend stations, and continuous logging station. Although chlorophyll-*a* concentrations and water clarity, as measured by PAR attenuation, were generally classified as being in fair to good condition throughout the majority of the park estuaries with improving or stable trends, poor conditions were still observed occasionally within the park over the timeframe between 2007 and 2021. Bottom dissolved oxygen concentrations exhibited significant improving trends and were consistently classified as being in good condition throughout the majority of the park estuaries. A significant increase in water temperature was observed in one stratum and across all trend stations over time, and summertime temperatures at the logging station, most trend stations, and in a large percentage of the estuary exceeded 25°C in several years. Significant declines in eelgrass in the park's reference seagrass beds between 2003 and 2022 suggest that conditions in the shallow and deep extremes are becoming less conducive for supporting eelgrass growth. Given that water temperatures in the park are increasing and that warmer temperatures may negatively affect both water quality and seagrass, 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.

Acronyms and Abbreviations

CACO: Cape Cod National Seashore

CI: Confidence interval

edf: Effective degrees of freedom

ENE: Estuarine nutrient enrichment

GAM: Generalized additive model

GLMM: General linear mixed model

MCT: Multiple comparison test

n: Number of observations

NCBN: Northeast Coastal and Barrier Network

NH: Nauset Harbor

NOAA: National Oceanic and Atmospheric Administration

NPS: National Park Service

NTU: Nephelometric turbidity units

PAR: Photosynthetically active radiation

PB: Pleasant Bay

psu: Practical salinity units

SAV: Submerged aquatic vegetation

SD: Standard deviation

SE: Standard error

SP: Salt Pond

TPRS: Thin plate regression spline

USEPA: United States Environmental Protection Agency

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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. Additionally, 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, the NCBN partnered with USGS scientists to develop a protocol (Kopp and Neckles 2009) for monitoring estuarine nutrient enrichment (ENE) in NCBN parks that was 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 NCBN reports by Kopp et al. (2009) and Caldwell et al. (2015) summarized water quality condition and trends during 2003–2006 and 2006–2011, respectively in NCBN parks. The current report summarizes conditions and trends for both water quality and seagrass condition data collected in Cape Cod 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; 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 was 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 condition 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.

Two reference seagrass beds that were considered to be representative of seagrass growth conditions in the park were used for seagrass condition monitoring. 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

Cape Cod National Seashore (CACO) is a 17,000-ha park located on the outer portion of Cape Cod, a large glacial moraine peninsula that extends 96.5 km into the Atlantic Ocean from the coast of Massachusetts. The park encompasses a wide range of upland, wetland, and tidal habitats, and the majority of the estuarine habitat at CACO is associated with two large coastal lagoon systems, Pleasant Bay (PB) and Nauset Harbor/Marsh (NH) (Figure 2). Because of restricted flushing with the ocean and severe residential development pressures in the land adjacent to the park, the spatial target area for estuarine monitoring extends beyond the park boundaries to cover the entirety of these coastal embayments. In addition, monitoring included the small, deep, glacially-formed kettle-hole salt ponds that flush with seawater from the lagoons. Because flushing may be restricted through density stratification and the presence of shallow sills at their mouths, these estuarine kettle holes are particularly susceptible to nutrient over-enrichment. Estuarine condition within these systems may serve as early indicators of broader trends, and so all of the estuarine kettle holes connected to PB and NH were selected for monitoring regardless of whether they fall within or outside the park boundary. Collectively, these are referred to as the Salt Pond (SP) stratum shown in Figure 2. The park and surrounding estuaries are subject to nutrient inputs from suburban residential and commercial sources, and poor water quality conditions have been reported for many of the coastal embayments on the Cape Cod peninsula in recent years (APCC 2023).

Historically, seagrass beds were a dominant feature in the shallow waters of and adjacent to CACO. However, human activities such as dredging and nutrient pollution in the region have led to significant declines in both seagrass abundance and distribution. Seagrass condition was monitored at two well-established eelgrass (*Zostera marina*) beds representing different growing conditions for seagrass within the park boundary (Figure 3). The bed in Pleasant Bay is located in a relatively low wave energy environment but is subject to nutrient inputs from suburban sources in the surrounding watershed. In contrast, the bed in Duck Harbor Beach is located in a higher wave energy environment with lower amounts of nutrient loading.

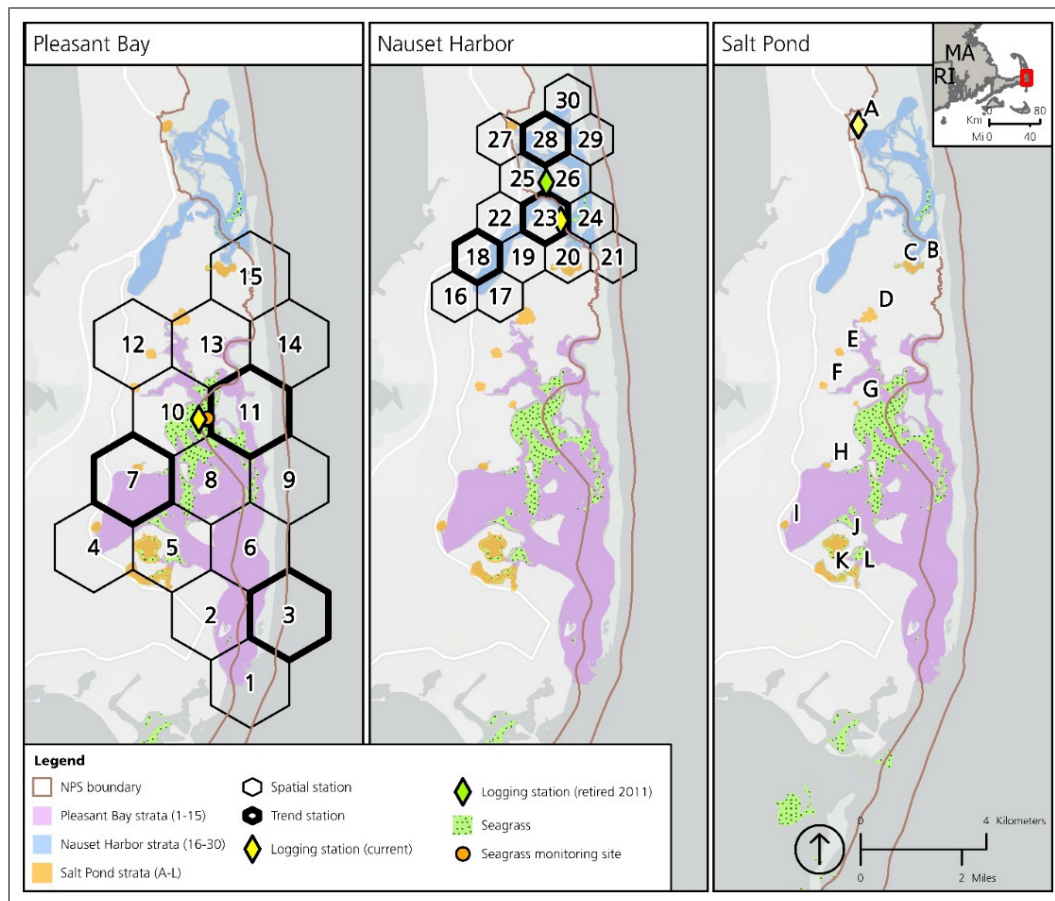


Figure 2. Spatial domain and sampling design for estuarine monitoring at three strata (subunits) within Cape Cod National Seashore, Massachusetts. Sampling hexagons with a bold outline represent those assigned with trend stations. Logging station locations and seagrass distribution in 2019–2021 are also shown.

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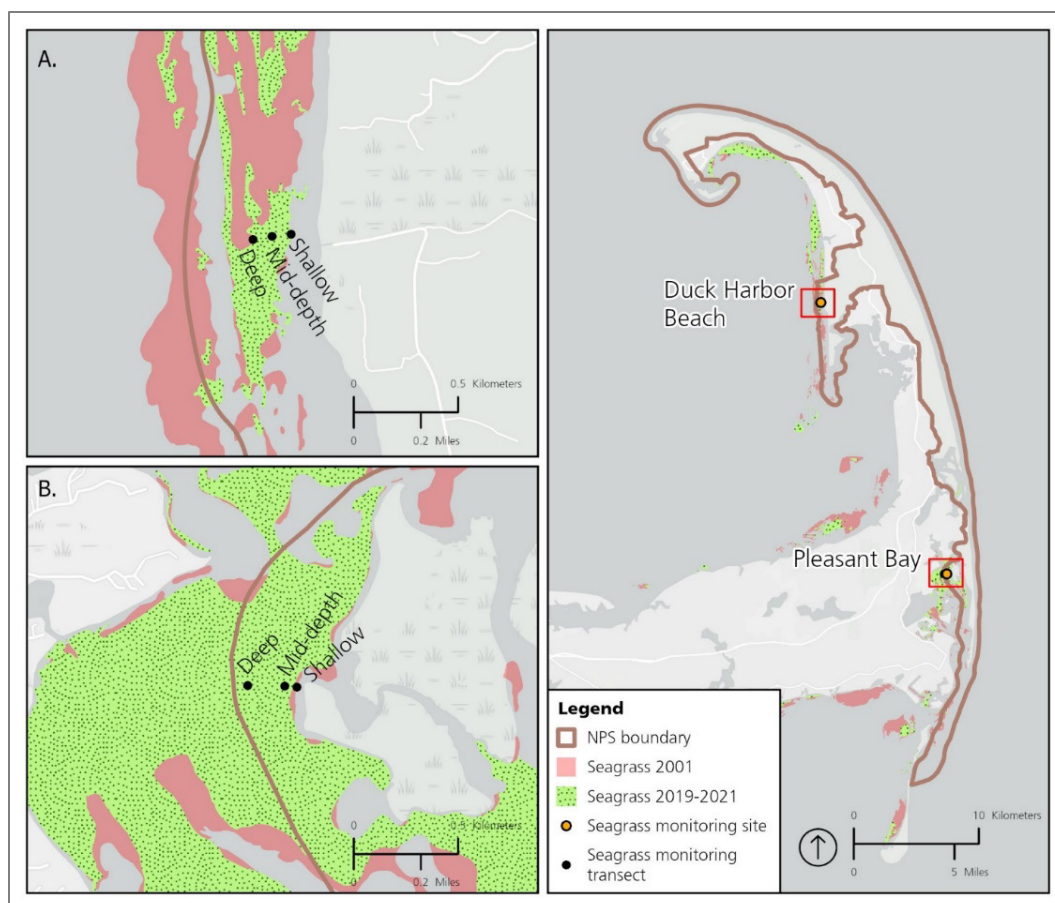


Figure 3. Location of seagrass reference beds at Duck Harbor Beach (A) and Pleasant Bay (B), Cape Cod National Seashore.

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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 and protocols can be found in the subsections below. Water quality monitoring was conducted in every year between 2007 and 2022 except for 2015, 2017, and 2020. Seagrass monitoring was conducted in every year between 2003 and 2022.

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 for the PB and NH strata were 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. For the SP stratum, each pond served as its own spatial station.

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 42 stations were sampled. Temperature, salinity, turbidity, dissolved oxygen, and pH (beginning in 2018) 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 LiCor 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 Cape Cod National Seashore.

Stratum	Year	Start	End
Pleasant Bay	2007	2007-07-25	2007-08-15
Pleasant Bay	2008	2008-07-08	2008-07-24
Pleasant Bay	2009	2009-07-29	2009-08-11
Pleasant Bay	2010	2010-07-07	2010-07-22
Pleasant Bay	2011	2011-07-12	2011-08-03
Pleasant Bay	2012	2012-07-17	2012-08-08
Pleasant Bay	2013	2013-07-09	2013-07-30
Pleasant Bay	2014	2014-07-02	2014-07-22
Pleasant Bay	2016	2016-07-06	2016-07-29
Pleasant Bay	2018	2018-07-19	2018-08-07
Pleasant Bay	2019	2019-07-15	2019-08-05
Pleasant Bay	2021	2021-07-07	2021-07-29
Nauset Harbor	2007	2007-08-02	2007-08-22
Nauset Harbor	2008	2008-07-10	2008-07-28
Nauset Harbor	2009	2009-07-15	2009-08-17
Nauset Harbor	2010	2010-07-26	2010-08-17
Nauset Harbor	2011	2011-07-06	2011-07-25
Nauset Harbor	2012	2012-07-09	2012-07-30
Nauset Harbor	2013	2013-07-08	2013-07-29
Nauset Harbor	2014	2014-07-01	2014-07-23
Nauset Harbor	2016	2016-07-12	2016-08-03
Nauset Harbor	2018	2018-08-27	2018-08-29

Table 1 (continued). Sampling start and end dates for each index period within Cape Cod National Seashore.

Stratum	Year	Start	End
Nauset Harbor	2019	2019-07-31	2019-08-16
Nauset Harbor	2021	2021-07-08	2021-07-27
Salt Pond	2007	2007-08-10	2007-08-13
Salt Pond	2008	2008-07-01	2008-07-02
Salt Pond	2009	2009-07-29	2009-08-18
Salt Pond	2010	2010-07-19	2010-08-17
Salt Pond	2011	2011-07-19	2011-07-26
Salt Pond	2012	2012-07-16	2012-07-20
Salt Pond	2013	2013-07-17	2013-07-29
Salt Pond	2014	2014-07-08	2014-07-17
Salt Pond	2016	2016-07-12	2016-07-20
Salt Pond	2018	2018-08-16	2018-08-23
Salt Pond	2019	2019-08-15	2019-08-19
Salt Pond	2021	2021-07-13	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 the PB and NH strata were selected as “trend” stations. To the extent possible, hexagons identified for trend stations were distributed systematically throughout the spatial domain (Figure 2). Trend stations were not established in the SP stratum.

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 2007 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. In the SP stratum, Salt Pond (labeled A in Figure 2) was selected for a continuous monitoring station because it falls within the park boundary, is very deep (12 m), has restricted flushing with NH, and already shows signs of degradation.

Continuous in situ measurements of water quality parameters were collected at a permanently established logging station in each stratum during each summer index period from 2007 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 structure a fixed distance from the estuary bottom in the PB and NH strata, so that the water depth of the data logger was tidally varying. For PB, the location of the logging station has been consistent across all years. For NH, the original logging station location was retired in 2011 due to limited accessibility caused by shoaling, and a new location was established in 2012 (Figure 2). The continuous data-logger in the SP stratum was suspended from a floating buoy through 2013, so that the water depth measured at this station did not exhibit regular tidal variation. From 2014 onward, the data logger was deployed on a structure a fixed distance from the estuary bottom.

Seagrass Condition

High-resolution seagrass monitoring data were collected annually between 2003 and 2022 from two permanently established sites (Figure 3) following the standardized monitoring protocol outlined in Kopp and Neckles (2009) and Short et al. (2004). Each monitoring site consists of three permanent 50-m transects that run parallel to shore across an increasing depth gradient. Data 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 2006 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-a (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
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

^AGood/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.

Pleasant Bay Stratum Results

Area-Weighted Condition Results

Data were missing for approximately 25% to 50% of the estuary in 2008, 2009, and 2010. Area-weighted condition summaries for each parameter are as follows:

Chlorophyll-*a* (Near Surface)

Area-weighted average near surface chlorophyll-*a* concentrations in the PB stratum ranged from 1.30 to 7.88 $\mu\text{g/L}$ and were classified as being in good condition (i.e., $< 5 \mu\text{g/L}$) since 2014 (Table 3). Fair area-weighted average condition was observed from 2008 to 2013. The majority of the estuary was categorized as being in fair to good condition in every year sampled, and more than 80% of the estuary was in good condition from 2016 on (Table 4). Poor conditions were observed in less than 6% of the estuary in 5 of the 12 years sampled.

Table 3. Area-weighted average water quality condition at spatial stations in the Pleasant Bay stratum of Cape Cod National Seashore during the index periods of 2007–2021. [% sat = percent saturation; NA = not available].

Parameter	Depth	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
Chlorophyll-a ($\mu\text{g/L}$)	Surface	4.00	5.20	6.24	7.88	5.85	5.87	6.07	4.73	3.09	4.15	2.55	1.30
Dissolved oxygen (% sat)	Surface	108.28	95.35	90.94	102.81	104.23	101.11	102.26	98.81	102.19	117.24	109.62	104.71
Dissolved oxygen (% sat)	Mid-Depth	111.30	95.72	88.10	103.62	101.13	100.66	96.87	98.23	98.70	121.55	107.88	106.75
Dissolved oxygen (% sat)	Bottom	110.24	94.14	90.18	102.88	104.80	100.95	100.86	99.04	102.31	117.79	110.13	108.42
Dissolved oxygen (mg/L)	Surface	8.28	6.98	6.65	7.37	7.84	7.22	7.47	7.62	7.41	8.41	7.88	7.87
Dissolved oxygen (mg/L)	Mid-Depth	8.42	6.94	6.38	7.46	7.68	7.23	7.04	7.62	7.28	9.08	7.98	8.15
Dissolved oxygen (mg/L)	Bottom	8.35	6.93	6.66	7.49	7.93	7.25	7.45	7.68	7.49	8.59	8.11	8.21
PAR attenuation (K_d (m^{-1}))	Water Column	0.89	0.67	0.64	1.47	0.71	0.58	0.55	0.70	0.55	0.63	0.63	0.57
pH	Surface	NA	NA	NA	NA	NA	NA	NA	NA	NA	7.91	7.89	7.90
pH	Mid-Depth	NA	NA	NA	NA	NA	NA	NA	NA	NA	7.97	7.92	7.91
pH	Bottom	NA	NA	NA	NA	NA	NA	NA	NA	NA	7.92	7.94	7.93
Salinity (psu)	Surface	31.86	32.44	31.28	31.84	30.18	32.97	31.00	31.25	31.49	31.50	30.49	31.95
Salinity (psu)	Mid-Depth	31.88	32.42	31.39	31.86	30.41	33.04	31.15	31.30	31.68	31.39	30.63	32.01
Salinity (psu)	Bottom	31.89	32.45	31.42	31.93	30.14	33.03	31.19	31.32	31.60	31.54	30.62	31.98
Temperature ($^{\circ}\text{C}$)	Surface	19.45	21.77	21.11	22.67	20.92	23.23	22.12	19.13	22.18	22.79	23.10	20.26
Temperature ($^{\circ}\text{C}$)	Mid-Depth	19.91	22.33	21.59	22.48	20.16	22.80	22.44	18.75	21.12	20.58	21.43	19.36
Temperature ($^{\circ}\text{C}$)	Bottom	19.55	22.12	20.40	21.69	21.19	22.92	21.57	18.87	21.57	21.92	21.70	19.71
Turbidity (NTU)	Surface	0.67	1.50	0.97	1.69	0.85	1.11	0.97	2.16	0.86	1.23	1.07	2.29
Turbidity (NTU)	Mid-Depth	0.72	1.29	1.47	1.90	1.13	0.85	1.12	2.50	0.85	1.02	1.05	2.34
Turbidity (NTU)	Bottom	0.94	3.00	1.73	1.81	1.63	1.41	1.33	4.77	0.97	1.52	1.70	2.93

Table 4. Proportion of monitored estuarine resources falling into each quality category at spatial stations in the Pleasant Bay stratum at Cape Cod National Seashore during the index periods of 2007–2021. Estuarine quality category thresholds as defined in Kopp and Neckles (2009) can be found in Table 2.

Parameter	Condition	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
Bottom dissolved oxygen (mg/L)	Good	91.7	57.5	44.5	61.6	100.0	100.0	99.9	100.0	99.9	100.0	100.0	99.5
Bottom dissolved oxygen (mg/L)	Fair	5.2	14.1	6.6	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.5
Bottom dissolved oxygen (mg/L)	Poor	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Bottom dissolved oxygen (mg/L)	Missing	3.1	28.4	48.9	38.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (μg/L)	Good	68.1	51.5	14.7	25.8	59.7	45.0	70.4	66.2	90.2	83.6	94.2	99.9
Chlorophyll- <i>a</i> (μg/L)	Fair	28.8	20.1	36.4	35.4	34.6	49.3	29.6	33.8	5.8	16.3	5.8	0.1
Chlorophyll- <i>a</i> (μg/L)	Poor	0.0	0.0	0.0	0.5	5.8	5.6	0.0	0.0	4.0	0.1	0.0	0.0
Chlorophyll- <i>a</i> (μg/L)	Missing	3.1	28.4	48.9	38.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Good	23.5	31.8	32.4	16.7	75.6	94.2	83.7	77.1	99.9	94.2	94.2	86.1
PAR attenuation (K_d (m ⁻¹))	Fair	14.0	10.6	2.2	20.9	19.2	5.8	16.3	22.9	0.1	5.7	5.8	13.9
PAR attenuation (K_d (m ⁻¹))	Poor	0.0	0.0	4.0	10.6	5.2	0.0	0.0	0.0	0.0	0.1	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Missing	62.5	57.6	61.4	51.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature (°C)	<25	90.3	64.5	45.9	47.1	94.2	64.2	87.7	94.2	94.7	84.7	77.5	94.7
Surface Temperature (°C)	25–28	0.0	7.1	5.2	14.6	5.8	30.1	11.8	5.8	5.3	12.3	21.9	5.3
Surface Temperature (°C)	>28	0.0	0.0	0.0	0.0	0.0	5.8	0.5	0.0	0.0	3.1	0.6	0.0
Surface Temperature (°C)	Missing	9.7	28.4	48.9	38.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Dissolved Oxygen (Near Bottom)

Area-weighted average near bottom dissolved oxygen concentrations in the PB stratum were classified as being in good condition (i.e., > 5 mg/L) for every index period and ranged from 6.66 to 8.59 mg/L (Table 3). For years in which the entire estuary was sampled, more than 90% of area within the PB stratum was characterized as being in good condition (Table 4).

PAR Attenuation K_d (SAV Standard)

Area-weighted average PAR attenuation ranged from 0.55 to 1.47 m^{-1} and was classified as being in good condition (i.e., < 0.92 m^{-1}) in every year except for 2010 when conditions were fair (Table 3). The majority of area (>75%) within the PB stratum was characterized as being in good condition after 2011 (Table 4). Considering only years in which the entire stratum was surveyed, poor conditions were observed in less than 5% of the estuary.

pH

Area-weighted average pH ranged from 7.89 to 7.97 (Table 3). Measurements of pH began in 2018.

Salinity

Area-weighted average salinity ranged from 30.14 to 33.04 psu (Table 3).

Temperature (Near Surface)

Area-weighted average near surface water temperature ranged from 19.13 to 23.23°C (Table 3). After 2007, temperatures exceeded 25°C in at least 5% and up to over 35% of the stratum (Table 4). In 2012, 2013, 2018, and 2019, temperatures exceeded 28°C in as much as 5% of the stratum.

Turbidity

Area-weighted average turbidity ranged from 0.67 (surface in 2007) to 4.77 NTU (bottom depth in 2014) (Table 3).

GAM Results

The generalized additive model summaries indicate that there were statistically significant (assuming a 0.05 significance level) spatial trends in all parameters and significant temporal trends for chlorophyll-*a*, temperature, and turbidity within the PB stratum (Table 5).

Table 5. Approximate significance of the generalized additive model smooth terms for each spatial station water quality parameter model in the Pleasant Bay stratum at Cape Cod National Seashore. 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	<i>F</i> -value	<i>p</i> -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	s(year)	3.57	5.58	< 0.001
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	s(long, lat)	8.66	4.10	< 0.001

Table 5 (continued). Approximate significance of the generalized additive model smooth terms for each spatial station water quality parameter model in the Pleasant Bay stratum at Cape Cod National Seashore. 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
Dissolved oxygen (mg/L)	Bottom	s(year)	0.60	0.12	0.115
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	3.30	0.47	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	1.23	0.25	0.104
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	4.70	0.86	< 0.001
Salinity (psu)	Surface	s(year)	0.94	0.18	0.202
Salinity (psu)	Surface	s(long, lat)	8.80	3.35	< 0.001
Temperature ($^{\circ}C$)	Surface	s(year)	5.15	1.92	0.001
Temperature ($^{\circ}C$)	Surface	s(long, lat)	13.18	5.97	< 0.001
Turbidity (NTU)	Surface	s(year)	0.90	0.70	0.004
Turbidity (NTU)	Surface	s(long, lat)	6.24	1.86	< 0.001

Notable observations from the fitted smooths for each parameter are as follows:

Chlorophyll- a (Near Surface)

Chlorophyll- a concentrations exhibited a slightly concave down trend with a significant increase observed between 2007 and 2008 and a significant decrease observed between 2019 and 2021 (Figure 4). Based on the fitted model, both time and location accounted for 63.9% of the variability in chlorophyll- a concentrations within the PB stratum.

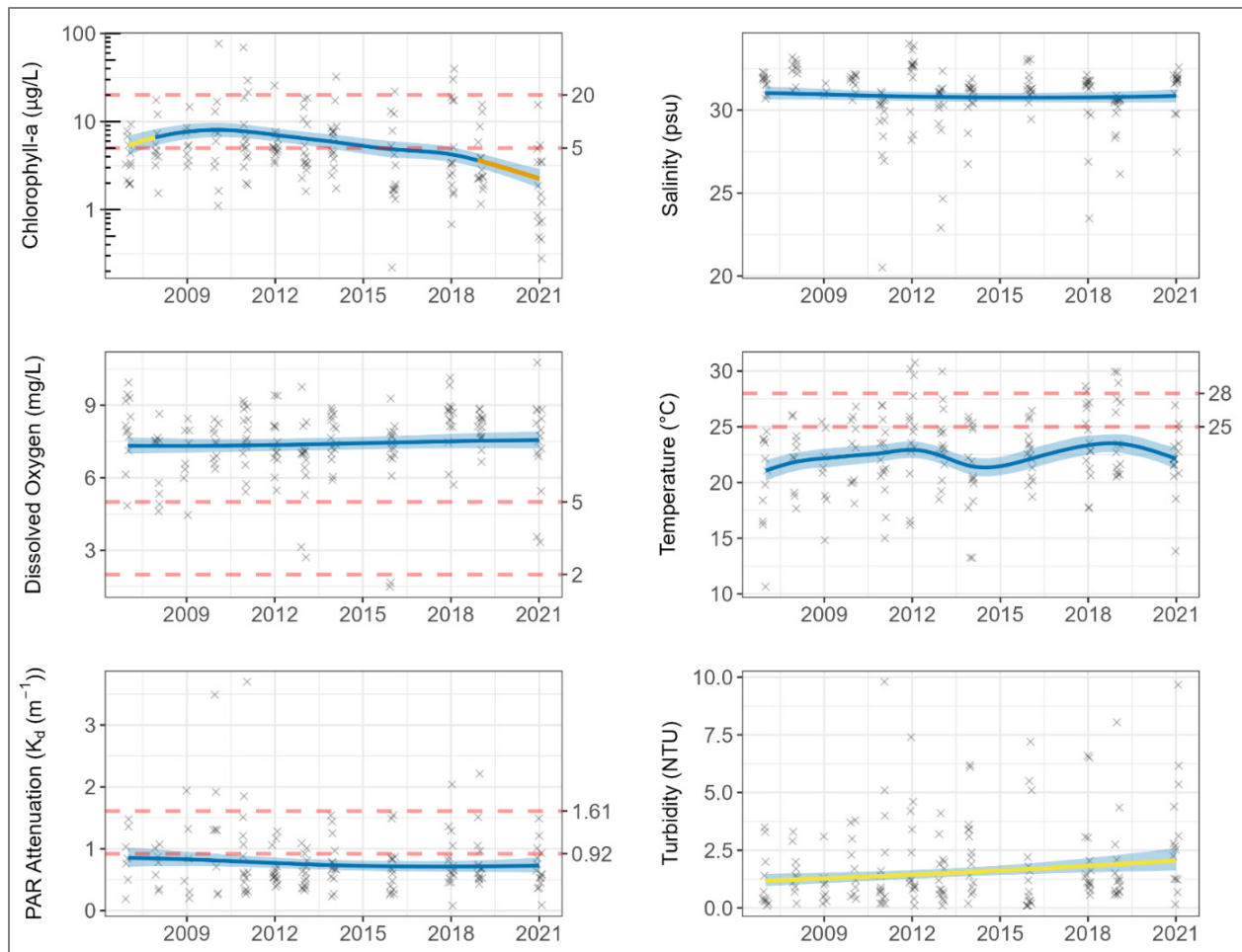


Figure 4. Trends in Cape Cod National Seashore Pleasant Bay spatial station water quality parameters based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2) plotted as red dashed lines. Note: in some instances, the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend.

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Dissolved Oxygen (Near Bottom)

Bottom dissolved oxygen concentrations remained relatively stable over time with no periods of statistically significant change (Figure 4). The fitted model did very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 12.1% of the variation within the PB stratum.

PAR Attenuation K_d (SAV Standard)

The temporal trend in PAR attenuation exhibited a slight decline with no periods of statistically significant change (Figure 4). Based on the fitted model, both time and location accounted for only 29.2% of the variability in PAR attenuation within the PB stratum.

Salinity (Near Surface)

Surface salinity remained relatively stable over time with no periods of statistically significant change (Figure 4). Based on the fitted model, both time and location accounted for 54.2% of the variability in salinity within the PB stratum.

Temperature (Near Surface)

Surface water temperature within the Pleasant Bay stratum exhibited a non-linear temporal trend with no periods of significant change (Figure 4). Based on the fitted model, both time and location accounted for 70.2% of the variability in water temperature within the PB stratum.

Turbidity (Near Surface)

Surface turbidity exhibited a significant increase between 2007 and 2021 (Figure 4). Time and location accounted for 44.4% of the variation in turbidity within the PB stratum.

Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate that there was a statistically significant decreasing monotonic trend in chlorophyll-*a* (p -value = 0.014) and increasing monotonic trend in surface turbidity (p -value = 0.039) within the PB stratum during the period of 2007 to 2021 (Table 6). In addition, there was marginal evidence (p -value = 0.066) of an increasing trend in surface temperature.

Table 6. Summary of multivariate Mann-Kendall test for monotonic trend for each spatial station water quality parameter in the Pleasant Bay stratum at Cape Cod National Seashore: 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	Z_{MK}	p -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	-2.46	0.014
Dissolved oxygen (mg/L)	Bottom	1.57	0.115
PAR attenuation (K_d (m^{-1}))	Water Column	1.26	0.206
Salinity (psu)	Surface	-0.11	0.913
Temperature ($^{\circ}\text{C}$)	Surface	1.84	0.066
Turbidity (NTU)	Surface	2.06	0.039

Nauset Harbor Stratum Results

Area-Weighted Condition Results

Data were missing for approximately 5% to 34% of the estuary in 2007, 2008, and 2009. Area-weighted condition summaries for each parameter are as follows:

Chlorophyll-*a* (Near Surface)

Area-weighted average near surface chlorophyll-*a* concentrations ranged from 2.85 to 10.08 $\mu\text{g/L}$ and were characterized as being in fair or good condition in every year sampled (Table 7). The

proportion of the NH stratum categorized as good condition ranged from 5% to 80% with the majority of the estuary in good condition in 2016, 2018, and 2021 (Table 8). Poor conditions were observed in approximately 5% to 14% of the estuary between 2007 and 2013. No area was characterized as being in poor condition after 2014.

Table 7. Area-weighted average water quality condition at spatial stations in the Nauset Harbor stratum of Cape Cod National Seashore during the index periods of 2007–2021. [% sat = percent saturation; NA = not available].

Parameter	Depth	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
Chlorophyll-a ($\mu\text{g/L}$)	Surface	8.14	10.08	9.97	12.29	8.72	9.37	9.26	9.96	4.65	4.08	7.84	2.85
Dissolved oxygen (% sat)	Surface	104.30	94.82	97.59	106.78	105.56	100.65	120.02	103.93	107.78	111.75	116.92	117.60
Dissolved oxygen (% sat)	Mid-Depth	103.51	89.96	94.69	102.25	106.54	97.33	129.60	98.83	114.33	108.33	97.03	107.46
Dissolved oxygen (% sat)	Bottom	100.24	91.20	93.18	100.33	100.65	99.43	119.73	102.59	105.38	105.72	108.26	110.64
Dissolved oxygen (mg/L)	Surface	7.78	7.18	7.06	8.02	7.88	7.26	8.44	7.72	7.84	8.10	8.18	8.55
Dissolved oxygen (mg/L)	Mid-Depth	7.81	6.86	6.92	7.73	7.86	7.02	8.98	7.51	8.23	8.08	7.16	7.82
Dissolved oxygen (mg/L)	Bottom	7.55	6.99	6.82	7.63	7.58	7.23	8.50	7.65	7.72	7.72	7.62	8.08
PAR attenuation (K_d (m^{-1}))	Water Column	1.69	1.20	1.82	0.67	0.63	0.76	0.52	0.88	0.64	0.69	0.93	0.95
pH	Surface	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.50	7.94	7.99
pH	Mid-Depth	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.58	7.88	7.93
pH	Bottom	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.48	7.90	7.94
Salinity (psu)	Surface	31.60	31.51	31.23	31.26	29.71	32.39	30.49	31.29	32.22	31.88	30.48	31.33
Salinity (psu)	Mid-Depth	31.77	31.69	31.32	31.64	30.08	32.46	30.57	31.11	32.43	32.04	30.68	31.46
Salinity (psu)	Bottom	31.79	31.50	31.40	31.46	29.97	32.60	30.82	31.36	32.29	31.92	30.58	31.41
Temperature ($^{\circ}\text{C}$)	Surface	21.17	20.03	21.28	20.42	21.34	22.58	24.01	21.10	21.89	22.16	24.42	22.05
Temperature ($^{\circ}\text{C}$)	Mid-Depth	20.56	19.72	20.58	20.08	21.83	22.55	25.02	20.08	22.43	20.64	21.92	22.00
Temperature ($^{\circ}\text{C}$)	Bottom	20.20	19.51	20.26	19.72	20.66	22.10	23.42	20.87	21.51	21.80	24.10	21.74
Turbidity (NTU)	Surface	1.95	1.92	2.47	3.12	2.20	2.47	1.70	3.55	2.99	1.76	2.38	2.45
Turbidity (NTU)	Mid-Depth	1.77	1.55	2.41	3.91	1.61	4.28	1.66	2.79	3.22	0.81	1.42	2.70
Turbidity (NTU)	Bottom	9.91	3.15	3.13	9.13	2.19	2.42	1.89	4.23	2.98	2.09	3.09	2.45

Table 8. Proportion of monitored estuarine resources falling into each quality category at spatial stations in the Nauset Harbor stratum of Cape Cod National Seashore during the index periods of 2007–2021. Estuarine quality category thresholds as defined in Kopp and Neckles (2009) can be found in Table 2.

Parameter	Condition	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
Bottom dissolved oxygen (mg/L)	Good	84.9	75.1	76.7	94.7	95.4	92.0	100.0	95.4	94.4	95.4	89.9	89.2
Bottom dissolved oxygen (mg/L)	Fair	10.1	12.4	4.7	0.0	0.0	8.0	0.0	4.6	5.6	0.0	5.6	6.3
Bottom dissolved oxygen (mg/L)	Poor	0.0	0.0	0.0	5.3	4.6	0.0	0.0	0.0	0.0	4.6	4.6	4.6
Bottom dissolved oxygen (mg/L)	Missing	4.9	12.5	18.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (µg/L)	Good	19.0	15.5	29.8	11.6	41.9	41.0	30.1	4.9	59.2	70.9	31.6	80.4
Chlorophyll- <i>a</i> (µg/L)	Fair	70.5	73.5	43.9	74.0	53.6	47.8	60.7	95.1	40.8	29.1	68.4	19.6
Chlorophyll- <i>a</i> (µg/L)	Poor	5.6	5.3	5.3	14.4	4.6	11.3	9.3	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (µg/L)	Missing	4.9	5.7	21.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Good	23.2	26.2	30.5	53.8	73.8	73.5	94.1	44.9	81.6	57.5	47.5	65.0
PAR attenuation (K_d (m ⁻¹))	Fair	53.3	38.8	0.0	12.5	26.2	26.5	0.0	49.2	18.4	37.2	51.7	20.0
PAR attenuation (K_d (m ⁻¹))	Poor	10.8	9.9	35.8	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.7	15.0
PAR attenuation (K_d (m ⁻¹))	Missing	12.7	25.2	33.7	32.6	0.0	0.0	5.9	5.9	0.0	5.3	0.0	0.0
Surface Temperature (°C)	<25	89.2	87.5	73.4	100.0	100.0	81.0	74.8	100.0	80.3	79.5	43.2	91.5
Surface Temperature (°C)	25–28	0.0	0.0	5.6	0.0	0.0	19.0	11.0	0.0	19.7	20.5	47.2	8.5
Surface Temperature (°C)	>28	0.0	0.0	0.0	0.0	0.0	0.0	14.2	0.0	0.0	0.0	9.6	0.0
Surface Temperature (°C)	Missing	10.8	12.5	21.0	0.0	0.0	0.0	0.0	0.0	0.0	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 6.82 to 8.50 mg/L (Table 7). The majority of area (75–100%) within the NH stratum was consistently characterized as being in good condition (Table 8). Approximately 5% of the stratum was characterized as having poor dissolved oxygen condition (i.e., < 2 mg/L) in years 2010, 2011, 2018, 2019, and 2021.

PAR Attenuation K_d (SAV Standard)

Area-weighted average PAR attenuation within Nauset Harbor ranged from 0.52 to 1.82 m^{-1} and was generally classified as being in fair to good condition in all years except for 2007 and 2009 when conditions were poor (i.e., >1.61 m^{-1}) (Table 7). Since 2010, a majority of the stratum was characterized as being in either fair or good condition (Table 8). Considering only years in which the entire stratum was sampled, poor conditions were typically observed in less than 6% of the estuary.

pH

Area-weighted average pH ranged from 7.88 to 8.58 (Table 7). Measurements of pH began in 2018.

Salinity

Area-weighted average salinity ranged from 29.71 (surface depth in 2011) to 32.60 psu (bottom depth in 2012) (Table 7).

Temperature (Near Surface)

Area-weighted average near surface water temperature ranged from 20.01 to 24.42°C (Table 7). In 2012, 2013, 2016, 2018, and 2019, temperatures exceeded 25°C in at least 19% and up to over 50% of the estuary (Table 8). Temperatures exceeded 28°C in 10% and 14% of the estuary in 2013 and 2019, respectively.

Turbidity

Area-weighted average turbidity ranged from 0.81 (mid-depth in 2018) to 9.91 NTU (bottom depth in 2007) (Table 7).

GAM results

The generalized additive model summaries indicate that there were statistically significant (assuming a 0.05 significance level) spatial trends for all water quality parameters except for PAR attenuation and significant temporal trends for all parameters except for dissolved oxygen and turbidity within the NH stratum (Table 9).

Table 9. Approximate significance of the generalized additive model smooth terms for each spatial station water quality parameter model in the Nauset Harbor stratum at Cape Cod National Seashore. 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)	6.79	8.05	< 0.001
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(long, lat)	4.93	2.54	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	0.00	0.00	0.477
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	2.17	0.63	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	2.95	2.06	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	0.00	0.00	0.523
Salinity (psu)	Surface	s(year)	5.63	4.76	< 0.001
Salinity (psu)	Surface	s(long, lat)	2.88	0.41	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	4.79	4.77	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	7.25	3.56	< 0.001
Turbidity (NTU)	Surface	s(year)	1.31	0.18	0.224
Turbidity (NTU)	Surface	s(long, lat)	1.83	0.22	0.004

Chlorophyll- a (Near Surface)

Chlorophyll- a concentrations exhibited a non-linear temporal trend with statistically significant declines occurring between 2014 and 2016 and again between 2019 and 2021 (Figure 5). Based on the fitted model, both time and location accounted for 58.1% of the variability in chlorophyll- a concentrations within the NH stratum.

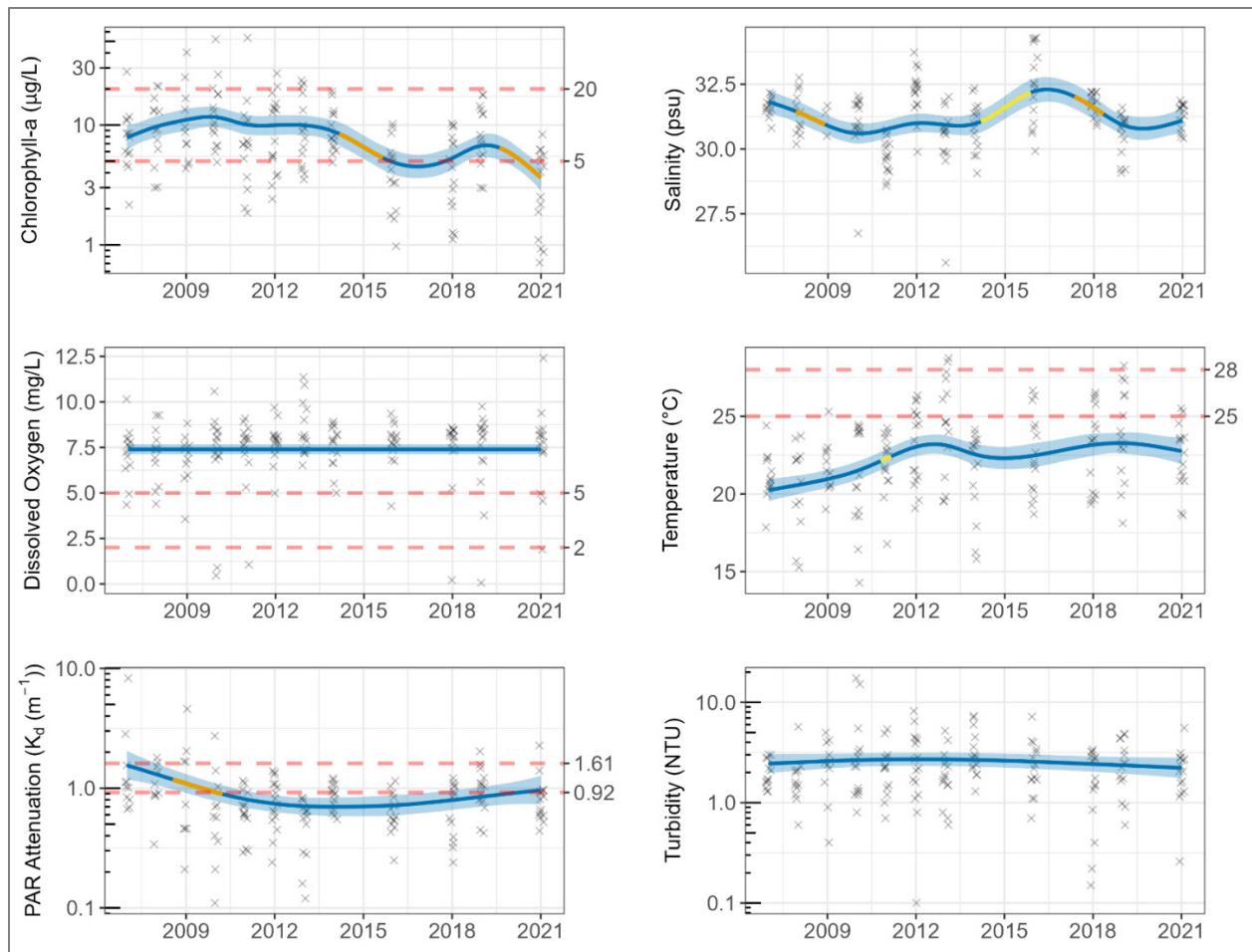


Figure 5. Trends in Cape Cod National Seashore Nauset Harbor spatial station water quality parameters based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2) plotted as red dashed lines. Note: in some instances, the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend.

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Dissolved Oxygen (Near Bottom)

No temporal trend existed in bottom dissolved oxygen concentrations, and the mean trend was estimated to be constant from 2007 to 2021 (Figure 5). The fitted model does very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 7.3% of the variation within the NH stratum.

PAR Attenuation K_d (SAV Standard)

The temporal trend in PAR attenuation was slightly concave upward with a statistically significant decrease occurring between 2009 and 2010 (Figure 5). Based on the fitted model, both time and location accounted for only 18.8% of the variability in PAR attenuation within the NH stratum.

Salinity (Near Surface)

Surface salinity exhibited a non-linear temporal trend with several periods of statistically significant change (Figure 5). Based on the fitted model, both time and location accounted for only 29.3% of the variation in salinity within the NH stratum.

Temperature (Near Surface)

Surface water temperature exhibited a non-linear increasing temporal trend with one period of significant increase between 2010 and 2012 (Figure 5). Based on the fitted model, both time and location accounted for 58% of the variability in water temperature within the NH stratum.

Turbidity (Near Surface)

The temporal trend in surface turbidity indicates measurements remained relatively constant with no periods of statistically significant change (Figure 5). Time and location accounted for only 10.7% of the variation in turbidity within the NH stratum.

Multivariate Mann-Kendall trend test results

The multivariate Mann-Kendall test results indicate there was a statistically significant monotonic increase in both bottom dissolved oxygen (p -value = 0.001) and surface temperature (p -value = 0.007) and a significant monotonic decrease in chlorophyll- a (p -value = 0.040) within the NH stratum during 2007 to 2021 (Table 10).

Table 10. Summary of multivariate Mann-Kendall test for monotonic trend for each spatial station water quality parameter in the Nauset Harbor stratum at Cape Cod National Seashore: 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	Z_{MK}	p -value
Chlorophyll- a ($\mu\text{g/L}$)	Surface	-2.05	0.040
Dissolved oxygen (mg/L)	Bottom	3.31	0.001
PAR attenuation (K_d (m^{-1}))	Water Column	0.33	0.739
Salinity (psu)	Surface	0.03	0.980
Temperature ($^{\circ}\text{C}$)	Surface	2.68	0.007
Turbidity (NTU)	Surface	1.27	0.204

Salt Pond Stratum Results

Area-Weighted Condition Results

Data were missing for approximately 5% to 75% of the estuary in 2007, 2008, and 2009. Area-weighted condition summaries for each parameter are as follows:

Chlorophyll- a (Near Surface)

Area-weighted average near surface chlorophyll- a concentration ranged from 4.59 to 29.53 $\mu\text{g/L}$ and was classified as being in fair condition (i.e., 5–20 $\mu\text{g/L}$) for every year sampled except for 2021

when conditions were good (Table 11). The majority of the SP stratum was consistently characterized as being in fair to good condition with the maximum observed proportion of area in good condition (i.e., $< 5 \mu\text{g/L}$) reaching 66% in 2021 (Table 12). Poor conditions were observed in every year and ranged from 1% to 35% of the monitored area.

Table 11. Area-weighted average water quality condition for each spatial station parameter in the Salt Pond stratum of Cape Cod National Seashore during the index periods of 2007–2021. [% sat = percent saturation; NA = not available].

Parameter	Depth	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
Chlorophyll-a ($\mu\text{g/L}$)	Surface	14.57	11.67	29.53	10.70	15.21	12.14	9.28	8.23	10.17	9.20	10.72	4.59
Dissolved oxygen (% sat)	Surface	96.86	90.29	108.14	95.17	93.47	98.44	109.50	91.45	101.99	98.11	108.07	94.76
Dissolved oxygen (% sat)	Mid-Depth	88.83	88.55	103.96	82.70	84.24	90.00	99.14	79.56	97.31	93.48	90.12	84.73
Dissolved oxygen (% sat)	Bottom	85.18	83.26	57.06	86.60	78.39	89.84	95.93	74.05	89.26	78.39	92.79	73.05
Dissolved oxygen (mg/L)	Surface	7.00	6.44	8.46	6.65	6.66	6.89	7.53	6.60	7.29	7.12	7.58	6.74
Dissolved oxygen (mg/L)	Mid-Depth	6.42	6.33	7.38	5.85	6.03	6.29	6.88	5.80	7.04	6.81	6.39	6.13
Dissolved oxygen (mg/L)	Bottom	6.15	5.97	4.07	6.09	5.65	6.28	6.65	5.46	6.48	5.79	6.59	5.32
PAR attenuation (K_d (m^{-1}))	Water Column	1.34	1.02	0.91	3.53	0.80	0.91	0.65	0.86	0.65	0.70	0.78	0.90
pH	Surface	NA	NA	NA	NA	NA	NA	NA	NA	NA	7.89	7.94	7.77
pH	Mid-Depth	NA	NA	NA	NA	NA	NA	NA	NA	NA	7.91	7.81	7.80
pH	Bottom	NA	NA	NA	NA	NA	NA	NA	NA	NA	7.87	7.86	7.66
Salinity (psu)	Surface	30.86	30.81	17.03	30.60	28.97	31.63	30.37	29.13	30.62	30.75	30.80	30.84
Salinity (psu)	Mid-Depth	31.09	31.27	30.04	30.78	29.71	31.94	30.38	30.25	30.86	30.97	30.94	31.29
Salinity (psu)	Bottom	31.12	31.39	30.25	31.12	29.74	32.09	31.06	30.45	30.92	31.23	31.29	31.17
Temperature ($^{\circ}\text{C}$)	Surface	22.64	23.50	22.75	24.62	23.99	24.45	26.01	23.39	23.20	22.54	24.33	23.42
Temperature ($^{\circ}\text{C}$)	Mid-Depth	22.54	23.29	23.67	23.94	23.56	24.45	25.08	22.40	22.55	22.30	23.56	22.46
Temperature ($^{\circ}\text{C}$)	Bottom	22.33	23.09	23.05	24.04	23.18	24.36	24.06	20.75	21.85	21.52	23.32	21.33
Turbidity (NTU)	Surface	3.09	2.24	21.42	2.72	1.73	2.59	2.71	1.62	1.67	1.32	1.12	1.31
Turbidity (NTU)	Mid-Depth	3.75	2.77	12.47	2.93	1.66	2.24	5.87	2.48	1.89	1.25	1.70	1.00
Turbidity (NTU)	Bottom	8.84	4.07	28.52	8.63	2.46	2.59	5.48	3.22	10.81	1.86	2.75	4.28

Table 12. Proportion of monitored estuarine resources falling into each quality category at spatial stations within the Salt Pond stratum of Cape Cod National Seashore during the index periods of 2007–2021. Estuarine quality category thresholds as defined in Kopp and Neckles (2009) can be found in Table 2.

Parameter	Condition	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
Bottom dissolved oxygen (mg/L)	Good	69.8	85.3	14.7	74.8	74.3	85.8	87.1	78.1	90.4	67.6	79.9	67.4
Bottom dissolved oxygen (mg/L)	Fair	15.6	14.7	8.3	25.2	25.7	14.2	3.3	12.3	0.0	32.4	15.4	19.7
Bottom dissolved oxygen (mg/L)	Poor	9.6	0.0	12.3	0.0	0.0	0.0	9.6	9.6	9.6	0.0	4.7	12.9
Bottom dissolved oxygen (mg/L)	Missing	5.0	0.0	64.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (μg/L)	Good	33.4	0.0	0.0	42.7	0.0	0.0	5.0	21.6	26.7	21.6	17.9	66.0
Chlorophyll- <i>a</i> (μg/L)	Fair	32.6	95.2	6.4	37.9	64.8	88.1	91.7	77.0	70.0	75.1	67.9	30.7
Chlorophyll- <i>a</i> (μg/L)	Poor	29.0	4.8	18.1	19.4	35.2	11.9	3.3	1.4	3.3	3.3	14.2	3.3
Chlorophyll- <i>a</i> (μg/L)	Missing	5.0	0.0	75.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Good	12.4	50.0	33.4	48.7	59.5	64.9	89.0	75.2	94.7	82.9	66.5	61.5
PAR attenuation (K_d (m ⁻¹))	Fair	21.4	19.5	54.3	6.4	40.5	25.8	11.0	23.4	2.0	17.1	30.2	38.5
PAR attenuation (K_d (m ⁻¹))	Poor	27.2	9.3	1.4	34.0	0.0	9.3	0.0	1.4	3.3	0.0	3.3	0.0
PAR attenuation (K_d (m ⁻¹))	Missing	39.0	21.2	10.9	10.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature (°C)	<25	95.0	85.3	17.4	79.2	82.0	66.0	46.6	95.3	95.3	82.0	78.6	95.0
Surface Temperature (°C)	25–28	0.0	14.7	7.1	20.8	18.0	34.0	35.4	4.7	4.7	18.0	21.4	5.0
Surface Temperature (°C)	>28	0.0	0.0	0.0	0.0	0.0	0.0	18.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature (°C)	Missing	5.0	0.0	75.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Dissolved Oxygen (Near Bottom)

Area-weighted average near bottom dissolved oxygen concentration ranged from 4.07 to 6.65 mg/L and was classified as being in good condition (i.e., > 5 mg/L) for every index period except 2009 when data were missing for the majority of the stratum (Table 11). Except for 2009, the majority of area ($>68\%$) within the stratum was characterized as in good condition (Table 12). Poor conditions were observed in 7 of the 12 years sampled and ranged from approximately 5% to 13% of the monitored area.

PAR Attenuation K_d (SAV Standard)

Area-weighted average PAR attenuation ranged from 0.65 to 3.53 m^{-1} (Table 11). The majority of the SP stratum was consistently characterized as being in fair to good condition with at least 60% of the stratum in good condition (i.e., $<0.92 \text{ m}^{-1}$) since 2011 (Table 12). Considering only years in which the entire stratum was sampled, poor conditions were typically observed in less than 10% of the stratum.

pH

Area-weighted average pH ranged from 7.66 to 7.94 (Table 11). Measurements of pH began in 2018.

Salinity

Area-weighted average salinity ranged from 17.03 (surface depth in 2009) to 32.09 psu (bottom depth in 2012) (Table 11).

Temperature (Near Surface)

Area-weighted average near surface water temperature ranged from 22.54 to 26.01°C (Table 11). In every year sampled after 2007, temperatures exceeded 25°C in at least 5% and up to over 50% of the stratum (Table 12). Temperatures exceeded 28°C in 18% of the stratum in 2013.

Turbidity

Area-weighted average turbidity ranged from 1.12 (surface in 2019) to 28.52 NTU (bottom depth in 2009) (Table 11).

GAM Results

The generalized additive model summaries indicate that there were statistically significant (assuming a 0.05 significance level) spatial and temporal trends within the Salt Pond stratum for all water quality parameters except for PAR attenuation (Table 13).

Table 13. Approximate significance of the generalized additive model smooth terms for each spatial station water quality parameter model in the Salt Pond stratum at Cape Cod National Seashore. 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)	1.46	1.65	< 0.001
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(long, lat)	8.19	1.46	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	1.24	0.35	0.047
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	1.74	0.18	0.004
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	1.37	0.19	0.213
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	0.00	0.00	0.851
Salinity (psu)	Surface	s(year)	1.86	0.87	0.019
Salinity (psu)	Surface	s(long, lat)	8.29	0.78	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	8.22	7.21	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	6.56	1.62	< 0.001
Turbidity (NTU)	Surface	s(year)	2.09	1.32	0.001
Turbidity (NTU)	Surface	s(long, lat)	10.07	0.64	0.001

Chlorophyll- a (Near Surface)

Chlorophyll- a concentrations exhibited a slightly decreasing temporal trend with a significant decline observed between 2014 and 2018 (Figure 6). Based on the fitted model, both time and location accounted for 46% of the variability in chlorophyll- a concentrations within the SP stratum.

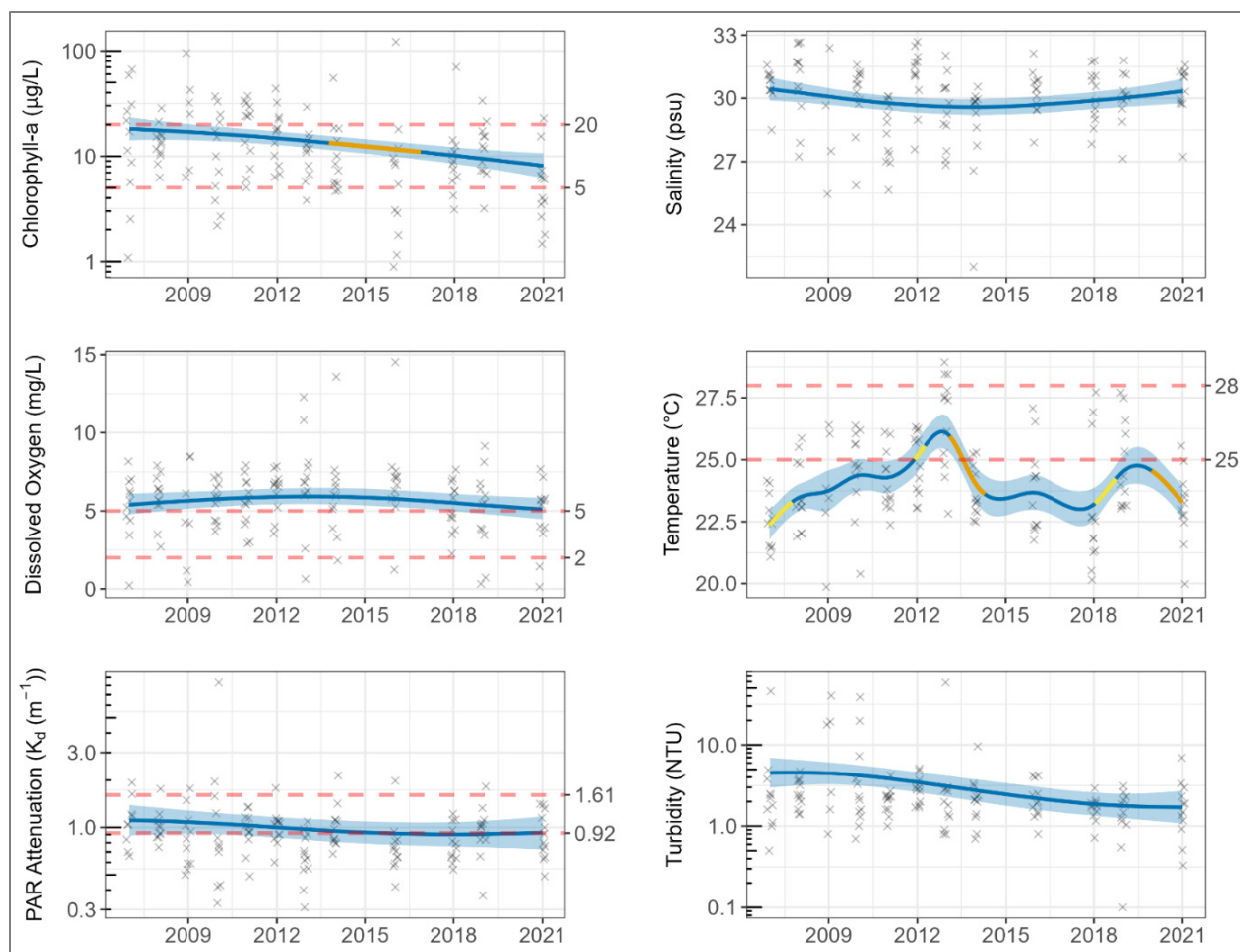


Figure 6. Trends in Cape Cod National Seashore Salt Pond spatial station water quality parameters based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: in some instances, the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend.

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Dissolved Oxygen (Near Bottom)

No significant changes were observed for bottom dissolved oxygen concentrations, and the mean trend was estimated to be constant from 2007 to 2021 (Figure 6). The fitted model did very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 6.8% of the variation within the SP stratum.

PAR Attenuation K_d (SAV Standard)

PAR attenuation remained relatively constant and no periods of statistically significant change occurred between 2007 and 2021 (Figure 6). The fitted model did very poorly explaining variation in PAR attenuation, with time and location accounting for only 4.4% of the variability within the SP stratum.

Salinity (Near Surface)

Surface salinity exhibited a slightly concave up temporal trend with no periods of statistically significant change (Figure 6). Based on the fitted model, both time and location accounted for 29.5% of the variability in surface salinity within the SP stratum.

Temperature (Near Surface)

Surface water temperature exhibited a highly non-linear temporal trend with several periods of statistically significant change (Figure 6). Temperatures increased from 2007 to 2013 before experiencing several periods of significant decrease and increase between 2013 and 2021. Based on the fitted model, both time and location accounted for 58.3% of the variability in surface water temperature within the SP stratum.

Turbidity (Near Surface)

The temporal trend in surface turbidity was slightly decreasing with no periods of statistically significant change (Figure 6). Time and location accounted for 47.2% of the variation in turbidity within the SP stratum.

Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate that there was a statistically significant decreasing monotonic trend in chlorophyll-*a* (p -value = 0.014) within the SP stratum during the period of 2007 to 2021 (Table 14).

Table 14. Summary of multivariate Mann-Kendall test for monotonic trend for each spatial station water quality parameter in the Salt Pond stratum at Cape Cod National Seashore: 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	Z_{MK}	p -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	-2.45	0.014
Dissolved oxygen (mg/L)	Bottom	-0.05	0.959
PAR attenuation (K_d (m^{-1}))	Water Column	-0.53	0.597
Salinity (psu)	Surface	-0.08	0.933
Temperature ($^{\circ}\text{C}$)	Surface	1.04	0.298
Turbidity (NTU)	Surface	-1.60	0.110

All Strata Results

Area-Weighted Condition Results

Data were missing for approximately 4% to 55% of the monitored estuarine area in 2007, 2008, and 2009. Area-weighted condition summaries for each parameter are as follows:

Chlorophyll-*a* (Near Surface)

Area-weighted average near surface chlorophyll-*a* concentrations ranged from 1.73 to 9.18 $\mu\text{g/L}$ and was classified as being in fair condition (i.e., 5–20 $\mu\text{g/L}$) from 2007 through 2015 and in good condition ($< 5 \mu\text{g/L}$) since 2016 (Table 15). The majority of the park estuaries were consistently classified as being in fair to good condition with more than 75% of the area in good condition after 2016 (Table 16). Poor conditions were observed in every year and ranged from 0.1% to 7.3%.

Table 15. Area-weighted average water quality condition at spatial stations in Cape Cod National Seashore (all strata) during the index periods of 2007–2021. [%sat = percent saturation; NA = not available]

Parameter	Depth	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
Chlorophyll-a ($\mu\text{g/L}$)	Surface	5.22	6.66	7.69	9.18	6.81	7.01	6.79	5.82	3.71	4.38	3.88	1.73
Dissolved oxygen (% sat)	Surface	107.01	94.92	93.00	103.28	103.94	100.87	105.74	99.36	103.16	115.35	110.83	106.50
Dissolved oxygen (% sat)	Mid-Depth	109.02	94.15	89.87	102.40	100.39	99.44	100.91	97.22	100.57	115.72	106.49	105.59
Dissolved oxygen (% sat)	Bottom	107.31	92.85	89.91	101.12	102.79	100.07	103.94	98.46	102.22	113.76	108.96	107.10
Dissolved oxygen (mg/L)	Surface	8.13	6.98	6.80	7.48	7.79	7.21	7.64	7.59	7.48	8.30	7.92	7.94
Dissolved oxygen (mg/L)	Mid-Depth	8.23	6.87	6.51	7.42	7.55	7.14	7.27	7.51	7.39	8.62	7.87	7.99
Dissolved oxygen (mg/L)	Bottom	8.11	6.88	6.62	7.43	7.76	7.19	7.59	7.57	7.48	8.30	7.95	8.05
PAR attenuation (K_d (m^{-1}))	Water Column	1.17	0.84	0.96	1.46	0.70	0.64	0.55	0.74	0.57	0.64	0.69	0.65
pH	Surface	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.01	7.90	7.91
pH	Mid-Depth	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.08	7.91	7.90
pH	Bottom	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.02	7.93	7.92
Salinity (psu)	Surface	31.76	32.14	30.36	31.61	30.04	32.77	30.88	31.15	31.57	31.53	30.51	31.79
Salinity (psu)	Mid-Depth	31.82	32.20	31.30	31.78	30.28	32.86	31.04	31.22	31.71	31.46	30.65	31.90
Salinity (psu)	Bottom	31.84	32.17	31.32	31.75	30.08	32.89	31.12	31.29	31.69	31.59	30.64	31.84
Temperature ($^{\circ}\text{C}$)	Surface	19.91	21.53	21.19	22.24	21.14	23.14	22.64	19.68	22.17	22.67	23.39	20.72
Temperature ($^{\circ}\text{C}$)	Mid-Depth	20.13	21.97	21.43	22.26	20.79	22.83	22.87	19.06	21.38	20.80	21.55	19.89
Temperature ($^{\circ}\text{C}$)	Bottom	19.79	21.64	20.46	21.36	21.18	22.81	22.01	19.31	21.58	21.88	22.20	20.15
Turbidity (NTU)	Surface	1.01	1.63	1.79	2.12	1.11	1.51	1.18	2.38	1.27	1.33	1.30	2.27
Turbidity (NTU)	Mid-Depth	1.03	1.46	1.94	2.21	1.27	1.61	1.41	2.52	1.22	1.01	1.10	2.31
Turbidity (NTU)	Bottom	2.84	3.11	2.91	4.11	1.78	1.69	1.63	4.60	1.80	1.64	2.00	2.92

Table 16. Proportion of monitored estuarine resources falling into each quality condition at spatial stations in Cape Cod National Seashore (all strata) during the index periods of 2007–2021. Estuarine quality category thresholds as defined in Kopp and Neckles (2009) can be found in Table 2.

Parameter	Condition	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
Bottom dissolved oxygen (mg/L)	Good	89.5	61.9	48.5	68.1	98.0	97.6	99.3	98.1	98.5	97.6	97.2	96.2
Bottom dissolved oxygen (mg/L)	Fair	6.6	13.8	6.4	1.2	1.2	2.4	0.2	1.4	1.0	1.6	1.7	2.4
Bottom dissolved oxygen (mg/L)	Poor	0.5	0.0	0.6	0.9	0.8	0.0	0.5	0.5	0.5	0.8	1.0	1.4
Bottom dissolved oxygen (mg/L)	Missing	3.5	24.2	44.5	29.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Chlorophyll- <i>a</i> (µg/L)	Good	57.8	42.7	16.6	24.1	53.6	41.9	60.2	53.3	81.7	78.4	79.5	94.8
Chlorophyll- <i>a</i> (µg/L)	Fair	36.3	33.1	36.3	42.3	39.4	50.8	38.0	46.6	15.0	21.4	19.8	5.0
Chlorophyll- <i>a</i> (µg/L)	Poor	2.4	1.2	1.8	3.8	7.0	7.3	1.8	0.1	3.3	0.2	0.7	0.2
Chlorophyll- <i>a</i> (µg/L)	Missing	3.5	23.0	45.3	29.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m ⁻¹))	Good	22.9	31.7	32.1	24.8	74.5	87.9	85.8	71.3	96.4	87.2	84.7	81.2
PAR attenuation (K_d (m ⁻¹))	Fair	21.3	16.0	4.3	18.7	21.5	11.7	13.2	27.6	3.4	11.8	15.0	16.1
PAR attenuation (K_d (m ⁻¹))	Poor	3.2	2.2	9.5	10.0	4.0	0.5	0.0	0.1	0.2	0.1	0.3	2.6
PAR attenuation (K_d (m ⁻¹))	Missing	52.6	50.2	54.1	46.5	0.0	0.0	1.0	1.0	0.0	0.9	0.0	0.0
Surface Temperature (°C)	<25	90.4	69.6	49.3	57.9	94.7	68.3	83.4	95.3	92.2	83.6	71.5	94.2
Surface Temperature (°C)	25–28	0.0	6.2	5.4	12.3	5.3	27.6	12.8	4.7	7.8	14.0	26.3	5.8
Surface Temperature (°C)	>28	0.0	0.0	0.0	0.0	0.0	4.1	3.7	0.0	0.0	2.4	2.1	0.0
Surface Temperature (°C)	Missing	9.6	24.2	45.3	29.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Dissolved Oxygen (Near Bottom)

Area-weighted average near bottom dissolved oxygen concentrations were characterized as being in good condition (i.e., > 5 mg/L) for every index period and ranged from 6.62 to 8.30 mg/L (Table 15). The majority of area within the park estuaries was consistently classified as being in good condition (Table 16). Poor conditions were observed in most years but generally represented less than 1% of the monitored area.

PAR Attenuation K_d (SAV Standard)

Area-weighted average PAR ranged from 0.55 to 1.46 m^{-1} and was classified as being in fair to good condition in every year sampled (Table 15). Since 2011, more than 70% of the monitored area was characterized as being in good quality condition (Table 16). Poor conditions were observed in almost every year but typically represented less than 5% of the park estuaries.

pH

Area-weighted average pH ranged from 7.90 to 8.08 (Table 15). Measurements of pH began in 2018.

Salinity

Area-weighted average salinity ranged from 30.04 (surface depth in 2011) to 32.89 psu (bottom depth in 2012) (Table 15).

Temperature (Near Surface)

Area-weighted average near surface water temperature ranged from 19.68 to 23.39°C (Table 15). In every year sampled after 2007, temperatures exceeded 25°C in at least 5% and up to over 30% of the park estuaries (Table 16). In 2012, 2013, 2018, and 2019, temperatures exceeded 28°C in as much as 4% of the monitored area.

Turbidity

Area-weighted average turbidity ranged from 1.01 (mid-depth in 2019) to 4.60 NTU (bottom depth in 2014) (Table 15).

GLMM Results

For all parameters except bottom dissolved oxygen and surface turbidity, the analysis of variance based on the fitted GLMM indicates that there is at least one year that is statistically different from the others assuming a significance level equal to 0.05 (Table 17).

Table 17. Analysis of variance for the general linear mixed model fit to log-transformed spatial station water quality measurements collected within Cape Cod National Seashore (all strata). 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	D.F.	F-value	p-value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	(11, 415)	15.19	< 0.005
Dissolved oxygen (mg/L)	Bottom	(11, 414)	1.01	0.43
PAR attenuation (K_d (m^{-1}))	Water Column	(11, 387)	3.22	< 0.005
Salinity (psu)	Surface	(11, 397)	18.90	< 0.005
Temperature ($^{\circ}\text{C}$)	Surface	(11, 412)	11.09	< 0.005
Turbidity (NTU)	Surface	(11, 410)	1.68	0.08

Chlorophyll-*a* (Near Surface)

The MCT results indicate that mean log near surface chlorophyll-*a* concentrations in 2016, 2018, and 2021 were significantly lower than most other index periods (Figure 7).

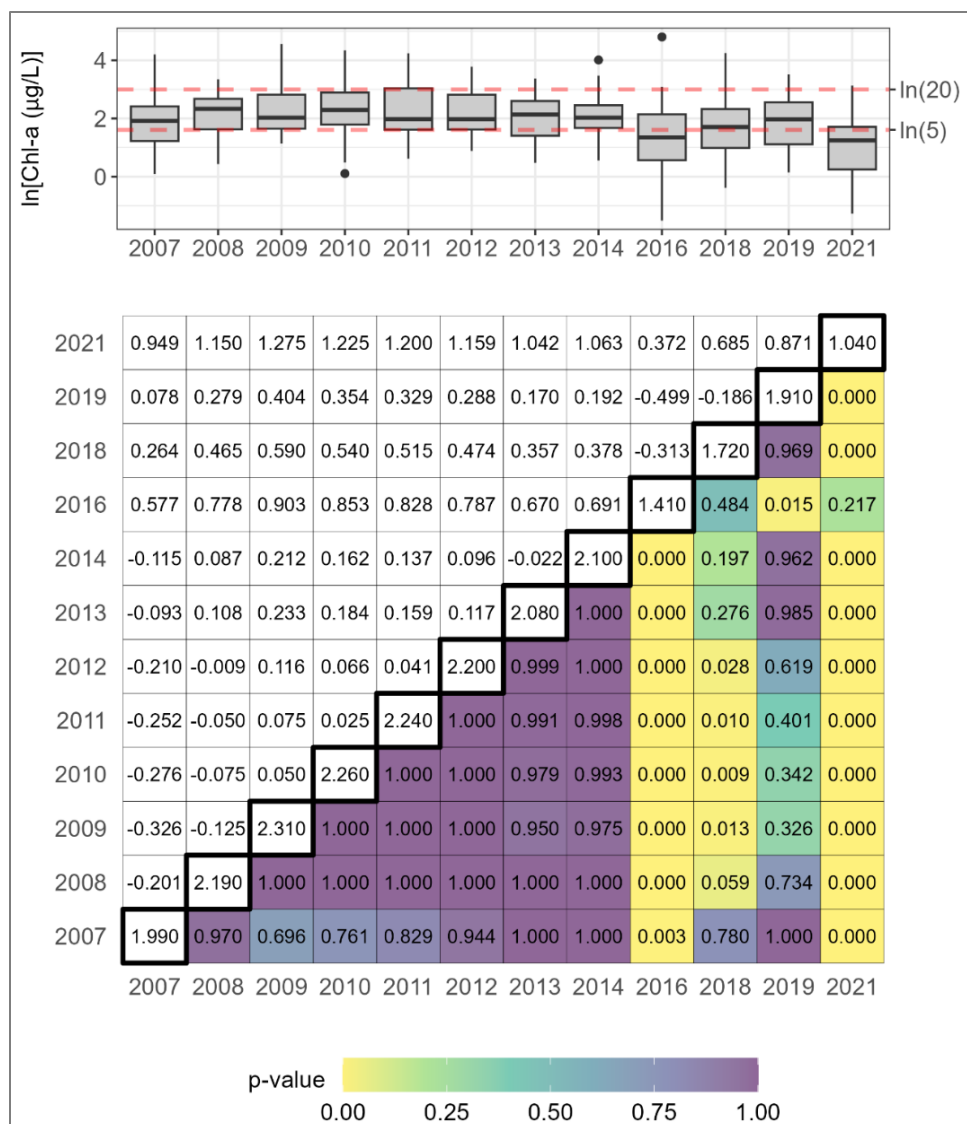


Figure 7. (Top): Boxplot of log surface chlorophyll-a concentration by year within Cape Cod National Seashore (all strata). Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements 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 38 of Appendix B](#).
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Dissolved Oxygen (Near Bottom)

The GLMM results indicate that there was insufficient evidence to conclude that there are differences in mean log bottom dissolved oxygen concentrations among the sampled years. Boxplots of mean log bottom dissolved oxygen indicate measurements were relatively constant with some low outliers (Figure 8).

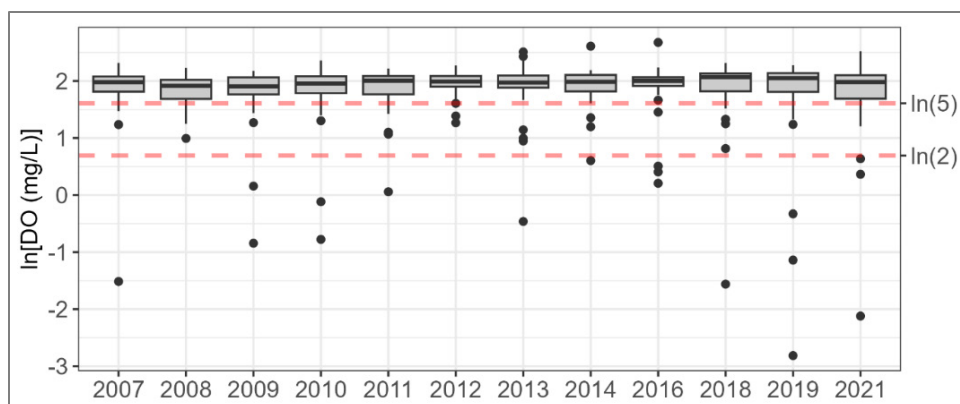


Figure 8. Boxplot of log bottom dissolved oxygen concentration by year within Cape Cod National Seashore (all strata). Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.
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PAR Attenuation K_d (SAV Standard)

The MCT results indicate that mean log PAR attenuation in 2013 was significantly lower than 4 other years (Figure 9). In addition, values in 2007 were significantly higher than in 2016.

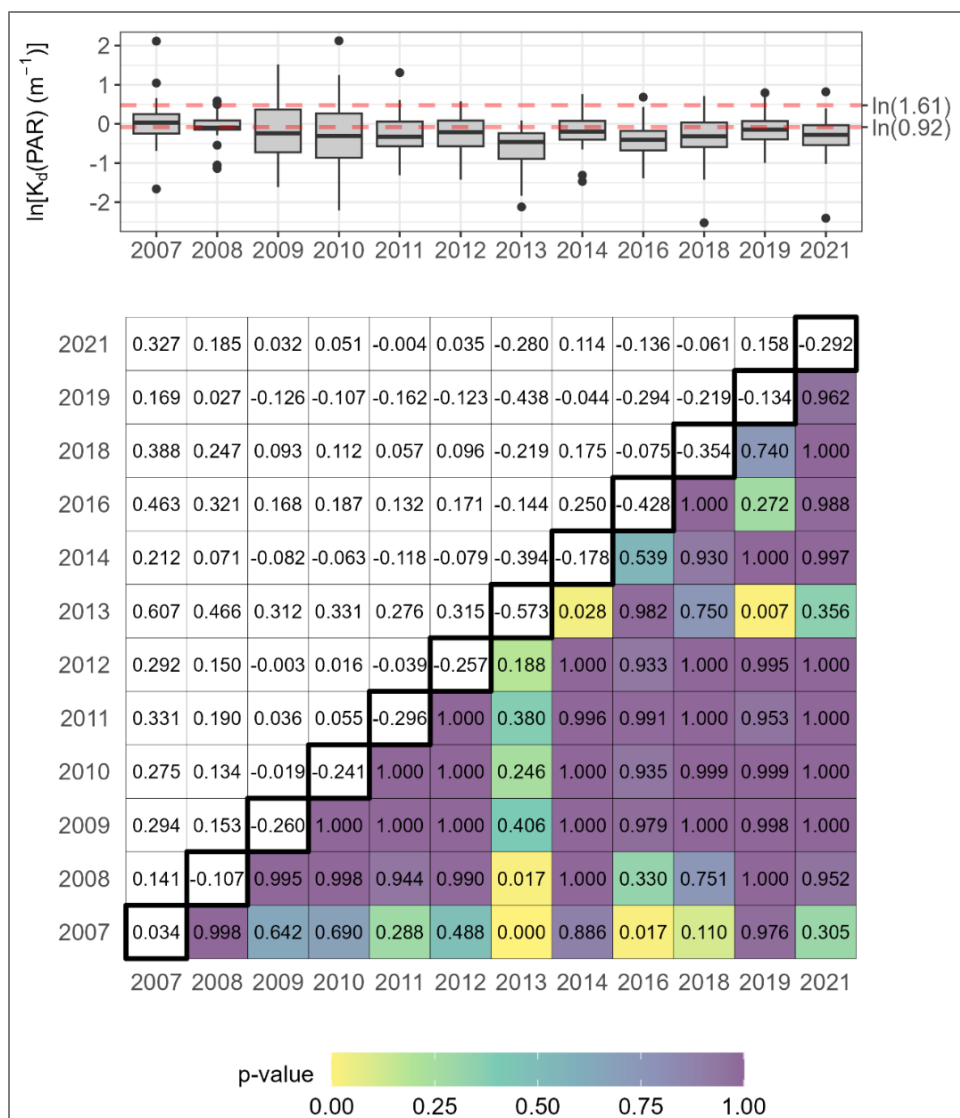


Figure 9. (Top): Boxplot of log PAR attenuation by year within Cape Cod National Seashore (all strata). Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. [Bottom]: Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log 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 39 of Appendix B](#).

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Salinity (Near Surface)

The MCT results indicate that mean log surface salinity was statistically different for several pairs of years due to the cyclic nature of the measurements (Figure 10).

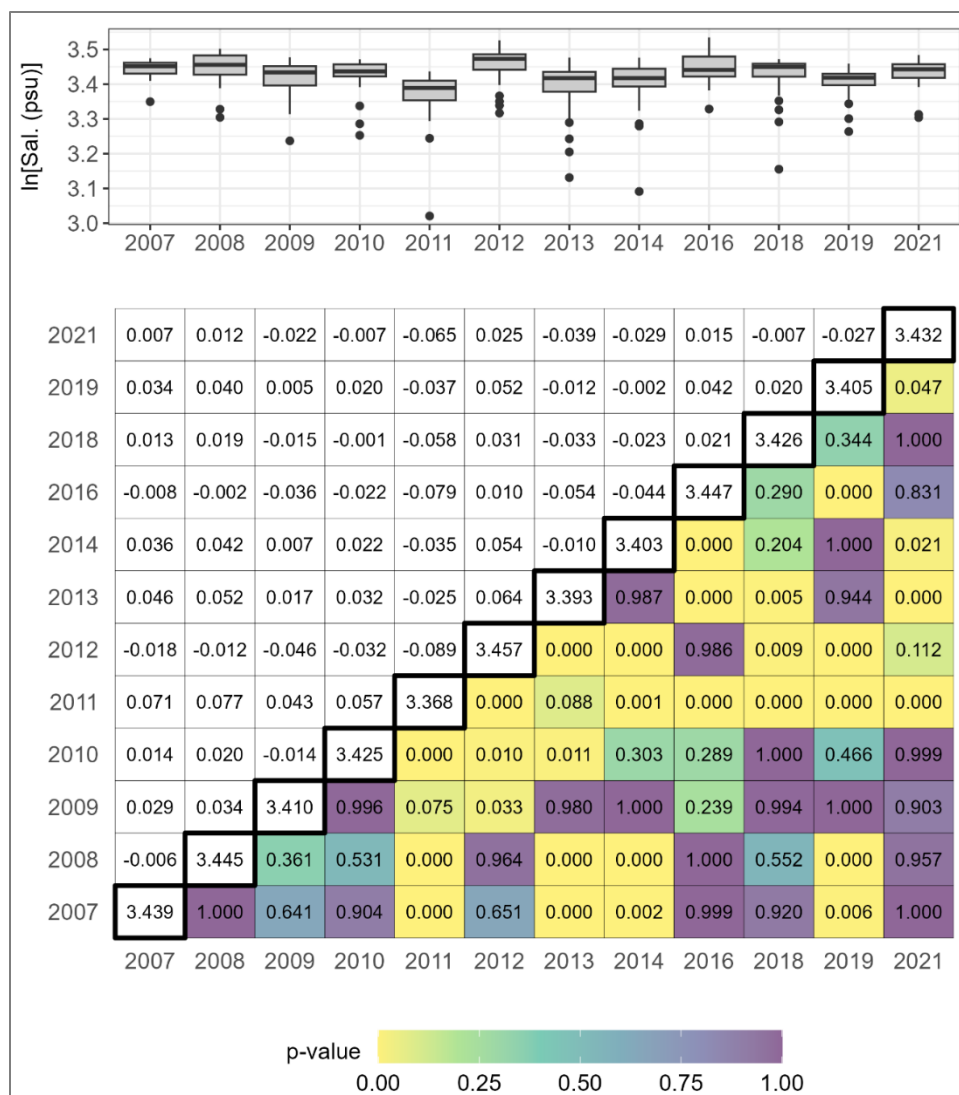


Figure 10. (Top): Boxplot of log surface salinity by year within Cape Cod National Seashore (all strata). (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface salinity within each year. Upper diagonal cells contain the difference 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 [Figure 40 of Appendix B](#).

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Temperature (Near Surface)

The MCT results indicate that mean log surface water temperatures in 2012, 2013, and 2019 were significantly higher than most other years (Figure 11).

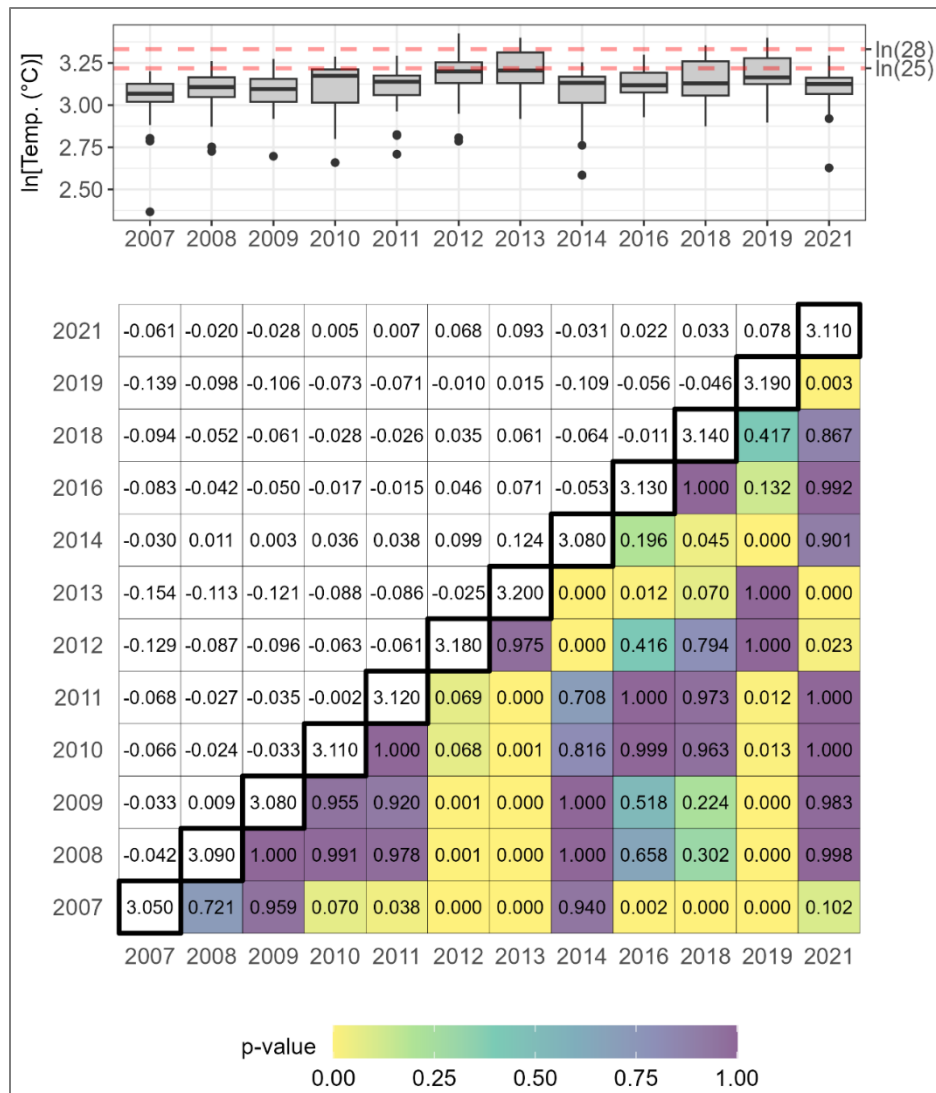


Figure 11. (Top): Boxplot of log surface temperature by year within Cape Cod National Seashore (all strata). Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean 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 41 in Appendix B](#).

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Turbidity (Near Surface)

The GLMM results indicate that there was insufficient evidence to conclude that there are differences in mean log surface turbidity among the sampled years. Boxplots of log surface turbidity indicate that within-year variability remained relatively constant over time (Figure 12).

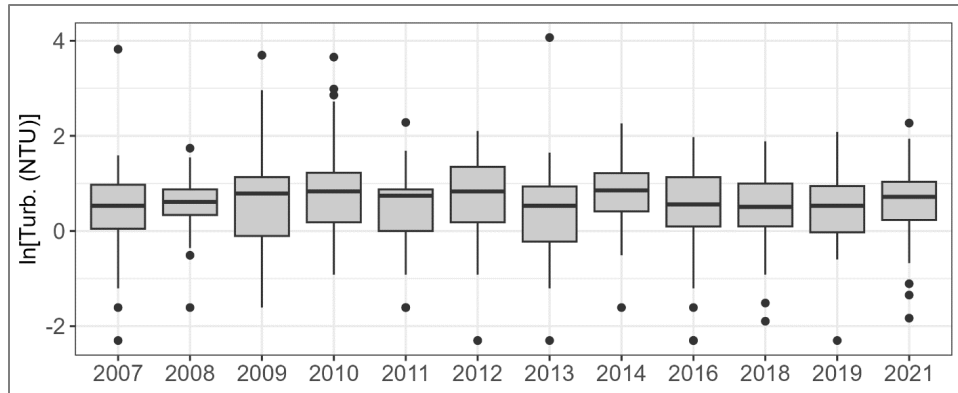


Figure 12. Boxplot of log surface turbidity by year within Cape Cod National Seashore (all strata).
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GAM Results

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 for bottom dissolved oxygen and turbidity, which only had significant spatial trends (Table 18).

Table 18. Approximate significance of the generalized additive model smooth terms for each spatial station water quality model at Cape Cod National Seashore (all strata). 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)	6.11	13.83	< 0.001
Chlorophyll- a ($\mu\text{g/L}$)	Surface	s(long, lat)	23.39	10.77	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	0.00	0.00	0.239
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	6.82	1.62	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	2.86	1.99	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	11.97	0.80	< 0.001
Salinity (psu)	Surface	s(year)	7.21	7.90	< 0.001
Salinity (psu)	Surface	s(long, lat)	26.13	6.45	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	8.52	10.86	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	23.48	14.63	< 0.001
Turbidity (NTU)	Surface	s(year)	4.34	0.70	0.105
Turbidity (NTU)	Surface	s(long, lat)	21.65	2.35	< 0.001

Chlorophyll- a (Near Surface)

Chlorophyll- a concentrations exhibited a non-linear temporal trend with two periods of statistically significant decline between 2014 and 2016 and between 2019 and 2021 (Figure 13). High

concentrations of chlorophyll-*a* were spatially concentrated along the northern and western shores of Pleasant Bay, the shores of East Orleans and Nauset Heights, and Town Cove (Figure 14). Based on the fitted model, both time and location accounted for 61.5% of the variability in chlorophyll-*a* concentrations.

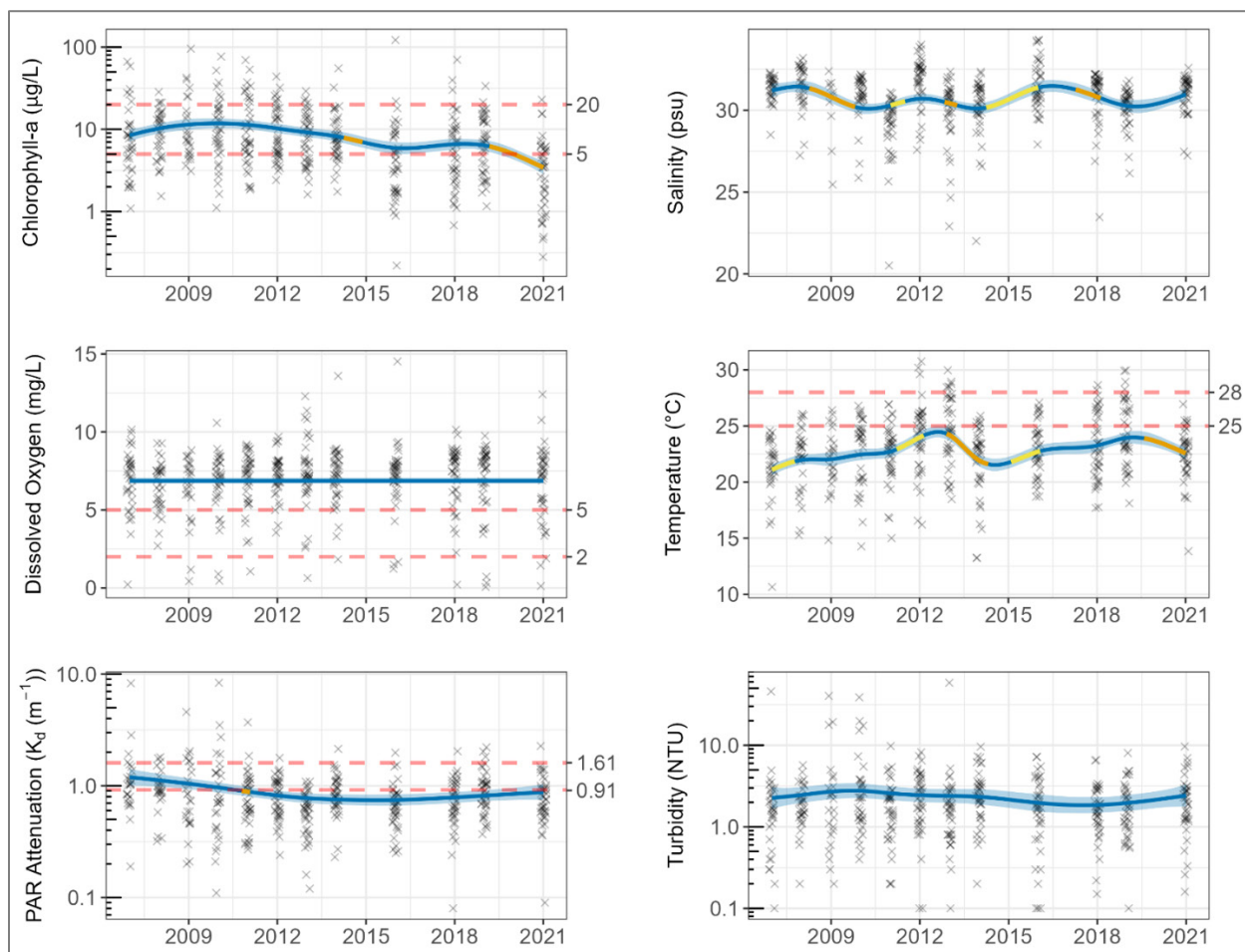


Figure 13. Trends in Cape Cod National Seashore (all strata) spatial station water quality parameters based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: in some instances, the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend.

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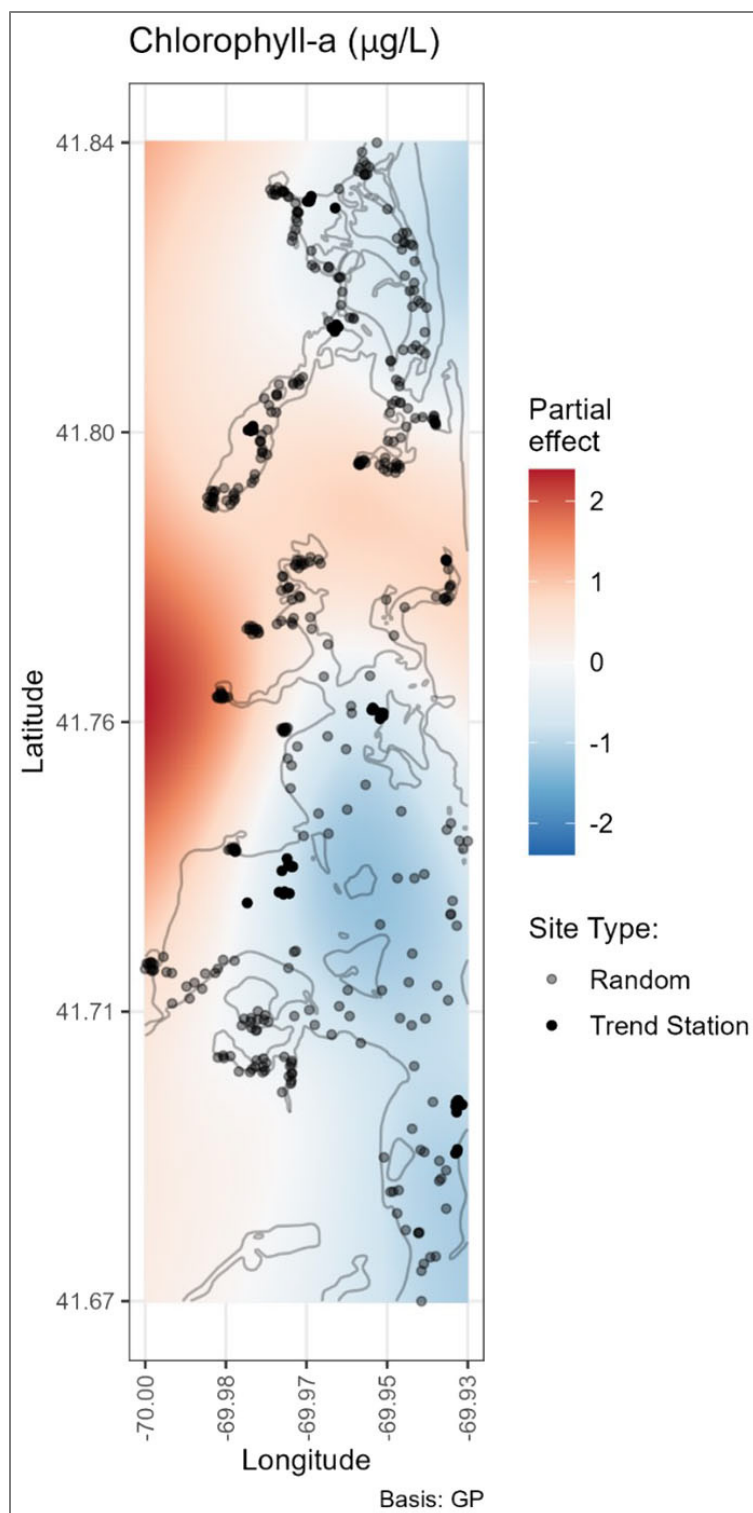


Figure 14. Mean surface for the generalized additive model latitude/longitude smooth of surface chlorophyll-a concentration within Cape Cod National Seashore (all strata) during 2007–2021.
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Dissolved Oxygen (Near Bottom)

Although there was no statistically significant temporal trend, there was a significant spatial trend in bottom dissolved oxygen, with lower concentrations occurring along the northern and western shores of Pleasant Bay and near South/East Orleans and Town Cove (Figure 15). The fitted model does very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 9.1% of the variation.

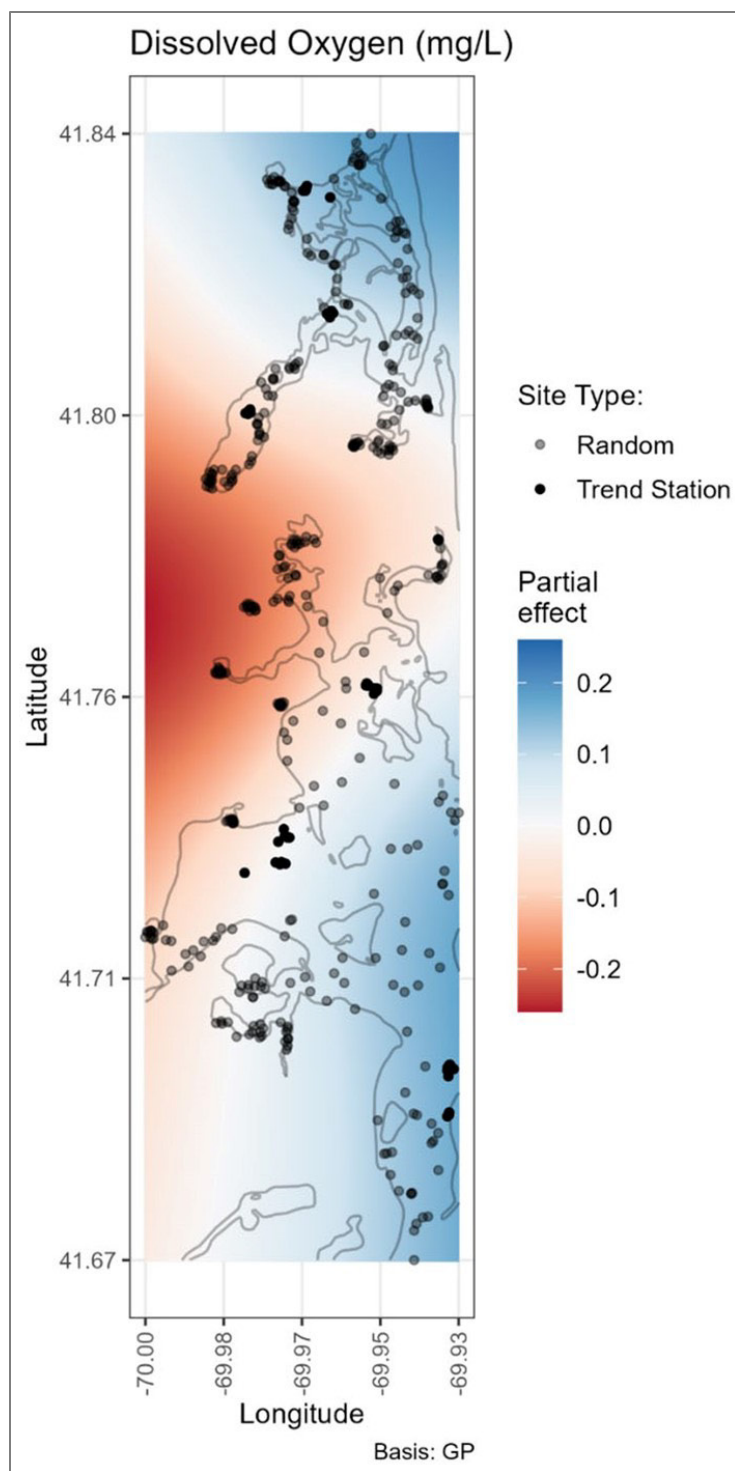


Figure 15. Mean surface for the generalized additive model latitude/longitude smooth of bottom dissolved oxygen concentration within Cape Cod National Seashore (all strata) during 2007–2021.
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PAR Attenuation K_d (SAV Standard)

The temporal trend in PAR attenuation was slightly concave upward with one period of significant decline between 2010 and 2012 (Figure 13). Spatially, PAR attenuation was higher along the northern and western shores of Pleasant Bay and near South/East Orleans and Town Cove (Figure 16). Based on the fitted model, both time and location accounted for only 20.4% of the variability in PAR attenuation.

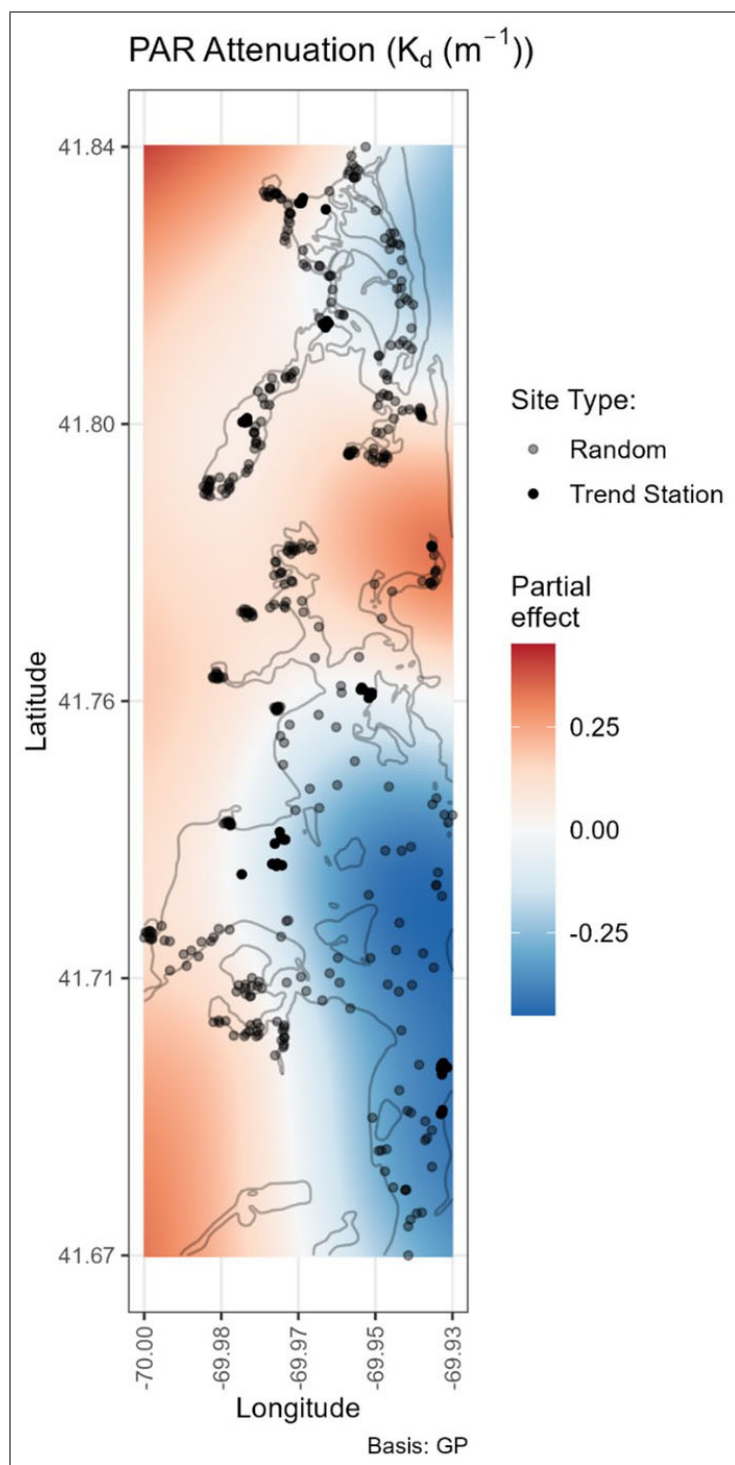


Figure 16. Mean surface for the generalized additive model latitude/longitude smooth of PAR attenuation within Cape Cod National Seashore (all strata) during 2007–2021.
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Salinity (Near Surface)

Surface salinity exhibited a highly non-linear temporal trend with cyclic periods of statistically significant increases and decreases (Figure 13). Spatially, salinity was lowest along the northern and western shores of Pleasant Bay and near South/East Orleans and Town Cove (Figure 17). Based on the fitted model, both time and location accounted for 48.6% of the variation in salinity.

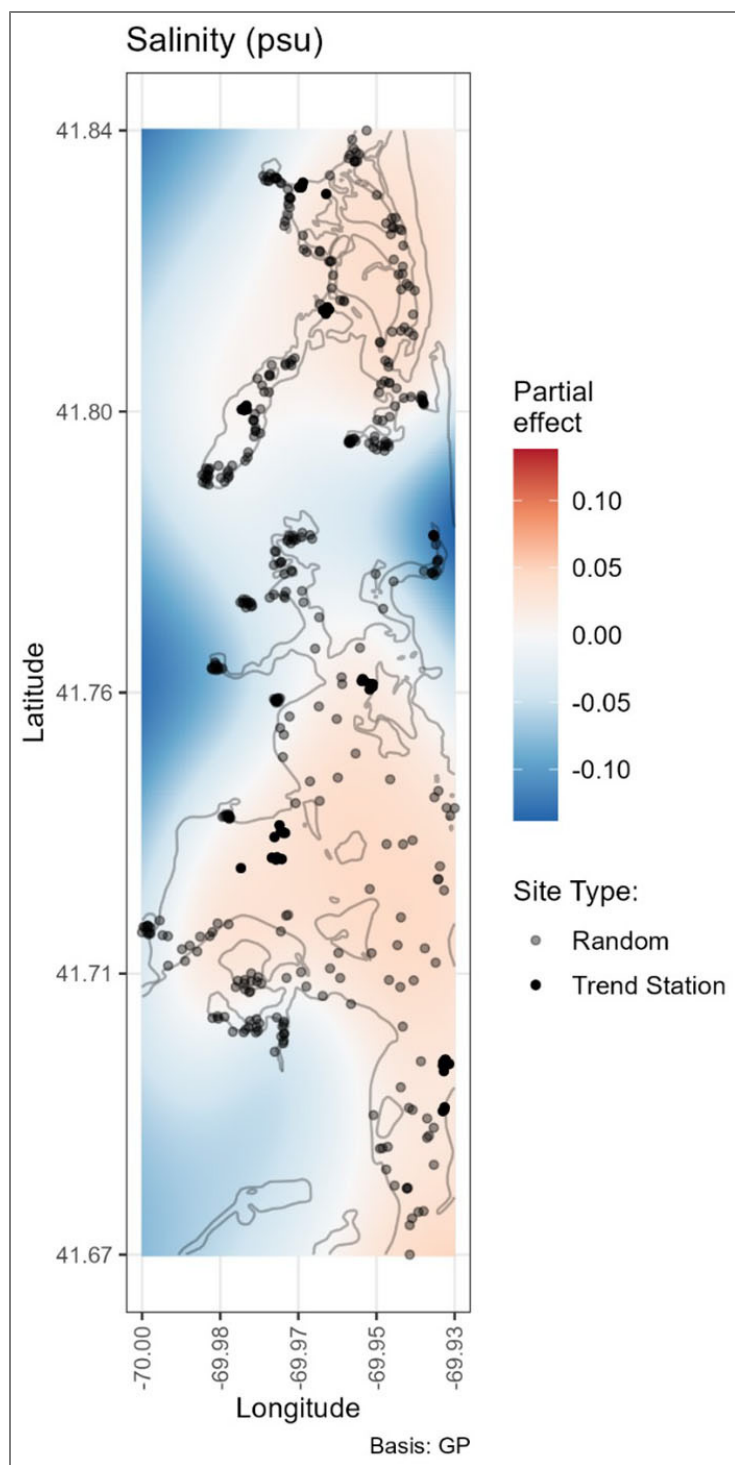


Figure 17. Mean surface for the generalized additive model latitude/longitude smooth of surface salinity within Cape Cod National Seashore (all strata) during 2007–2021.
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Temperature (Near Surface)

Surface water temperature exhibited a non-linear temporal trend with a few periods of statistically significant increases and decreases (Figure 13). Spatially, surface temperatures were highest along the northern and western shores of Pleasant Bay and near South/East Orleans and Town Cove, and cooler temperatures were observed on the eastern shores of Nauset Harbor and near Chatham Harbor (Figure 18). Based on the fitted model, both time and location accounted for 65.5% of the variability in water temperature.

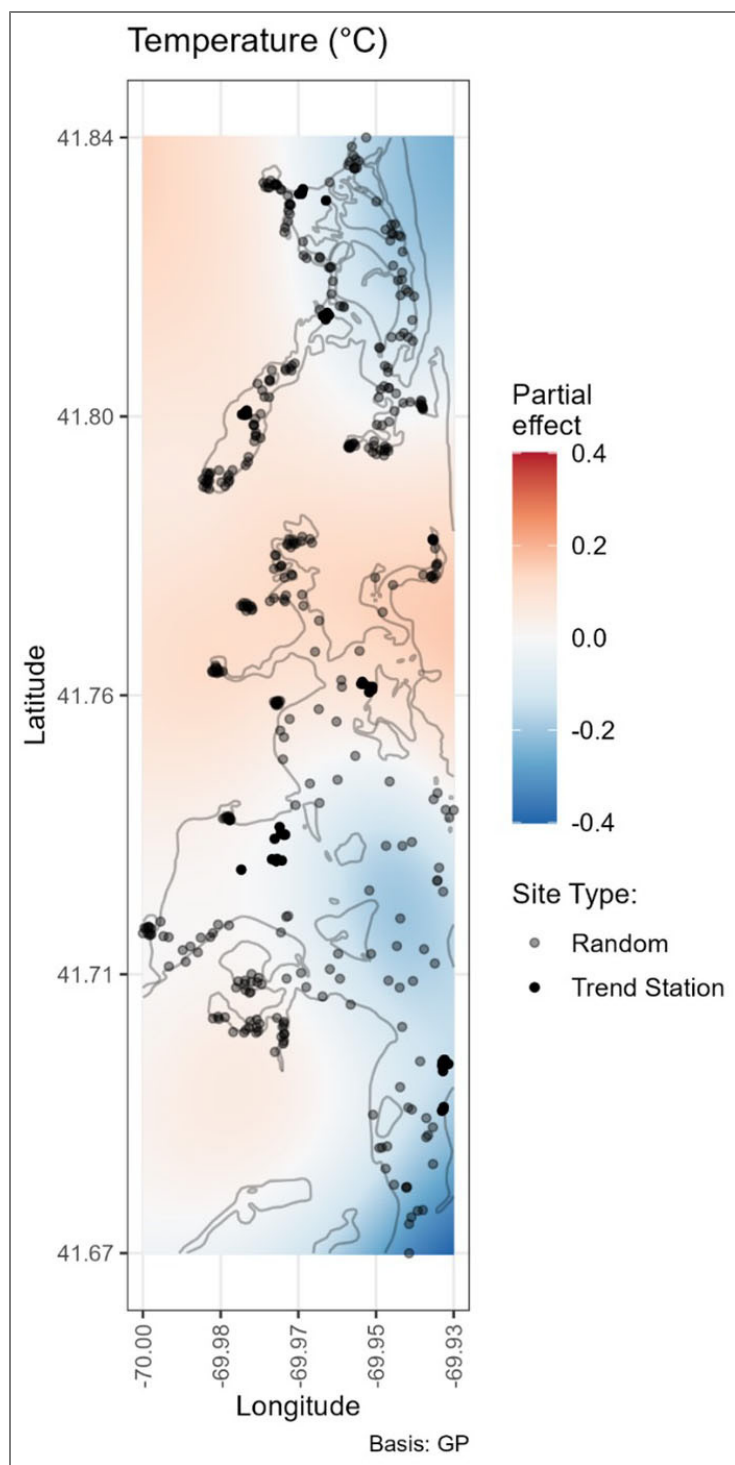


Figure 18. Mean surface for the generalized additive model latitude/longitude smooth of surface temperature within Cape Cod National Seashore (all strata) during 2007–2021.
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Turbidity (Near Surface)

The temporal trend in surface turbidity was relatively constant with no periods of statistically significant change (Figure 13). Spatially, turbidity was higher along the northern and western shores of Pleasant Bay and near South/East Orleans and Town Cove (Figure 19). Time and location accounted for 37.6% of the variation in turbidity.

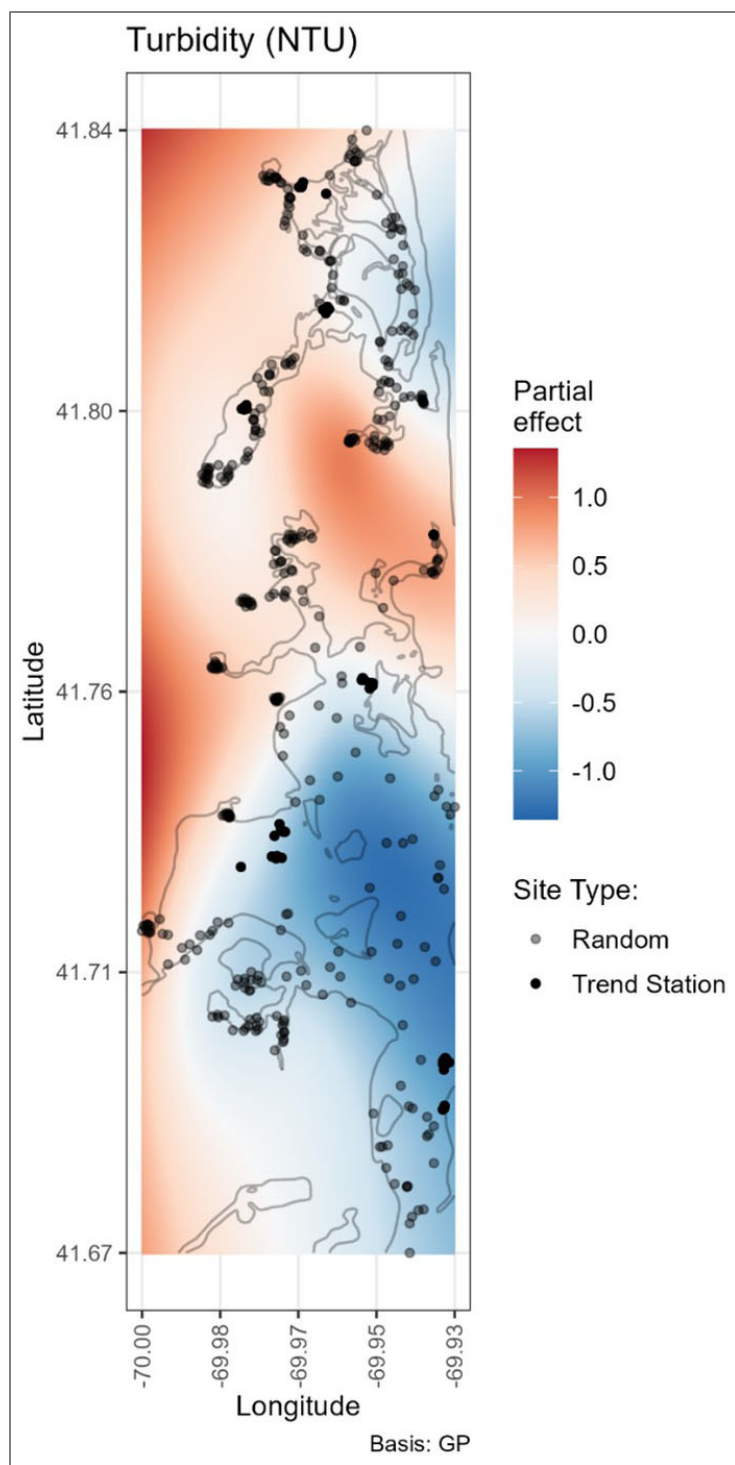


Figure 19. Mean surface for the generalized additive model latitude/longitude smooth of surface turbidity within Cape Cod National Seashore (all strata) during 2007–2021.
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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate that there were statistically significant increasing monotonic trends in bottom dissolved oxygen (p -value = 0.048) and marginal evidence of increasing surface temperature (p -value = 0.071) during the period of 2007 to 2021 (Table 19). Additionally, there was a statistically significant decreasing monotonic trend in surface chlorophyll-*a* concentrations (p -value = 0.006).

Table 19. Summary of multivariate Mann-Kendall test for monotonic trend for each Cape Cod National Seashore (all strata) spatial stations 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	Z_{MK}	p -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	-2.75	0.006
Dissolved oxygen (mg/L)	Bottom	1.98	0.048
PAR attenuation (K_d (m^{-1}))	Water Column	-0.47	0.636
Salinity (psu)	Surface	-0.39	0.697
Temperature ($^{\circ}\text{C}$)	Surface	1.81	0.071
Turbidity (NTU)	Surface	0.01	0.994

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 exists statistically significant temporal trends (assuming a significance level of 0.05) at the trend stations in all water quality parameters except salinity (Table 20). Yearly summary statistics for each parameter trend station can be found in Appendix C.

Table 20. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore trend station 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; hex = hexagon].

Parameter	Depth	Model Term	edf (df_{ref})	F-value	p-value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	s(year,hex)	21.10 (71)	4.03	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year,hex)	14.47 (71)	1.09	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year,hex)	15.77 (71)	0.94	< 0.001
Salinity (psu)	Surface	s(year,hex)	2.97 (71)	0.09	0.061
Temperature ($^{\circ}\text{C}$)	Surface	s(year,hex)	10.34 (71)	3.45	< 0.001
Turbidity (NTU)	Surface	s(year,hex)	21.01 (71)	2.31	< 0.001

Chlorophyll-a (Near Surface)

Temporal trends in chlorophyll-*a* concentrations were non-linear and differ by station (Figure 20). In general, concentrations declined at most trend stations between 2007 and 2021; however, no periods of statistically significant change were observed. Mean concentrations were generally classified as being in fair to good condition. Concentrations were highest at hexagon 18 near Orleans, which also experienced poor conditions (i.e., > 20 µg/L) in some years.

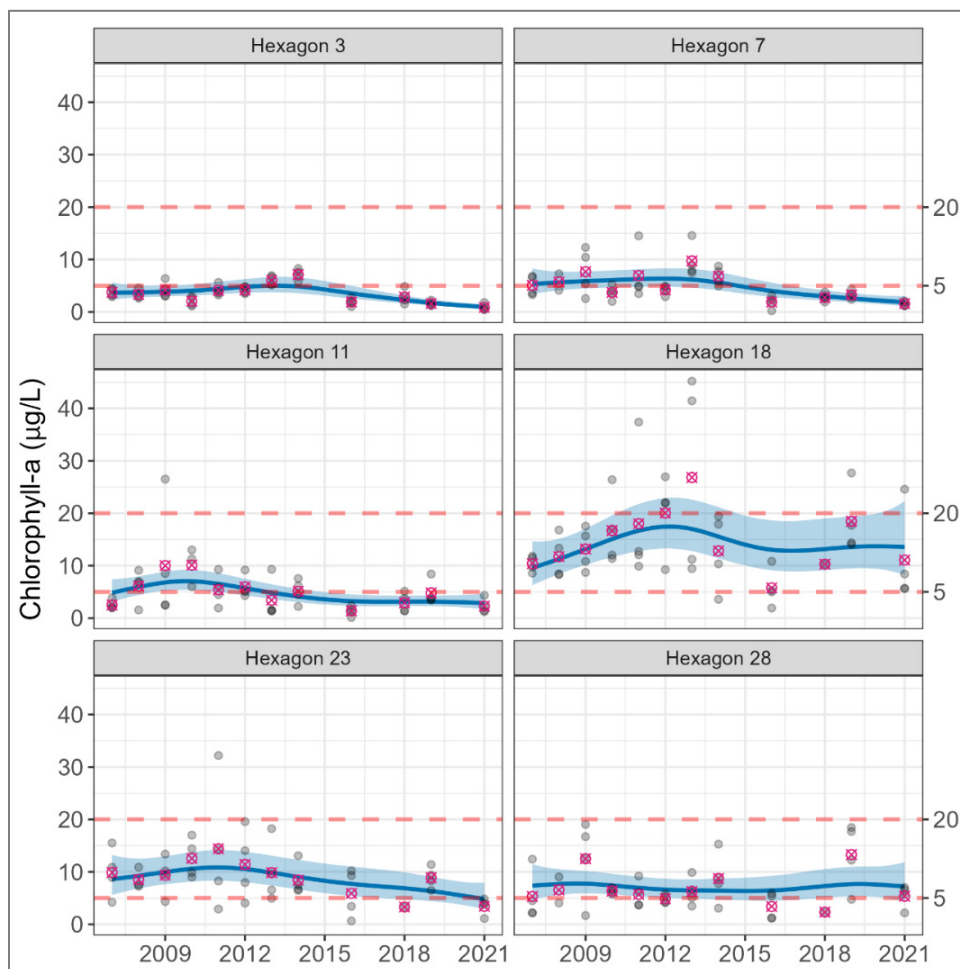


Figure 20. Mean surface chlorophyll-*a* concentration (µg/L) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), 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) plotted as red dashed lines.

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Dissolved Oxygen (Near Bottom)

The temporal trend in the bottom dissolved oxygen concentrations was slightly non-linear and relatively constant for each trend station (Figure 21). The yearly average concentrations were all above the 5 mg/L threshold (i.e., good quality category).

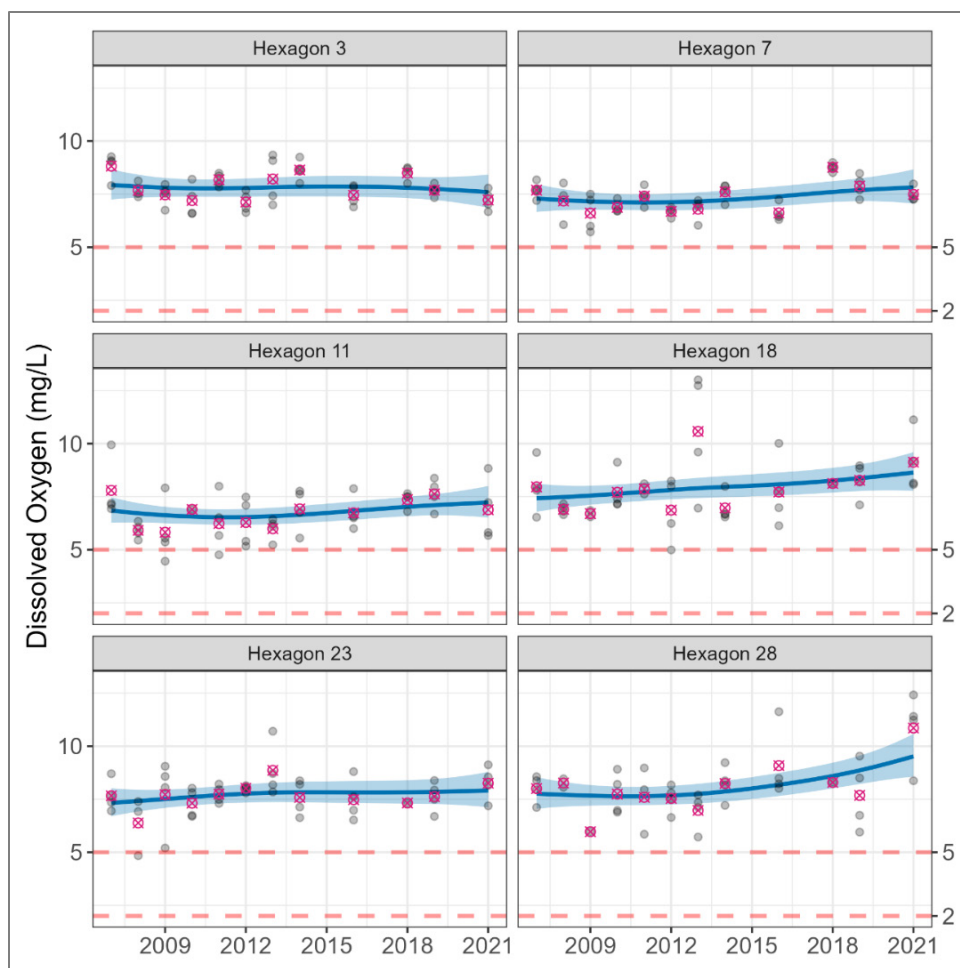


Figure 21. Mean bottom dissolved oxygen concentration (mg/L) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), 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) plotted as red dashed lines.

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PAR Attenuation K_d (SAV Standard)

Temporal trends for PAR attenuation were slightly non-linear and similar across trend stations with no periods of significant change (Figure 22). Mean attenuation values were typically classified as being in fair to good condition (i.e., $<1.61 \text{ m}^{-1}$), with some stations experiencing poor conditions in some years.

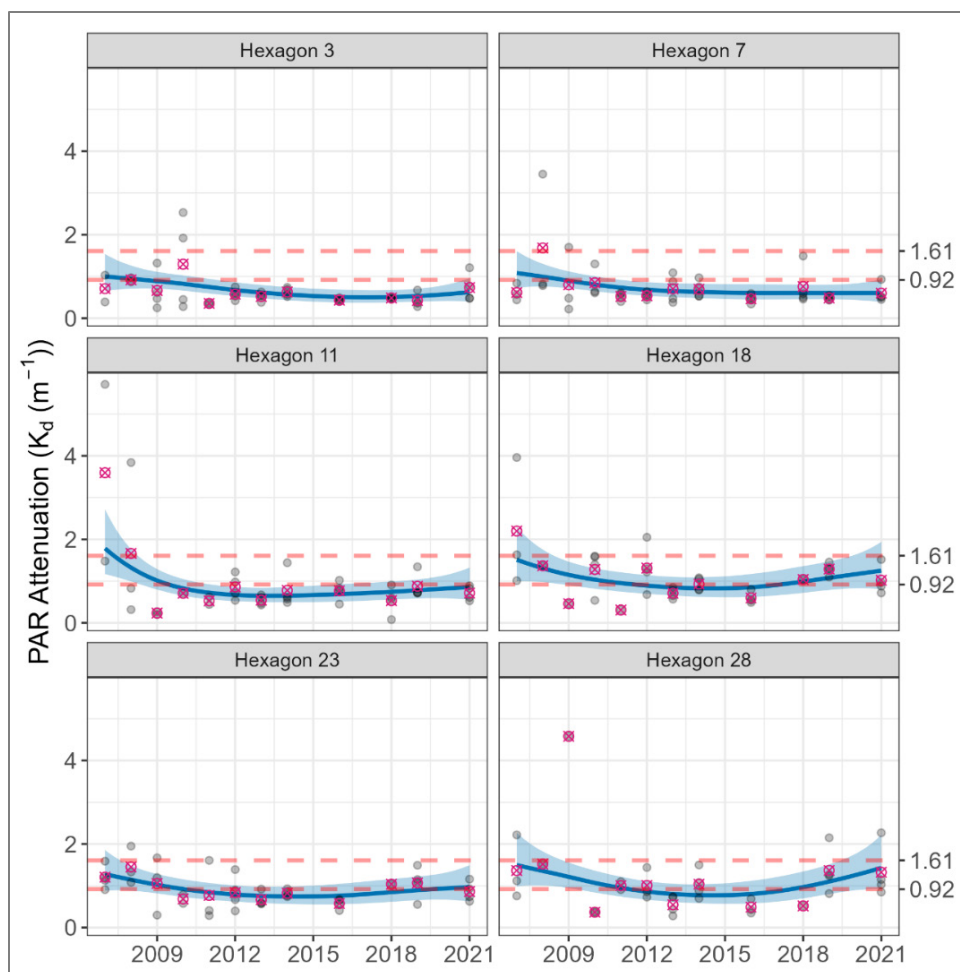


Figure 22. Mean PAR attenuation (K_d (m^{-1})) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if 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) plotted as red dashed lines.

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Salinity (Near Surface)

There was no temporal trend in surface salinity and measurements tended to be slightly cyclical (Figure 23). No periods of significant temporal change were identified.

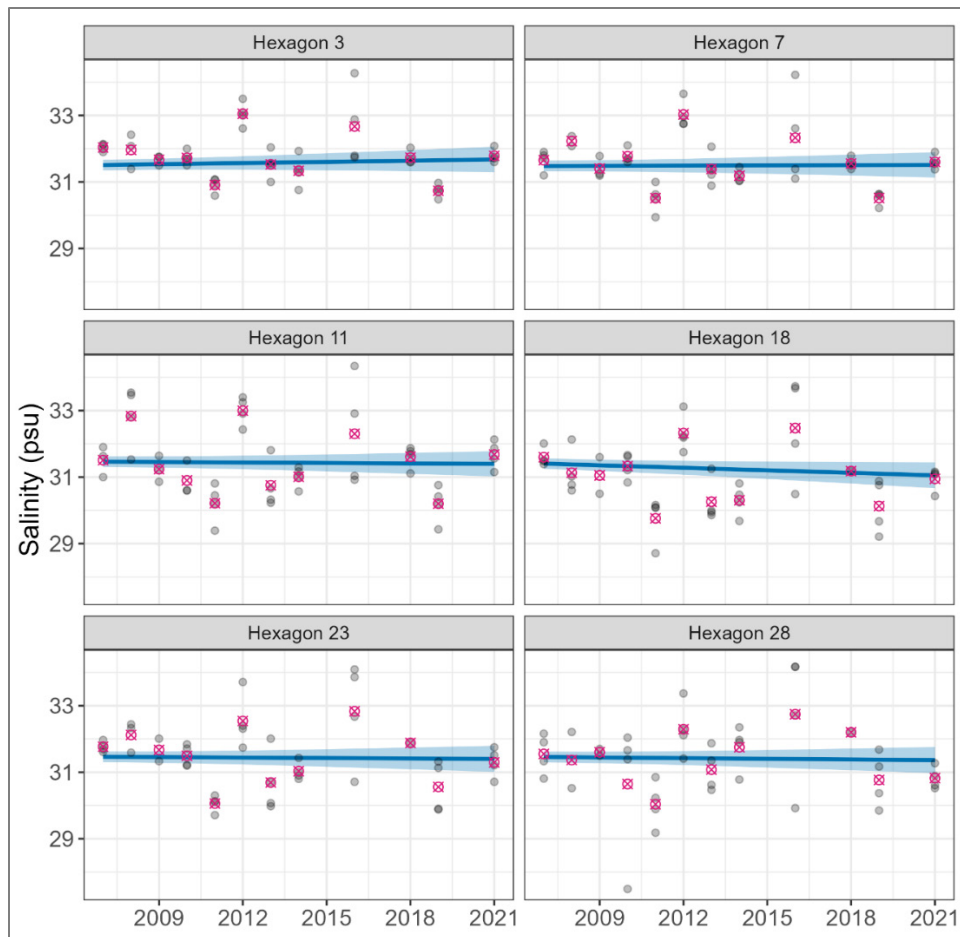


Figure 23. Mean surface salinity (psu) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, 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)

Temporal trends for all stations indicate a slight increase in surface water temperature with statistically significant increases occurring at hexagons 18 and 23 (Figure 24). Mean temperatures exceeded 25°C in 2013, 2018, and 2019 at hexagons 11 and 18.

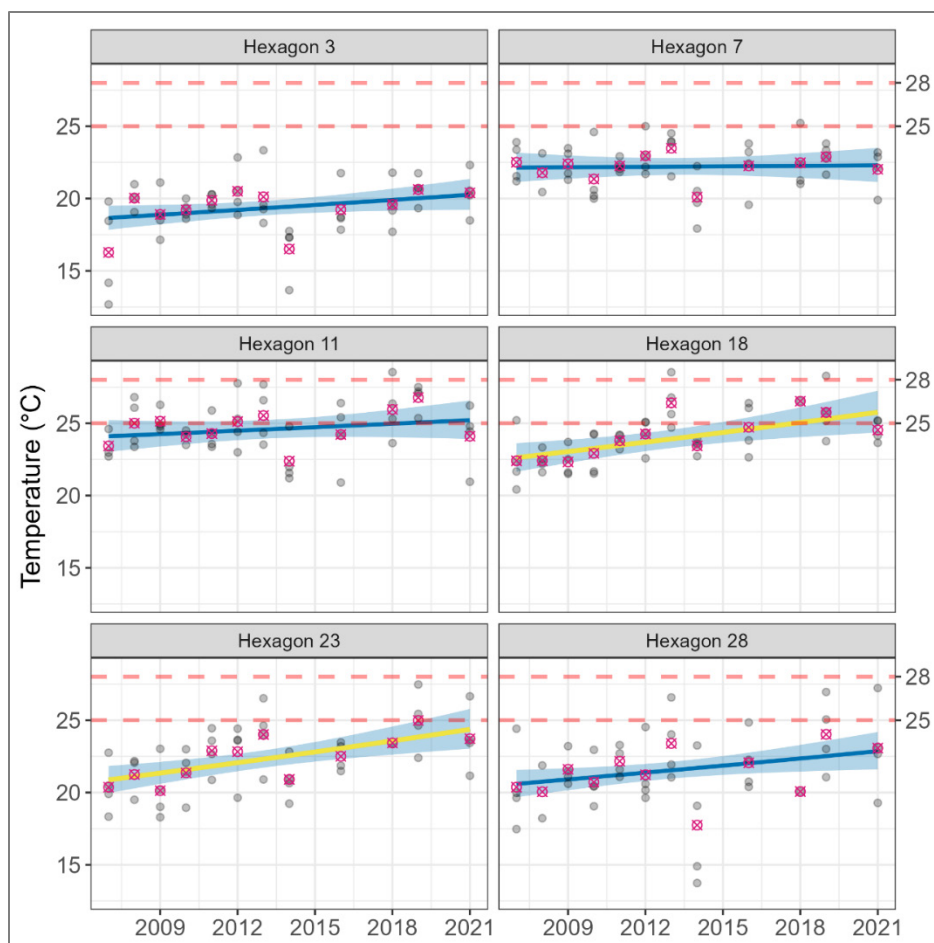


Figure 24. Mean surface temperature (°C) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, 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) plotted as red dashed lines.

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Turbidity (Near Surface)

Temporal trends in surface turbidity were slightly non-linear at most stations (Figure 25). No periods of statistically significant change were observed.

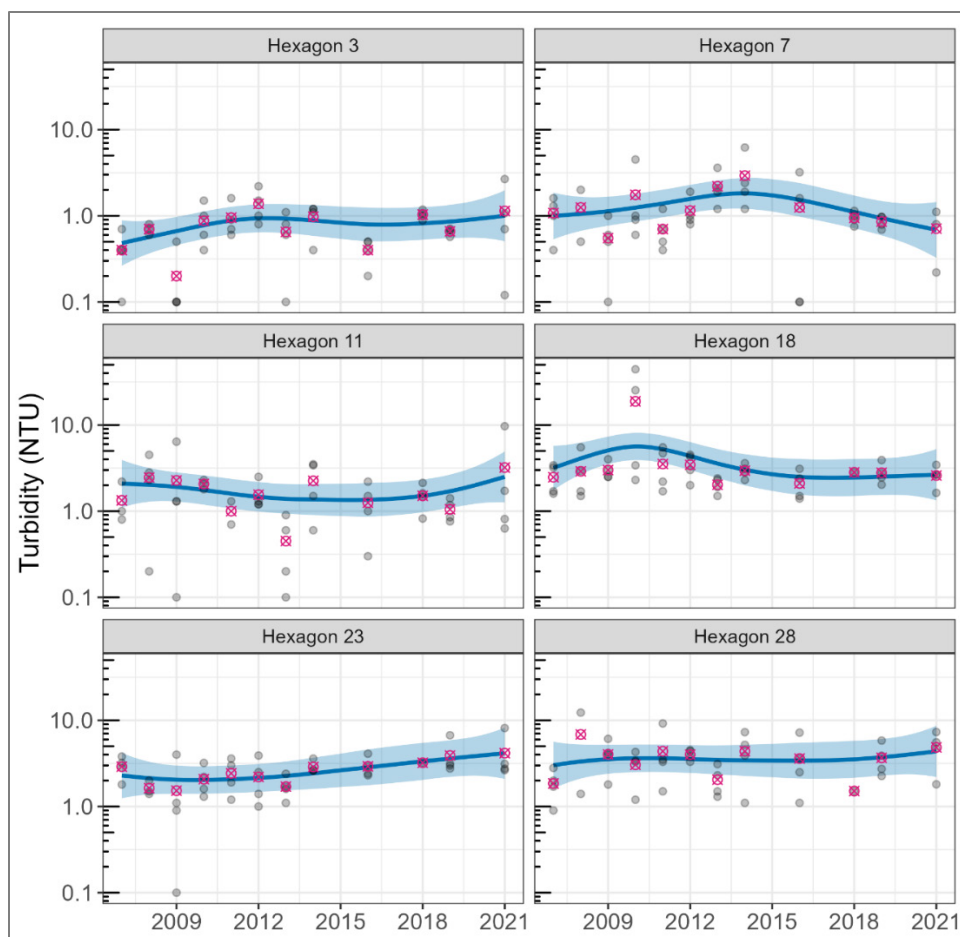


Figure 25. Mean surface turbidity (NTU) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, 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 a monotonically increasing trend in bottom dissolved oxygen concentrations, surface temperature, and turbidity at the trend stations during 2007 to 2021 (Table 21).

Table 21. Summary of multivariate Mann-Kendall test for monotonic trend in each parameter for Cape Cod National Seashore trend stations: 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	Z_{MK}	p -value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	-0.68	0.494
Dissolved oxygen (mg/L)	Bottom	2.48	0.013
PAR attenuation (K_d (m^{-1}))	Water Column	-0.25	0.800
Salinity (psu)	Surface	0.28	0.779
Temperature ($^{\circ}\text{C}$)	Surface	2.70	0.007
Turbidity (NTU)	Surface	2.18	0.030

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, and $f_{\text{year}_i}(\text{doy})$ is a rank 20 TRPS smooth of doym for the i th year, $f(\text{hour})$ is a rank 24 cyclic cubic spline. The doym 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.

Pleasant Bay Stratum Results

An example time series plot of dissolved oxygen measurements over the course of the instrument deployment is provided in Figure 26. Yearly summary statistics for each parameter and year can be found in Table 22. Notable observations from the fitted smooths and data summaries for each parameter are provided in the subsections below.

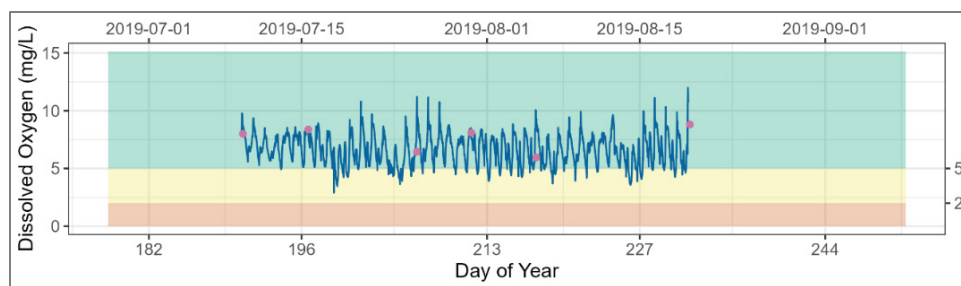


Figure 26. Example continuous dissolved oxygen readings from a data logger deployed at Cape Cod National Seashore Pleasant Bay logging station in 2019. Magenta points represent discrete grab samples collected every week for quality assurance. Estuarine quality category thresholds (Table 2) are delineated by the background color (green = good condition; yellow = fair; orange = poor).

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Table 22. Yearly summary statistics for water quality parameters collected at the Cape Cod National Seashore Pleasant Bay logging station. [SD = standard deviation; n = number of observations; NA = not available].

Parameter	Statistic	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
Chlorophyll- <i>a</i> (µg/L)	Mean	2.51	3.15	3.64	13.63	4.30	6.55	4.71	2.60	4.96	1.20	4.24	3.44
Chlorophyll- <i>a</i> (µg/L)	SD	1.51	1.09	2.83	9.98	1.13	2.83	2.78	1.68	7.28	0.92	2.42	1.42
Chlorophyll- <i>a</i> (µg/L)	n	2840	1837	2719	4510	2502	3163	3692	2995	3399	3529	3812	2669
Dissolved oxygen (mg/L)	Mean	9.28	8.38	8.19	8.08	7.27	6.18	6.97	7.21	7.35	6.95	6.62	7.40
Dissolved oxygen (mg/L)	SD	1.59	1.77	1.13	1.40	1.27	1.18	1.42	1.40	1.95	1.42	1.32	1.88
Dissolved oxygen (mg/L)	n	2852	4411	2771	727	2506	3163	3737	3068	3651	3564	3935	2669
Depth (m)	Mean	0.89	1.02	1.04	1.12	1.29	1.12	1.26	1.09	1.13	1.09	1.23	0.99
Depth (m)	SD	0.46	0.48	0.47	0.48	0.47	0.43	0.45	0.43	0.39	0.40	0.37	0.38
Depth (m)	n	2878	5722	4611	5429	2506	3163	3738	3068	3651	3564	3935	2669
PAR attenuation (<i>K_d</i> (m ⁻¹))	Mean	0.75	1.04	0.83	0.68	0.49	0.52	0.53	0.64	0.56	0.76	0.81	0.49
PAR attenuation (<i>K_d</i> (m ⁻¹))	SD	0.48	0.72	0.75	0.66	0.43	0.33	0.44	0.71	0.42	0.43	0.65	0.33
PAR attenuation (<i>K_d</i> (m ⁻¹))	n	392	921	730	673	469	578	774	551	342	740	989	538
pH	Mean	NA	NA	NA	NA	NA	NA	NA	7.94	NA	7.99	7.94	7.95
pH	SD	NA	NA	NA	NA	NA	NA	NA	0.16	NA	0.12	0.13	0.16
pH	n	0	0	0	0	0	0	0	3068	0	3564	3935	2669
Salinity (psu)	Mean	31.58	30.59	32.13	31.64	31.40	33.20	30.27	29.44	33.37	30.76	30.52	31.71
Salinity (psu)	SD	0.23	0.68	0.71	0.59	0.43	0.47	0.53	1.95	0.27	0.62	0.54	0.19
Salinity (psu)	n	2876	5722	2772	2386	2506	3163	3736	3068	3651	3564	3933	2668
Temperature (°C)	Mean	21.85	22.00	21.55	22.70	23.03	24.13	24.35	22.33	24.43	23.99	24.51	23.44
Temperature (°C)	SD	2.13	2.11	2.48	2.57	2.11	1.85	2.13	1.64	2.04	2.04	1.73	2.22
Temperature (°C)	n	2878	5722	4611	5429	2506	3163	3738	3068	3651	3564	3935	2669
Turbidity (NTU)	Mean	0.89	1.66	NA	NA	1.41	2.25	2.78	1.65	1.95	1.57	3.51	1.54
Turbidity (NTU)	SD	0.76	3.30	NA	NA	1.01	4.18	3.86	4.80	0.87	0.72	1.89	1.82
Turbidity (NTU)	n	1745	2038	0	0	2504	3102	3527	3048	3631	3526	3902	2666

Chlorophyll-*a*

Mean chlorophyll-*a* concentrations ranged from 1.20 to 13.63 µg/L and were classified as being in good condition (i.e., <5 µg/L) except for 2010 and 2012, when conditions were fair (Table 22). Intra-annual mean trends in chlorophyll-*a* concentration were generally smooth for most years except for 2010, 2012, and 2016 (Figure 27), and the associated distribution of measurements tended to be extremely long-tailed (Figure 28). In most years, the majority of the day within the PB stratum was spent alternating between good and fair conditions. There were several years (e.g., 2010, 2012, 2013, and 2016) where chlorophyll-*a* condition was poor for several hours throughout the day (Figure 29).

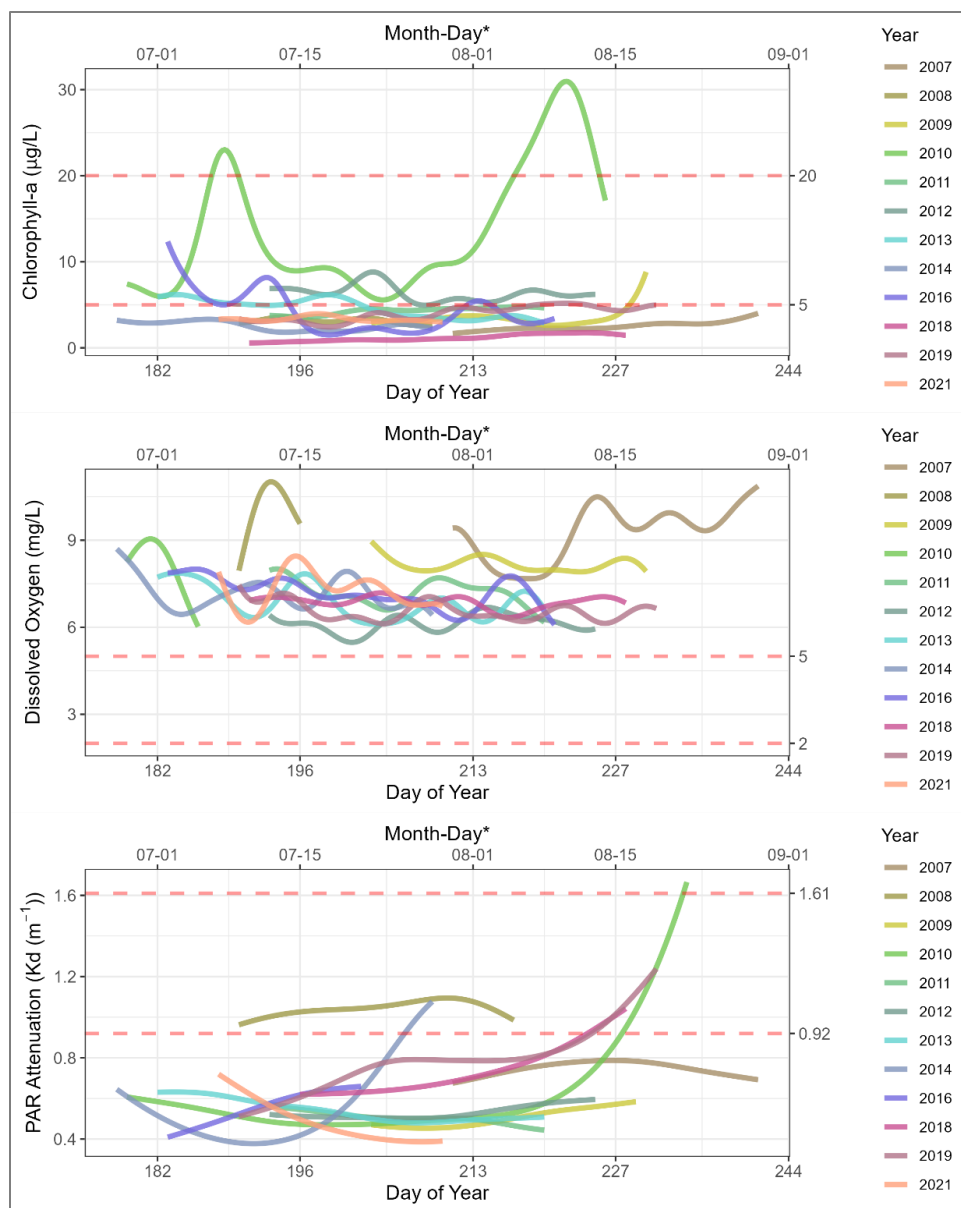


Figure 27. Intra-annual trends in chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Pleasant Bay logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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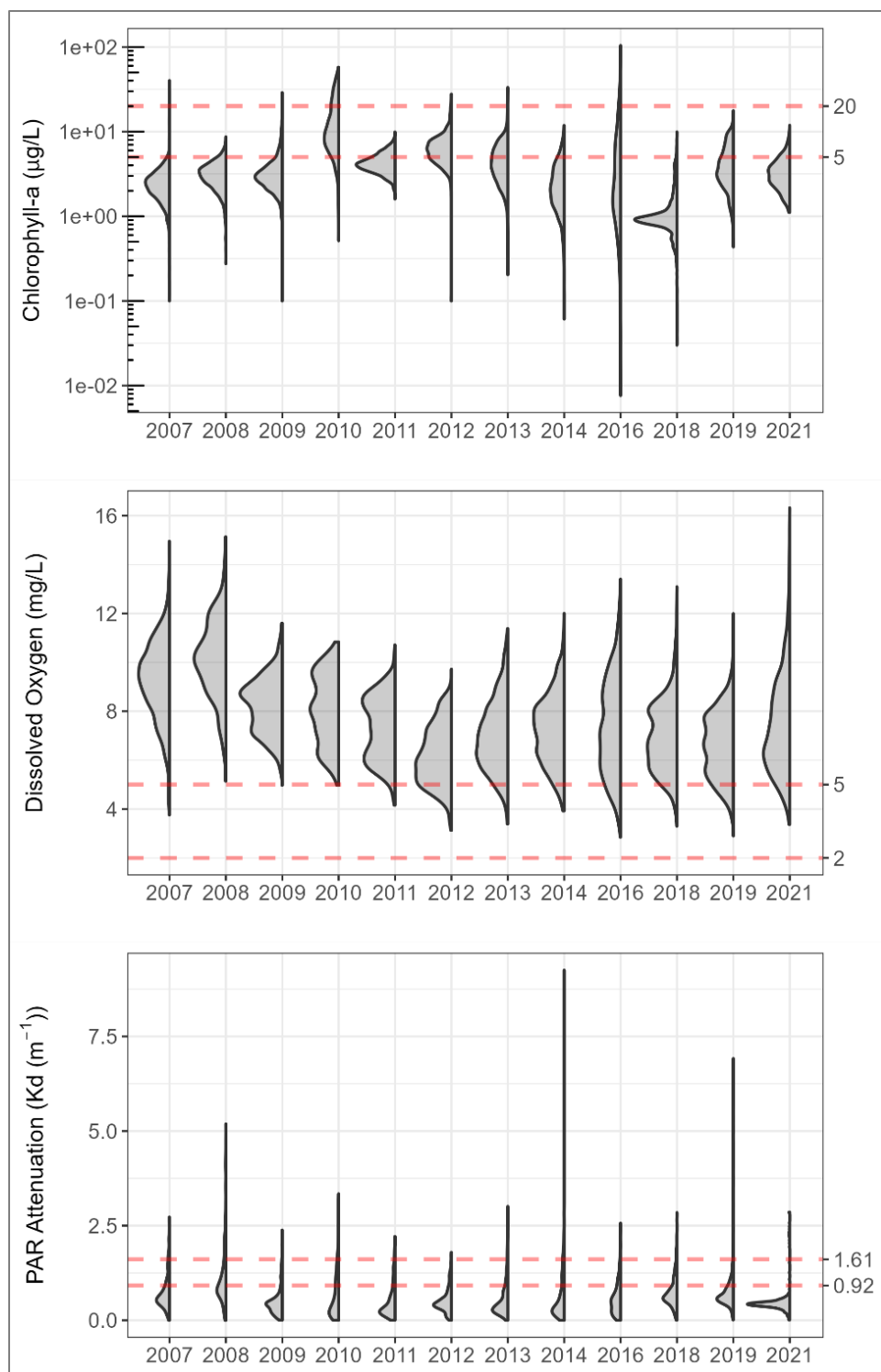


Figure 28. Distribution of index period time series values for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Pleasant Bay logging station. Estuarine quality category thresholds (Table 2) are plotted 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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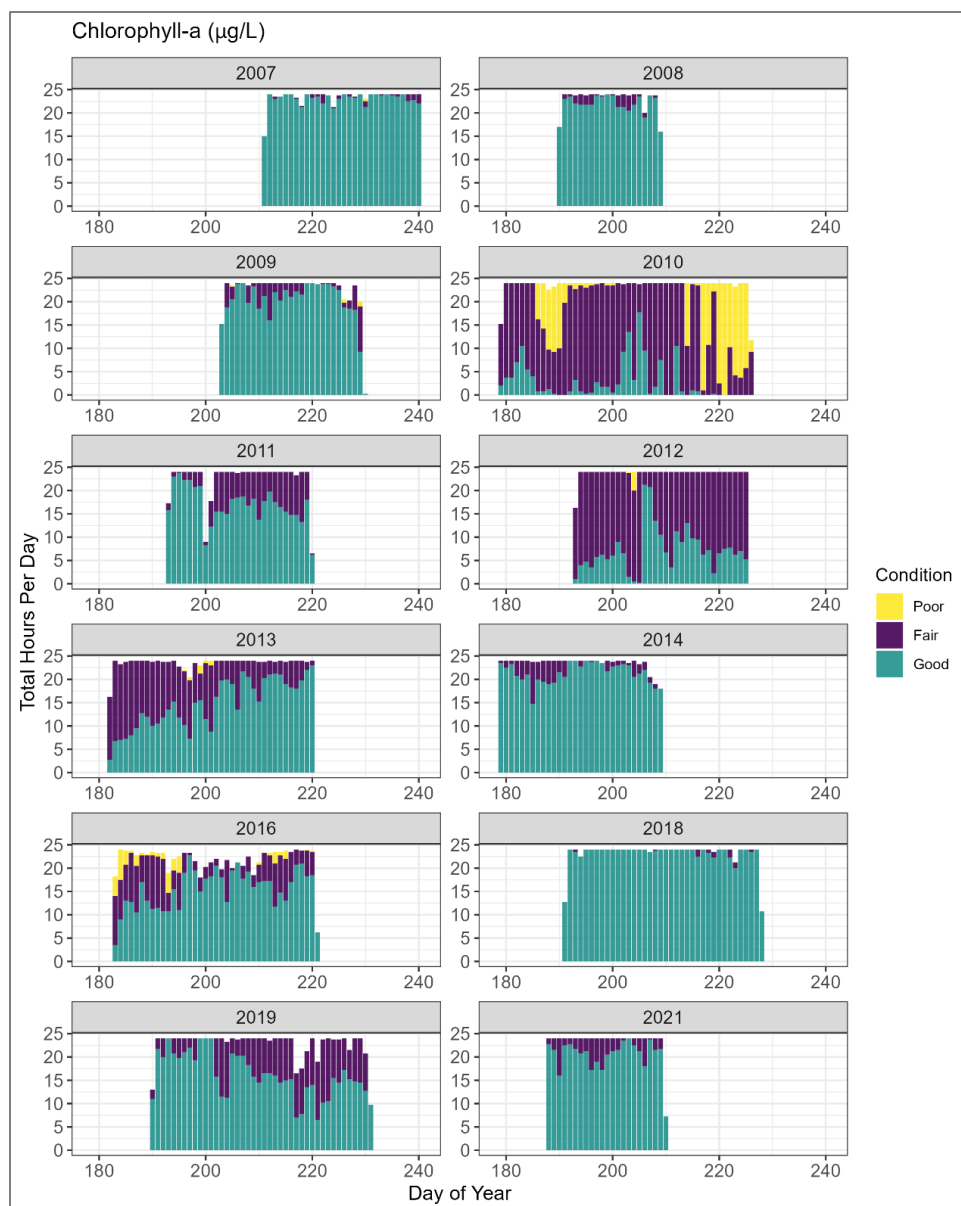


Figure 29. Total hours per day that surface chlorophyll-a concentration was observed within each condition category at the Cape Cod National Seashore Pleasant Bay logging station.
JESSICA NAGEL

Dissolved Oxygen

Mean dissolved oxygen concentrations ranged from 6.18 to 9.28 mg/L (Table 22). Intra-annual mean trends in dissolved oxygen were non-linear at this temporal scale and the cyclic nature was consistent across years (Figure 27). The distribution of measurements was long-tailed in many years (Figure 28). Dissolved oxygen conditions in the PB stratum were generally good across all years with some days experiencing fair conditions for part of the day (Figure 30).

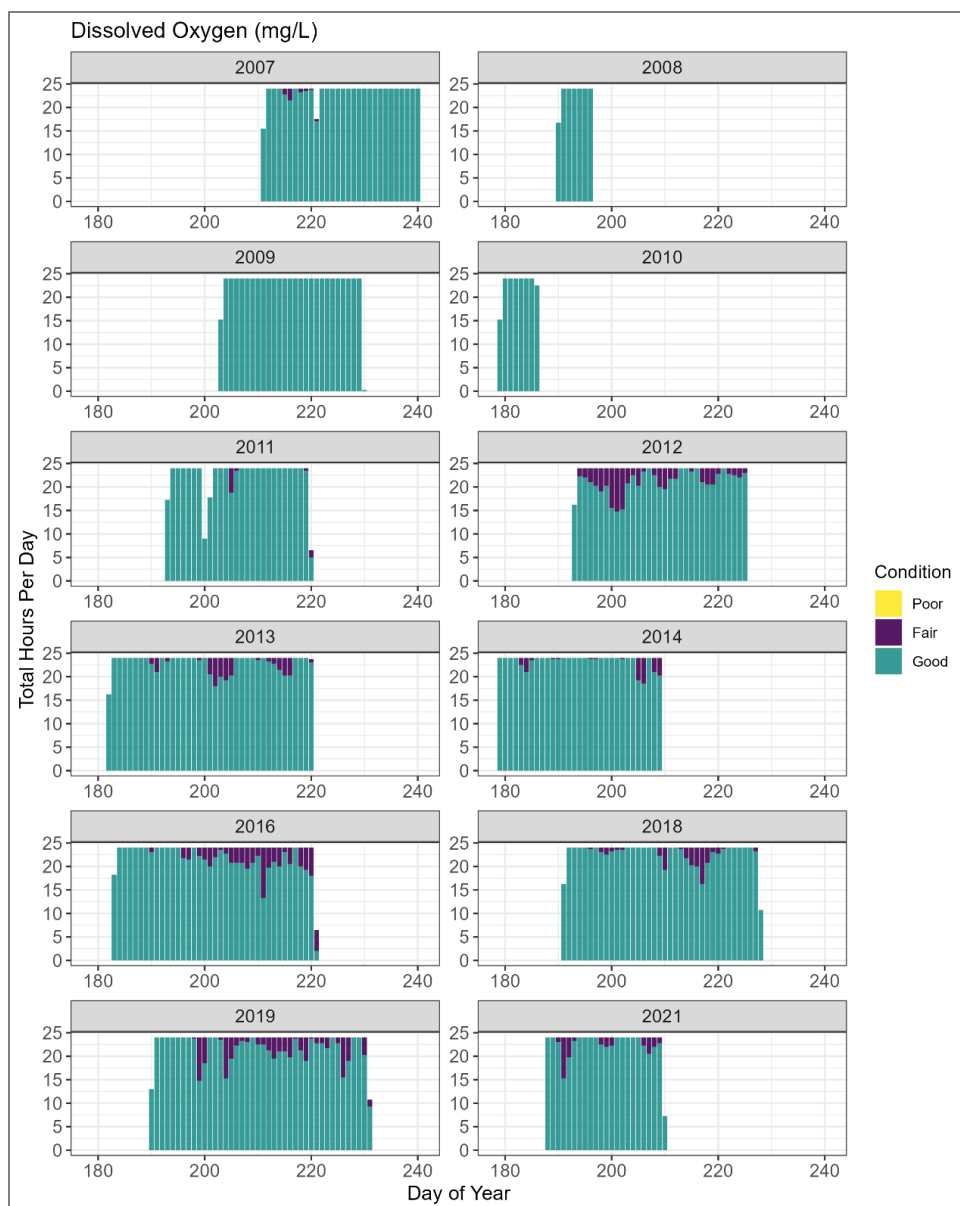


Figure 30. Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the Cape Cod National Seashore Pleasant Bay logging station.
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PAR Attenuation K_d

The highest mean PAR attenuation (1.04 m^{-1}) was observed in 2008 (Table 22). Intra-annual mean trends were relatively smooth with some years exhibiting increasing trends from late July through early August (Figure 27). The distribution of measurements was highly skewed in all years, and poor conditions ($> 1.61 \text{ m}^{-1}$) were observed in every year (Figure 28). PAR attenuation condition within the PB stratum was generally good with a majority of days experiencing both fair and poor conditions for the part of the day during which PAR could be measured (Figure 31).

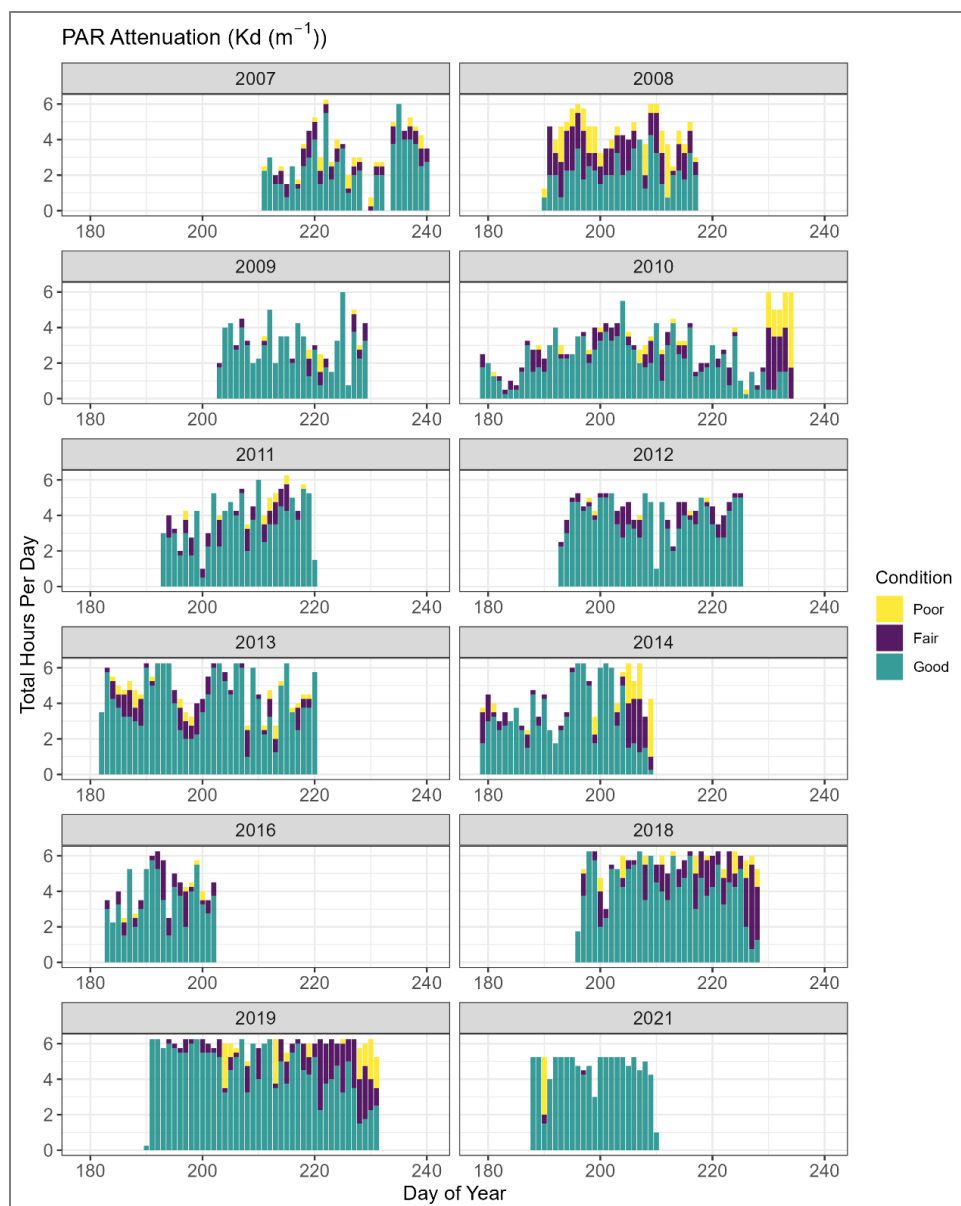


Figure 31. Total hours per day that PAR attenuation was observed within each condition category at the Cape Cod National Seashore Pleasant Bay logging station.

JESSICA NAGEL

Salinity

Mean salinity ranged from 30 to 33 psu (Table 22). Intra-annual mean trends in salinity were non-linear with 2014 experiencing a large decreasing trend that appears somewhat anomalous (Figure 32). For most years, salinity measurements within each summer index period typically spanned approximately 2–5 psu (Figure 33). The distribution of measurements was abnormal in 2014 and 2019 with ranges of approximately 6 and 10 psu, respectively.

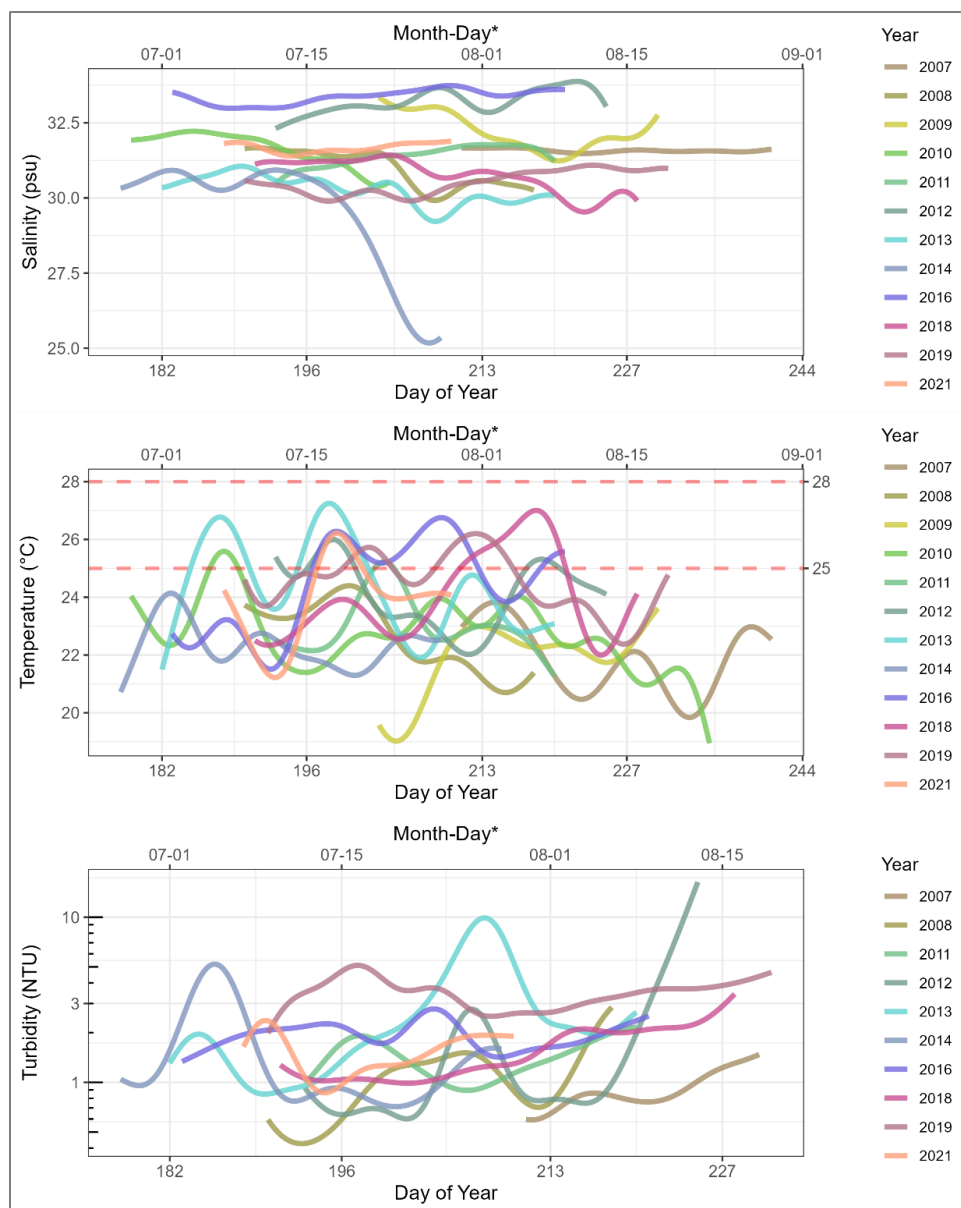


Figure 32. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Pleasant Bay logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trends for surface turbidity.

JESSICA NAGEL

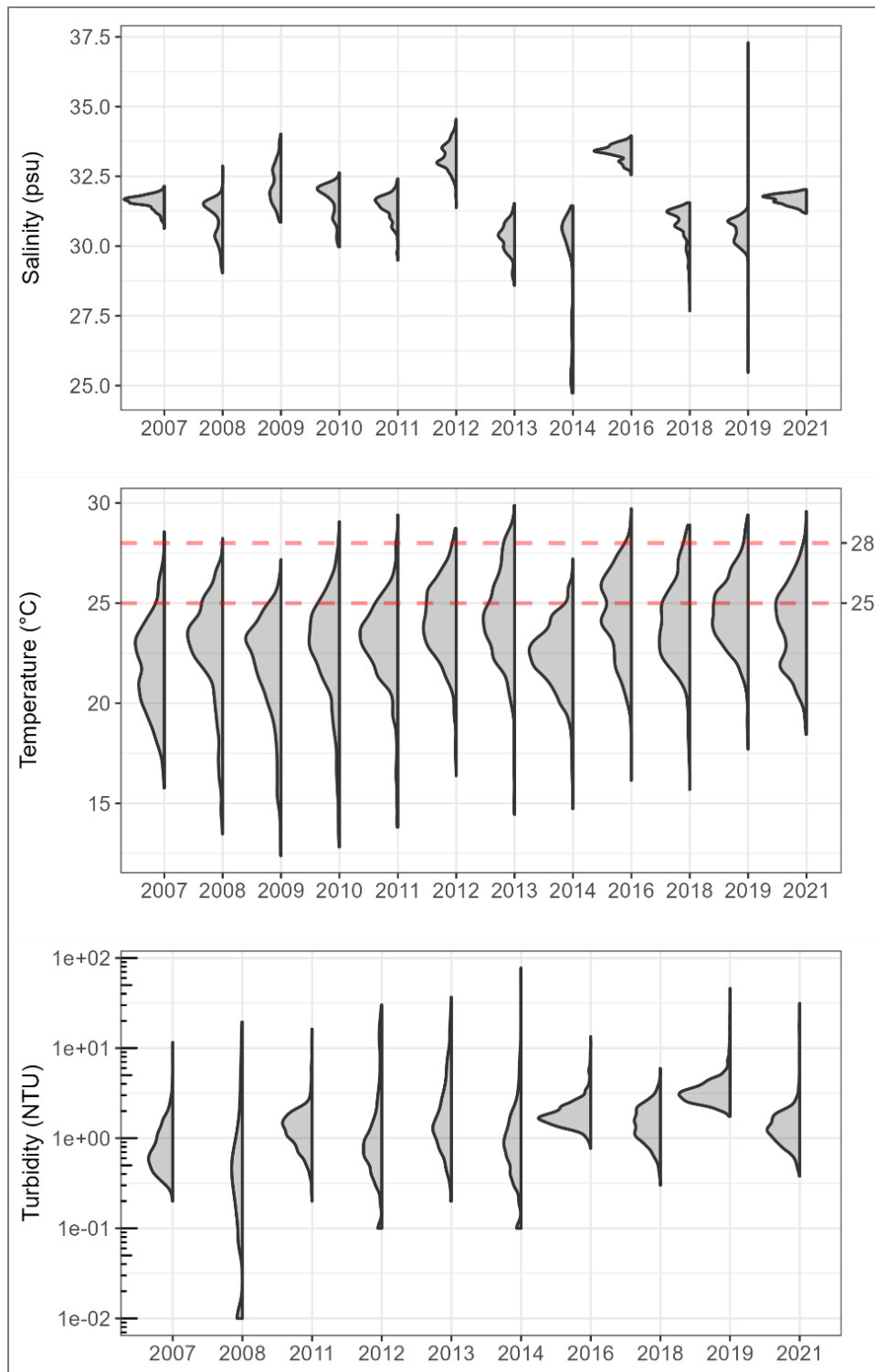


Figure 33. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Pleasant Bay logging station. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated distributions for surface turbidity.

JESSICA NAGEL

Temperature

Mean temperatures ranged from 21.5 to 24.5°C (Table 22). Intra-annual mean trends in water temperature were highly non-linear with a cyclic nature that appears to be consistent among years (Figure 32). Water temperature measurements within each summer index period typically spanned approximately 10–15°C (Figure 33), and temperatures exceeded 28°C at some point in almost every year.

Turbidity

Mean turbidity ranged from 0.89 to 3.51 NTU, with the highest values observed in 2019 (Table 22). Intra-annual mean trends in turbidity were non-linear with most years experiencing an increasing trend between July and August (Figure 32). Turbidity measurements within the PB stratum were highly variable, spanning from approximately 10 to over 100 NTU (Figure 33).

pH

Mean values for pH ranged between 7.94 and 7.99 (Table 22). Intra-annual mean trends in pH were highly non-linear (Figure 34). The distribution of measurements typically spanned about 0.75 units (Figure 35).

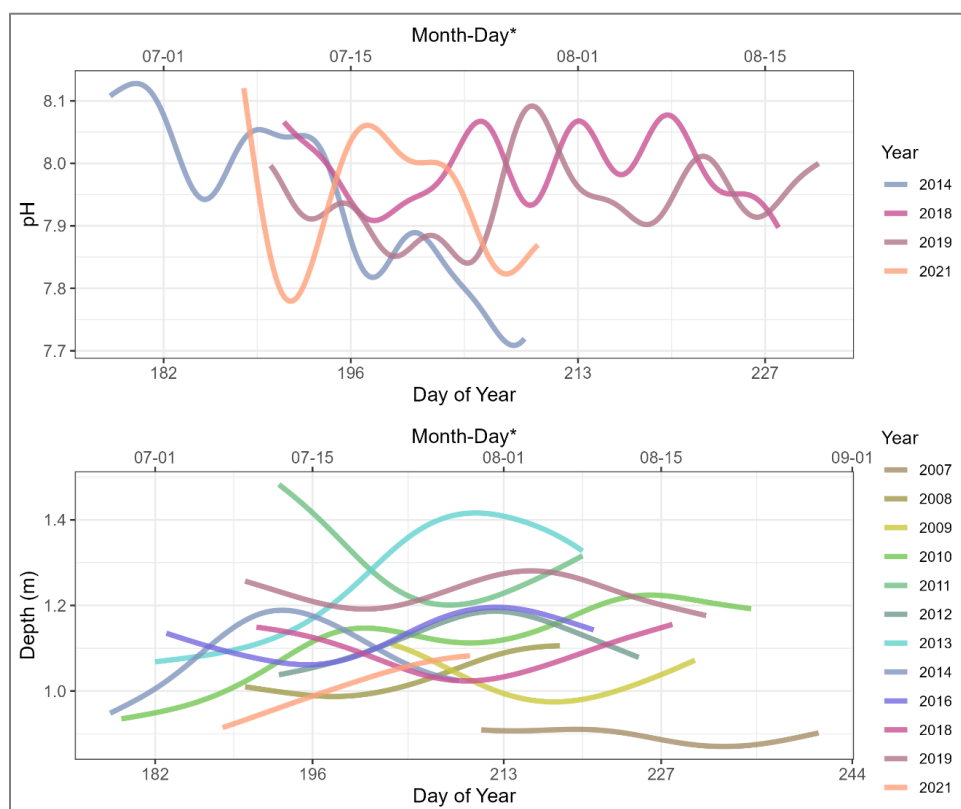


Figure 34. Intra-annual trends in pH (top) and depth (bottom) at the Cape Cod National Seashore Pleasant Bay logging station based on estimated generalized additive model smooths.

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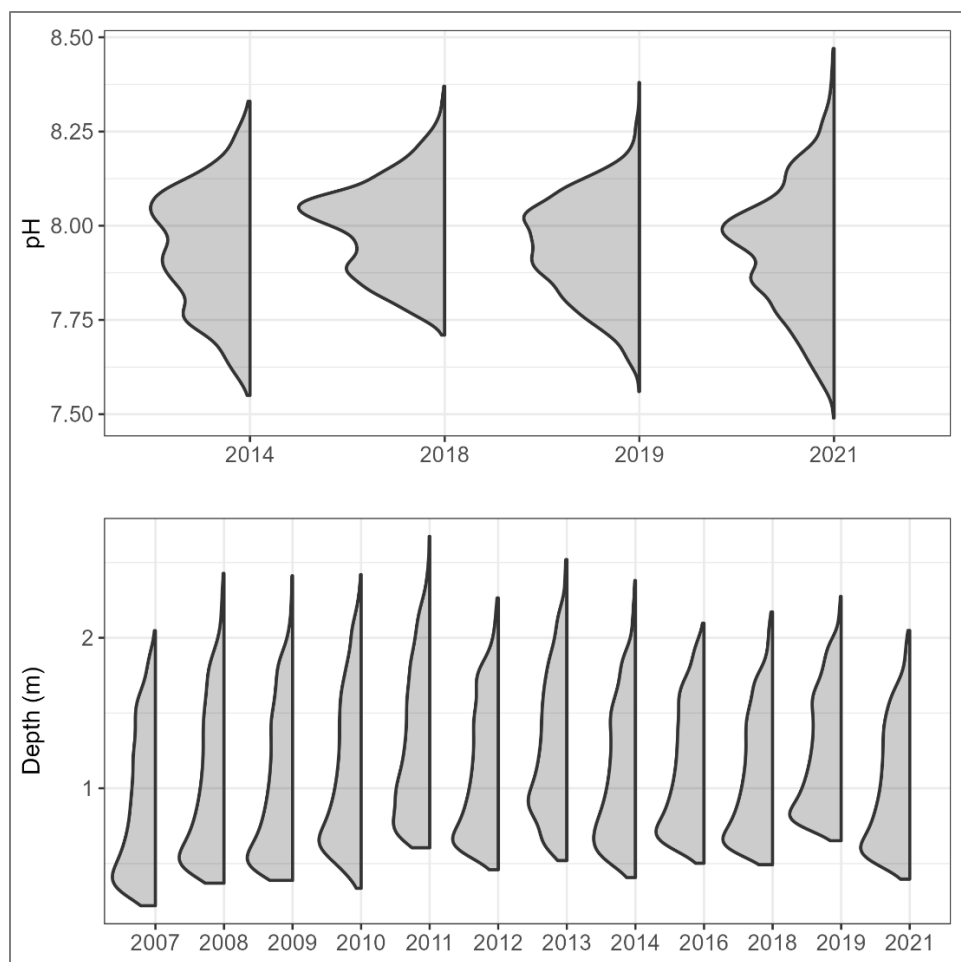


Figure 35. Distribution of index period time series values for pH (top) and depth (bottom) at the Cape Cod National Seashore Pleasant Bay logging station.

JESSICA NAGEL

Depth

Mean depth typically ranged from 0.9 to 1.3 m (Table 22). All years exhibited a non-linear intra-annual mean trend (Figure 34). Within a given year, the depth range was generally less than 1.75 m (Figure 35).

Nauset Harbor Stratum Results

Notable observations from the fitted smooths and data summaries for each parameter are described below. Note that a new location was used starting in 2012.

Chlorophyll-*a*

Mean chlorophyll-*a* concentrations ranged from 4.22 to 11.95 $\mu\text{g/L}$ and were classified as being in good to fair condition in every year (Table 23). Intra-annual mean trends in chlorophyll-*a* concentration were highly non-linear for most years and concentrations at the end of the deployment in 2021 were abnormally high (Figure 36). The associated distribution of measurements was highly skewed most years and poor conditions were observed at some point during the deployment every

year (Figure 37). Chlorophyll-*a* condition within NH stratum was generally variable and typically alternated between fair and good condition throughout the day (Figure 38). Extensive periods of poor conditions were observed for consecutive days in 2007, 2012, 2013, 2016, 2018, and 2021.

Table 23. Yearly summary statistics for parameters collected at the Cape Cod National Seashore Nauset Harbor logging station. Note: new location was used starting in 2012. [SD = standard deviation; n = number of observations; NA = not available].

Parameter	Statistic	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
Chlorophyll- <i>a</i> (µg/L)	Mean	7.69	6.89	5.10	4.22	7.12	11.95	7.26	7.74	9.06	10.92	4.80	7.71
Chlorophyll- <i>a</i> (µg/L)	SD	10.83	3.89	3.02	3.72	4.19	7.05	4.62	4.19	5.34	7.53	3.50	12.37
Chlorophyll- <i>a</i> (µg/L)	n	2391	4115	4749	4492	3741	3261	3341	3241	3820	2599	2313	2646
Dissolved oxygen (mg/L)	Mean	8.37	6.70	6.84	9.31	7.95	7.87	7.68	8.01	8.04	7.72	7.89	7.60
Dissolved oxygen (mg/L)	SD	1.55	1.73	0.97	2.13	0.96	1.04	1.23	0.82	0.88	0.90	0.87	0.77
Dissolved oxygen (mg/L)	n	2000	4308	5463	6231	3751	3247	3011	3268	3820	2606	2319	2667
Depth (m)	Mean	0.95	1.09	1.15	0.83	0.93	1.42	0.93	1.29	1.26	0.87	1.43	1.13
Depth (m)	SD	0.45	0.47	0.43	0.42	0.44	0.41	0.36	0.39	0.31	0.30	0.30	0.30
Depth (m)	n	2919	6734	5467	6234	3750	3260	3356	3265	3820	2606	2319	2667
PAR attenuation (K_d (m ⁻¹))	Mean	1.13	0.74	0.66	1.92	0.84	0.66	0.58	0.84	0.98	0.67	0.85	0.45
PAR attenuation (K_d (m ⁻¹))	SD	0.73	0.73	0.63	1.02	0.66	0.48	0.38	0.42	1.16	0.39	0.23	0.18
PAR attenuation (K_d (m ⁻¹))	n	356	268	147	742	413	522	515	839	781	585	613	560
pH	Mean	NA	NA	NA	NA	NA	NA	NA	7.88	7.96	7.96	8.06	7.89
pH	SD	NA	NA	NA	NA	NA	NA	NA	0.07	0.07	0.08	0.07	0.07
pH	n	0	0	0	0	0	0	0	3268	3818	2606	2319	2667
Salinity (psu)	Mean	31.58	32.65	33.59	31.81	30.07	32.00	30.95	30.41	31.50	31.65	30.94	31.78
Salinity (psu)	SD	0.29	0.60	0.45	0.65	0.53	0.39	0.52	0.45	0.28	0.28	0.32	0.20
Salinity (psu)	n	2891	4346	4506	6219	3751	3259	3355	3240	3820	2605	2319	2667
Temperature (°C)	Mean	18.29	18.65	19.03	18.92	19.53	18.90	21.16	17.76	19.44	20.51	20.13	19.90
Temperature (°C)	SD	2.43	2.55	2.42	3.21	2.75	2.76	2.80	2.92	2.50	2.04	2.50	2.39
Temperature (°C)	n	2919	6734	5467	6234	3751	3261	3356	3268	3820	2606	2319	2667
Turbidity (NTU)	Mean	5.07	3.43	2.07	2.73	2.40	1.94	2.33	3.00	2.39	1.73	3.20	1.35
Turbidity (NTU)	SD	6.02	4.28	2.34	2.54	1.48	1.04	2.92	1.78	4.11	0.70	1.14	0.67
Turbidity (NTU)	n	2427	3718	1580	3193	3741	2990	2692	3233	3815	2601	2299	2663

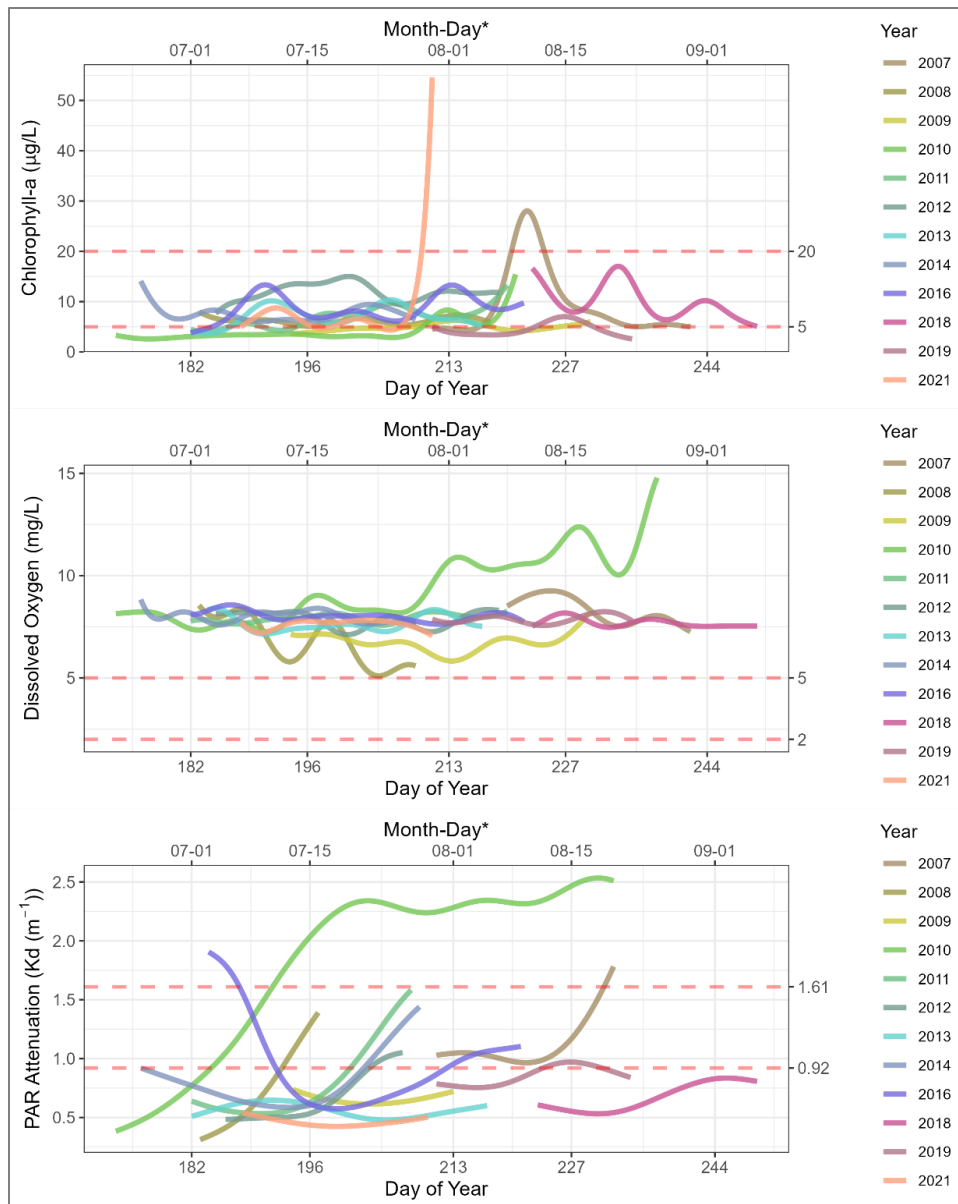


Figure 36. Intra-annual trends in surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Nauset Harbor logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: new location was used starting in 2012.
JESSICA NAGEL

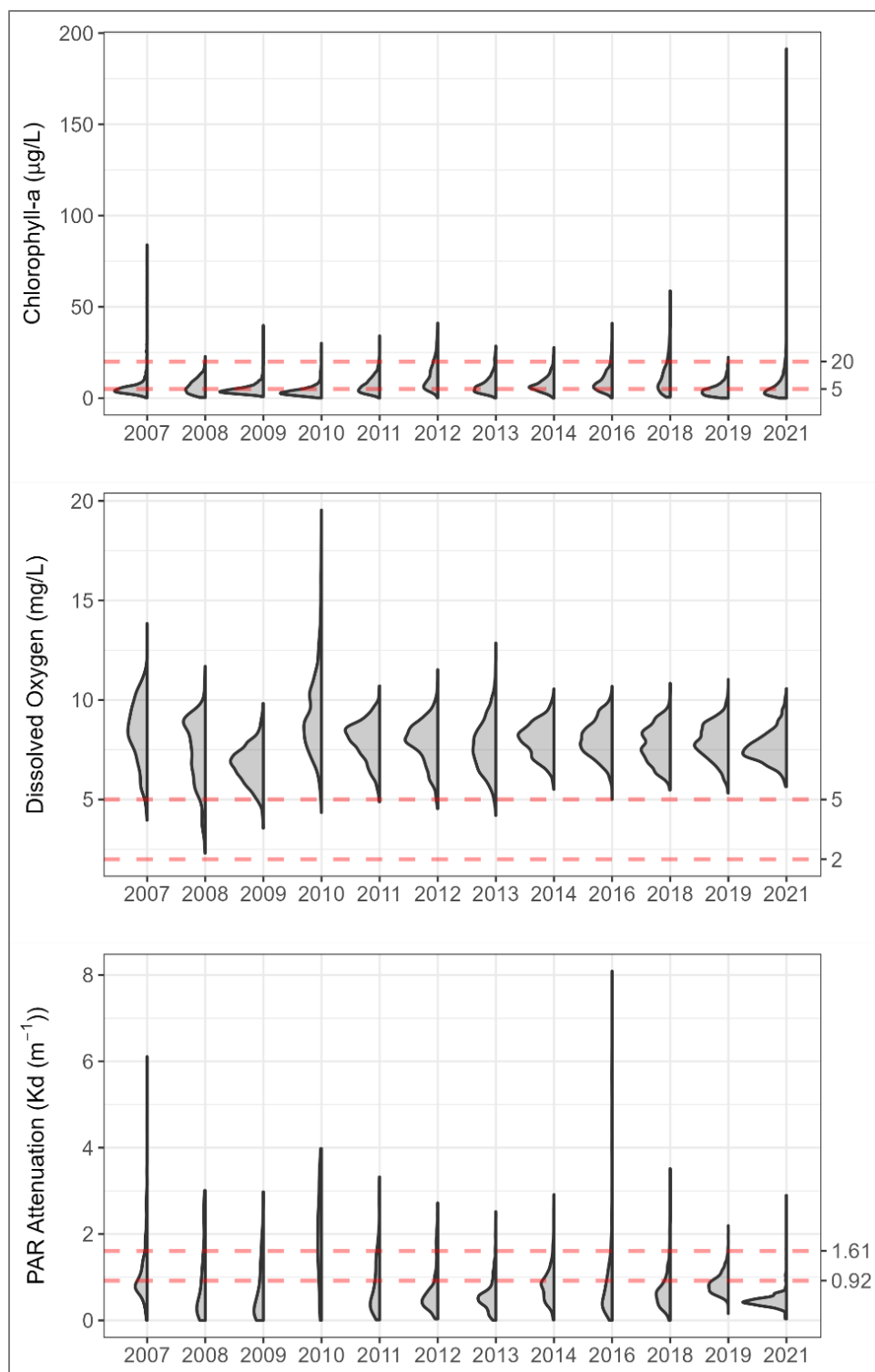


Figure 37. Distribution of index period time series values for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Nauset Harbor logging station. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: new location was used starting in 2012.

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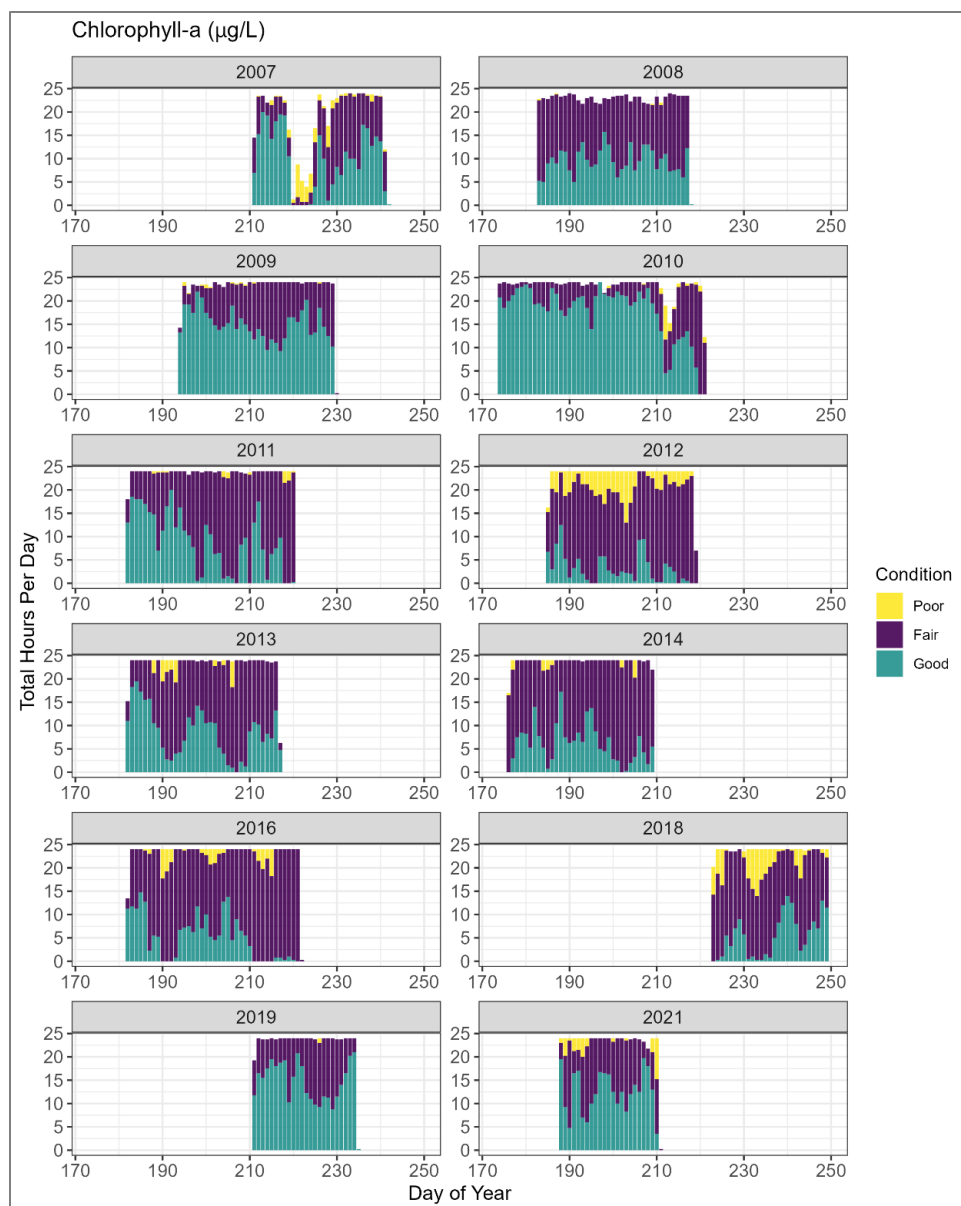


Figure 38. Total hours per day that surface chlorophyll-a concentration was observed within each condition category at the Cape Cod National Seashore Nauset Harbor logging station. Note: new location was used starting in 2012.

JESSICA NAGEL

Dissolved Oxygen

Mean dissolved oxygen concentrations ranged from 6.70 to 9.31 mg/L (Table 23). Intra-annual mean trends in dissolved oxygen were non-linear at this temporal scale and the cyclic nature was consistent across years (Figure 36). The distribution of measurements in 2010 was noticeably different from most other years (Figure 37). Dissolved oxygen conditions in the NH stratum were generally good throughout the day with occasional periods of fair conditions observed in several years (Figure 39).

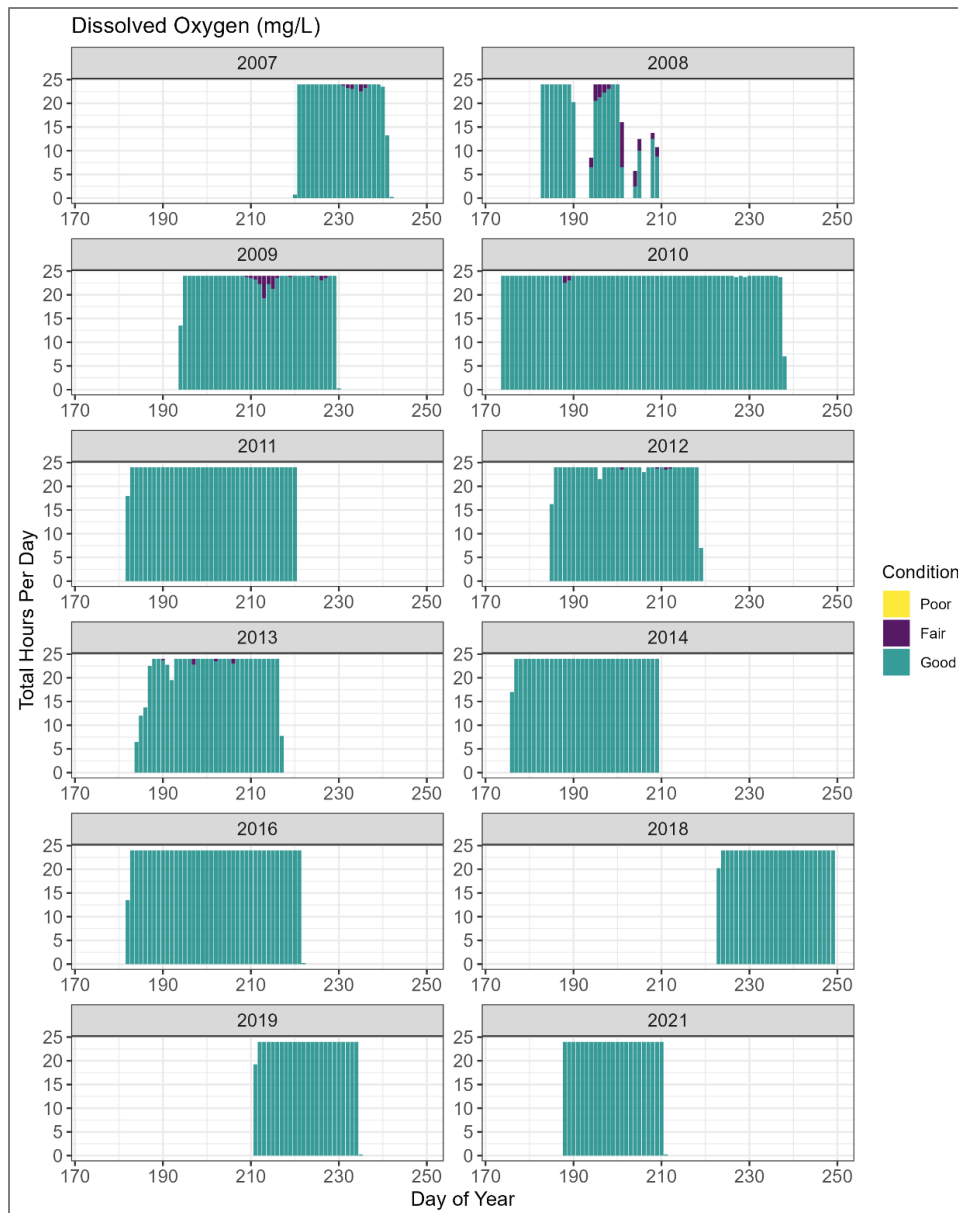


Figure 39. Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the Cape Cod National Seashore Nauset Harbor logging station. Note: new location was used starting in 2012.

JESSICA NAGEL

PAR Attenuation K_d

The highest mean PAR attenuation observed in the NH stratum was 1.92 m^{-1} in 2010 (Table 23). Intra-annual trends were non-linear and tended to increase throughout the month of July and into August for most years (Figure 36). The distribution of measurements in 2007 and 2016 was more highly skewed than other years (Figure 37). While the majority of the hours during the day in which PAR attenuation could be measured was spent in good to fair condition, poor conditions were

observed in almost every year (Figure 40). Extensive periods of poor conditions were observed in 2010.

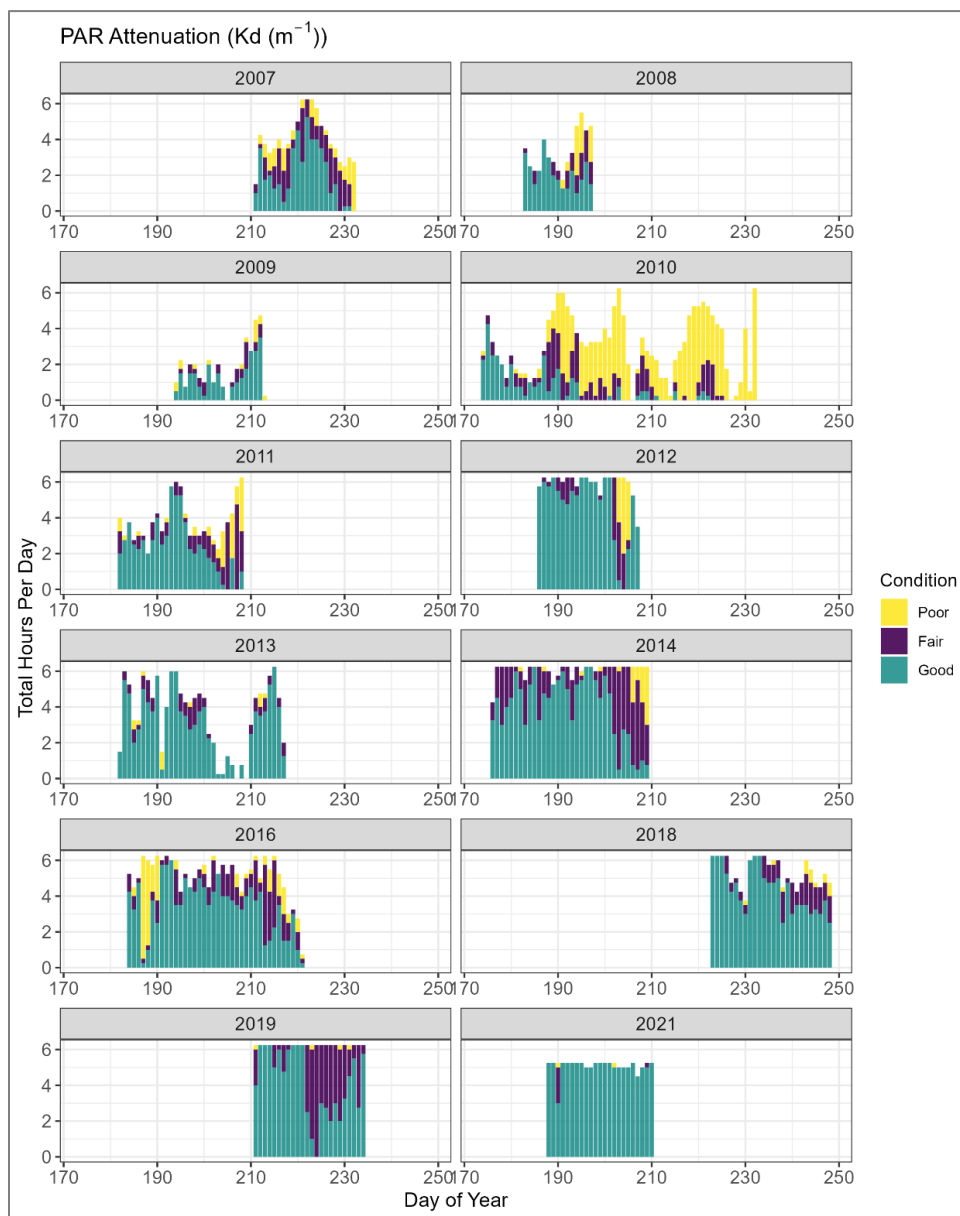


Figure 40. Total hours per day that PAR attenuation was observed within each condition category at the Cape Cod National Seashore Nauset Harbor logging station. Note: new location was used starting in 2012.

JESSICA NAGEL

Salinity

Mean salinity ranged from 30.1 to 33.6 (Table 23). Intra-annual mean trends in salinity were non-linear and highly variable year-to-year (Figure 41). Except for 2011, salinity measurements typically spanned between 2–5 psu (Figure 42).

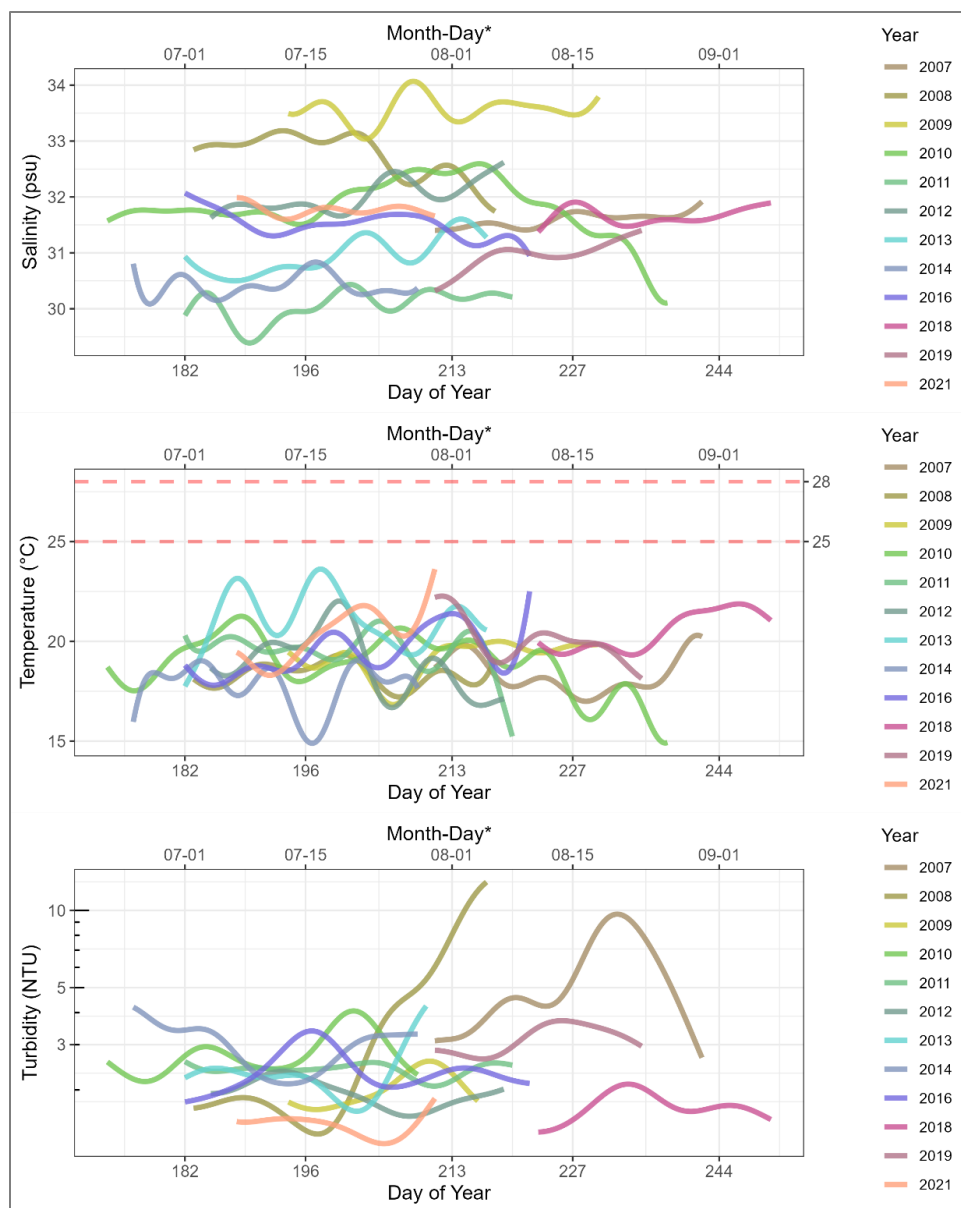


Figure 41. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Nauset Harbor logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trends for surface turbidity. Note: new location was used starting in 2012.

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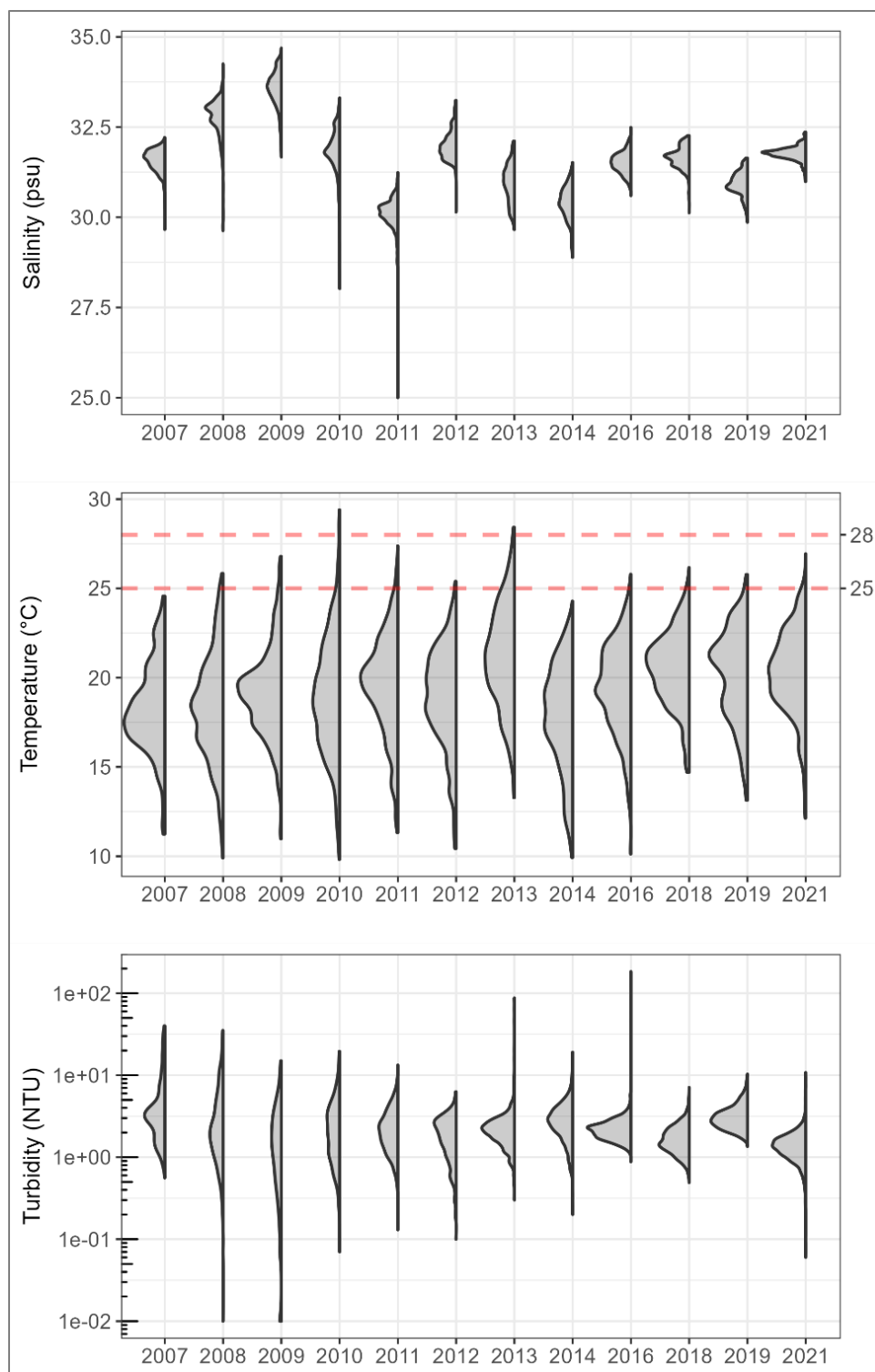


Figure 42. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Nauset Harbor logging station. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Notes: new location was used starting in 2012; the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated distributions for surface turbidity.

JESSICA NAGEL

Temperature

Mean temperature ranged from 17.8 to 21.2 (Table 23). Intra-annual mean trends in water temperature were non-linear and often increased from early July through August (Figure 41). Water temperature measurements within each year typically spanned approximately 10–15°C (Figure 42). Temperatures exceeded 25°C at some point during the deployment every year.

Turbidity

Mean turbidity ranged from 1.35 to 5.07 NTU (Table 23). Intra-annual mean trends in turbidity were non-linear with 2007 and 2008 having somewhat anomalous trends (Figure 41). Turbidity measurements were highly variable, spanning from approximately 10 to over 100 NTU (Figure 42).

pH

Mean pH ranged from 7.88 to 8.06 (Table 23). Intra-annual trends in pH within the NH stratum were non-linear and appeared to be non-stationary for some years (Figure 43). The distribution of measurements typically spanned approximately 0.5 units (Figure 44).

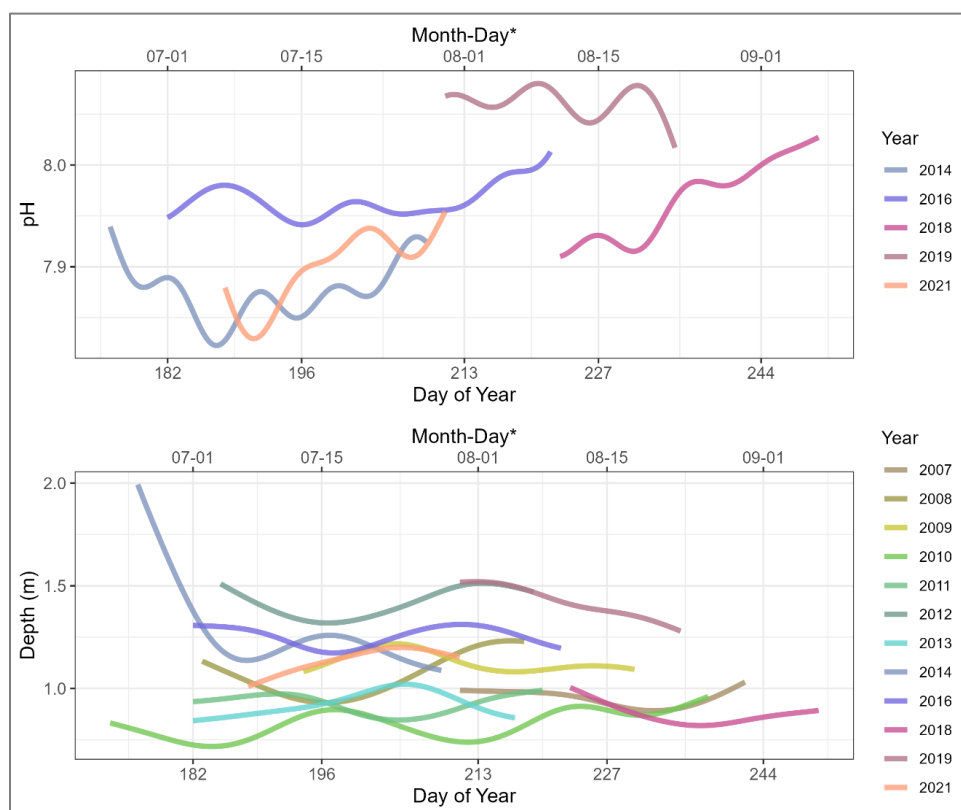


Figure 43. Intra-annual trends in pH (top) and depth (bottom) at the Cape Cod National Seashore Nauset Harbor logging station based on estimated generalized additive model smooths. Note: new location was used starting in 2012.

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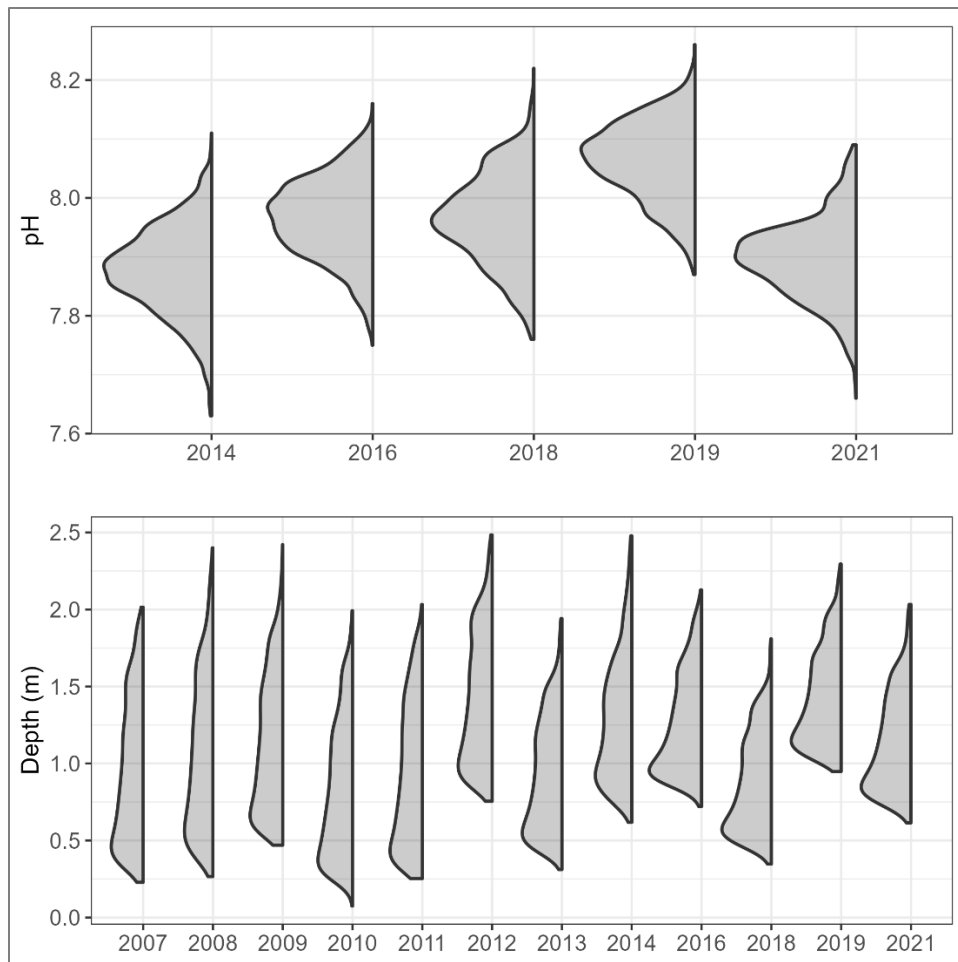


Figure 44. Distribution of index period time series values for pH (top) and depth (bottom) at the Cape Cod National Seashore Nauset Harbor logging station. Note: new location was used starting in 2012.

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Depth

Mean depth typically ranged from 0.8 to 1.4 m (Table 23). Except for 2014, most years exhibited a relatively smooth intra-annual mean trend (Figure 43). Within a given year, the depth range was generally less than 1.75 m (Figure 44).

Salt Pond Stratum Results

Notable observations from the fitted smooths and data summaries for each parameter are described below. Note that the data-logger was suspended from a floating buoy through 2013, and from 2014 onward, it was deployed on a structure a fixed distance from the estuary bottom.

Chlorophyll-*a*

Mean chlorophyll-*a* concentrations ranged from 7.66 to 99.1 $\mu\text{g/L}$ and were classified as being in fair condition in every year except for 2008, 2009, 2012, and 2018 when conditions were poor (Table 24). Intra-annual mean trends in chlorophyll-*a* concentration within the SP stratum were non-linear with a slight increase occurring between July and August in most years (Figure 45). The distribution

of measurements in 2011 and 2016 was more highly skewed than other years and poor conditions were observed in every year (Figure 46). Although there were several years when the majority of the days were spent in fair to good condition, extensive periods of poor chlorophyll-*a* conditions were observed throughout the day in most years (Figure 47). Concentrations were abnormally high and conditions were extremely poor in 2018.

Table 24. Yearly summary statistics for parameters collected at the Cape Cod National Seashore Salt Pond logging station. Note: The data logger deployment method changed from being suspended from a float (2007–2013) to being fixed at a set distance from the bottom (2014–2021). [SD = standard deviation; n = number of observations; NA = not available].

Parameter	Statistic	Sampling Year										
		2007	2008	2009	2010	2011	2012	2014	2016	2018	2019	2021
Chlorophyll- <i>a</i> (µg/L)	Mean	11.65	20.90	22.97	15.17	18.50	21.74	16.41	9.11	99.07	16.50	7.66
Chlorophyll- <i>a</i> (µg/L)	SD	10.28	11.25	10.87	19.02	30.94	16.13	9.16	8.08	46.91	5.68	5.66
Chlorophyll- <i>a</i> (µg/L)	n	3277	3073	2100	6159	2335	3261	3217	3478	2604	1667	1078
Dissolved oxygen (mg/L)	Mean	4.88	6.63	5.75	1.01	0.90	4.39	7.97	7.16	6.41	6.76	7.32
Dissolved oxygen (mg/L)	SD	1.66	1.51	1.20	1.68	1.29	1.85	2.18	2.08	1.92	2.06	1.89
Dissolved oxygen (mg/L)	n	3277	3079	3349	2381	2350	3272	3266	3733	2609	2008	1078
Depth (m)	Mean	5.41	2.78	3.20	5.30	5.03	2.86	1.00	1.19	0.98	0.83	1.13
Depth (m)	SD	0.06	0.05	0.05	0.34	0.05	0.09	0.30	0.35	0.34	0.31	0.30
Depth (m)	n	3276	3078	3341	5115	4003	3256	3266	3733	2609	2008	1078
PAR attenuation (K_d (m ⁻¹))	Mean	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.64	0.86
PAR attenuation (K_d (m ⁻¹))	SD	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.22	0.20
PAR attenuation (K_d (m ⁻¹))	n	0	0	0	0	0	0	0	0	0	409	547
pH	Mean	NA	NA	NA	NA	NA	NA	7.88	NA	7.78	7.94	7.80
pH	SD	NA	NA	NA	NA	NA	NA	0.18	NA	0.17	0.17	0.17
pH	n	0	0	0	0	0	0	3266	0	2609	2008	1078
Salinity (psu)	Mean	31.18	29.84	31.34	32.13	31.89	30.22	30.37	32.13	30.52	29.86	30.73
Salinity (psu)	SD	0.13	0.25	0.25	0.71	1.33	0.45	0.56	0.55	0.26	0.22	0.33
Salinity (psu)	n	3277	3079	3160	6065	3014	1569	3265	3733	2609	2008	1078
Temperature (°C)	Mean	19.12	20.29	20.25	19.20	19.96	21.52	20.83	22.94	24.07	24.47	22.40
Temperature (°C)	SD	0.93	1.04	1.04	1.46	1.22	1.10	1.85	1.60	1.87	1.49	1.58
Temperature (°C)	n	3277	3079	3349	6235	4021	3272	3266	3733	2609	2008	2657
Turbidity (NTU)	Mean	4.01	3.42	2.11	22.25	8.14	3.07	2.34	3.88	3.86	4.49	2.80
Turbidity (NTU)	SD	2.50	2.46	1.65	25.06	7.29	1.57	1.33	0.88	0.91	1.04	0.52
Turbidity (NTU)	n	3275	3068	3314	6126	3960	3251	3260	3688	2600	2002	1074

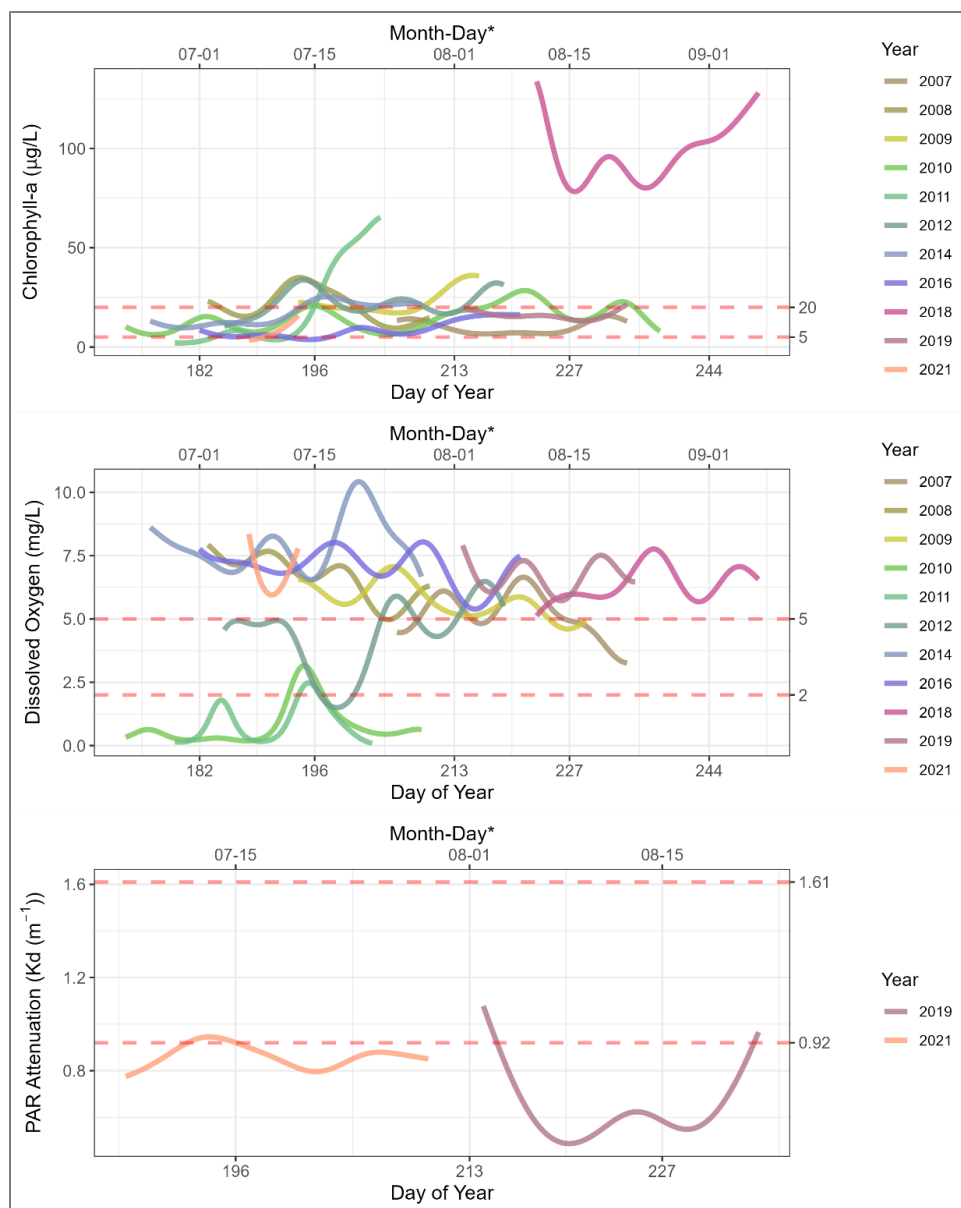


Figure 45. Intra-annual trends in surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Salt Pond logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: The data logger deployment method changed from being suspended from a float (2007–2013) to being fixed at a set distance from the bottom (2014–2021).

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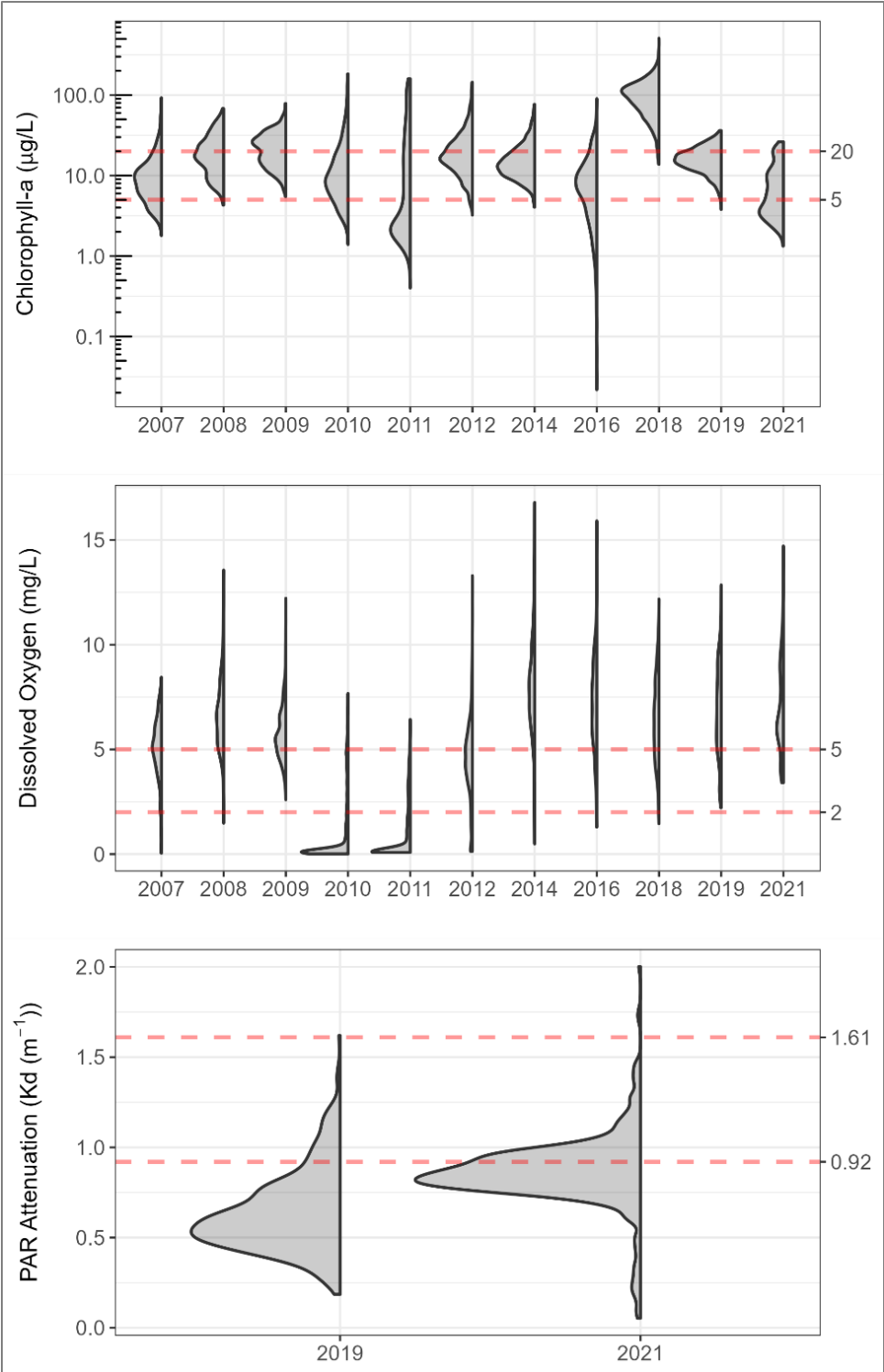


Figure 46. Distribution of index period time series values for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Salt Pond logging station. Estuarine quality category thresholds (Table 2) are plotted 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. Note: The data logger deployment method changed from being suspended from a float (2007–2013) to being fixed at a set distance from the bottom (2014–2021).
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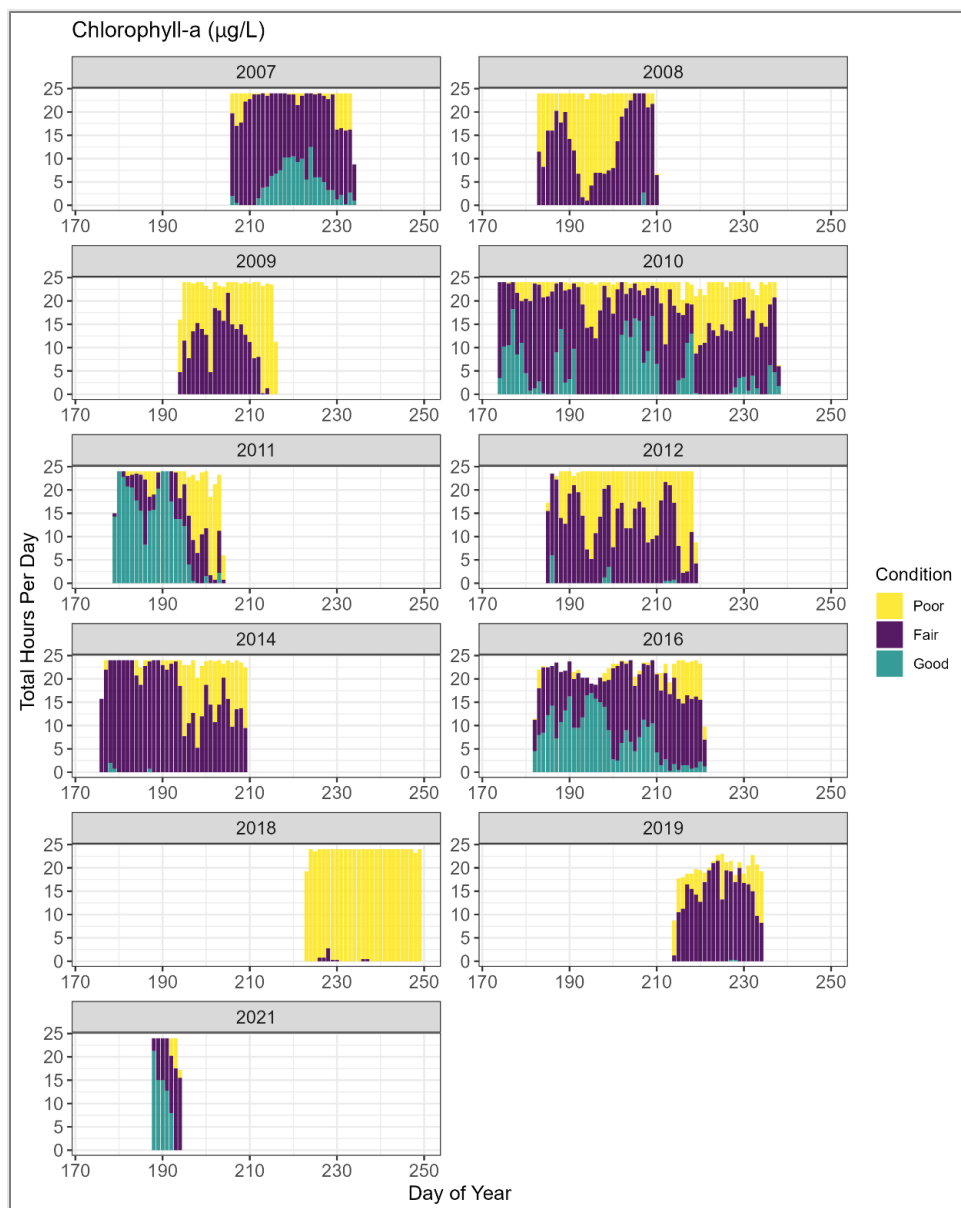


Figure 47. Total hours per day that surface chlorophyll-a concentration was observed within each condition category at the Cape Cod National Seashore Salt Pond logging station. Note: The data logger deployment method changed from being suspended from a float (2007–2013) to being fixed at a set distance from the bottom (2014–2021).

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Dissolved Oxygen

Mean dissolved oxygen concentrations ranged from 0.90 to 7.97 mg/L and were characterized as being in fair to good condition in every year except for 2010 and 2011 when conditions were poor (Table 24). Intra-annual mean trends in dissolved oxygen were non-linear and cyclic at this temporal scale (Figure 45). The distribution of measurements was unusually skewed in 2010 and 2011 (Figure 46). In most years, dissolved oxygen conditions alternated between good and fair throughout the day

with occasional short periods of poor conditions (Figure 48). Concentrations were abnormally low and conditions were extremely poor in 2010 and 2011.

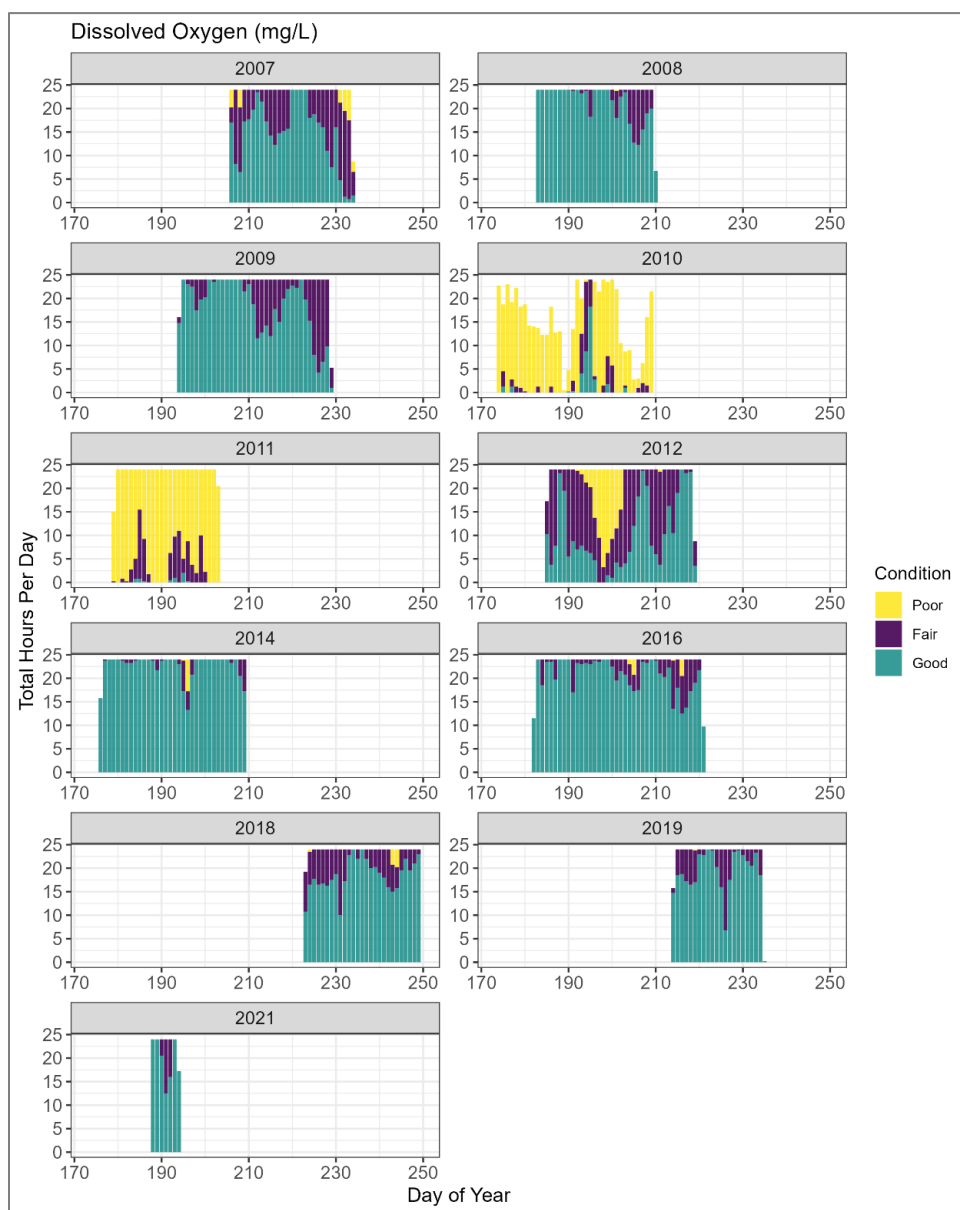


Figure 48. Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the Cape Cod National Seashore Salt Pond logging station. Note: The data logger deployment method changed from being suspended from a float (2007–2013) to being fixed at a set distance from the bottom (2014–2021).

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PAR Attenuation K_d

PAR attenuation data were only available for the SP stratum for 2019 and 2021. Inter-annual mean trends were non-linear (Figure 45). Conditions typically fluctuated between fair and good with

occasional periods of poor conditions throughout the portion of the day in which PAR attenuation could be measured (Figure 49).

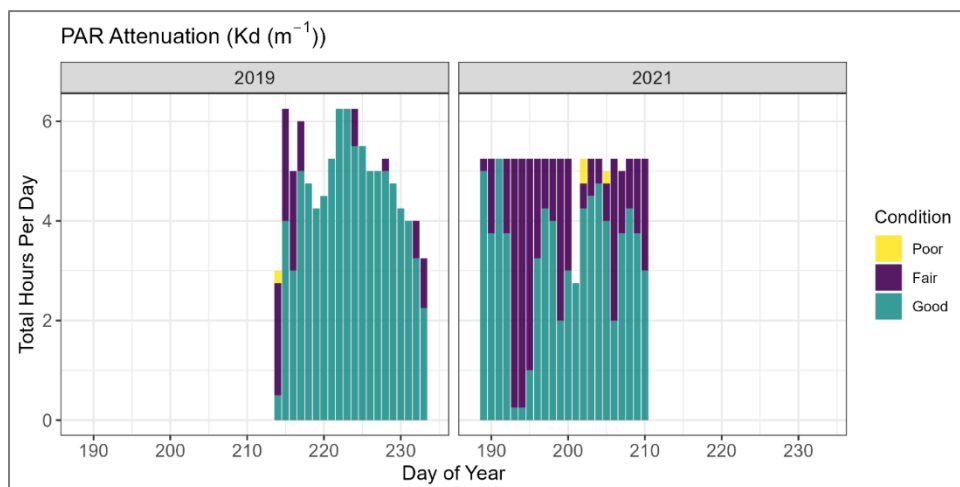


Figure 49. Total hours per day that PAR attenuation was observed within each condition category at the Cape Cod National Seashore Salt Pond logging station.

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Salinity

Mean salinity ranged from 29.8 to 32.1 psu (Table 24). Intra-annual mean trends in salinity were non-linear and ranged from being relatively smooth to very variable (Figure 50). Salinity measurements within each year typically spanned approximately 1–5 psu but distributions were more skewed between 2010 to 2016 (Figure 51).

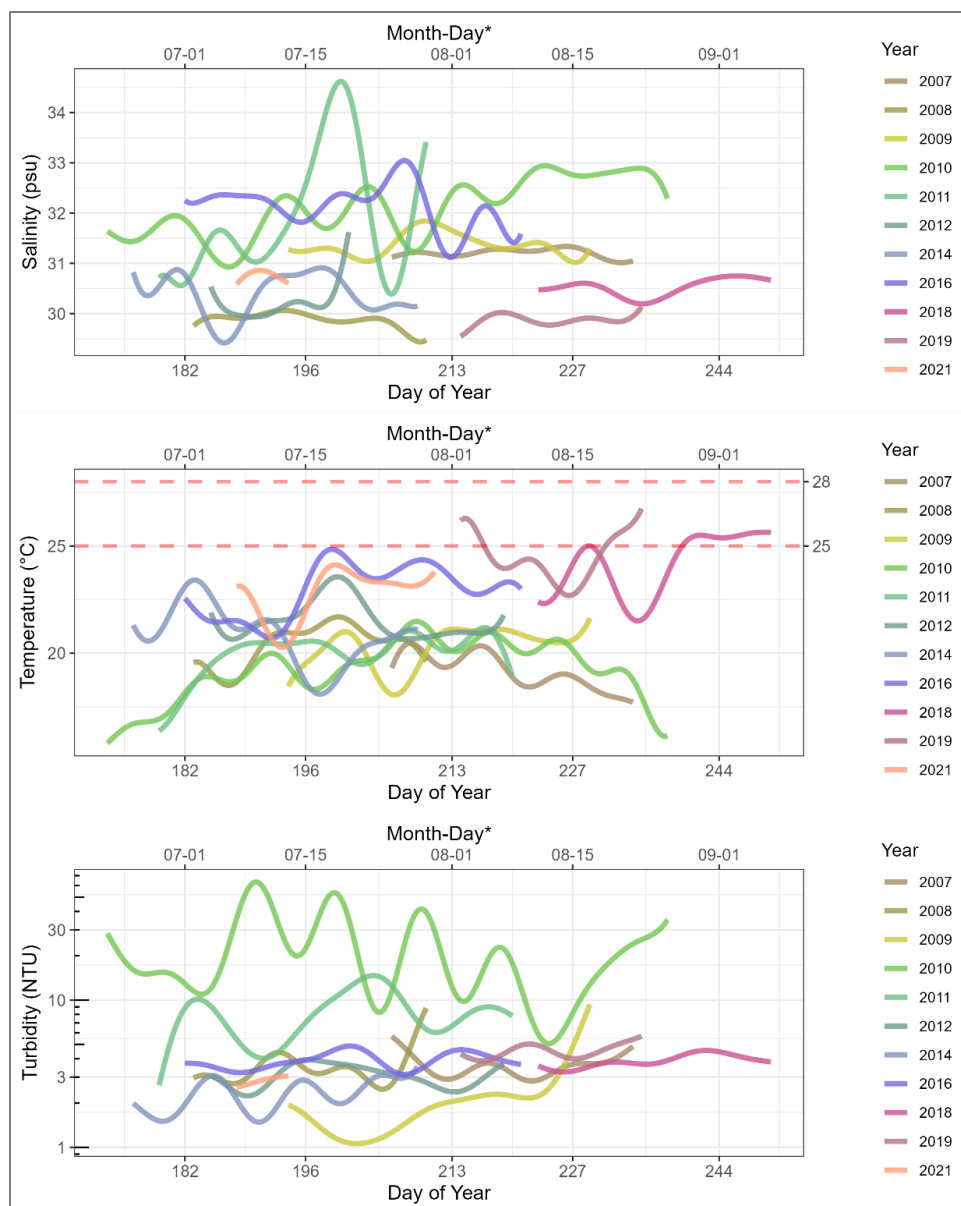


Figure 50. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Salt Pond logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: the surface turbidity y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trends. Note: The data logger deployment method changed from being suspended from a float (2007–2013) to being fixed at a set distance from the bottom (2014–2021).

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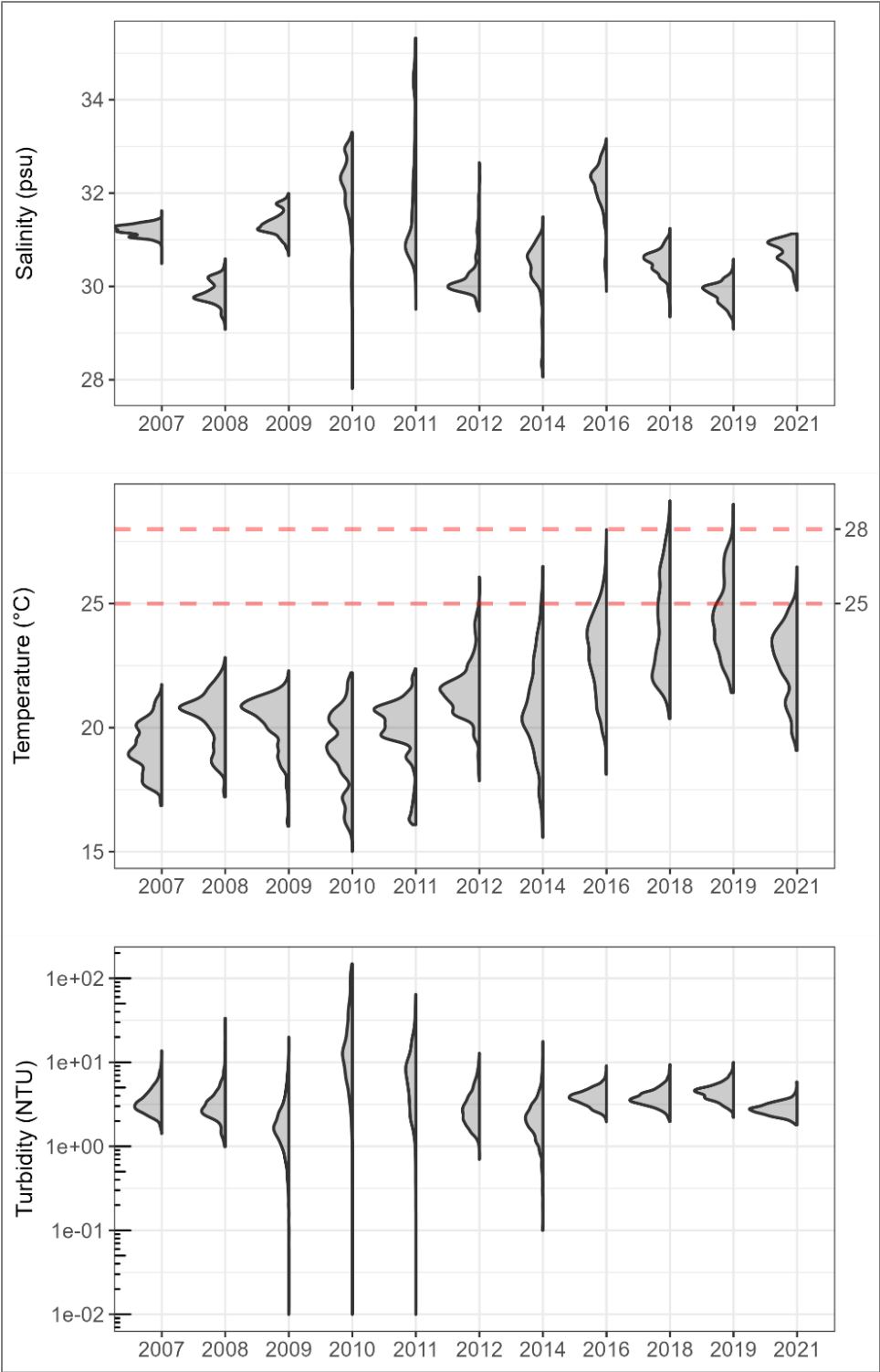


Figure 51. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Salt Pond logging station. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: the surface turbidity y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated distributions. Note: The data logger deployment method changed from being suspended from a float (2007–2013) to being fixed at a set distance from the bottom (2014–2021).

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Temperature

Mean temperatures ranged from 19.1 to 24.5°C (Table 24). Intra-annual mean trends in water temperature were highly non-linear (Figure 50). The distribution of measurements has become more variable within each year over time and there is a clear increasing trend over time (Figure 51). Temperatures exceeded 25°C in every year after 2012 and exceeded 28°C in 2018 and 2019.

Turbidity

Mean turbidity ranged from 2.11 to 22.3 NTU (Table 24). Intra-annual mean trends in turbidity were generally fairly smooth except for 2009, 2010, and 2011 (Figure 50). Measurements in those years were also more skewed than other years, and values exceeded 100 NTU in 2010 (Figure 51).

pH

Mean pH ranged from 7.78 to 7.94 (Table 24). Intra-annual trends in pH were non-linear and non-stationary (Figure 52). Measurements spanned approximately 0.75 units each year (Figure 53).

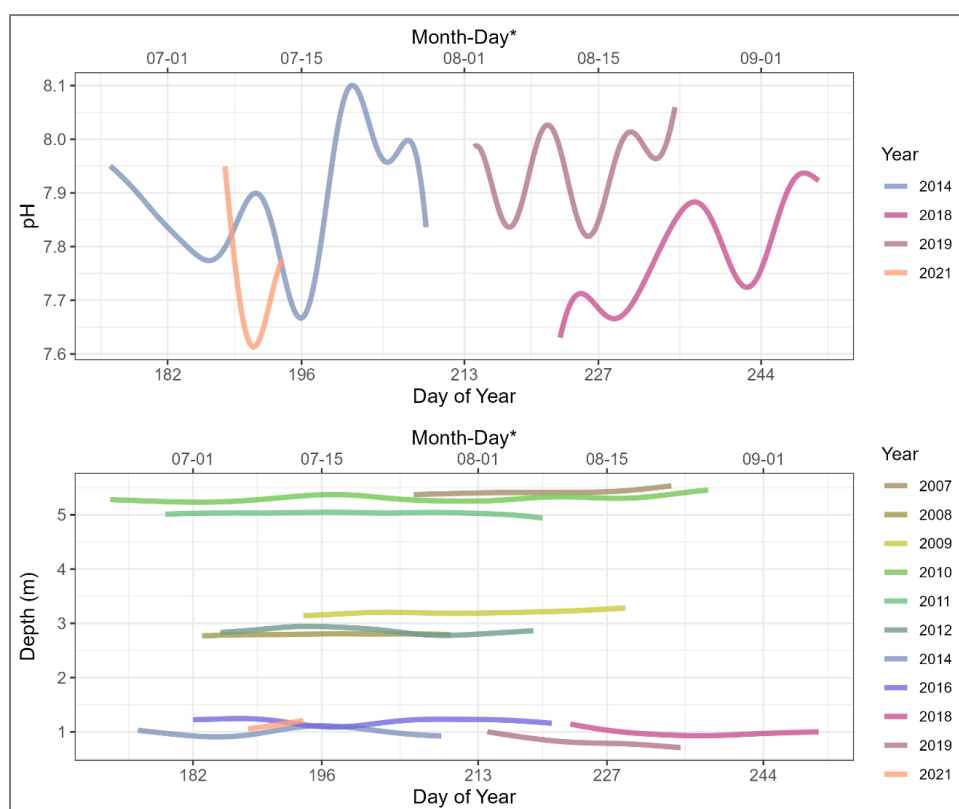


Figure 52. Intra-annual trends in pH (top) and depth (bottom) at the Cape Cod National Seashore Salt Pond logging station based on estimated generalized additive model smooths. Note: The data logger deployment method changed from being suspended from a float (2007–2013) to being fixed at a set distance from the bottom (2014–2021).

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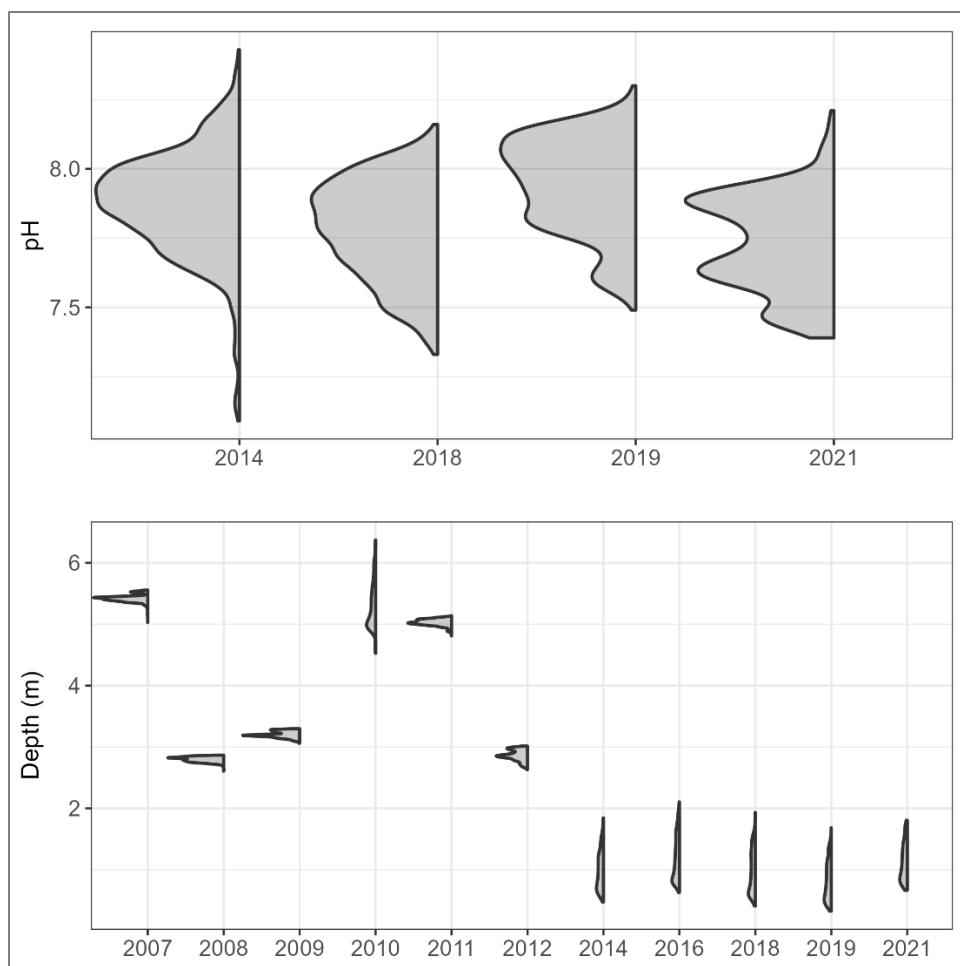


Figure 53. Distribution of index period time series values for pH (top) and depth (bottom) at the Cape Cod National Seashore Salt Pond logging station. Note: The data logger deployment method changed from being suspended from a float (2007–2013) to being fixed at a set distance from the bottom (2014–2021).
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Depth

Mean depth typically ranged from 0.8 to 1.4 m (Table 24). While all years exhibited a relatively smooth intra-annual mean trend (Figure 52), both the average depth and distribution of measurements were extremely variable prior to 2014 (Figure 53). After 2014, the average depth was relatively constant at approximately 1 m with a range of 1.5.

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. Total biomass for eelgrass (*Zostera marina*) 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.

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 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 25).

Table 25. Summary of the distribution, link function, and offset used to model each seagrass parameter.

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: 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 all trend station 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.

Duck Harbor Beach Results

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

GAM Results

The generalized additive model summaries indicate that there were statistically significant temporal trends within transects for all *Zostera marina* parameters (Table 26) and ancillary sediment parameters except for percentage of fine sediment (Table 27).

Table 26. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Duck Harbor Beach *Zostera marina* 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].

Parameter	Model Term	edf	p-value
Shoot density	s(year, transect)	27.09	< 0.001
Percent cover	s(year, transect)	15.90	< 0.001
Canopy height	s(year, transect)	26.19	< 0.001
Total biomass	s(year, transect)	20.66	< 0.001
Above:belowground biomass	s(year, transect)	11.04	< 0.001

Table 27. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Duck Harbor Beach 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)	3.41	0.058
Percent organic material	s(year, transect)	9.12	< 0.001

Shoot Density

Temporal trends in *Zostera marina* shoot density differ between transects (Figure 54). When monitoring began, shoot density exceeded 400 shoots m⁻² in all three transects and often exceeded 800 shoots m⁻² in both the shallow and mid-depth transects. Shoot density declined significantly after 2005 in the deep transect and after 2012 in the shallow transect and remained below 5 shoots m⁻² in the following years. Shoot density within the mid-depth transect remained relatively constant but experienced a slight decline between 2009–2010 and between 2019–2022, when densities were less than 170 shoots m⁻².

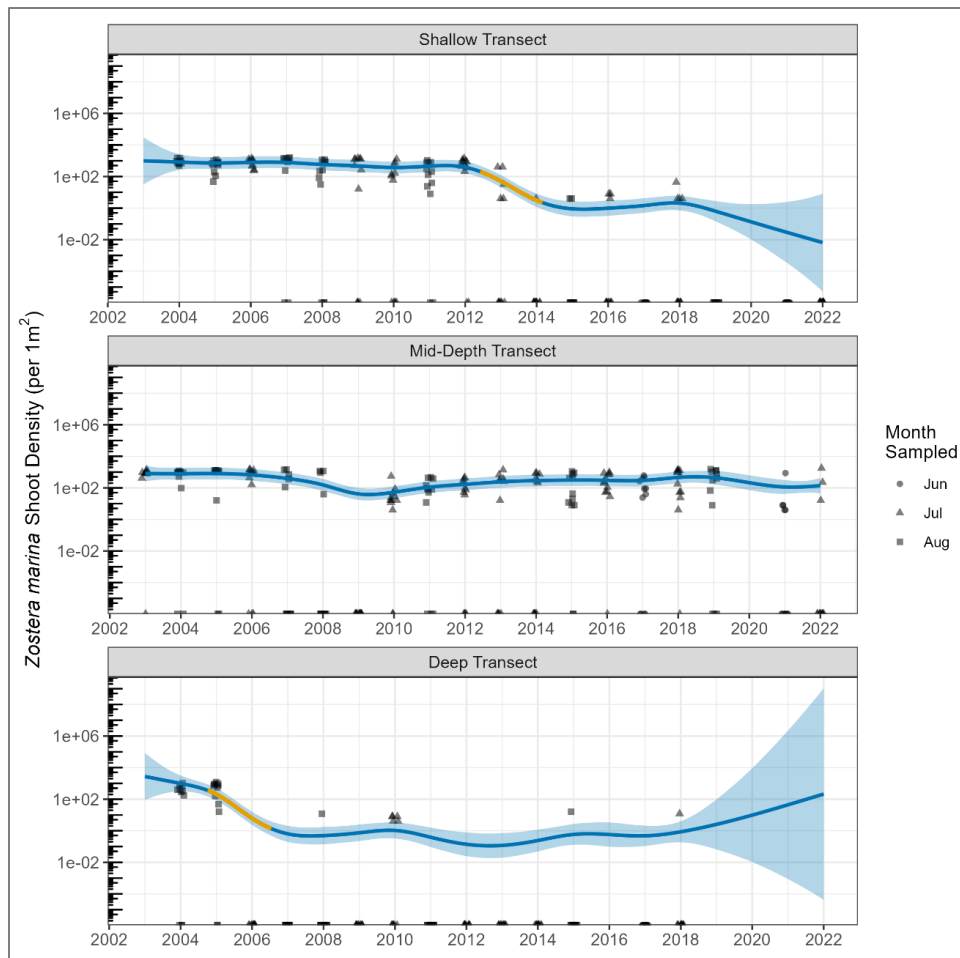


Figure 54. Trend in *Zostera marina* shoot density (per 1 m²) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: y-axes are transformed to the log₁₀ scale to better visualize the estimated trends.

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Percent Cover

Percent cover of *Zostera marina* declined in all three transects over the monitoring timeframe (Figure 55). There was a significant decline in percent cover within the mid-depth transect between 2006 and 2009 after which time values were relatively stable until 2019 when there was a slight decline. In the deep transect, there was a statistically significant decrease in percent cover from 2003 to 2006 that led to a complete die off. The shallow transect experienced decreasing percent cover from 2003 to 2013 which also led to a complete die off.

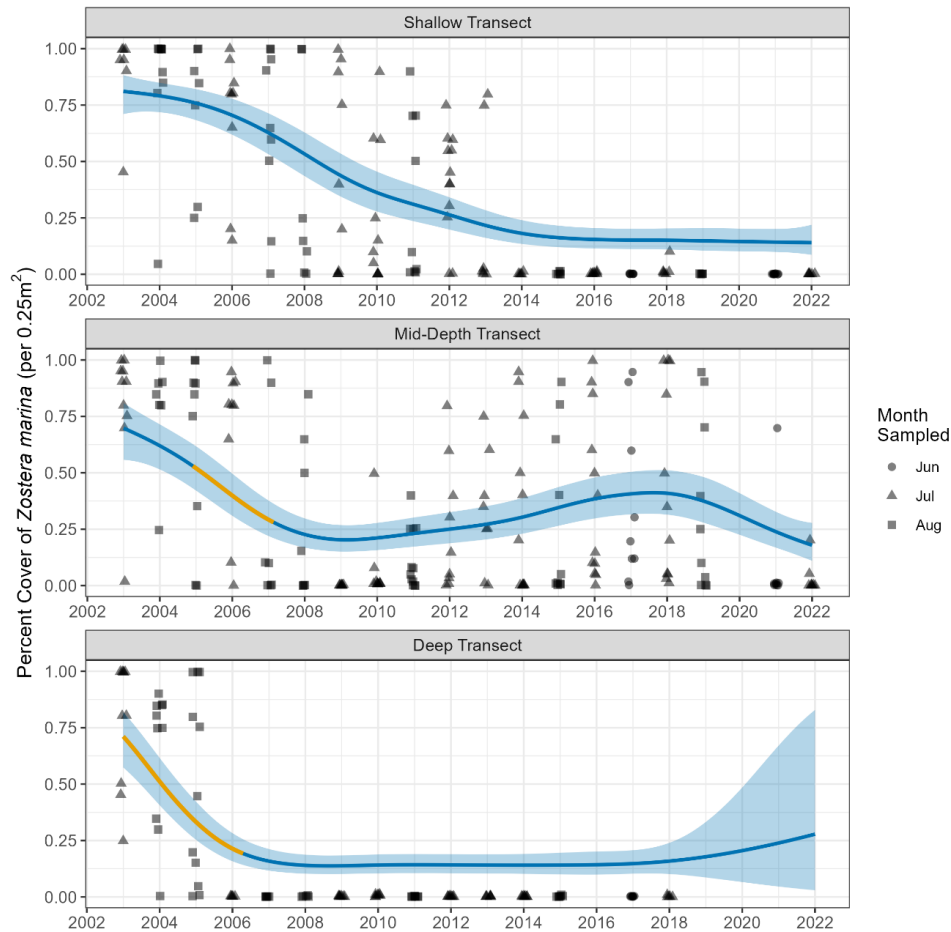


Figure 55. Trend in percent cover of *Zostera marina* (per 0.25 m²) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Canopy Height

Canopy height at Duck Harbor Beach generally ranged from 10 to 40 cm. In the shallow transect, there was a significant increase in *Zostera marina* canopy height prior to 2005 followed by an overall decreasing trend (Figure 56). The mid-depth transect experienced several periods of significant change in canopy height during the monitoring timeframe. Canopy height in the deep transect declined slightly before eelgrass vanished entirely.

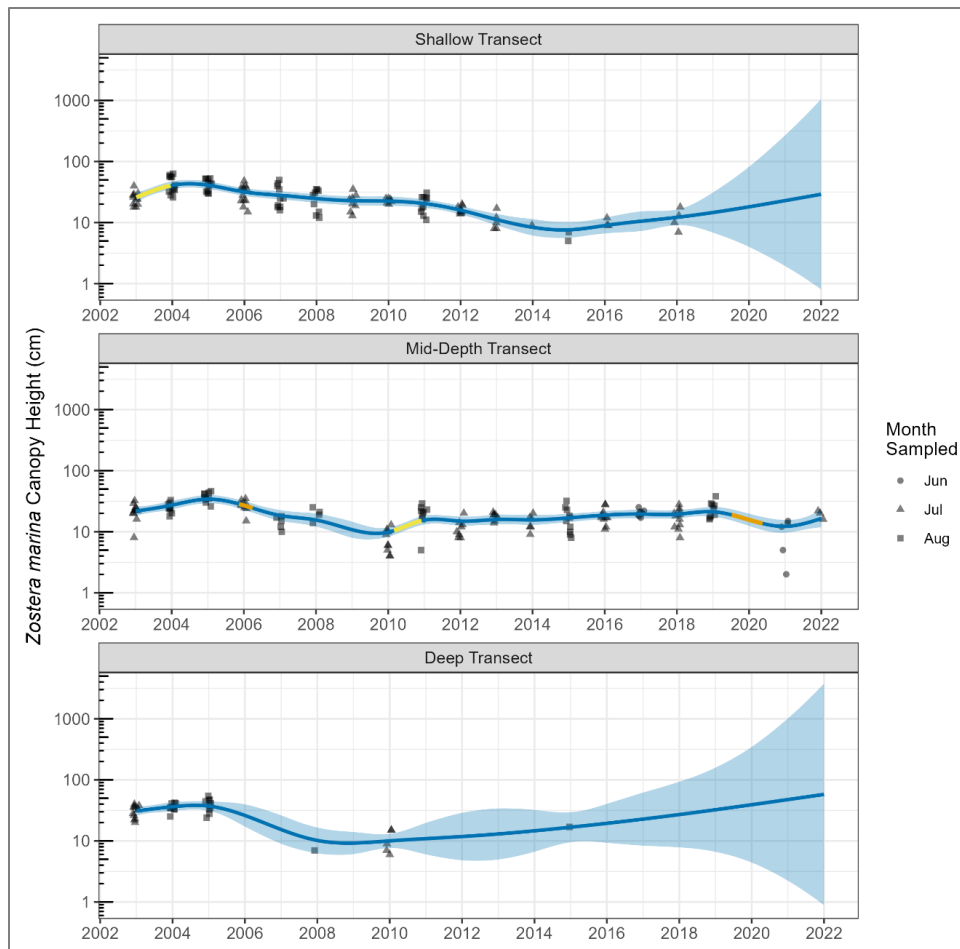


Figure 56. Trend in *Zostera marina* canopy height by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant 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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Total Biomass

Temporal trends in *Zostera marina* total biomass also differ between transects (Figure 57). When monitoring began, biomass exceeded 100 g m^{-2} in all three transects. Total biomass declined significantly after 2005 in the deep transect and after 2012 in the shallow transect and did not recover in the following years. Biomass within the mid-depth transect remained relatively constant but experienced a slight decline between 2009–2010 and between 2019–2022.

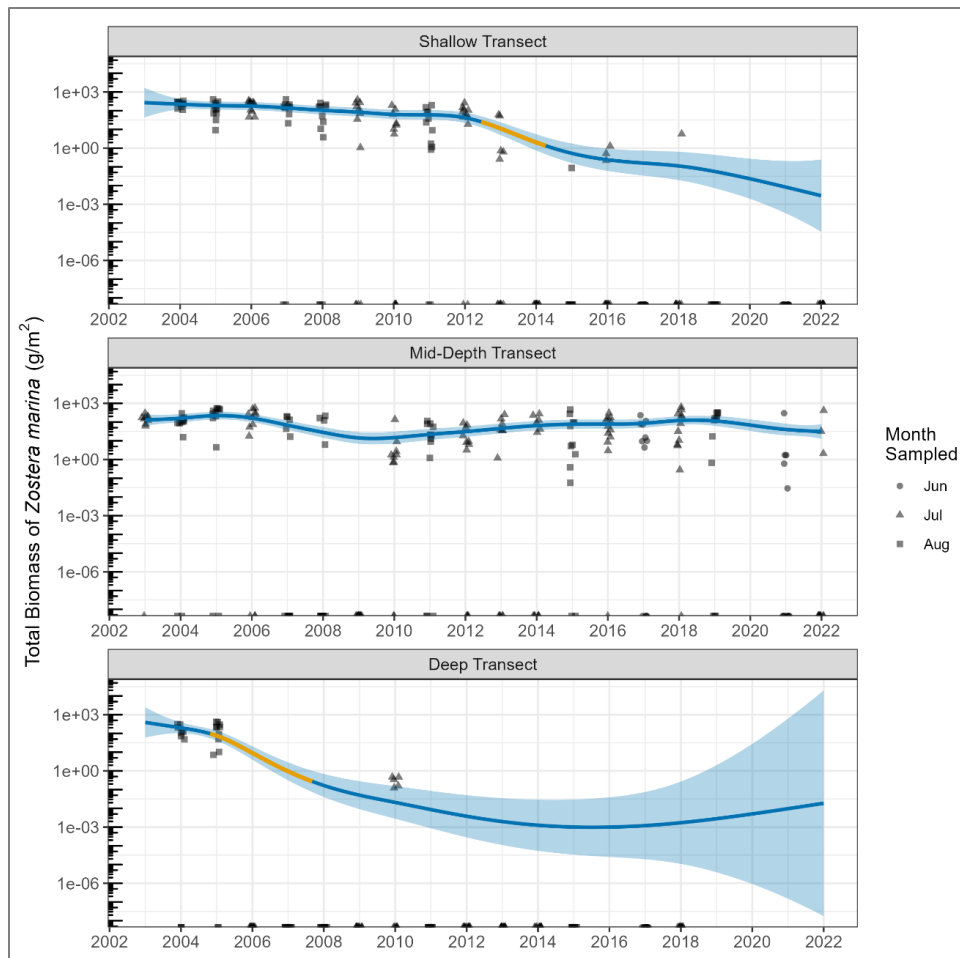


Figure 57. Trend in *Zostera marina* total biomass (g/m^2) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant 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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Above- to Belowground Biomass Ratio

Zostera marina above- to belowground biomass ratios typically ranged from 1 to 3 and remained relatively constant with no periods of statistically significant change in any of the three transects (Figure 58).

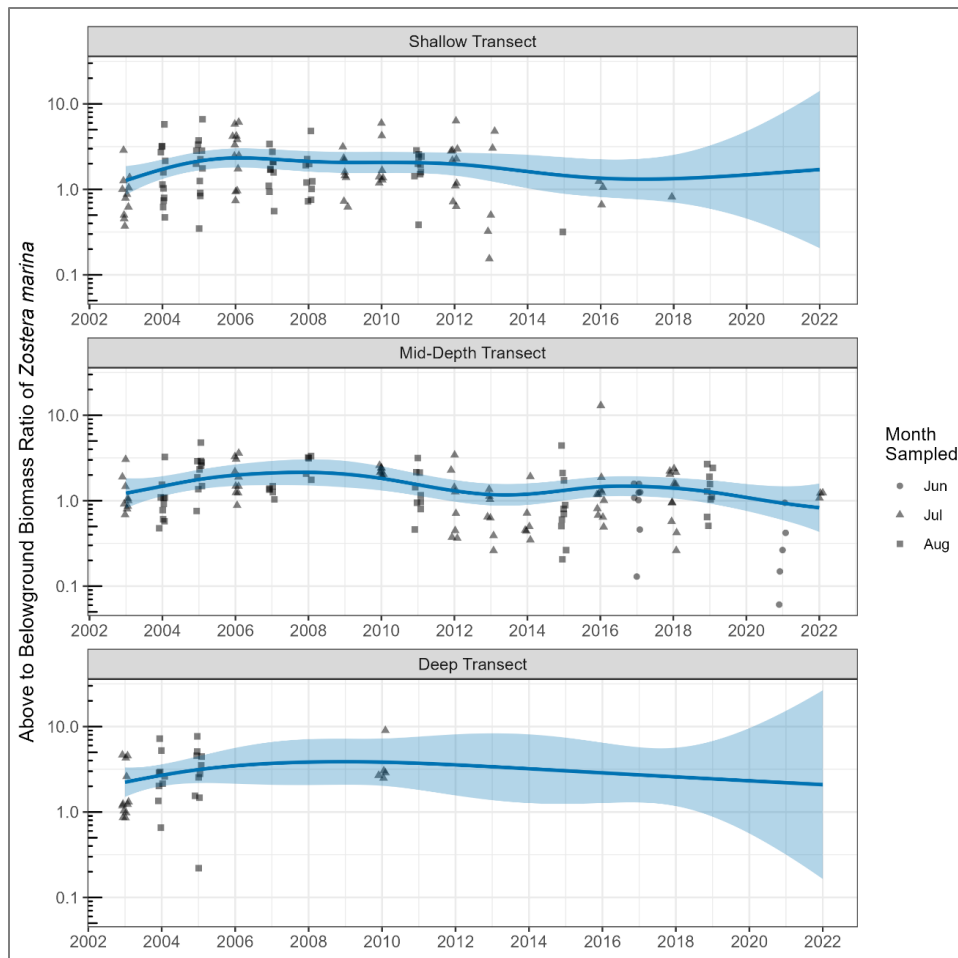


Figure 58. Trend in above- to belowground biomass ratio of *Zostera marina* by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. 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 less than 5% and no periods of significant change were observed in any transect (Figure 59). Since 2014, the percent fine sediment within the mid-depth and shallow transects have become more variable.

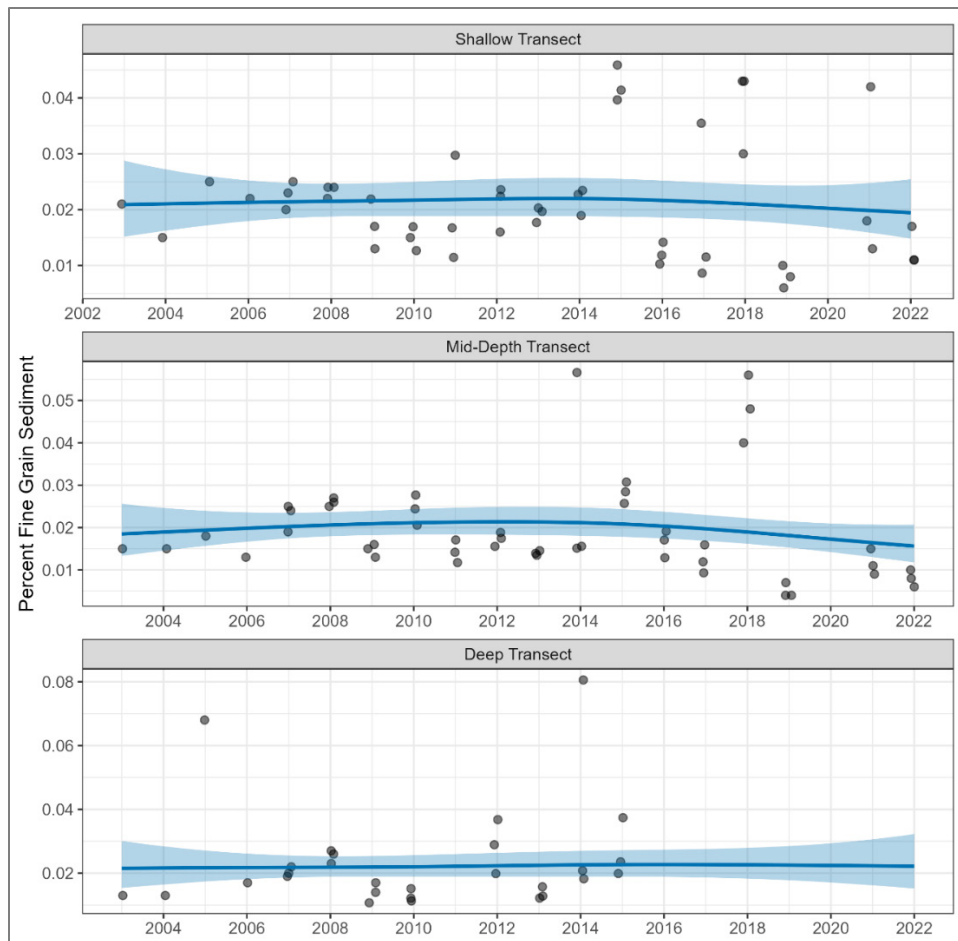


Figure 59. Trend in percent fine sediment (i.e., clay and silt) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of 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 at less than 1%. Temporal trends differ by transect and no periods of statistically significant change were identified (Figure 60).

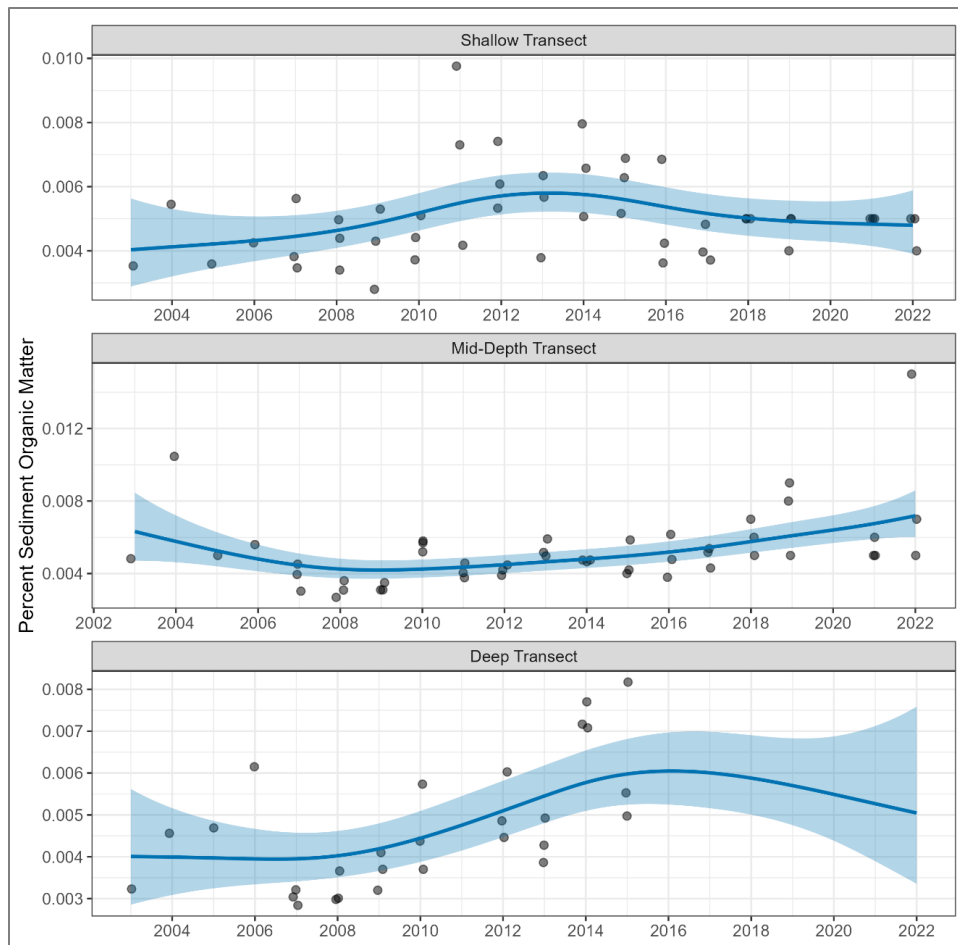


Figure 60. Trend in percent sediment organic material by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.
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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 *Zostera marina* canopy height, total biomass, percent cover, and shoot density in both the shallow and deep transects within the Duck Harbor Beach reference seagrass bed (Table 28). In addition, there was a significant decreasing monotonic trend in the above- to belowground biomass ratio within the mid-depth transect.

Table 28. Summary of multivariate Mann-Kendall test for monotonic trend in each seagrass parameter transect in the Duck Harbor Beach reference seagrass bed at Cape Cod National Seashore. 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	Transect	Z_{MK}	p -value
Canopy Height (cm)	Shallow	-4.61	< 0.001
Canopy Height (cm)	Mid-Depth	-0.93	0.352
Canopy Height (cm)	Deep	-3.31	0.001
Total Biomass (g/m ²)	Shallow	4.36	< 0.001
Total Biomass (g/m ²)	Mid-Depth	-0.94	0.347
Total Biomass (g/m ²)	Deep	-2.75	0.006
Above- to Belowground Biomass Ratio	Shallow	-0.51	0.607
Above- to Belowground Biomass Ratio	Mid-Depth	-2.69	0.007
Above- to Belowground Biomass Ratio	Deep	0.33	0.745
Percent Cover (per 0.25 m ²)	Shallow	-4.28	< 0.001
Percent Cover (per 0.25 m ²)	Mid-Depth	-1.15	0.249
Percent Cover (per 0.25 m ²)	Deep	-2.61	0.009
Shoot Density (per 1 m ²)	Shallow	-3.92	< 0.001
Shoot Density (per 1 m ²)	Mid-Depth	-1.02	0.309
Shoot Density (per 1 m ²)	Deep	-2.45	0.014

Water Temperature Summaries

Mean water temperatures within Duck Harbor Beach transect A (shallow) were comparable to those in transect C (deep) but had slightly higher range overall (Figure 61). 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 62). Days wherein the daily average temperature exceeded 25°C occurred between the months of June to August, with more days observed in the shallow transect and more days observed since 2012 (Table 29).

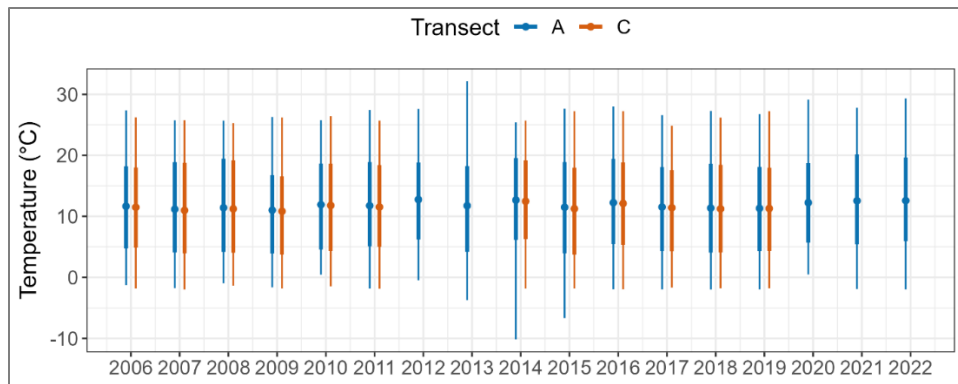


Figure 61. Dot and whisker plots depicting the mean (dot), range (thin line) and middle 50% of observed water temperatures (°C) (thick line) within the shallow (A) and deep (C) transects at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed. Only years in which complete data records were available are included here.

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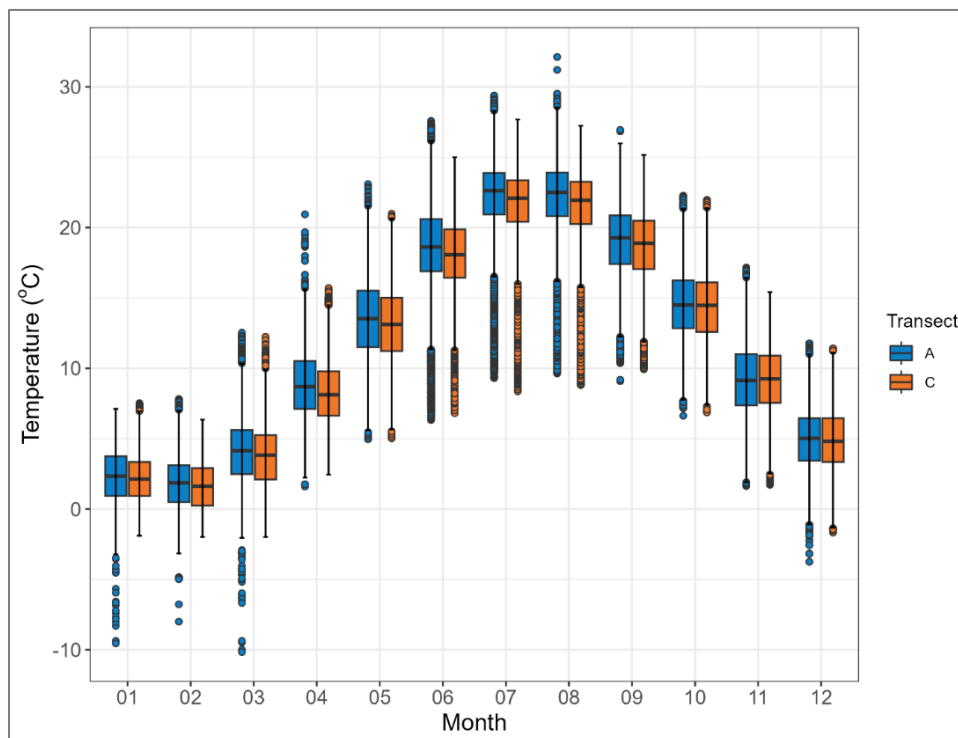


Figure 62. Box plots of mean temperature by month for the shallow (A) and deep (C) transects at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed from 2003 to 2022. Circles indicate outliers.

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Table 29. Number of days per month wherein average daily water temperature exceeded 25°C for the shallow (A) and deep (C) transects at the Cape Cod National Seashore Duck Harbor Beach 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 7 days, and blue to purple representing 8 to 10 days. [NA = not available]

Transect	Year	Number of Days per Month Daily Average Temperature > 25°C											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Shallow (A)	2022	0	NA	0	0	0	0	10	6	0	0	0	0
	2021	0	NA	0	0	0	1	1	6	0	0	0	0
	2020	0	0	0	0	0	0	8	8	0	0	0	0
	2019	0	NA	0	0	0	0	2	3	0	0	0	0
	2018	0	NA	0	0	0	0	0	4	0	0	0	0
	2017	0	NA	0	0	0	0	0	0	0	0	0	0
	2016	0	0	0	0	0	0	4	6	0	0	0	0
	2015	0	NA	0	0	0	0	3	8	0	0	0	0
	2014	0	NA	0	0	0	0	0	0	0	0	0	0
	2013	0	NA	0	0	0	0	10	0	0	0	0	0
	2012	0	0	0	0	0	0	7	6	0	0	0	0
	2011	0	NA	0	0	0	0	1	0	0	0	0	0
	2010	0	NA	0	0	0	0	2	0	0	0	0	0
	2009	0	NA	0	0	0	0	0	2	0	0	0	0
	2008	0	0	0	0	0	0	0	0	0	0	0	0
	2007	0	NA	0	0	0	0	0	0	0	0	0	0
	2006	0	NA	0	0	0	0	0	2	0	0	0	0
	2005	NA	NA	NA	NA	0	0	0	1	0	0	0	0
	2004	0	0	0	0	0	0	0	0	NA	NA	NA	NA
	2003	NA	NA	NA	NA	NA	NA	NA	0	0	0	0	0
Deep (C)	2020	0	0	0	0	0	0	8	4	0	NA	NA	NA
	2019	0	NA	0	0	0	0	2	1	0	0	0	0

Table 29 (continued). Number of days per month wherein average daily water temperature exceeded 25°C for the shallow (A) and deep (C) transects at the Cape Cod National Seashore Duck Harbor Beach 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 7 days, and blue to purple representing 8 to 10 days. [NA = not available]

Transect	Year	Number of Days per Month Daily Average Temperature > 25°C											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Deep (C) (continued)	2018	0	NA	0	0	0	0	0	0	0	0	0	0
	2017	0	NA	0	0	0	0	0	0	0	0	0	0
	2016	0	0	0	0	0	0	2	4	0	0	0	0
	2015	0	NA	0	0	0	0	2	5	0	0	0	0
	2014	0	NA	0	0	0	0	0	0	0	0	0	0
	2013	NA	NA	NA	NA	NA	NA	3	0	0	0	0	0
	2012	0	0	0	0	0	NA	NA	NA	NA	NA	NA	NA
	2011	0	NA	0	0	0	0	0	0	0	0	0	0
	2010	0	NA	0	0	0	0	2	0	0	0	0	0
	2009	0	NA	0	0	0	0	0	2	0	0	0	0
	2008	0	0	0	0	0	0	0	0	0	0	0	0
	2007	0	NA	0	0	0	0	0	0	0	0	0	0
	2006	0	NA	0	0	0	0	0	0	0	0	0	0
	2005	NA	NA	NA	NA	0	0	0	0	0	0	0	0
	2004	0	0	0	0	0	0	0	0	NA	NA	NA	NA
	2003	NA	NA	NA	NA	NA	NA	0	0	0	NA	0	0

Pleasant Bay Results

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

GAM Results

The generalized additive model summaries indicate that there were statistically significant temporal trends within transects for all *Zostera marina* parameters (Table 30) and ancillary sediment parameters (Table 31).

Table 30. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Pleasant Bay *Zostera marina* 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
Shoot density	s(year, transect)	44.98	< 0.001
Percent cover	s(year, transect)	50.98	< 0.001
Canopy height	s(year, transect)	53.26	< 0.001
Total biomass	s(year, transect)	47.28	< 0.001
Above- to belowground biomass	s(year, transect)	35.54	< 0.001

Table 31. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Pleasant Bay 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)	13.32	< 0.001
Percent organic material	s(year, transect)	15.25	< 0.001

Shoot Density

Zostera marina shoot density was generally highest within the shallow and mid-depth transects and often exceeded over 800 shoots m⁻². Temporal trends differ between transects (Figure 63). Shoot density within the shallow transect declined significantly in 2006, experienced a significant recovery in the following years, and then underwent a significant decline between 2021 and 2022. In the deep transect, there were several periods of significant change between 2016 and 2022. Variability within a given year was lowest within the mid-depth transect and no significant changes were observed.

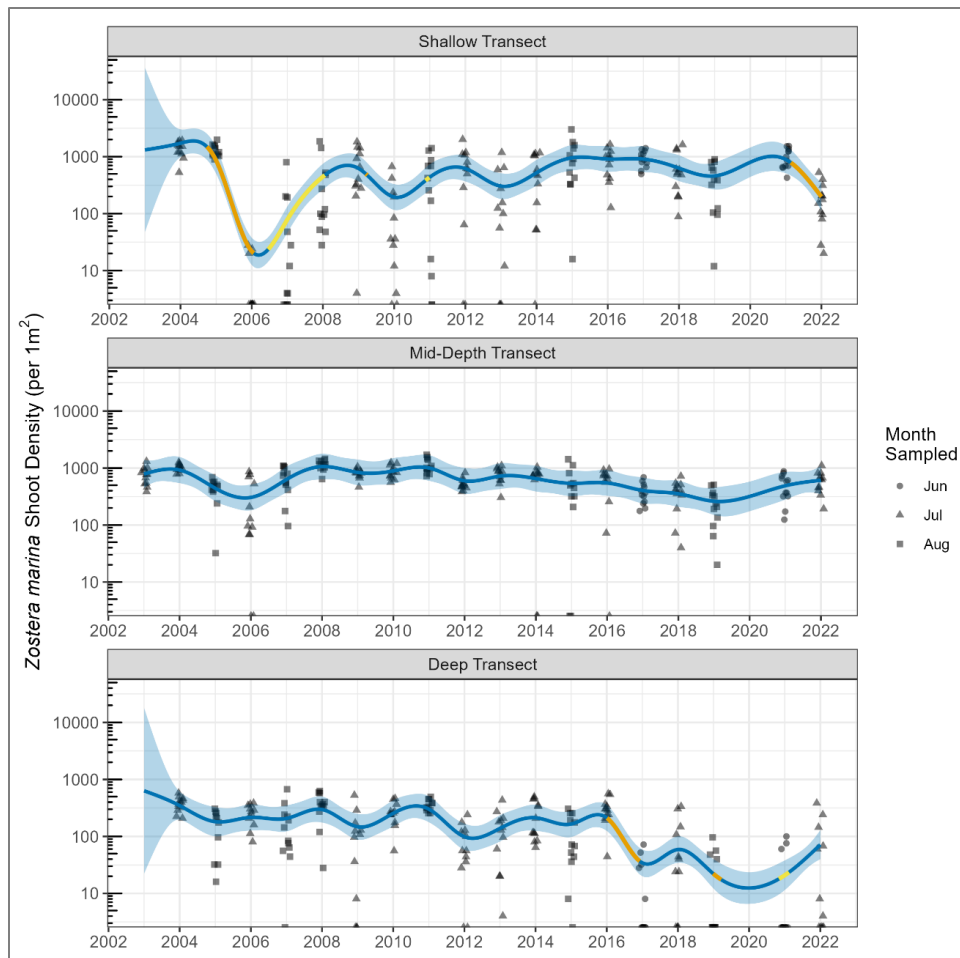


Figure 63. Trend in *Zostera marina* shoot density (per 1 m²) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: y-axes are transformed to the log₁₀ scale to better visualize the estimated trends.

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Percent Cover

Trends in *Zostera marina* percent cover were highly non-linear and differ by transect (Figure 64). There was a statistically significant decrease in percent cover within the shallow transect around 2006 followed by a period of recovery with a high degree of interannual variability. The deep transect experienced several periods of statistically significant change but has remained below 25% since a decline occurred in 2017. The mid-depth transect also experienced several periods of significant change, and while historically it had the highest percent cover, measurements since 2014 have exhibited more variability within a given year.

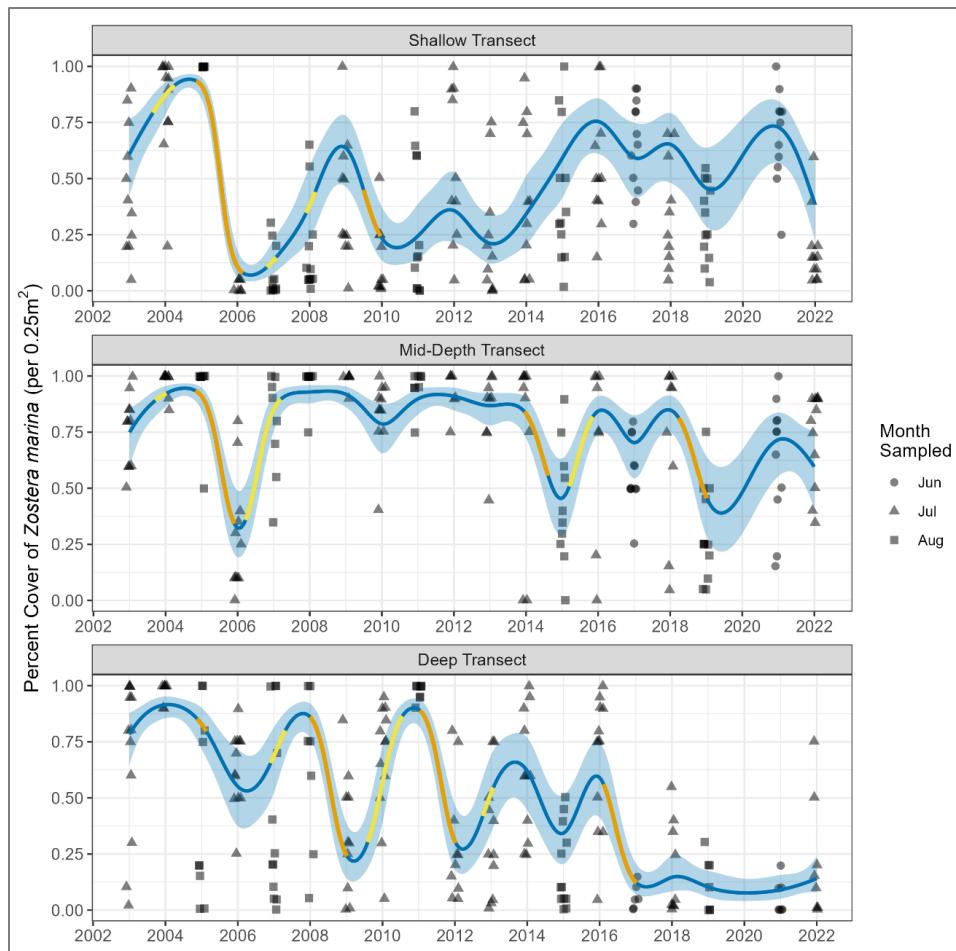


Figure 64. Trend in percent cover (per 0.25 m²) of *Zostera marina* by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Canopy Height

Zostera marina canopy height at Pleasant Bay generally ranged from 10 to 90 cm and was typically the highest in the deep transect. The trends in canopy height were cyclical in nature in all three transects with multiple periods of significant change observed (Figure 65).

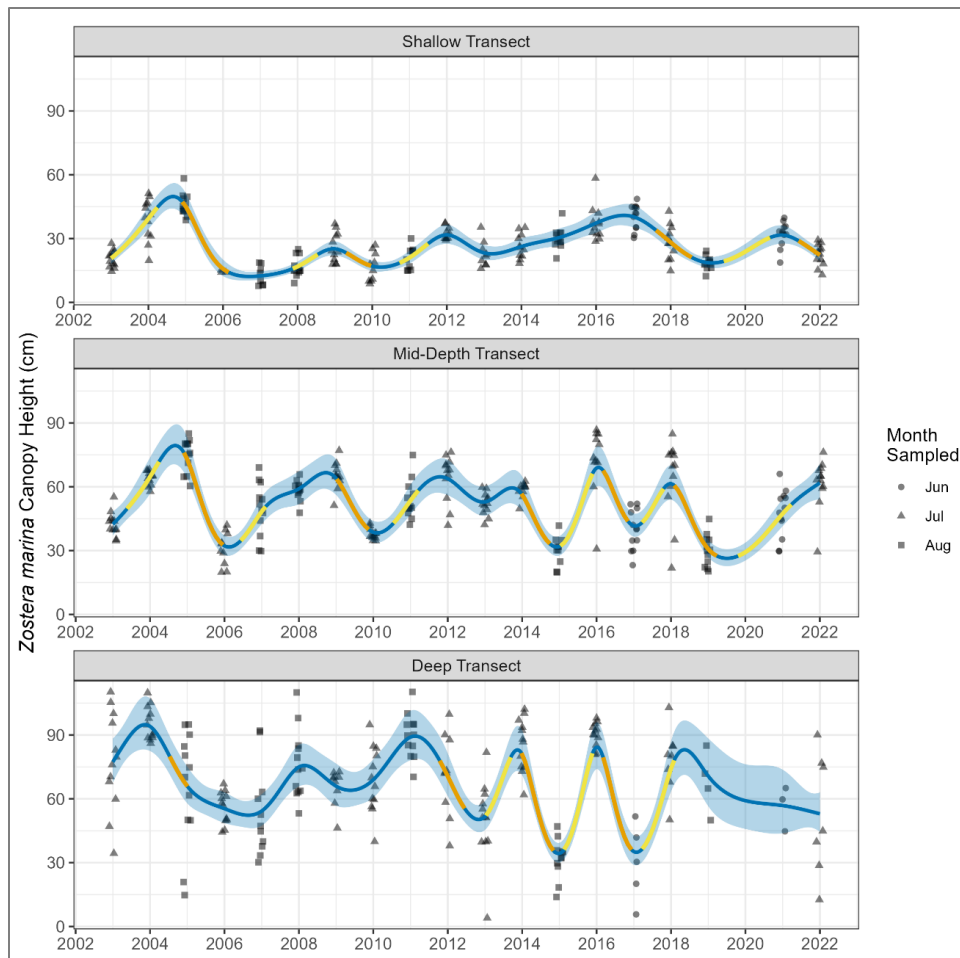


Figure 65. Trend in *Zostera marina* canopy height (cm) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Total Biomass

While *Zostera marina* total biomass often exceeded 120 g m^{-2} in all three transects, temporal trends differ between transects (Figure 66). Similar to shoot density, biomass within the shallow transect declined significantly in 2006, experienced a significant recovery in the following years, and then underwent a significant decline between 2021 and 2022. Biomass in the deep transect has experienced several periods of significant change but has not yet recovered from a significant decline in 2017. Biomass within mid-depth transect has remained relatively constant with few periods of significant change.

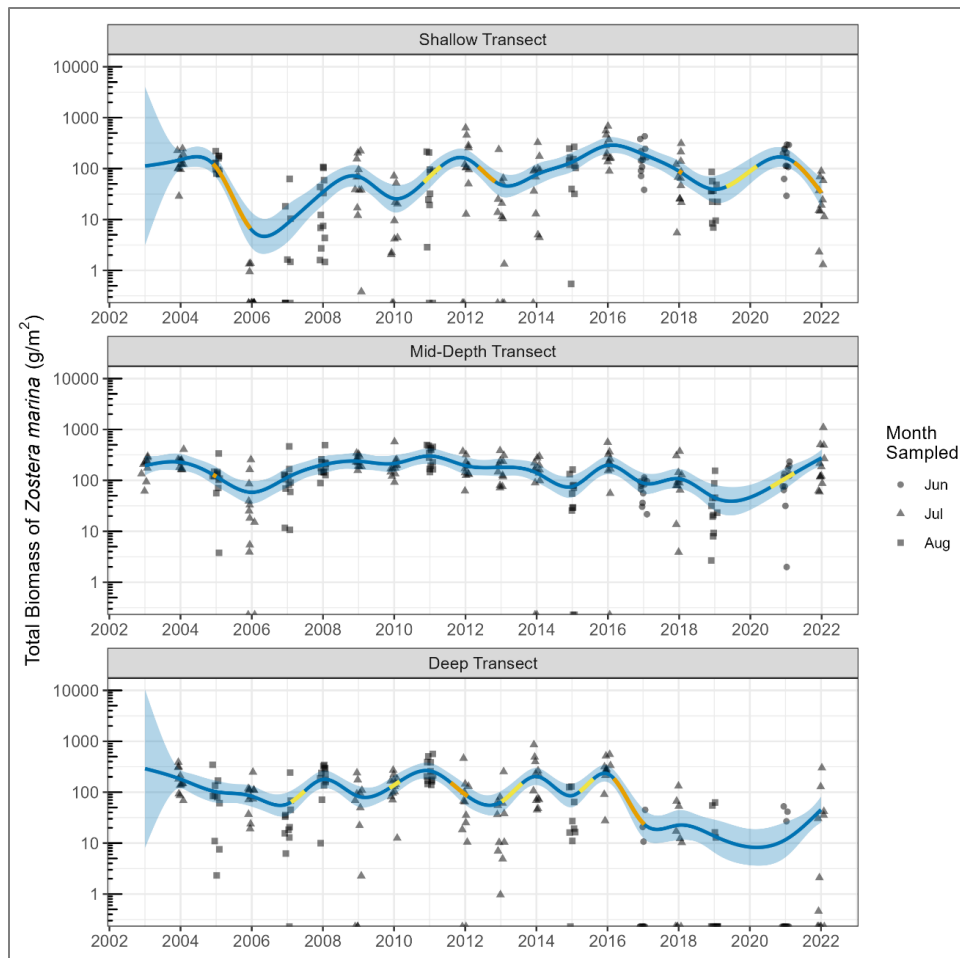


Figure 66. Trend in *Zostera marina* total biomass (g/m^2) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant 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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Above- to Belowground Biomass Ratio

Zostera marina above- to belowground biomass ratios generally ranged from 1 to 10 and were highest in the deep transect. Ratios remained relatively constant within each transect (Figure 67).

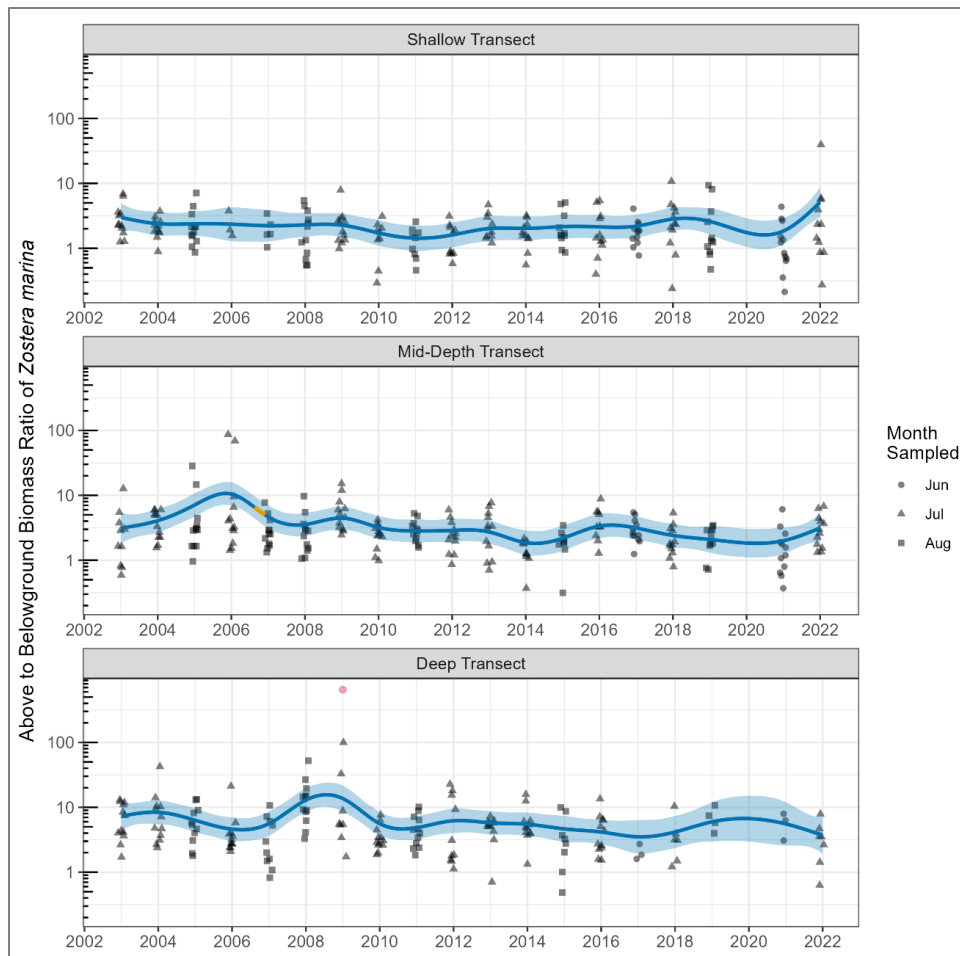


Figure 67. Trend in above- to belowground biomass ratio of *Zostera marina* by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: y-axes are transformed to the log₁₀ scale to better visualize the estimated trends.

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Percent Fine Sediment

Percent fine sediment within the transects was less than 5% and was more variable within the deep and mid-depth transects. A significant increase was observed around 2011 within the deep transect (Figure 68). No significant changes were observed in the other two transects.

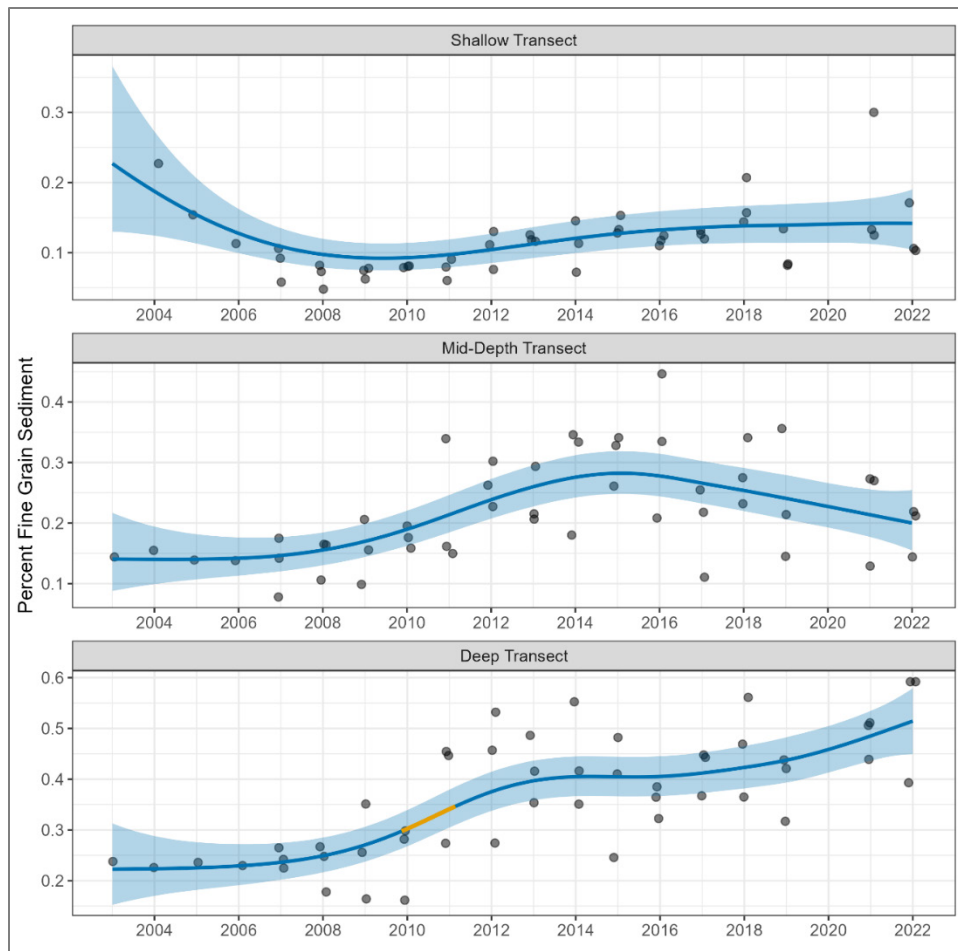


Figure 68. Trend in percent fine sediment (i.e., clay and silt) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant 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 at less than 1%. No significant changes were observed in either the deep or the mid-depth transect (Figure 69). There was a significant decline in percentage of organic material within the shallow transect after which time the percentage remained at approximately 0%.

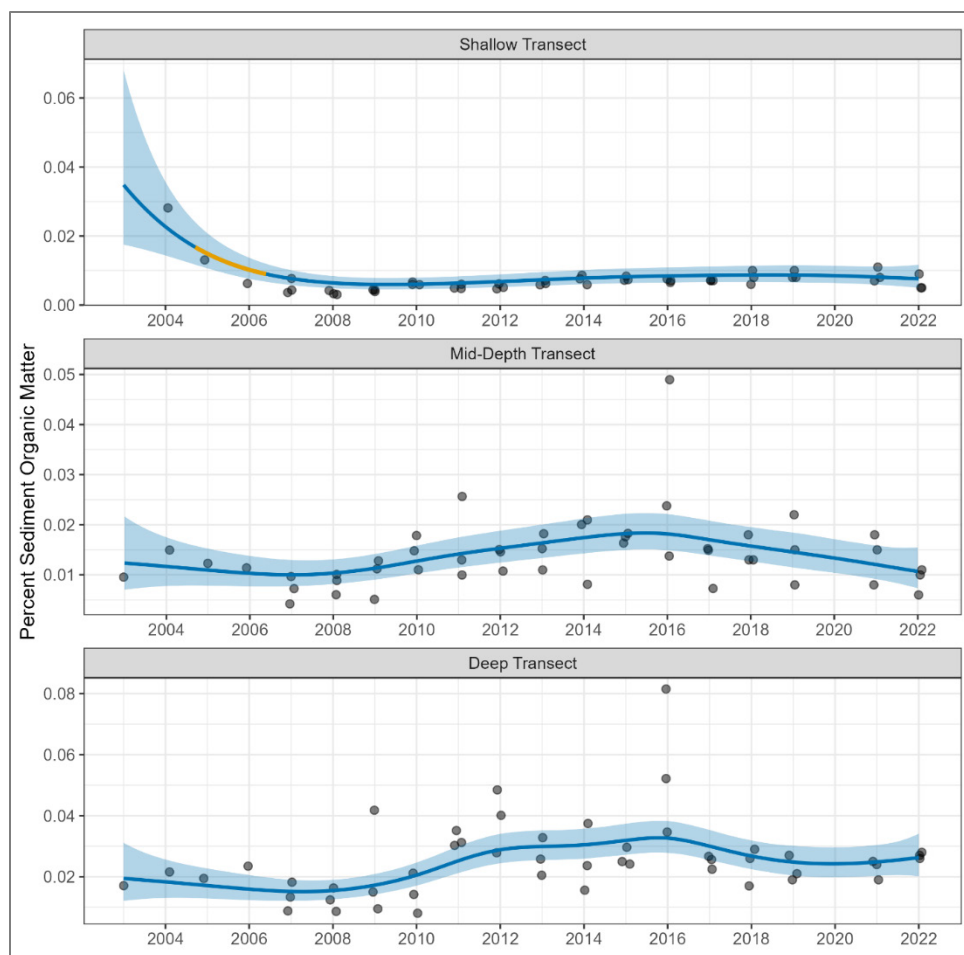


Figure 69. Trend in percent sediment organic material by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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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 *Zostera marina* total biomass, percent cover, and shoot density in the deep transect within the Pleasant Bay reference seagrass bed (Table 32). In addition, there was a significant decreasing monotonic trend in the above- to belowground biomass ratio within both the shallow and mid-depth transects.

Table 32. Summary of multivariate Mann-Kendall test for monotonic trend in each seagrass parameter transect in the Pleasant Bay reference seagrass bed at Cape Cod National Seashore. 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	Transect	Z_{MK}	p -value
Canopy Height (cm)	Shallow	0.35	0.730
Canopy Height (cm)	Mid-Depth	-0.50	0.618
Canopy Height (cm)	Deep	-0.08	0.936
Total Biomass (g/m ²)	Shallow	0.91	0.364
Total Biomass (g/m ²)	Mid-Depth	-1.41	0.157
Total Biomass (g/m ²)	Deep	-2.52	0.012
Above- to Belowground Biomass Ratio	Shallow	-2.28	0.023
Above- to Belowground Biomass Ratio	Mid-Depth	-2.30	0.021
Above- to Belowground Biomass Ratio	Deep	-1.51	0.132
Percent Cover (per 0.25 m ²)	Shallow	0.53	0.597
Percent Cover (per 0.25 m ²)	Mid-Depth	-1.62	0.106
Percent Cover (per 0.25 m ²)	Deep	-3.23	0.001
Shoot Density (per 1 m ²)	Shallow	-0.29	0.773
Shoot Density (per 1 m ²)	Mid-Depth	-1.91	0.056
Shoot Density (per 1 m ²)	Deep	-2.79	0.005

Water temperature summaries

Mean water temperatures within Pleasant Bay seagrass transect A (shallow) were comparable to those in transect C (deep) but had slightly higher range overall (Figure 70). Temperatures were highest in July and August, and summer temperatures exceeded 28°C in every year monitored, with some years exceeding 30°C (Figure 71). Days wherein the daily average temperature exceeded 25°C occurred between the months of June to September, with more days observed in the shallow transect and more days observed since 2012 (Table 33).

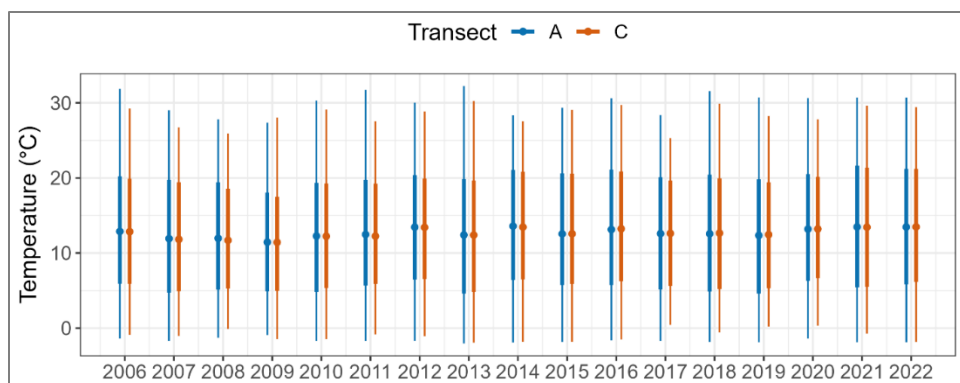


Figure 70. Dot and whisker plots depicting the mean (dot), range (thin line) and middle 50% of observed water temperatures (°C) (thick line) within the shallow (A) and deep (C) transects at the Cape Cod National Seashore Pleasant Bay reference seagrass bed. Only years in which complete data records were available are included here.

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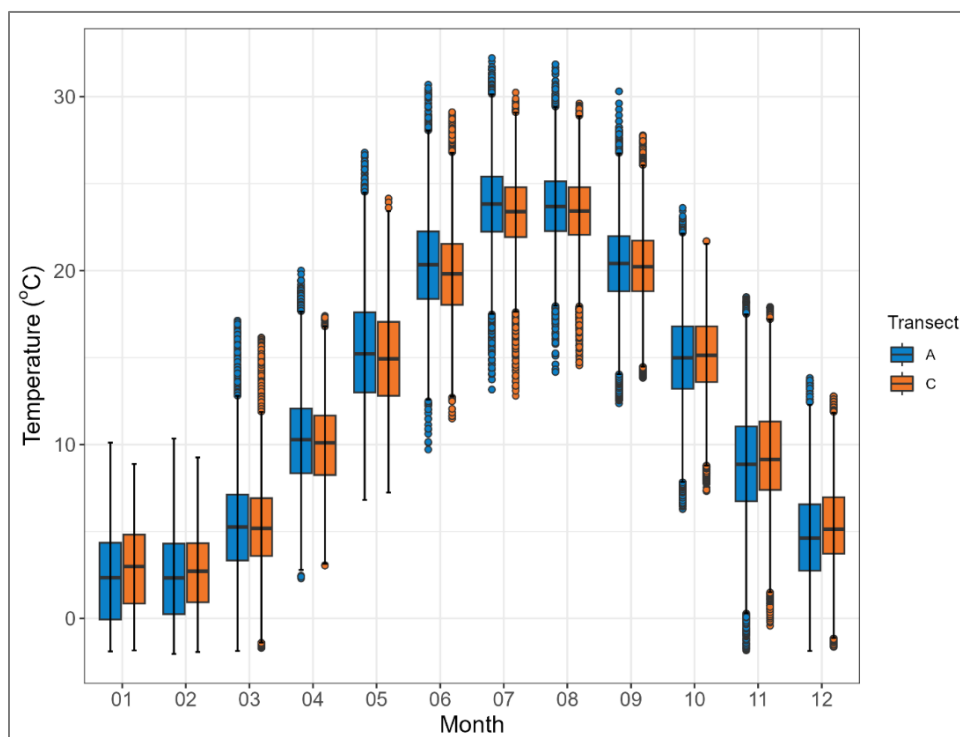


Figure 71. Box plots of mean temperature by month for the shallow (A) and deep (C) transects at the Cape Cod National Seashore Pleasant Bay reference seagrass bed from 2003 to 2022. Circles indicate outliers.

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Table 33. Number of days per month wherein average daily water temperature exceeded 25°C for the shallow (A) and deep (C) transects at the Cape Cod National Seashore Pleasant 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 > 25°C											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Shallow (A)	2022	0	NA	0	0	0	3	17	18	0	0	0	0
	2021	0	NA	0	0	0	2	9	8	0	0	0	0
	2020	0	0	0	0	0	0	15	13	0	0	0	0
	2019	0	NA	0	0	0	0	17	9	0	0	0	0
	2018	0	NA	0	0	0	0	8	15	3	0	0	0
	2017	0	NA	0	0	0	0	4	0	0	0	0	0
	2016	0	0	0	0	0	0	15	11	0	0	0	0
	2015	0	NA	0	0	0	0	9	10	0	0	0	0
	2014	0	NA	0	0	0	0	0	0	0	0	0	0
	2013	0	NA	0	0	0	0	15	0	0	0	0	0
	2012	0	0	0	0	0	3	8	8	0	0	0	0
	2011	0	NA	0	0	0	0	2	0	0	0	0	0
	2010	0	NA	0	0	0	0	3	0	2	0	0	0
	2009	0	NA	0	0	0	0	0	0	0	0	0	0
	2008	0	0	0	0	0	0	0	0	0	0	0	0
	2007	0	NA	0	0	0	0	0	0	0	0	0	0
	2006	0	NA	0	0	0	0	10	8	0	0	0	0
	2005	NA	NA	NA	NA	0	0	9	15	1	0	0	0
	2004	0	0	0	0	0	0	5	5	NA	NA	NA	NA
	2003	NA	NA	NA	NA	NA	NA	12	13	0	0	0	0
Deep (C)	2022	0	NA	0	0	0	0	15	15	0	0	0	0
	2021	0	NA	0	0	0	2	7	8	0	0	0	0

Table 33 (continued). Number of days per month wherein average daily water temperature exceeded 25°C for the shallow (A) and deep (C) transects at the Cape Cod National Seashore Pleasant 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 > 25°C											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Deep (C) (continued)	2020	0	0	0	0	0	0	9	10	0	0	0	0
	2019	0	NA	0	0	0	0	11	5	0	0	0	0
	2018	0	NA	0	0	0	0	7	13	3	0	0	0
	2017	0	NA	0	0	0	0	0	0	0	0	0	0
	2016	0	0	0	0	0	0	10	10	0	0	0	0
	2015	0	NA	0	0	0	0	9	8	0	0	0	0
	2014	0	NA	0	0	0	0	0	0	0	0	0	0
	2013	0	NA	0	0	0	0	12	0	0	0	0	0
	2012	0	0	0	0	0	1	6	4	0	0	0	0
	2011	0	NA	0	0	0	0	0	0	0	0	0	0
	2010	0	NA	0	0	0	0	3	0	0	0	0	0
	2009	0	NA	0	0	0	0	0	0	0	0	0	0
	2008	0	0	0	0	0	0	0	0	0	0	0	0
	2007	0	NA	0	0	0	0	0	0	0	0	0	0
	2006	0	NA	0	0	0	0	5	8	0	0	0	0
	2005	NA	NA	NA	NA	0	0	4	6	0	0	0	0
	2004	0	0	0	0	0	0	2	1	NA	NA	NA	NA
	2003	NA	NA	NA	NA	NA	NA	6	8	0	NA	0	0

Discussion

Routine long-term water quality monitoring was conducted at Cape Cod National Seashore during summer months from 2007 through 2021 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 majority of area within the park estuaries was consistently classified as being in good condition with respect to bottom dissolved oxygen concentrations, and conditions improved in all three strata. While poor conditions were generally observed in less than 1% of the entire monitored area (i.e., all three strata combined), poor conditions were observed in most years and represented as much as 5% (NH stratum) to 13% (SP stratum) of the monitored area within individual strata. Concentrations were lowest along the densely populated northern and western shores of Pleasant Bay (PB stratum) and near South/East Orleans and Town Cove (NH stratum). Similarly, bottom dissolved oxygen concentrations at the trend stations were consistently good with significant increases observed over time. For the PB and NH strata, the majority of each day at the logging station was spent in good condition, and no extensive periods of poor conditions were observed. For the SP stratum, there were several years when extensive periods of poor conditions were observed at the logging station throughout the day. This is not surprising given the limited flushing and high degree of stratification typical of the estuarine kettle holes in this region. Overall, these results are consistent with another recent study in the eastern portion of the Cape Cod peninsula (Pleasant Bay Alliance 2015) and indicate that dissolved oxygen concentrations within the park estuaries are sufficient to protect critical living estuarine resources.

The majority of the area within the park estuaries was classified as being in fair to good condition with respect to chlorophyll-*a* concentrations, and significant improvements in condition (i.e., declining concentrations) were observed in all three strata. After 2014, poor conditions were observed in less than 5% of the area within the PB and NH strata, and the SP stratum generally had the highest percentage of area characterized as being in poor condition. Chlorophyll-*a* concentrations at the trend stations were also generally characterized as being in fair to good condition, and although concentrations appeared to decline, no significant changes were observed over time. Continuous monitoring at the logging stations showed that conditions in the PB and NH strata typically alternated between fair and good throughout the day with few periods of poor conditions observed in most years. Conditions at the SP logging station were more variable with extensive periods of poor conditions observed in most years. Spatially, both the spatial station and trend station data indicate that conditions were worse along the northern and western shores of Pleasant Bay (PB stratum) and near South/East Orleans and Town Cove (NH stratum). Higher chlorophyll-*a* concentrations in these specific areas are likely the result of higher nutrient loading associated with relatively dense housing and commercial development compared to the rest of the monitored area (Balogh et al. 2022).

Water clarity, as measured by PAR attenuation, was typically fair to good throughout the majority of the monitored area in most years sampled. Despite a significant increase in turbidity over time, water clarity within the PB stratum remained relatively constant with no periods of significant change. Water clarity also remained constant within the SP stratum. In the NH stratum, a significant decline in PAR attenuation (i.e., improving water clarity) was observed prior to 2012 but remained constant after that time. Poor conditions were observed in several years and generally represented less than 10% of the area within individual strata. Water clarity at the trend stations was also typically classified as being in fair to good condition with no significant changes observed. Continuous monitoring at the logging station in each stratum revealed that conditions often alternated between fair and good condition for the majority of daylight hours during which PAR attenuation could be monitored each day and that poor conditions were observed most years. Spatially, both the spatial station and trend station data indicate that conditions were worse along the northern and western shores of Pleasant Bay (PB stratum) and near South/East Orleans and Town Cove (NH stratum) and are likely related to the higher phytoplankton abundance in these areas.

A significant increase in water temperature was observed in the NH stratum and across all trend stations between 2007 and 2021. Summertime temperatures at the logging station, most trend stations, and in a large percentage of the park estuaries exceeded 25°C in most years and often exceeded 28°C in some areas. 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) and have been implicated in driving recent severe hypoxic events in nearby Cape Cod Bay (Scully et al. 2022). 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.

Trends in seagrass condition within the park's reference beds varied by depth and location. Prior to 2006, all three transects at Duck Harbor Beach contained eelgrass in moderate to high abundance. During the next seven years, eelgrass in both the shallow and deep transects experienced a precipitous decline and vanished with no signs of recovery between 2014 and 2022. Eelgrass biomass, density, and percent cover remained relatively constant in the mid-depth transect. At the Pleasant Bay reference bed, eelgrass in the mid-depth transect also remained relatively stable, whereas the shallow and deep transects experienced several periods of significant decline and recovery. While eelgrass has persisted in all three transects, biomass, shoot density, and percent cover in the deep transect have all declined significantly over the entire monitoring timeframe. Other recent studies have also reported declines in seagrass distribution and abundance on the Cape Cod peninsula and nearby islands (Long and Mora 2023; Novak et al. 2023). Possible causes of eelgrass decline in the park may be related to physical disturbance causing erosion or burial, relatively poor

water clarity 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). Management efforts to prevent further loss of eelgrass in this system should focus on improvements in water clarity and possibly seeding or transplanting with more heat-tolerant genotypes.

Conclusions

Although most aspects of water quality and water clarity were generally classified as being in fair to good condition with improving or stable trends, poor conditions were still observed occasionally at Cape Cod National Seashore over the timeframe between 2007 and 2021 especially in the Salt Pond stratum. Significant declines in eelgrass in the park's reference seagrass beds between 2003 and 2022 suggest that conditions in the shallow and deep extremes are becoming less conducive for supporting eelgrass growth. Given that water temperatures in the park are increasing and that warmer temperatures may negatively affect both water quality and seagrass, 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 Summaries of Multiple Comparison Test Results

This Appendix contains summaries of the multiple comparison test results for all possible yearly contrasts for each spatial station water quality parameter (Tables 34–37). Note that tables for bottom dissolved oxygen and surface turbidity are not included because no significant differences were found between years for these parameters.

Table 34. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-a concentration within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{416}	p-value	95% CI
2007–2008	-0.201	0.148	-1.360	0.970	(-0.687, 0.285)
2007–2009	-0.326	0.164	-1.994	0.696	(-0.864, 0.211)
2007–2010	-0.276	0.146	-1.893	0.762	(-0.756, 0.203)
2007–2011	-0.252	0.142	-1.776	0.829	(-0.717, 0.214)
2007–2012	-0.210	0.142	-1.483	0.944	(-0.675, 0.255)
2007–2013	-0.093	0.142	-0.656	1.000	(-0.558, 0.372)
2007–2014	-0.115	0.142	-0.809	1.000	(-0.580, 0.351)
2007–2016	0.577	0.142	4.071	0.003	(0.111, 1.042)
2007–2018	0.264	0.142	1.862	0.780	(-0.201, 0.729)
2007–2019	0.078	0.142	0.547	1.000	(-0.388, 0.543)
2007–2021	0.949	0.142	6.698	0.000	(0.484, 1.414)
2008–2009	-0.125	0.165	-0.756	1.000	(-0.668, 0.418)
2008–2010	-0.075	0.148	-0.507	1.000	(-0.561, 0.411)
2008–2011	-0.050	0.144	-0.349	1.000	(-0.523, 0.423)
2008–2012	-0.009	0.144	-0.061	1.000	(-0.482, 0.464)
2008–2013	0.108	0.144	0.753	1.000	(-0.364, 0.581)
2008–2014	0.087	0.144	0.602	1.000	(-0.386, 0.560)
2008–2016	0.778	0.144	5.404	0.000	(0.305, 1.251)
2008–2018	0.465	0.144	3.231	0.059	(-0.008, 0.938)
2008–2019	0.279	0.144	1.937	0.734	(-0.194, 0.752)
2008–2021	1.150	0.144	7.988	0.000	(0.677, 1.623)
2009–2010	0.050	0.163	0.306	1.000	(-0.487, 0.587)
2009–2011	0.075	0.160	0.467	1.000	(-0.450, 0.600)
2009–2012	0.116	0.160	0.726	1.000	(-0.409, 0.642)
2009–2013	0.233	0.160	1.460	0.950	(-0.292, 0.759)
2009–2014	0.212	0.160	1.324	0.976	(-0.313, 0.737)

Table 34 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-*a* concentration within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{416}	<i>p</i> -value	95% CI
2009–2016	0.903	0.160	5.646	0.000	(0.378, 1.428)
2009–2018	0.590	0.160	3.690	0.013	(0.065, 1.115)
2009–2019	0.404	0.160	2.525	0.326	(-0.121, 0.929)
2009–2021	1.275	0.160	7.972	0.000	(0.750, 1.800)
2010–2011	0.025	0.142	0.175	1.000	(-0.440, 0.490)
2010–2012	0.066	0.142	0.468	1.000	(-0.399, 0.532)
2010–2013	0.184	0.142	1.295	0.979	(-0.282, 0.649)
2010–2014	0.162	0.142	1.142	0.992	(-0.303, 0.627)
2010–2016	0.853	0.142	6.021	0.000	(0.388, 1.318)
2010–2018	0.540	0.142	3.813	0.008	(0.075, 1.005)
2010–2019	0.354	0.142	2.498	0.343	(-0.111, 0.819)
2010–2021	1.225	0.142	8.648	0.000	(0.760, 1.690)
2011–2012	0.041	0.137	0.303	1.000	(-0.408, 0.491)
2011–2013	0.159	0.137	1.161	0.991	(-0.290, 0.608)
2011–2014	0.137	0.137	1.002	0.998	(-0.312, 0.586)
2011–2016	0.828	0.137	6.060	0.000	(0.379, 1.277)
2011–2018	0.515	0.137	3.771	0.010	(0.067, 0.964)
2011–2019	0.329	0.137	2.408	0.401	(-0.120, 0.778)
2011–2021	1.200	0.137	8.783	0.000	(0.751, 1.649)
2012–2013	0.117	0.137	0.857	0.999	(-0.332, 0.566)
2012–2014	0.096	0.137	0.698	1.000	(-0.354, 0.545)
2012–2016	0.787	0.137	5.753	0.000	(0.338, 1.236)
2012–2018	0.474	0.137	3.466	0.029	(0.025, 0.923)
2012–2019	0.288	0.137	2.103	0.620	(-0.161, 0.737)
2012–2021	1.159	0.137	8.474	0.000	(0.710, 1.608)
2013–2014	-0.022	0.137	-0.159	1.000	(-0.471, 0.427)
2013–2016	0.670	0.137	4.899	0.000	(0.221, 1.118)
2013–2018	0.357	0.137	2.610	0.275	(-0.092, 0.805)
2013–2019	0.170	0.137	1.247	0.985	(-0.278, 0.619)
2013–2021	1.042	0.137	7.622	0.000	(0.593, 1.490)
2014–2016	0.691	0.137	5.058	0.000	(0.242, 1.140)
2014–2018	0.378	0.137	2.769	0.195	(-0.070, 0.827)
2014–2019	0.192	0.137	1.406	0.962	(-0.257, 0.641)
2014–2021	1.063	0.137	7.781	0.000	(0.615, 1.512)

Table 34 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-*a* concentration within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{416}	<i>p</i> -value	95% CI
2016–2018	-0.313	0.137	-2.289	0.484	(-0.762, 0.136)
2016–2019	-0.499	0.137	-3.652	0.015	(-0.948, -0.050)
2016–2021	0.372	0.137	2.722	0.218	(-0.077, 0.821)
2018–2019	-0.186	0.137	-1.363	0.970	(-0.635, 0.263)
2018–2021	0.685	0.137	5.012	0.000	(0.236, 1.134)
2019–2021	0.871	0.137	6.375	0.000	(0.422, 1.320)

Table 35. Summary of the multiple comparison test results for all possible yearly contrasts of mean log PAR attenuation within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{388}	<i>p</i> -value	95% CI
2007–2008	0.141	0.141	1.003	0.998	(-0.321, 0.603)
2007–2009	0.294	0.142	2.069	0.642	(-0.173, 0.761)
2007–2010	0.275	0.138	2.002	0.689	(-0.176, 0.727)
2007–2011	0.331	0.128	2.588	0.289	(-0.089, 0.750)
2007–2012	0.292	0.128	2.282	0.489	(-0.128, 0.711)
2007–2013	0.607	0.128	4.725	0.000	(0.185, 1.028)
2007–2014	0.212	0.128	1.654	0.886	(-0.209, 0.634)
2007–2016	0.463	0.128	3.620	0.017	(0.043, 0.882)
2007–2018	0.388	0.129	3.001	0.111	(-0.036, 0.812)
2007–2019	0.169	0.128	1.319	0.976	(-0.251, 0.588)
2007–2021	0.327	0.128	2.555	0.307	(-0.093, 0.746)
2008–2009	0.153	0.142	1.077	0.995	(-0.314, 0.620)
2008–2010	0.134	0.137	0.977	0.998	(-0.317, 0.585)
2008–2011	0.190	0.128	1.483	0.944	(-0.230, 0.609)
2008–2012	0.150	0.128	1.176	0.990	(-0.269, 0.570)
2008–2013	0.466	0.129	3.623	0.017	(0.044, 0.887)
2008–2014	0.071	0.129	0.554	1.000	(-0.351, 0.493)
2008–2016	0.321	0.128	2.515	0.332	(-0.098, 0.741)
2008–2018	0.247	0.129	1.909	0.750	(-0.177, 0.671)
2008–2019	0.027	0.128	0.215	1.000	(-0.392, 0.447)
2008–2021	0.185	0.128	1.451	0.952	(-0.234, 0.605)
2009–2010	-0.019	0.139	-0.137	1.000	(-0.474, 0.436)

Table 35 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log PAR attenuation within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{388}	p-value	95% CI
2009–2011	0.036	0.129	0.281	1.000	(-0.388, 0.461)
2009–2012	-0.003	0.129	-0.022	1.000	(-0.428, 0.422)
2009–2013	0.312	0.130	2.400	0.406	(-0.115, 0.739)
2009–2014	-0.082	0.130	-0.630	1.000	(-0.509, 0.345)
2009–2016	0.168	0.129	1.300	0.978	(-0.257, 0.593)
2009–2018	0.093	0.131	0.714	1.000	(-0.336, 0.523)
2009–2019	-0.126	0.129	-0.972	0.998	(-0.551, 0.299)
2009–2021	0.032	0.129	0.249	1.000	(-0.393, 0.457)
2010–2011	0.055	0.124	0.448	1.000	(-0.351, 0.461)
2010–2012	0.016	0.124	0.131	1.000	(-0.390, 0.422)
2010–2013	0.331	0.124	2.663	0.246	(-0.077, 0.740)
2010–2014	-0.063	0.124	-0.506	1.000	(-0.471, 0.345)
2010–2016	0.187	0.124	1.514	0.935	(-0.219, 0.593)
2010–2018	0.112	0.125	0.899	0.999	(-0.298, 0.523)
2010–2019	-0.107	0.124	-0.863	0.999	(-0.513, 0.299)
2010–2021	0.051	0.124	0.414	1.000	(-0.355, 0.457)
2011–2012	-0.039	0.112	-0.349	1.000	(-0.408, 0.330)
2011–2013	0.276	0.113	2.439	0.379	(-0.095, 0.647)
2011–2014	-0.118	0.113	-1.046	0.996	(-0.490, 0.253)
2011–2016	0.132	0.112	1.173	0.990	(-0.237, 0.501)
2011–2018	0.057	0.114	0.501	1.000	(-0.317, 0.431)
2011–2019	-0.162	0.112	-1.443	0.954	(-0.531, 0.207)
2011–2021	-0.004	0.112	-0.037	1.000	(-0.373, 0.365)
2012–2013	0.315	0.113	2.786	0.188	(-0.056, 0.687)
2012–2014	-0.079	0.113	-0.699	1.000	(-0.450, 0.292)
2012–2016	0.171	0.112	1.522	0.933	(-0.198, 0.540)
2012–2018	0.096	0.114	0.845	0.999	(-0.278, 0.470)
2012–2019	-0.123	0.112	-1.094	0.995	(-0.492, 0.246)
2012–2021	0.035	0.112	0.312	1.000	(-0.334, 0.404)
2013–2014	-0.394	0.114	-3.466	0.028	(-0.768, -0.021)
2013–2016	-0.144	0.113	-1.274	0.982	(-0.515, 0.227)
2013–2018	-0.219	0.115	-1.911	0.750	(-0.595, 0.157)
2013–2019	-0.438	0.113	-3.873	0.007	(-0.809, -0.067)
2013–2021	-0.280	0.113	-2.476	0.355	(-0.651, 0.091)

Table 35 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log PAR attenuation within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{388}	<i>p</i> -value	95% CI
2014–2016	0.250	0.113	2.212	0.539	(-0.121, 0.622)
2014–2018	0.175	0.115	1.531	0.930	(-0.201, 0.551)
2014–2019	-0.044	0.113	-0.387	1.000	(-0.415, 0.327)
2014–2021	0.114	0.113	1.009	0.997	(-0.257, 0.485)
2016–2018	-0.075	0.114	-0.657	1.000	(-0.449, 0.299)
2016–2019	-0.294	0.112	-2.616	0.271	(-0.663, 0.075)
2016–2021	-0.136	0.112	-1.210	0.988	(-0.505, 0.233)
2018–2019	-0.219	0.114	-1.925	0.740	(-0.593, 0.155)
2018–2021	-0.061	0.114	-0.537	1.000	(-0.435, 0.313)
2019–2021	0.158	0.112	1.406	0.961	(-0.211, 0.527)

Table 36. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface salinity within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{398}	<i>p</i> -value	95% CI
2007–2008	-0.006	0.009	-0.616	1.000	(-0.035, 0.024)
2007–2009	0.029	0.014	2.063	0.641	(-0.017, 0.074)
2007–2010	0.014	0.009	1.601	0.905	(-0.015, 0.043)
2007–2011	0.071	0.009	8.237	0.000	(0.043, 0.100)
2007–2012	-0.018	0.009	-2.049	0.651	(-0.046, 0.011)
2007–2013	0.046	0.009	5.316	0.000	(0.018, 0.074)
2007–2014	0.036	0.009	4.160	0.002	(0.008, 0.064)
2007–2016	-0.008	0.009	-0.887	0.999	(-0.036, 0.021)
2007–2018	0.013	0.009	1.557	0.920	(-0.015, 0.042)
2007–2019	0.034	0.009	3.916	0.006	(0.006, 0.062)
2007–2021	0.007	0.009	0.788	1.000	(-0.022, 0.035)
2008–2009	0.034	0.014	2.460	0.360	(-0.011, 0.080)
2008–2010	0.020	0.009	2.215	0.531	(-0.009, 0.049)
2008–2011	0.077	0.009	8.808	0.000	(0.048, 0.106)
2008–2012	-0.012	0.009	-1.389	0.964	(-0.041, 0.016)
2008–2013	0.052	0.009	5.912	0.000	(0.023, 0.080)
2008–2014	0.042	0.009	4.767	0.000	(0.013, 0.070)
2008–2016	-0.002	0.009	-0.237	1.000	(-0.031, 0.027)
2008–2018	0.019	0.009	2.186	0.552	(-0.009, 0.048)

Table 36 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface salinity within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{398}	p-value	95% CI
2008–2019	0.040	0.009	4.524	0.000	(0.011, 0.068)
2008–2021	0.012	0.009	1.423	0.956	(-0.016, 0.041)
2009–2010	-0.014	0.014	-1.044	0.996	(-0.059, 0.031)
2009–2011	0.043	0.014	3.139	0.074	(-0.002, 0.087)
2009–2012	-0.046	0.014	-3.408	0.033	(-0.091, -0.002)
2009–2013	0.017	0.014	1.279	0.980	(-0.027, 0.062)
2009–2014	0.007	0.014	0.544	1.000	(-0.037, 0.052)
2009–2016	-0.036	0.014	-2.669	0.239	(-0.081, 0.008)
2009–2018	-0.015	0.014	-1.114	0.994	(-0.060, 0.029)
2009–2019	0.005	0.014	0.388	1.000	(-0.039, 0.050)
2009–2021	-0.022	0.014	-1.603	0.903	(-0.066, 0.023)
2010–2011	0.057	0.009	6.695	0.000	(0.029, 0.085)
2010–2012	-0.032	0.009	-3.757	0.010	(-0.060, -0.004)
2010–2013	0.032	0.009	3.727	0.011	(0.004, 0.060)
2010–2014	0.022	0.009	2.553	0.303	(-0.006, 0.050)
2010–2016	-0.022	0.009	-2.576	0.289	(-0.050, 0.006)
2010–2018	-0.001	0.009	-0.093	1.000	(-0.029, 0.027)
2010–2019	0.020	0.009	2.304	0.466	(-0.008, 0.048)
2010–2021	-0.007	0.009	-0.875	0.999	(-0.035, 0.020)
2011–2012	-0.089	0.008	-10.828	0.000	(-0.116, -0.062)
2011–2013	-0.025	0.008	-3.077	0.088	(-0.052, 0.002)
2011–2014	-0.035	0.008	-4.295	0.001	(-0.062, -0.008)
2011–2016	-0.079	0.008	-9.612	0.000	(-0.106, -0.052)
2011–2018	-0.058	0.008	-7.037	0.000	(-0.085, -0.031)
2011–2019	-0.037	0.008	-4.552	0.000	(-0.064, -0.011)
2011–2021	-0.065	0.008	-7.848	0.000	(-0.091, -0.038)
2012–2013	0.064	0.008	7.753	0.000	(0.037, 0.091)
2012–2014	0.054	0.008	6.537	0.000	(0.027, 0.081)
2012–2016	0.010	0.008	1.224	0.986	(-0.017, 0.037)
2012–2018	0.031	0.008	3.796	0.008	(0.004, 0.058)
2012–2019	0.052	0.008	6.280	0.000	(0.025, 0.079)
2012–2021	0.025	0.008	2.987	0.113	(-0.002, 0.052)
2013–2014	-0.010	0.008	-1.217	0.987	(-0.037, 0.017)
2013–2016	-0.054	0.008	-6.534	0.000	(-0.081, -0.027)

Table 36 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface salinity within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{398}	p-value	95% CI
2013–2018	-0.033	0.008	-3.960	0.005	(-0.059, -0.006)
2013–2019	-0.012	0.008	-1.475	0.944	(-0.039, 0.015)
2013–2021	-0.039	0.008	-4.770	0.000	(-0.066, -0.012)
2014–2016	-0.044	0.008	-5.317	0.000	(-0.071, -0.017)
2014–2018	-0.023	0.008	-2.743	0.203	(-0.049, 0.004)
2014–2019	-0.002	0.008	-0.258	1.000	(-0.029, 0.025)
2014–2021	-0.029	0.008	-3.553	0.020	(-0.056, -0.002)
2016–2018	0.021	0.008	2.575	0.290	(-0.006, 0.048)
2016–2019	0.042	0.008	5.060	0.000	(0.015, 0.069)
2016–2021	0.015	0.008	1.764	0.831	(-0.012, 0.041)
2018–2019	0.020	0.008	2.485	0.344	(-0.006, 0.047)
2018–2021	-0.007	0.008	-0.810	1.000	(-0.034, 0.020)
2019–2021	-0.027	0.008	-3.295	0.047	(-0.054, -0.000)

Table 37. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{413}	p-value	95% CI
2007–2008	-0.042	0.021	-1.957	0.721	(-0.111, 0.028)
2007–2009	-0.033	0.023	-1.419	0.959	(-0.109, 0.043)
2007–2010	-0.066	0.021	-3.175	0.069	(-0.134, 0.002)
2007–2011	-0.068	0.020	-3.374	0.038	(-0.134, -0.002)
2007–2012	-0.129	0.020	-6.389	0.000	(-0.195, -0.063)
2007–2013	-0.154	0.020	-7.654	0.000	(-0.221, -0.088)
2007–2014	-0.030	0.020	-1.498	0.940	(-0.096, 0.036)
2007–2016	-0.083	0.020	-4.127	0.003	(-0.149, -0.017)
2007–2018	-0.094	0.020	-4.647	0.000	(-0.160, -0.028)
2007–2019	-0.139	0.020	-6.912	0.000	(-0.206, -0.073)
2007–2021	-0.061	0.020	-3.035	0.101	(-0.127, 0.005)
2008–2009	0.009	0.023	0.367	1.000	(-0.068, 0.085)
2008–2010	-0.024	0.021	-1.167	0.991	(-0.093, 0.044)
2008–2011	-0.027	0.020	-1.303	0.978	(-0.093, 0.040)
2008–2012	-0.087	0.020	-4.294	0.001	(-0.154, -0.021)
2008–2013	-0.113	0.020	-5.546	0.000	(-0.180, -0.046)

Table 37 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{413}	p-value	95% CI
2008–2014	0.011	0.020	0.556	1.000	(-0.055, 0.078)
2008–2016	-0.042	0.020	-2.049	0.658	(-0.108, 0.025)
2008–2018	-0.052	0.020	-2.565	0.302	(-0.119, 0.014)
2008–2019	-0.098	0.020	-4.810	0.000	(-0.165, -0.031)
2008–2021	-0.020	0.020	-0.967	0.998	(-0.086, 0.047)
2009–2010	-0.033	0.023	-1.440	0.955	(-0.108, 0.042)
2009–2011	-0.035	0.022	-1.565	0.920	(-0.109, 0.038)
2009–2012	-0.096	0.022	-4.280	0.001	(-0.169, -0.023)
2009–2013	-0.121	0.022	-5.416	0.000	(-0.195, -0.048)
2009–2014	0.003	0.022	0.123	1.000	(-0.071, 0.076)
2009–2016	-0.050	0.022	-2.242	0.517	(-0.124, 0.023)
2009–2018	-0.061	0.022	-2.711	0.225	(-0.134, 0.013)
2009–2019	-0.106	0.022	-4.748	0.000	(-0.180, -0.033)
2009–2021	-0.028	0.022	-1.260	0.983	(-0.102, 0.045)
2010–2011	-0.002	0.020	-0.106	1.000	(-0.067, 0.063)
2010–2012	-0.063	0.020	-3.173	0.070	(-0.128, 0.002)
2010–2013	-0.088	0.020	-4.456	0.001	(-0.154, -0.023)
2010–2014	0.036	0.020	1.800	0.817	(-0.029, 0.101)
2010–2016	-0.017	0.020	-0.871	0.999	(-0.082, 0.048)
2010–2018	-0.028	0.020	-1.400	0.963	(-0.093, 0.037)
2010–2019	-0.073	0.020	-3.701	0.013	(-0.139, -0.008)
2010–2021	0.005	0.020	0.238	1.000	(-0.060, 0.070)
2011–2012	-0.061	0.019	-3.179	0.069	(-0.124, 0.002)
2011–2013	-0.086	0.019	-4.509	0.000	(-0.149, -0.024)
2011–2014	0.038	0.019	1.976	0.709	(-0.025, 0.101)
2011–2016	-0.015	0.019	-0.793	1.000	(-0.078, 0.048)
2011–2018	-0.026	0.019	-1.341	0.973	(-0.088, 0.037)
2011–2019	-0.071	0.019	-3.727	0.012	(-0.134, -0.009)
2011–2021	0.007	0.019	0.357	1.000	(-0.056, 0.070)
2012–2013	-0.025	0.019	-1.327	0.975	(-0.088, 0.037)
2012–2014	0.099	0.019	5.153	0.000	(0.036, 0.162)
2012–2016	0.046	0.019	2.386	0.416	(-0.017, 0.109)
2012–2018	0.035	0.019	1.838	0.795	(-0.028, 0.098)
2012–2019	-0.010	0.019	-0.545	1.000	(-0.073, 0.052)

Table 37 (continued). Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval].

Contrast	Estimate	SE	t_{413}	<i>p</i> -value	95% CI
2012–2021	0.068	0.019	3.535	0.022	(0.005, 0.131)
2013–2014	0.124	0.019	6.485	0.000	(0.061, 0.187)
2013–2016	0.071	0.019	3.716	0.012	(0.008, 0.134)
2013–2018	0.061	0.019	3.168	0.070	(-0.002, 0.123)
2013–2019	0.015	0.019	0.782	1.000	(-0.048, 0.078)
2013–2021	0.093	0.019	4.866	0.000	(0.030, 0.156)
2014–2016	-0.053	0.019	-2.769	0.197	(-0.116, 0.010)
2014–2018	-0.064	0.019	-3.317	0.045	(-0.126, -0.001)
2014–2019	-0.109	0.019	-5.703	0.000	(-0.172, -0.046)
2014–2021	-0.031	0.019	-1.619	0.901	(-0.094, 0.032)
2016–2018	-0.011	0.019	-0.548	1.000	(-0.073, 0.052)
2016–2019	-0.056	0.019	-2.934	0.132	(-0.119, 0.007)
2016–2021	0.022	0.019	1.150	0.992	(-0.041, 0.085)
2018–2019	-0.046	0.019	-2.386	0.416	(-0.108, 0.017)
2018–2021	0.033	0.019	1.698	0.867	(-0.030, 0.095)
2019–2021	0.078	0.019	4.084	0.003	(0.015, 0.141)

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 7, 9, 10, and 11 (Tables 38–41).

Table 38. 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 chlorophyll-a concentration by year within Cape Cod National Seashore (all strata) are 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	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
2021	0.949	1.150	1.275	1.225	1.200	1.159	1.042	1.063	0.372	0.685	0.871	1.040
2019	0.078	0.279	0.404	0.354	0.329	0.288	0.170	0.192	-0.499	-0.186	1.910	0.000
2018	0.264	0.465	0.590	0.540	0.515	0.474	0.357	0.378	-0.313	1.720	0.969	0.000
2016	0.577	0.778	0.903	0.853	0.828	0.787	0.670	0.691	1.410	0.484	0.015	0.217
2014	-0.115	0.087	0.212	0.162	0.137	0.096	-0.022	2.100	0.000	0.197	0.962	0.000
2013	-0.093	0.108	0.233	0.184	0.159	0.117	2.080	1.000	0.000	0.276	0.985	0.000
2012	-0.210	-0.009	0.116	0.066	0.041	2.200	0.999	1.000	0.000	0.028	0.619	0.000
2011	-0.252	-0.050	0.075	0.025	2.240	1.000	0.991	0.998	0.000	0.010	0.401	0.000
2010	-0.276	-0.075	0.050	2.260	1.000	1.000	0.979	0.993	0.000	0.009	0.342	0.000
2009	-0.326	-0.125	2.310	1.000	1.000	1.000	0.950	0.975	0.000	0.013	0.326	0.000
2008	-0.201	2.190	1.000	1.000	1.000	1.000	1.000	1.000	0.000	0.059	0.734	0.000
2007	1.990	0.970	0.696	0.761	0.829	0.944	1.000	1.000	0.003	0.780	1.000	0.000

Table 39. 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 PAR attenuation by each year within Cape Cod National Seashore (all strata) are 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	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
2021	0.327	0.185	0.032	0.051	-0.004	0.035	-0.280	0.114	-0.136	-0.061	0.158	-0.292
2019	0.169	0.027	-0.126	-0.107	-0.162	-0.123	-0.438	-0.044	-0.294	-0.219	-0.134	0.960
2018	0.388	0.247	0.093	0.112	0.057	0.096	-0.219	0.175	-0.075	-0.354	0.740	1.000
2016	0.463	0.321	0.168	0.187	0.132	0.171	-0.144	0.250	-0.428	1.000	0.272	0.980
2014	0.212	0.071	-0.082	-0.063	-0.118	-0.079	-0.394	-0.178	0.539	0.930	1.000	0.990
2013	0.607	0.466	0.312	0.331	0.276	0.315	-0.573	0.028	0.982	0.750	0.007	0.356
2012	0.292	0.150	-0.003	0.016	-0.039	-0.257	0.188	1.000	0.933	1.000	0.995	1.000
2011	0.331	0.190	0.036	0.055	-0.296	1.000	0.380	0.996	0.991	1.000	0.953	1.000
2010	0.275	0.134	-0.019	-0.241	1.000	1.000	0.246	1.000	0.935	0.999	0.999	1.000
2009	0.294	0.153	-0.260	1.000	1.000	1.000	0.406	1.000	0.979	1.000	0.998	1.000
2008	0.141	-0.107	0.995	0.998	0.944	0.990	0.017	1.000	0.330	0.751	1.000	0.950
2007	0.034	0.998	0.642	0.690	0.288	0.488	0.000	0.886	0.017	0.110	0.976	0.305

Table 40. Shows an accessible version of the grid values displayed in [Figure 10](#). 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 Cape Cod National Seashore (all strata) are 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	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
2021	0.007	0.012	-0.022	-0.007	-0.065	0.025	-0.039	-0.029	0.015	-0.007	-0.027	3.432
2019	0.034	0.040	0.005	0.020	-0.037	0.052	-0.012	-0.002	0.042	0.020	3.405	0.047
2018	0.013	0.019	-0.015	-0.001	-0.058	0.031	-0.033	-0.023	0.021	3.426	0.344	1.000
2016	-0.008	-0.002	-0.036	-0.022	-0.079	0.010	-0.054	-0.044	3.447	0.290	0.000	0.831
2014	0.036	0.042	0.007	0.022	-0.035	0.054	-0.010	3.403	0.000	0.204	1.000	0.021
2013	0.046	0.052	0.017	0.032	-0.025	0.064	3.393	0.987	0.000	0.005	0.944	0.000
2012	-0.018	-0.012	-0.046	-0.032	-0.089	3.457	0.000	0.000	0.986	0.009	0.000	0.112
2011	0.071	0.077	0.043	0.057	3.368	0.000	0.088	0.001	0.000	0.000	0.000	0.000
2010	0.014	0.020	-0.014	3.425	0.000	0.010	0.011	0.303	0.289	1.000	0.466	0.999
2009	0.029	0.034	3.410	0.996	0.075	0.033	0.980	1.000	0.239	0.994	1.000	0.903
2008	-0.006	3.445	0.361	0.531	0.000	0.964	0.000	0.000	1.000	0.552	0.000	0.957
2007	3.439	1.000	0.641	0.904	0.000	0.651	0.000	0.002	0.999	0.920	0.006	1.000

Table 41. Shows an accessible version of the grid values displayed in [Figure 11](#). 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 within each year by year within Cape Cod National Seashore (all strata) are 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	Mean log surface temperature (°C)											
	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
2021	-0.061	-0.020	-0.028	0.005	0.007	0.068	0.093	-0.031	0.022	0.033	0.078	3.110
2019	-0.139	-0.098	-0.106	-0.073	-0.071	-0.010	0.015	-0.109	-0.056	-0.046	3.190	0.003
2018	-0.094	-0.052	-0.061	-0.028	-0.026	0.035	0.061	-0.064	-0.011	3.140	0.417	0.867
2016	-0.083	-0.042	-0.050	-0.017	-0.015	0.046	0.071	-0.053	3.130	1.000	0.132	0.990
2014	-0.030	0.011	0.003	0.036	0.038	0.099	0.124	3.080	0.196	0.045	0.000	0.901
2013	-0.154	-0.113	-0.121	-0.088	-0.086	-0.025	3.200	0.000	0.012	0.070	1.000	0.000
2012	-0.129	-0.087	-0.096	-0.063	-0.061	3.180	0.975	0.000	0.416	0.794	1.000	0.023
2011	-0.068	-0.027	-0.035	-0.002	3.120	0.069	0.000	0.708	1.000	0.973	0.012	1.000
2010	-0.066	-0.024	-0.033	3.110	1.000	0.068	0.001	0.816	0.999	0.963	0.013	1.000
2009	-0.033	0.009	3.080	0.955	0.920	0.001	0.000	1.000	0.518	0.224	0.000	0.983
2008	-0.042	3.090	1.000	0.991	0.978	0.001	0.000	1.000	0.658	0.302	0.000	0.998
2007	3.050	0.721	0.959	0.070	0.038	0.000	0.000	0.940	0.002	0.000	0.000	0.102

Appendix C: Trend Station Water Quality Data Summaries

This Appendix contains yearly summary statistics for water quality parameters for each trend station within Cape Cod National Seashore (Tables 42–47).

Table 42. Yearly summary statistics for surface chlorophyll-*a* concentration ($\mu\text{g/L}$) at Cape Cod National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available].

Station	Statistic	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
3	Mean	3.73	3.34	4.16	2.05	4.09	4.18	6.02	7.11	1.90	2.85	1.58	0.87
3	SD	0.81	1.06	1.57	0.94	1.07	0.70	0.91	1.07	0.70	1.43	0.48	0.63
3	n	4	3	4	4	4	4	4	4	4	4	4	4
7	Mean	5.06	5.70	7.67	3.71	6.93	4.20	9.73	6.79	1.88	2.75	3.24	1.57
7	SD	1.90	2.23	4.49	1.34	5.10	0.91	3.28	1.73	1.23	0.79	0.84	0.49
7	n	4	2	4	4	4	4	4	4	4	4	4	4
11	Mean	2.51	6.11	10.00	10.10	5.40	5.96	3.40	5.11	1.37	2.91	4.81	2.29
11	SD	0.90	3.22	11.37	3.65	3.07	2.18	3.93	2.30	0.95	1.85	2.39	1.43
11	n	4	4	4	3	4	4	4	4	4	4	4	4
18	Mean	10.39	11.71	13.18	16.69	18.02	20.04	26.83	12.82	5.76	10.29	18.46	11.07
18	SD	1.51	4.13	4.12	6.94	12.97	7.57	19.13	7.33	3.70	NA	6.37	9.10
18	n	4	4	4	4	4	4	4	4	4	1	4	4
23	Mean	9.88	8.54	9.35	12.56	14.40	11.41	9.85	8.45	5.89	3.30	8.88	3.44
23	SD	4.69	2.04	3.75	3.79	12.73	6.83	5.93	3.13	4.61	NA	2.06	1.62
23	n	4	3	4	4	4	4	4	4	4	1	4	4
28	Mean	5.32	6.56	12.50	6.34	5.68	4.85	6.25	8.75	3.40	2.31	13.28	5.36
28	SD	4.86	3.51	7.70	0.60	2.61	0.81	2.73	5.03	2.58	NA	6.33	2.19
28	n	4	2	4	4	4	4	4	4	4	1	4	4

Table 43. Yearly summary statistics for bottom dissolved oxygen concentration (mg/L) at Cape Cod National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available].

Station	Statistic	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
3	Mean	8.81	7.67	7.46	7.20	8.17	7.13	8.21	8.63	7.45	8.49	7.68	7.22
3	SD	0.62	0.40	0.52	0.77	0.30	0.48	1.18	0.50	0.50	0.34	0.28	0.48
3	n	4	3	4	4	4	4	4	4	4	4	4	4
7	Mean	7.69	7.17	6.61	6.88	7.40	6.69	6.79	7.61	6.62	8.76	7.88	7.48
7	SD	0.40	1.01	0.88	0.29	0.44	0.23	0.52	0.42	0.41	0.20	0.53	0.34
7	n	4	3	4	4	4	4	4	4	4	4	4	4
11	Mean	7.80	5.91	5.82	6.90	6.23	6.28	5.99	6.92	6.73	7.36	7.63	6.88
11	SD	1.43	0.38	1.47	NA	1.37	1.17	0.53	1.02	0.80	0.38	0.72	1.48
11	n	4	4	4	1	4	4	4	4	4	4	4	4
18	Mean	7.96	6.90	6.70	7.70	7.86	6.86	10.57	6.97	7.72	8.12	8.27	9.12
18	SD	1.25	0.22	0.21	0.95	0.35	1.53	2.86	0.68	1.67	NA	0.85	1.42
18	n	4	4	2	4	2	4	4	4	4	1	4	4
23	Mean	7.66	6.38	7.72	7.31	7.74	8.02	8.86	7.58	7.48	7.32	7.62	8.25
23	SD	0.75	1.36	1.73	0.70	0.42	0.15	1.28	0.84	0.99	NA	0.72	0.81
23	n	4	3	4	4	4	4	4	4	4	1	4	4
28	Mean	8.00	8.26	5.97	7.74	7.59	7.54	6.97	8.24	9.08	8.29	7.68	10.85
28	SD	0.65	0.28	NA	0.98	1.59	0.65	0.87	0.83	1.70	NA	1.63	1.74
28	n	4	2	1	4	3	4	4	4	4	1	4	4

Table 44. Yearly summary statistics for PAR attenuation (K_d (m^{-1})) at Cape Cod National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available].

Station	Statistic	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
3	Mean	0.71	0.92	0.66	1.29	0.36	0.58	0.52	0.63	0.44	0.48	0.43	0.74
3	SD	0.45	0.07	0.46	1.10	0.02	0.14	0.10	0.10	0.04	0.02	0.17	0.34
3	n	2	2	4	4	2	4	4	4	4	4	4	4
7	Mean	0.62	1.68	0.80	0.85	0.52	0.54	0.71	0.70	0.46	0.76	0.48	0.60
7	SD	0.20	1.53	0.79	0.39	0.09	0.08	0.34	0.21	0.10	0.49	0.05	0.22
7	n	3	3	3	3	4	4	4	4	4	4	4	4
11	Mean	3.59	1.66	0.24	0.71	0.53	0.86	0.54	0.78	0.77	0.54	0.88	0.72
11	SD	2.99	1.90	0.05	NA	0.13	0.30	0.11	0.44	0.24	0.34	0.31	0.17
11	n	2	3	2	1	2	4	4	4	4	4	4	4
18	Mean	2.20	1.37	0.46	1.28	0.31	1.31	0.71	0.93	0.60	1.04	1.29	1.02
18	SD	1.56	NA	NA	0.50	NA	0.56	0.13	0.16	0.14	NA	0.15	0.35
18	n	3	1	1	4	1	4	4	4	4	1	4	4
23	Mean	1.21	1.45	1.06	0.69	0.77	0.84	0.67	0.82	0.58	1.04	1.07	0.86
23	SD	0.28	0.45	0.70	0.15	0.73	0.42	0.17	0.09	0.12	NA	0.39	0.23
23	n	4	3	3	2	3	4	4	4	4	1	4	4
28	Mean	1.37	1.52	4.58	0.37	1.01	1.01	0.55	1.04	0.49	0.52	1.37	1.32
28	SD	0.76	NA	NA	0.01	0.13	0.38	0.23	0.34	0.18	NA	0.56	0.64
28	n	3	1	1	2	2	3	4	4	3	1	4	4

Table 45. Yearly summary statistics for surface salinity (psu) at Cape Cod National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available].

Station	Statistic	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
3	Mean	32.04	31.96	31.67	31.73	30.91	33.05	31.53	31.34	32.67	31.73	30.74	31.79
3	SD	0.11	0.52	0.15	0.21	0.23	0.37	0.43	0.48	1.19	0.20	0.20	0.21
3	n	4	3	3	4	4	4	4	4	4	4	4	4
7	Mean	31.66	32.23	31.40	31.77	30.52	33.03	31.39	31.19	32.33	31.56	30.52	31.60
7	SD	0.31	0.21	0.33	0.22	0.44	0.43	0.49	0.20	1.42	0.17	0.20	0.22
7	n	4	2	3	4	4	4	4	4	4	4	4	4
11	Mean	31.51	32.84	31.24	30.90	30.21	33.00	30.75	31.01	32.30	31.61	30.20	31.68
11	SD	0.46	0.93	0.39	0.52	0.60	0.43	0.73	0.31	1.64	0.34	0.56	0.42
11	n	3	4	3	3	4	4	4	4	4	4	4	4
18	Mean	31.60	31.13	31.05	31.33	29.76	32.33	30.26	30.30	32.48	31.18	30.13	30.95
18	SD	0.28	0.69	0.78	0.39	0.70	0.57	0.66	0.48	1.54	NA	0.82	0.35
18	n	4	4	2	4	4	4	4	4	4	1	4	4
23	Mean	31.77	32.12	31.67	31.49	30.06	32.54	30.69	31.03	32.83	31.88	30.56	31.30
23	SD	0.16	0.46	0.48	0.33	0.25	0.83	0.94	0.28	1.55	NA	0.77	0.45
23	n	4	3	2	4	4	4	4	4	4	1	4	4
28	Mean	31.55	31.37	31.60	30.64	30.04	32.29	31.08	31.75	32.74	32.20	30.77	30.82
28	SD	0.60	1.20	0.14	2.12	0.70	0.81	0.65	0.68	2.00	NA	0.82	0.34
28	n	4	2	2	4	4	4	4	4	4	1	4	4

Table 46. Yearly summary statistics for surface temperature (°C) at Cape Cod National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available].

Station	Statistic	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
3	Mean	16.28	20.04	18.90	19.23	19.88	20.51	20.12	16.51	19.24	19.60	20.63	20.40
3	SD	3.39	0.96	1.64	0.61	0.49	1.70	2.21	1.91	1.72	1.69	0.99	1.57
3	n	4	3	4	4	4	4	4	4	4	4	4	4
7	Mean	22.51	21.79	22.41	21.35	22.25	22.95	23.48	20.10	22.25	22.47	22.89	22.03
7	SD	1.33	1.90	1.05	2.18	0.47	1.45	1.33	1.79	1.88	1.93	0.93	1.49
7	n	4	2	4	4	4	4	4	4	4	4	4	4
11	Mean	23.42	25.00	25.14	24.07	24.28	25.12	25.53	22.38	24.22	25.95	26.77	24.10
11	SD	1.03	1.69	0.77	0.51	1.14	2.00	1.93	1.63	2.39	2.05	0.97	2.24
11	n	3	4	4	3	4	4	4	4	4	4	4	4
18	Mean	22.40	22.41	22.32	22.92	23.79	24.25	26.41	23.43	24.72	26.52	25.74	24.53
18	SD	2.03	0.72	1.02	1.54	0.48	1.18	1.64	0.51	1.80	NA	1.88	0.77
18	n	4	4	4	4	4	4	4	4	4	1	4	4
23	Mean	20.36	21.24	20.13	21.36	22.89	22.82	24.01	20.90	22.50	23.42	24.98	23.72
23	SD	1.83	1.51	2.08	1.73	1.53	2.15	2.33	1.48	0.97	NA	2.09	2.25
23	n	4	3	4	4	4	4	4	4	4	1	4	4
28	Mean	20.37	20.05	21.60	20.72	22.16	21.23	23.39	17.74	22.06	20.07	24.01	23.07
28	SD	2.91	2.58	1.13	1.63	1.01	2.23	2.46	4.33	2.02	NA	2.54	3.25
28	n	4	2	4	4	4	4	4	4	4	1	4	4

Table 47. Yearly summary statistics for surface turbidity (NTU) at Cape Cod National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available].

Station	Statistic	Sampling Year											
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	2021
3	Mean	0.40	0.70	0.12	0.88	0.95	1.38	0.65	0.98	0.40	1.03	0.66	1.14
3	SD	0.24	0.10	0.25	0.49	0.45	0.62	0.42	0.39	0.14	0.13	0.06	1.09
3	n	4	3	4	4	4	4	4	4	4	4	4	4
7	Mean	1.07	1.25	0.52	1.75	0.70	1.15	2.20	2.92	1.25	0.94	0.86	0.71
7	SD	0.51	1.06	0.41	1.84	0.36	0.51	1.01	2.24	1.48	0.16	0.14	0.45
7	n	4	2	4	4	4	4	4	4	4	4	4	3
11	Mean	1.33	2.45	2.28	2.07	1.00	1.55	0.45	2.25	1.25	1.51	1.05	3.21
11	SD	0.76	1.77	2.81	0.25	0.42	0.64	0.37	1.43	0.80	0.54	0.30	4.33
11	n	3	4	4	3	2	4	4	4	4	4	4	4
18	Mean	2.48	2.90	3.00	18.82	3.52	3.45	2.02	2.95	2.10	2.82	2.79	2.59
18	SD	0.96	1.84	0.71	20.02	1.86	1.17	0.41	0.54	0.80	NA	0.80	0.74
18	n	4	4	4	4	4	4	4	4	4	1	4	4
23	Mean	2.90	1.63	1.53	2.08	2.42	2.20	1.70	2.88	2.92	3.22	3.90	4.16
23	SD	0.84	0.32	1.71	0.84	1.08	1.30	0.54	0.49	0.83	NA	1.88	2.66
23	n	4	3	4	4	4	4	4	4	4	1	4	4
28	Mean	1.85	6.85	4.03	3.05	4.38	4.00	2.05	4.38	3.60	1.51	3.67	4.84
28	SD	0.79	7.71	1.76	1.31	3.34	0.56	0.82	2.59	2.61	NA	1.59	2.30
28	n	4	2	4	4	4	4	4	4	4	1	4	4

Appendix D: Seagrass Data Summaries

This Appendix contains seasonal summary statistics for seagrass condition parameters in the Cape Cod National Seashore seagrass reference beds from 2003–2022.

Duck Harbor Beach

Yearly and monthly (if applicable) summary statistics are provided for *Zostera marina* at the Duck Harbor Beach reference seagrass bed for the following: shoot density, percent cover, canopy height, total biomass, and ratio of above to below ground biomass (Tables 48–52).

Table 48. Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* shoot density (per 1 m²) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed. [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
2003–07	NA	NA	NA	830.5	363.9	11	NA	NA	NA
2003–10	758.7	296.1	12	610.7	363.6	12	NA	NA	NA
2004–01	932.4	285.6	11	NA	NA	NA	NA	NA	NA
2004–05	989.1	284.5	11	936.0	594.9	12	457.6	336.9	10
2004–08	919.3	328.9	11	725.3	447.9	12	376.7	343.6	11
2005–04	354.7	172.4	12	NA	NA	NA	168.0	145.5	6
2005–08	609.3	351.9	12	857.3	523.3	12	509.3	443.1	12
2006–07	836.0	376.5	12	686.7	554.6	12	0.0	0.0	12
2007–08	925.3	556.8	12	333.3	545.7	12	0.0	0.0	12
2008–08	452.3	474.3	12	275.3	494.5	12	1.0	3.5	12
2009–07	610.0	635.3	12	0.0	0.0	12	0.0	0.0	12
2010–07	261.7	412.1	12	66.0	152.3	12	2.7	3.6	12
2011–08	338.0	385.8	12	144.7	176.4	12	0.0	0.0	12
2012–07	636.0	450.0	12	133.7	162.8	12	0.0	0.0	12
2013–07	70.0	154.4	12	274.7	407.5	12	0.0	0.0	12
2014–07	0.3	1.2	12	279.0	352.3	12	0.0	0.0	12
2015–08	0.7	1.6	12	310.3	408.1	12	1.3	4.6	12
2016–07	1.7	3.2	12	362.7	358.6	12	NA	NA	NA
2017–06	0.0	0.0	12	165.3	215.3	12	0.0	0.0	12
2018–07	4.7	12.5	12	562.0	571.2	12	1.0	3.5	12
2019–08	0.0	0.0	12	545.0	579.0	12	NA	NA	NA
2019–10	NA	NA	NA	NA	NA	NA	0.0	0.0	12
2021–06	0.0	0.0	12	74.0	248.8	12	NA	NA	NA
2022–07	0.0	0.0	12	166.7	505.8	12	NA	NA	NA

Table 49. Yearly (monthly within year, if applicable) summary statistics for percent cover of *Zostera marina* by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed. [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
2003-07	85.4	31.1	12	74.8	35.8	12	81.7	26.8	12
2003-10	89.2	28.7	12	73.3	40.3	12	NA	NA	NA
2004-01	79.2	26.5	12	NA	NA	NA	NA	NA	NA
2004-05	82.2	28.8	12	61.7	36.1	12	33.3	28.3	12
2004-08	88.3	27.2	12	70.8	38.9	12	53.3	37.4	12
2005-04	51.2	24.9	12	NA	NA	NA	19.2	19.6	6
2005-08	83.8	27.5	12	72.9	38.7	12	45.1	43.0	12
2006-07	76.7	29.8	12	57.5	41.6	12	0.0	0.0	12
2007-08	64.6	40.0	12	25.8	42.9	12	0.0	0.0	12
2008-08	45.9	48.3	12	17.9	30.6	12	0.1	0.3	12
2009-07	43.4	44.9	12	0.0	0.0	12	0.0	0.0	12
2010-07	22.1	30.8	12	5.6	14.1	12	0.4	0.5	12
2011-08	32.9	39.9	12	11.8	13.4	12	0.0	0.0	12
2012-07	40.4	23.4	12	19.5	27.3	12	0.0	0.0	12
2013-07	13.3	30.0	12	21.8	26.3	12	0.0	0.0	12
2014-07	0.1	0.3	12	30.8	37.9	12	0.0	0.0	12
2015-08	0.2	0.4	12	32.0	40.5	12	0.1	0.3	12
2016-07	0.2	0.5	12	39.2	37.0	12	NA	NA	NA
2017-06	0.0	0.0	12	26.8	35.3	12	0.0	0.0	12
2018-07	1.1	2.8	12	42.0	42.9	12	0.1	0.3	12
2019-08	0.0	0.0	12	44.5	43.3	12	NA	NA	NA
2019-10	NA	NA	NA	NA	NA	NA	0.0	0.0	12
2021-06	0.0	0.0	12	6.2	20.1	12	NA	NA	NA
2022-07	0.0	0.0	12	10.4	20.8	12	NA	NA	NA

Table 50. Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* canopy height (cm) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed. [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
2003-07	25.3	6.5	11	21.8	6.3	11	30.8	6.8	12
2003-10	46.8	12.5	11	37.5	10.7	10	NA	NA	NA
2004-01	19.4	10.3	12	NA	NA	NA	NA	NA	NA

Table 50 (continued). Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* canopy height (cm) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed. [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
2004–05	16.6	2.4	12	14.6	2.0	10	14.3	4.1	11
2004–08	43.4	13.7	12	25.1	4.4	10	35.6	5.3	9
2005–04	13.9	4.6	12	NA	NA	NA	12.0	3.5	4
2005–08	41.9	9.0	12	37.0	6.3	10	39.2	9.5	10
2006–07	30.2	10.0	12	27.0	5.8	9	–	–	0
2007–08	29.0	12.3	10	14.4	3.4	5	–	–	0
2008–08	24.7	9.7	9	19.8	4.6	4	7.0	–	1
2009–07	22.4	7.2	8	–	–	0	–	–	0
2010–07	22.9	2.0	7	7.8	3.2	10	10.4	4.3	5
2011–08	20.7	6.7	10	19.8	6.8	9	–	–	0
2012–07	16.2	2.1	10	11.8	4.0	8	–	–	0
2013–07	11.0	3.7	5	17.7	2.5	7	–	–	0
2014–07	9.0	–	1	14.3	4.0	6	–	–	0
2015–08	6.0	1.4	2	16.9	7.8	10	17.0	–	1
2016–07	10.0	1.7	3	18.5	5.5	11	NA	NA	NA
2017–06	–	–	0	20.4	2.5	8	–	–	0
2018–07	12.0	4.7	4	17.4	6.1	11	–	–	0
2019–08	–	–	0	24.0	7.2	9	NA	NA	NA
2019–10	NA	NA	NA	NA	NA	NA	–	–	0
2021–06	0.0	0.0	0	9.6	5.8	5	NA	NA	NA
2022–07	0.0	0.0	0	19.3	3.1	3	NA	NA	NA

Table 51. Yearly (monthly within year, if applicable) summary statistics for total biomass (g m⁻²) of *Zostera marina* by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed. [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
2003–07	–	–	0	141.8	82.4	10	–	–	0
2003–10	118.0	67.0	12	112.3	66.4	12	NA	NA	NA
2004–01	87.8	52.8	5	NA	NA	NA	NA	NA	NA
2004–05	150.9	61.0	11	133.1	119.7	12	59.5	44.7	10
2004–08	233.2	71.6	11	104.2	80.8	12	119.5	113.1	11

Table 51 (continued). Yearly (monthly within year, if applicable) summary statistics for total biomass (g m⁻²) of *Zostera marina* by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed. [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
2005–04	74.9	62.1	6	NA	NA	NA	26.7	27.9	6
2005–08	162.0	114.4	12	282.5	207.4	12	160.5	155.4	12
2006–07	202.1	102.8	12	184.4	198.5	12	0.0	0.0	12
2007–08	140.7	111.6	12	48.4	78.1	12	0.0	0.0	12
2008–08	88.6	97.6	12	42.5	78.2	12	0.0	0.0	11
2009–07	108.8	132.2	12	0.0	0.0	12	0.0	0.0	12
2010–07	35.6	60.6	12	15.5	42.9	10	0.1	0.2	12
2011–08	49.4	66.8	12	33.2	39.9	12	0.0	0.0	12
2012–07	77.8	74.2	12	21.3	30.9	12	0.0	0.0	12
2013–07	9.5	21.9	12	49.4	77.8	12	0.0	0.0	12
2014–07	0.0	0.0	11	66.1	96.4	12	0.0	0.0	12
2015–08	0.0	0.0	11	82.9	142.9	12	0.0	0.0	11
2016–07	0.2	0.4	12	84.1	92.3	12	NA	NA	NA
2017–06	0.0	0.0	12	44.7	70.2	12	0.0	0.0	12
2018–07	0.6	1.9	9	159.3	206.1	12	0.0	0.0	11
2019–08	0.0	0.0	12	126.0	127.0	12	NA	NA	NA
2019–10	NA	NA	NA	NA	NA	NA	0.0	0.0	12
2021–06	0.0	0.0	12	25.0	85.3	12	NA	NA	NA
2022–07	0.0	0.0	12	37.5	119.5	12	NA	NA	NA

Table 52. Yearly (monthly within year, if applicable) summary statistics for ratio of above- to belowground biomass of *Zostera marina* by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed. [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
2003–07	1.0	0.7	11	1.3	0.8	9	2.1	1.5	12
2003–10	1.6	0.5	11	2.4	2.1	10	NA	NA	NA
2004–01	2.0	0.9	5	NA	NA	NA	NA	NA	NA
2004–05	1.5	0.8	12	0.6	0.3	10	1.4	0.9	11
2004–08	1.9	1.6	12	1.1	0.8	10	3.0	2.0	9
2005–04	1.0	0.5	6	NA	NA	NA	1.1	0.7	4

Table 52 (continued). Yearly (monthly within year, if applicable) summary statistics for ratio of above- to belowground biomass of *Zostera marina* by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed. [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
2005–08	2.4	1.7	12	2.4	1.1	10	3.4	2.2	10
2006–07	3.1	1.8	12	2.0	1.0	10	–	–	0
2007–08	1.8	0.9	10	1.3	0.2	5	–	–	0
2008–08	1.8	1.3	9	2.7	0.7	5	–	–	0
2009–07	1.7	0.8	8	–	–	0	–	–	0
2010–07	2.4	1.9	7	2.2	0.2	8	4.0	2.8	5
2011–08	1.9	0.7	10	1.5	0.9	9	–	–	0
2012–07	2.3	1.7	10	1.3	1.1	8	–	–	0
2013–07	1.8	2.1	5	0.8	0.4	7	–	–	0
2014–07	–	–	0	0.7	0.6	6	–	–	0
2015–08	0.3	–	1	1.2	1.3	10	–	–	0
2016–07	1.0	0.3	3	2.1	3.6	11	NA	NA	NA
2017–06	–	–	0	1.0	0.5	8	–	–	0
2018–07	0.8	–	1	1.4	0.8	11	–	–	0
2019–08	–	–	0	1.5	0.8	9	NA	NA	NA
2019–10	NA	NA	NA	NA	NA	NA	–	–	0
2021–06	0.0	0.0	0	0.4	0.3	5	NA	NA	NA
2022–07	0.0	0.0	0	1.2	0.1	3	NA	NA	NA

Pleasant Bay

Yearly and monthly (if applicable) summary statistics are provided for *Zostera marina* at the Pleasant Bay reference seagrass bed for the following: shoot density, percent cover, canopy height, total biomass, and ratio of above- to belowground biomass (Tables 53–57).

Table 53. Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* shoot density (per 1 m²) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed. [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
2003–07	NA	NA	NA	766.7	267.2	12	NA	NA	NA
2003–10	834.7	444.0	12	857.3	178.2	12	NA	NA	NA
2004–05	1358.7	818.9	12	1201.3	291.3	12	493.3	212.0	12
2004–07	1412.0	421.7	12	1014.7	149.5	12	377.3	109.3	12

Table 53 (continued). Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* shoot density (per 1 m²) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed. [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
2005-04	1204.0	517.3	12	NA	NA	NA	141.1	125.9	11
2005-08	1296.0	322.9	12	442.7	170.9	12	161.6	108.9	10
2006-07	6.0	11.0	12	293.7	325.1	12	248.0	98.3	12
2007-08	107.3	230.0	12	657.3	333.4	12	181.7	188.4	12
2008-08	423.7	598.5	12	1138.7	224.4	12	367.0	178.3	12
2009-07	744.3	592.1	12	808.0	148.6	12	124.0	154.0	12
2010-07	143.7	210.0	12	872.0	228.0	12	265.7	116.5	12
2011-08	483.0	503.2	12	1118.7	326.9	12	352.0	79.9	12
2012-07	688.3	594.3	12	526.7	125.3	12	82.0	73.2	12
2013-07	261.7	365.5	12	777.3	230.8	12	146.3	123.2	12
2014-07	546.7	452.4	12	652.0	322.4	12	239.7	167.8	12
2015-08	1013.0	836.8	12	518.7	425.3	12	122.0	108.1	12
2016-07	858.7	457.5	12	580.7	313.7	12	302.3	143.3	12
2017-06	944.0	303.2	12	379.0	159.8	12	16.0	24.7	12
2018-07	650.7	508.7	12	374.7	196.5	12	85.7	118.9	12
2019-08	430.7	311.9	12	249.0	160.9	12	20.0	32.3	12
2021-06	986.3	380.6	12	494.0	249.1	12	19.7	36.6	12
2022-07	192.7	153.2	12	596.0	247.6	12	75.7	122.6	12

Table 54. Yearly (monthly within year, if applicable) summary statistics for percent cover of *Zostera marina* by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed. [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
2003-07	50.4	31.4	12	77.9	16.8	12	68.9	35.8	12
2003-10	82.5	26.7	12	96.7	8.9	12	NA	NA	NA
2004-05	71.7	23.0	12	77.5	12.7	12	68.8	21.8	12
2004-07	84.6	23.7	12	97.9	5.0	12	98.3	3.9	12
2005-04	75.0	16.2	12	NA	NA	NA	30.3	35.2	12
2005-08	100.0	0.0	12	95.8	14.4	12	59.3	43.5	12
2006-07	1.2	2.3	12	26.7	26.1	12	62.9	17.4	12
2007-08	7.3	11.0	12	85.4	21.6	12	41.2	40.1	12
2008-08	17.6	21.1	12	97.9	7.2	12	78.3	32.8	12

Table 54 (continued). Yearly (monthly within year, if applicable) summary statistics for percent cover of *Zostera marina* by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed. [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
2009-07	45.1	31.8	12	99.2	2.9	12	28.4	28.1	12
2010-07	11.4	15.5	12	84.6	16.3	12	66.7	27.0	12
2011-08	27.2	29.9	12	96.7	7.2	12	98.3	3.3	12
2012-07	45.4	37.4	12	96.2	7.7	12	25.0	27.2	12
2013-07	21.3	26.4	12	88.3	16.4	12	38.7	31.8	12
2014-07	38.8	33.7	12	80.0	38.1	12	60.4	26.8	12
2015-08	43.1	30.8	12	44.2	32.6	12	18.8	18.3	12
2016-07	59.2	28.5	12	80.4	34.5	12	67.1	29.3	12
2017-06	65.4	20.5	12	60.4	19.5	12	3.0	4.9	12
2018-07	45.8	33.6	12	78.8	34.5	12	13.8	19.6	12
2019-08	31.2	17.1	12	30.0	21.1	12	6.7	10.7	12
2021-06	71.7	21.9	12	66.2	28.4	12	3.3	6.5	12
2022-07	18.3	16.3	12	73.3	20.8	12	14.3	24.1	12

Table 55. Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* canopy height (cm) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed. [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
2003-07	20.6	4.0	12	42.5	5.5	12	77.4	23.3	12
2003-10	32.9	7.0	12	48.2	5.5	12	NA	NA	NA
2004-05	10.9	2.2	12	16.4	2.6	12	39.9	7.0	12
2004-07	38.9	9.7	12	64.2	3.3	12	95.3	7.8	12
2005-04	11.3	1.7	12	NA	NA	NA	32.6	12.9	11
2005-08	45.9	5.2	12	74.9	7.9	12	65.7	27.1	12
2006-07	14.3	0.6	3	31.0	7.9	10	55.8	7.6	12
2007-08	12.5	4.6	8	49.4	12.5	12	53.8	21.3	11
2008-08	16.7	4.7	12	58.3	4.6	12	76.1	16.3	12
2009-07	25.6	6.9	12	65.2	6.4	12	65.7	8.7	9
2010-07	16.7	6.7	10	37.8	2.6	12	68.8	15.6	12
2011-08	20.9	5.3	10	54.0	9.2	12	89.6	10.5	12
2012-07	32.3	3.1	10	64.3	10.8	12	71.5	18.7	10
2013-07	22.8	5.9	9	51.9	5.4	12	50.0	18.8	12

Table 55 (continued). Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* canopy height (cm) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed. [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
2014-07	26.5	5.9	11	58.5	3.7	10	85.4	12.4	12
2015-08	30.3	5.0	12	30.1	6.9	10	31.7	9.5	11
2016-07	37.2	7.9	12	72.6	16.0	11	90.3	5.6	12
2017-06	40.4	6.0	12	39.8	9.5	12	30.0	18.1	5
2018-07	28.3	7.9	12	63.8	18.5	12	78.2	15.3	8
2019-08	18.5	3.1	12	30.1	7.5	12	68.0	14.6	4
2021-06	71.7	21.9	12	47.6	11.3	12	56.7	10.4	3
2022-07	22.2	5.1	12	61.7	11.9	12	52.7	28.4	7

Table 56. Yearly (monthly within year, if applicable) summary statistics for total biomass (g m⁻²) of *Zostera marina* by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed. [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
2003-07	NA	NA	NA	193.6	76.9	10	NA	NA	NA
2003-10	63.2	57.0	12	67.1	23.5	12	NA	NA	NA
2004-05	59.4	37.0	12	107.5	41.0	12	103.1	65.9	12
2004-07	138.2	60.2	12	232.2	66.3	12	185.0	100.9	12
2005-04	48.2	12.4	6	NA	NA	NA	19.5	19.1	6
2005-08	125.5	47.4	12	123.4	79.4	12	97.9	102.3	10
2006-07	0.3	0.6	12	53.7	79.0	12	92.9	60.5	12
2007-08	10.5	20.6	9	119.7	118.3	12	45.3	68.1	11
2008-08	32.0	39.1	12	202.2	104.2	12	204.4	102.2	12
2009-07	79.8	74.9	12	243.7	60.2	12	71.3	76.6	12
2010-07	17.1	23.7	11	207.2	125.1	12	137.4	71.0	12
2011-08	70.0	78.4	11	314.8	133.6	12	276.1	148.1	12
2012-07	176.0	196.6	12	189.4	86.0	12	88.4	128.0	12
2013-07	36.6	66.6	12	181.5	98.4	12	51.9	68.9	12
2014-07	83.4	92.3	12	150.7	93.9	12	238.4	242.5	12
2015-08	126.0	83.6	11	60.3	51.8	11	45.4	49.7	9
2016-07	295.9	194.1	11	230.5	152.0	11	279.8	147.5	12
2017-06	184.3	119.4	12	72.3	30.3	12	7.6	14.9	10
2018-07	94.0	90.8	12	122.7	109.2	12	29.2	43.3	10

Table 56 (continued). Yearly (monthly within year, if applicable) summary statistics for total biomass (g m⁻²) of *Zostera marina* by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed. [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
2019-08	33.6	23.8	11	40.8	44.8	11	12.2	22.5	12
2021-06	172.1	87.7	12	113.2	67.2	12	10.1	19.0	12
2022-07	31.1	29.0	11	277.7	299.3	12	44.9	88.8	12

Table 57. Yearly (monthly within year, if applicable) summary statistics for ratio of above- to belowground biomass of *Zostera marina* by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed. [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
2003-07	3.0	1.8	12	3.3	3.6	10	7.0	4.1	12
2003-10	2.0	0.8	12	2.0	0.5	12	NA	NA	NA
2004-05	0.9	0.4	12	1.3	0.3	12	5.0	2.1	12
2004-07	2.2	0.7	12	3.9	1.8	12	9.6	11.0	12
2005-04	0.6	0.1	6	NA	NA	NA	2.7	1.2	5
2005-08	2.5	1.8	12	5.7	8.0	12	6.4	4.0	11
2006-07	2.4	1.2	3	16.2	29.1	12	4.7	5.3	12
2007-08	2.0	0.9	5	3.0	1.9	12	3.9	3.3	10
2008-08	2.2	1.7	12	3.1	2.4	12	15.3	13.4	12
2009-07	2.5	1.8	12	6.0	3.9	12	90.1	211.8	9
2010-07	1.6	0.9	9	2.5	1.0	12	3.6	1.7	12
2011-08	1.3	0.7	9	3.0	1.2	12	4.9	2.7	12
2012-07	1.5	0.8	10	2.7	1.5	12	7.6	8.2	10
2013-07	2.3	1.2	9	3.3	2.3	12	5.0	1.7	12
2014-07	1.8	0.8	11	1.4	0.5	10	6.1	4.1	12
2015-08	2.3	1.5	11	2.0	0.8	9	4.0	3.5	8
2016-07	2.2	1.7	11	4.1	2.2	10	4.7	3.4	12
2017-06	1.9	0.9	12	3.0	1.3	12	2.1	0.6	3
2018-07	3.1	2.8	12	2.2	1.3	12	3.9	3.3	6
2019-08	2.8	3.1	11	2.2	0.9	11	7.0	2.9	4
2021-06	1.5	1.2	12	1.8	1.6	12	5.8	2.5	3
2022-07	5.8	11.3	11	3.2	1.8	12	3.5	2.4	7

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