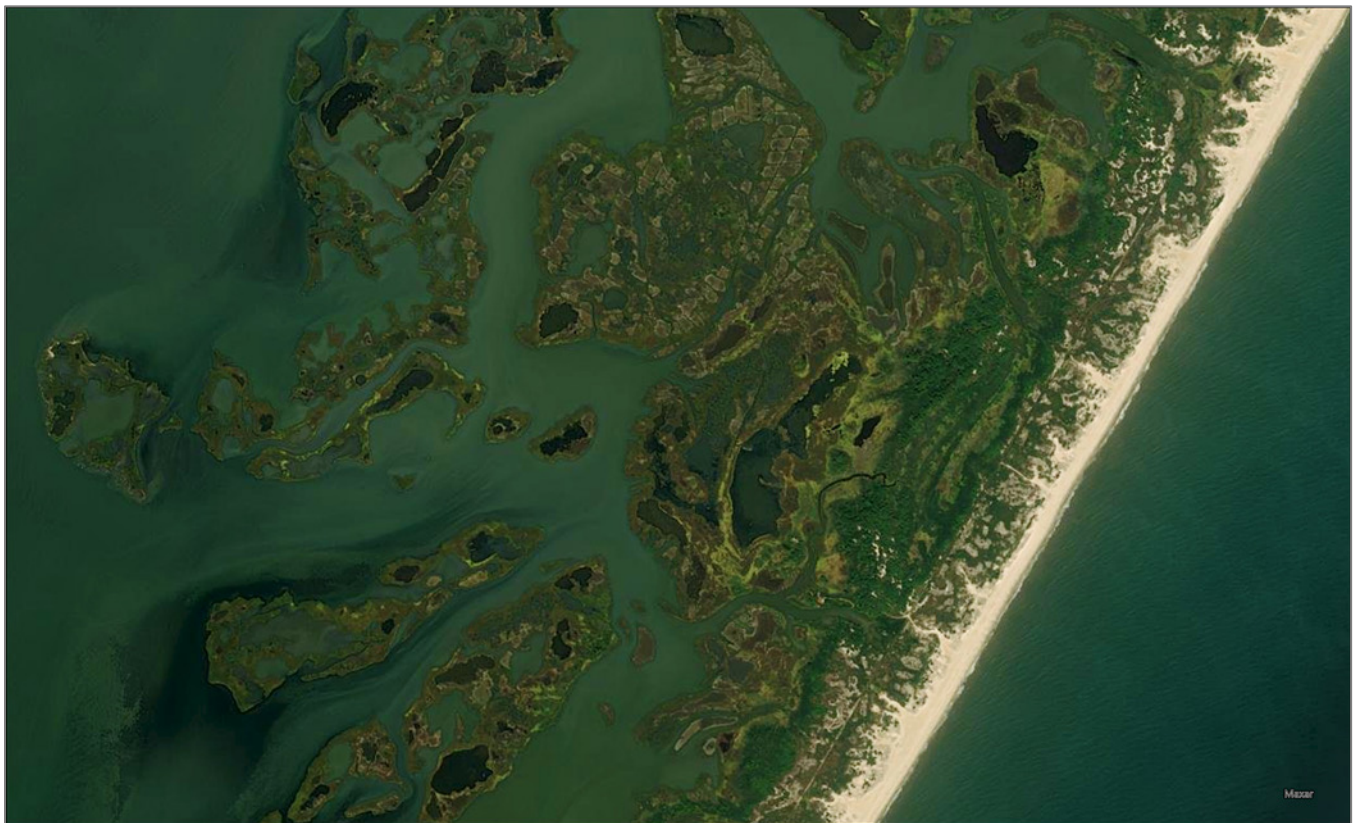




Condition and Trends of Estuarine Water Quality and Seagrass in Assateague Island National Seashore

Northeast Coastal and Barrier Network, 2005–2022



Aerial image of barrier island at Assateague Island National Seashore, Maryland, USA (ESRI 2025).

NPS

Condition and trends of estuarine water quality and seagrass in Assateague Island National Seashore: Northeast Coastal and Barrier Network, 2005–2022

Science Report NPS/SR—2025/273

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

¹ Bryantown, Maryland

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

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

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Abstract

This report summarizes conditions and trends in routine long-term water quality monitoring and seagrass data collected at Assateague Island National Seashore in Maryland and Virginia from 2005 through 2022 as part of the NPS NCBN Vital Signs Estuarine Nutrient Enrichment monitoring program. This comprehensive program incorporates spatial surveys, repeated monitoring at trend stations, and continuous monitoring at a fixed logging station in an effort to establish overall water quality condition of the estuary as well as to identify potential trends or changes in condition over time. All monitoring was conducted during a four-week summer index period, biennially. Monitored variables included dissolved oxygen concentration, chlorophyll-a concentration, attenuation of downwelling photosynthetically available radiation (PAR), salinity, temperature, turbidity, and pH. In addition, long-term monitoring of seagrass condition was conducted at permanently established transects. Water quality condition and trends were generally consistent between the spatial station surveys, the trend stations, and the continuous logging station. Despite declines in turbidity over time, water clarity, as measured by PAR attenuation, was typically poor throughout the majority of the monitored area in most years sampled. Although there were several years when approximately 50% of the estuary was classified as being in poor condition with respect to chlorophyll-a concentrations, the majority of the estuary was typically classified as being in fair condition in most years. Bottom dissolved oxygen concentrations were consistently classified as being in good condition throughout the majority of the estuary. While there was no statistical evidence of significantly increasing water temperature over time, summertime temperatures at the logging station, most trend stations, and in a large percentage of the estuary exceeded 28°C in several years. Trends in seagrass condition varied by species with eelgrass experiencing significant declines and widgeon grass increasing significantly over the monitoring timeframe. The identification of status and trends may help managers to make better informed decisions, develop effective mitigation measures, reduce management costs, and provide a means of measuring progress towards goals.

Acronyms and Abbreviations

ASIS: Assateague Island National Seashore

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

NOAA: National Oceanic and Atmospheric Administration

NPS: National Park Service

NTU: Nephelometric turbidity units

PAR: Photosynthetically active radiation

psu: Practical salinity units

SAV: Submerged aquatic vegetation

SD: Standard deviation

SE: Standard error

TPRS: Thin plate regression spline

USEPA: United States Environmental Protection Agency

Acknowledgments

This report is the culmination of efforts by many people who contributed to the National Park Service Northeast Coastal and Barrier Network (NCBN) estuarine Vital Signs monitoring at Assateague Island National Seashore from 2005 through 2022. We are grateful to the many scientists and technicians who served on field crews (FC) and the technical steering committee (TSC) or facilitated with data management and analysis (DMA) and reporting (R), including: Kelly Medeiros (TSC), Sophia Fox (TSC), James Caldwell (DMA, R), Blaine Kopp (DMA, R), Dennis Skidds (DMA), Scott Rasmussen (DMA), Robin Baranowski (DMA), Bradley Peterson (TSC), Ken Moore (FC, TSC), Betty Neikirk (FC, TSC), and Erin Shields (FC, TSC). Their dedication to the program and their attention to quality assurance during data collection and data management is paramount and provides the foundation for this report. We also wish to thank Michaela Compo for help with the cover photos and Andrew Weber for his insightful review of the manuscript. We are particularly grateful to Hilary Neckles for her effusive enthusiasm and leadership on all aspects of this program. We greatly appreciate the support and leadership provided by Sara Stevens, NCBN Program Manager, throughout this project. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Introduction

Six parks within the National Park Service (NPS) Northeast Coastal and Barrier Network (NCBN) contain critical estuarine habitat (Figure 1). Roman et al. (2000) identified nutrient enrichment as the primary threat to the ecological integrity of estuaries within this region. 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 Assateague Island National Seashore from 2005 through 2022.

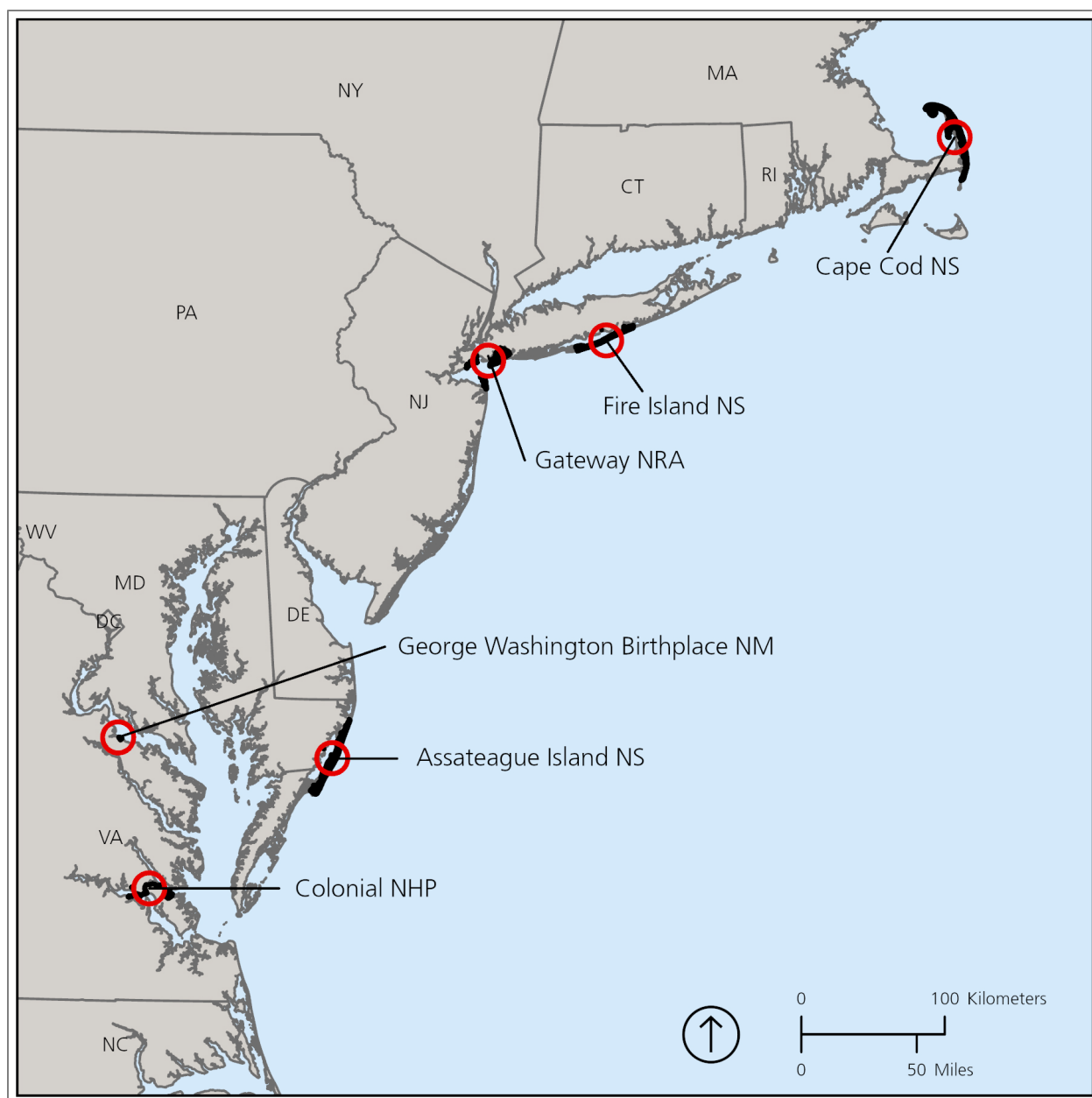


Figure 1. Locations of Northeast Coastal and Barrier Inventory & Monitoring (I&M) Network parks monitored for estuarine nutrient enrichment. NS: National Seashore; NRA: National Recreation Area; NM: National Monument; NHP: National Historical Park.

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Vital Signs Monitoring

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

using customized and relevant monitoring approaches. All networks in the program share the following five goals:

- Determine the status of and trends in selected indicators of the condition of park ecosystems to allow managers to make better informed decisions and to work more effectively with other agencies and individuals for the benefit of park resources.
- Provide early warning of abnormal conditions of selected resources to help develop effective mitigation measures and reduce costs of management.
- Provide data to better understand the dynamic nature and condition of park ecosystems and to provide reference points for comparisons with other altered environments.
- Provide data to meet certain legal and Congressional mandates related to natural resource protection and visitor enjoyment.
- Provide a means of measuring progress towards performance goals.

Goals of NCBN Monitoring

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

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

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

Conceptual Monitoring Approach

The ENE monitoring protocol incorporates both spatial and temporal sampling designs to address questions at a hierarchy of scales (Kopp and Neckles 2009). Characteristics that address the Vital Signs of water quality, water clarity, and water chemistry were 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 was sampled repeatedly during the index period and was 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.

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

Methods

Study Area

Assateague Island National Seashore includes a barrier island along the Atlantic coastlines of Maryland and Virginia. Bordered by the Atlantic Ocean to the east and the Maryland Coastal Bays and Chincoteague Bay to the west, the park includes more than 19,400 ha, with the majority (> 60%) of the area as submerged oceanic and estuarine habitat (Figure 2). Because the park encompasses land holdings of both the NPS and the U.S. Fish and Wildlife Service as well as Maryland's Assateague State Park, the management of estuarine natural resources at the park is a joint effort between federal and state partners. Consequently, the natural resource management interests for the park are not confined to areas within the park boundary. The spatial design for ENE monitoring is consistent with these interests and encompasses approximately 37,300 ha of estuary in the Coastal Bays region, of which approximately 6,800 ha fall inside park boundaries. While the land surrounding the monitored area is predominantly forested, wetlands or agricultural, the larger surrounding watershed is subject to nutrient inputs from agricultural and urban sources and is also under pressure for further development.

Historically, seagrass beds were a dominant feature in the shallow waters of and adjacent to ASIS. However, nutrient pollution in the region has led to significant declines in both seagrass abundance and distribution. Seagrass condition was monitored in a well-established seagrass bed at Tingles Island containing a mix of eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*) (Figure 3).

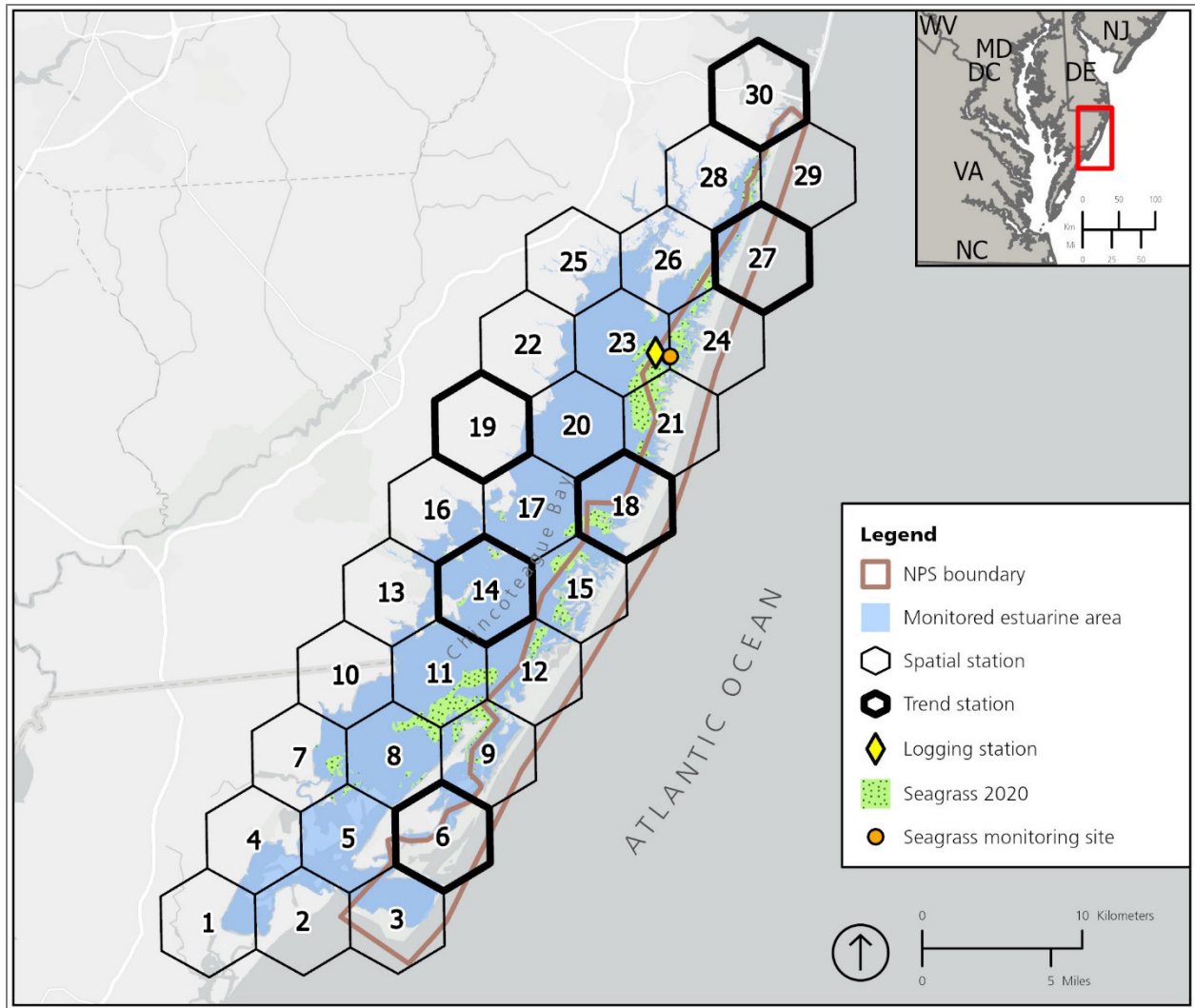


Figure 2. Spatial domain and sampling design for estuarine monitoring at Assateague Island National Seashore, Maryland and Virginia. Sampling hexagons with a bold outline represent those assigned with trend stations.

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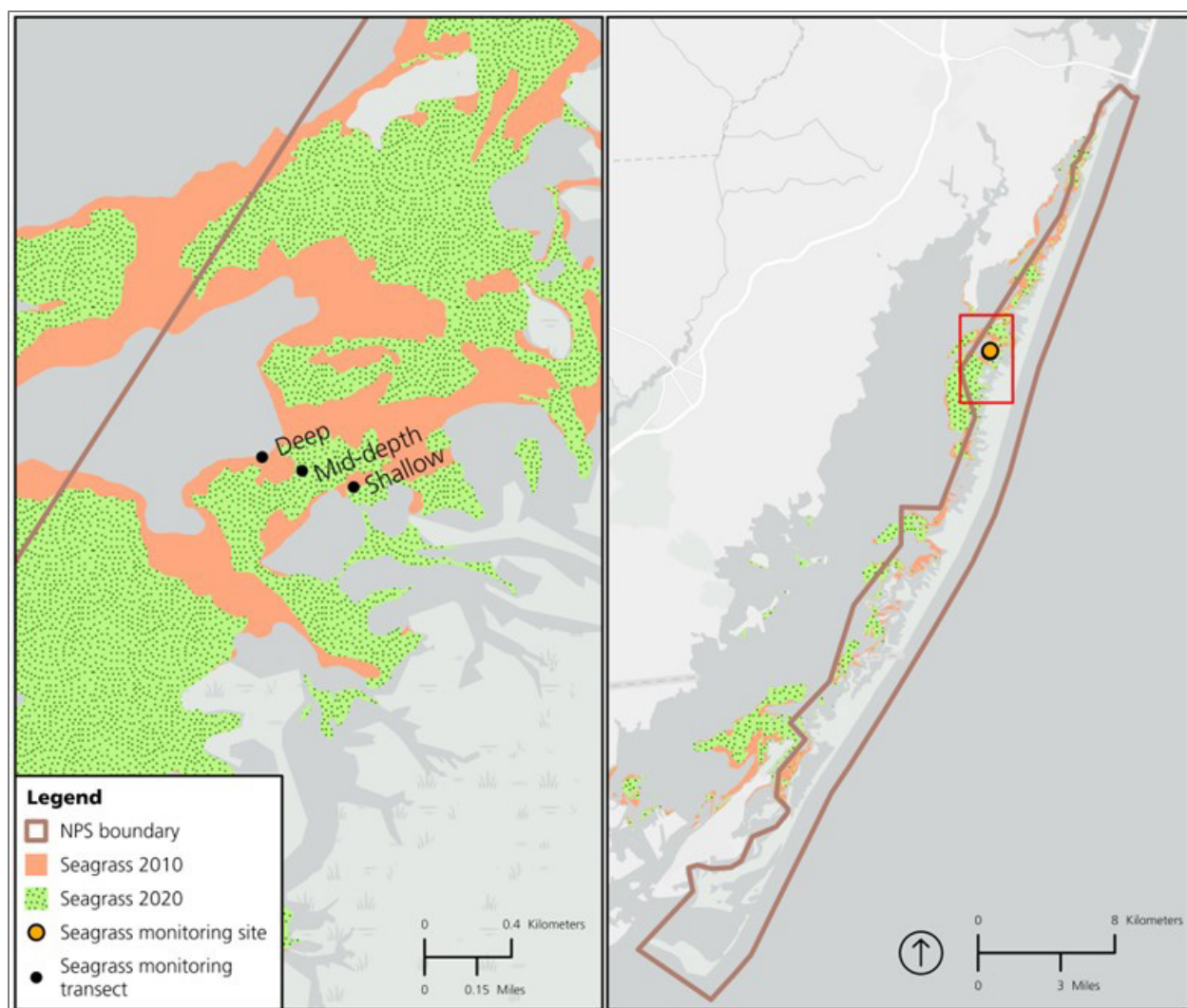


Figure 3. Location of seagrass sampling transects at Tingles Island reference bed, Assateague Island National Seashore. Seagrass coverage in 2010 and 2020 is shown for reference.

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Sampling Designs

The methods and procedures for the monitoring of water quality and seagrass condition are described in detail in the NCBN ENE protocol (Kopp and Neckles 2009). A brief summary of the sampling design can be found in the subsections below. Water quality monitoring was conducted in 2005, 2006, 2008, 2010, 2012, 2014, 2016, 2018, 2020, and 2022. Seagrass monitoring was conducted annually between 2009 and 2022 except for 2020.

Spatial Station Water Quality

The spatial sampling survey design adopted for NCBN estuaries treats each park estuary as a continuous resource and uses a randomized-tessellation stratified design as the basis for sample site selection (Stevens 1997; Stevens and Olsen 2003). The spatial domain was overlaid with a grid of tessellated hexagons with one random site selected for monitoring within each hexagon (Figure 2).

This approach results in a set of samples that is balanced spatially over the entire estuary of interest with the statistical advantages of random sampling. In addition, this sampling design is comparable to that used by the USEPA National Coastal Assessment Program (USEPA 2001a) thus allowing for data from NCBN estuaries to be evaluated within the context of other estuaries in the region and also contribute toward overall regional condition assessments.

Spatial stations were sampled during a summer index period in 2005 and in every other year between 2006 and 2022 following the standardized monitoring protocol (Kopp and Neckles 2009). In all years except 2005, sampling was spread over the 4-week index period. In most years, a minimum of 29 stations were sampled. Note that sampling in 2005 was conducted over a span of only 3 days and, thus, may not be representative of the typical variation observed over the standard 4-week sampling period. 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 LI-COR quantum sensors within 3 hours of local solar noon (i.e., the time when the sun crosses the local meridian). Sampling start and end dates for each index period are provided in Table 1.

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

Year	Start	End
2005	2005–08–01	2005–08–03
2006	2006–07–25	2006–08–09
2008	2008–07–23	2008–08–14
2010	2010–07–07	2010–07–30
2012	2012–08–08	2012–08–30
2014	2014–08–04	2014–08–28
2016	2016–07–12	2016–08–03
2018	2018–08–07	2018–08–27
2020	2020–07–07	2020–07–28
2022	2022–08–01	2022–08–23

Trend Station Water Quality

While monitoring for overall estuary condition is best accomplished by obtaining the greatest overall number of random sampling locations, monitoring for trends is best accomplished by revisiting one set of sampling locations through time (Urquhart et al. 1998). For the water quality parameters reported here, 20 percent of the hexagons in each park were selected as “trend” stations. To the extent possible, hexagons identified for trend stations were distributed systematically throughout the spatial domain (Figure 2). At ASIS, more than 20 percent of the hexagons already contained suitable

pre-existing permanent trend-monitoring stations that were deemed representative of the estuary and were incorporated into the ENE design (Caldwell et al. 2015).

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 2005 and 2022. Sampling start and end dates for each index period are provided in Table 1. Parameters measured included water column PAR attenuation (K_d), as well as surface chlorophyll-a, dissolved oxygen, salinity, temperature, and turbidity using the same protocols as for spatial surveys.

Continuous Logging Station Water Quality

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

Continuous in situ measurements of water quality parameters were collected at a permanently established logging station during the summer index period from 2005 through 2022 following the standardized monitoring protocol outlined in Kopp and Neckles (2009) (Figure 2). Sampling start and end dates for each index period are provided in Table 1. Parameters measured included chlorophyll-a, dissolved oxygen, PAR attenuation (K_d), salinity, temperature, turbidity, pH, and depth. Measurements of in situ PAR were collected at 15-min intervals using two LI-192 underwater quantum sensors positioned 0.5 m vertically apart below the water surface. Measurements of all the other parameters were collected at 15-min intervals using a multiparameter data logger that was mounted to a pier, piling, or other structure a fixed distance from the estuary bottom, so that the water depth of the data logger is tidally varying.

Seagrass Condition

High-resolution seagrass monitoring data were collected three times annually (e.g., spring, summer, and fall) in most years between 2009 and 2022 (excluding 2020) from a permanently established site (Figure 2) following the standardized monitoring protocol outlined in Kopp and Neckles (2009) and Short et al. (2004). The monitoring site at Tingles Island contains a mix of both eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*) and consists of three permanent 50-m transects that run parallel to shore across an increasing depth gradient. Data for both species were collected at twelve 0.25 m² quadrats located at fixed random locations along each transect. Seagrass attributes measured included percent cover, canopy height, and shoot density in 0.25-m² quadrats and above- and belowground biomass in 0.0035-m² cores. In addition to seagrass data, sediment samples for percentage of fine-grain (i.e., silt and clay) sediment and organic material were also collected from each transect.

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

transects. Data were recorded year-round at 15- to 30-min intervals in most years from 2010 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).

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

Parameter	Quality Category ^A		
	Good	Fair	Poor
Chlorophyll- <i>a</i> (near surface)	< 5 µg/L	5–20 µg/L	> 20 µg/L
Dissolved oxygen (near bottom)	> 5 mg/L	2–5 mg/L	< 2 mg/L
PAR attenuation K_d (SAV standard)	< 0.92 m ⁻¹	0.92–1.61 m ⁻¹	> 1.61 m ⁻¹
Water temperature (near surface)	< 28°C	28–33°C	> 33°C

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

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).

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

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

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

where μ_i is a vector of response values, year and hexagon location (longitude, latitude) are covariate vectors, β_0 is the intercept, f_1 and f_2 are non-linear smoothing functions, and $i = 1, \dots, n$ indexes the respective year or hexagon within the estuary. Thin plate regression splines (TPRS; rank of basis expansion equal to number of years of data) and Gaussian process splines (rank 50 basis expansion) were utilized for the year and location smooths, respectively. The spatial dependence of observations

was modeled in the mean structure (i.e., first-order model specification; Hefley et al. 2017) through the inclusion of the interaction smooth between longitude and latitude. Attempts to model temporal autocorrelation in a majority of cases resulted in unidentifiable models. Factors likely contributing to this include: (1) the relatively short time series, (2) irregular intervals of data collection, and (3) insufficient information in the data to uniquely distinguish between the wiggly trend and autocorrelation since they can both be used to describe similar patterns in the data (Simpson 2018). Therefore, for consistency across all models, temporal autocorrelation was not modeled. Residual analysis indicated a lack of temporal autocorrelation in a majority of parameters. For parameters that did exhibit significant temporal autocorrelation, the lag-1 autocorrelation was generally less than 0.4.

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

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

Multivariate Mann-Kendall Trend Analysis

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

Area-Weighted Condition Results

Chlorophyll-a (Near Surface)

Area-weighted average near surface chlorophyll-a concentrations ranged from 6.69 to 25.43 $\mu\text{g/L}$ and were classified as being in fair condition (i.e., 5–20 $\mu\text{g/L}$) for a majority of the index periods (Table 3). Poor area-weighted average condition ($> 20 \mu\text{g/L}$) was observed in both 2010 and 2012. The proportion of the estuary categorized as fair condition ranged from 33 to 89% (Table 4). Approximately 50% of the estuary was in poor condition during 2010 and 2016. The maximum proportion of area in good condition (i.e., $< 5 \mu\text{g/L}$) across all index periods was 33.3% observed in 2022.

Table 3. Area-weighted average water quality condition estimated from spatial station surveys at Assateague Island National Seashore during the index periods of 2005–2022. [NA = not available].

Parameter	Depth	Sampling Year									
		2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
Chlorophyll-a ($\mu\text{g/L}$)	Surface	16.11	17.16	13.91	21.40	25.43	9.48	19.64	13.04	12.65	6.69
Dissolved oxygen (% saturation)	Surface	102.57	106.42	96.43	104.02	100.21	101.05	99.70	93.60	102.48	95.14
Dissolved oxygen (% saturation)	Mid-Depth	100.06	100.08	93.43	93.47	96.34	98.27	95.40	90.43	98.84	94.73
Dissolved oxygen (% saturation)	Bottom	95.45	91.47	90.79	100.44	94.65	101.40	96.00	89.50	97.08	93.51
Dissolved oxygen (mg/L)	Surface	6.91	6.94	6.43	6.78	6.70	6.93	6.57	6.26	6.50	6.28
Dissolved oxygen (mg/L)	Mid-Depth	6.76	6.61	6.23	6.16	6.44	6.76	6.28	6.06	6.30	6.24
Dissolved oxygen (mg/L)	Bottom	6.45	6.08	6.07	6.54	6.35	6.96	6.34	6.01	6.18	6.19
PAR attenuation (K_d (m^{-1}))	Water Column	2.73	2.85	2.21	2.84	2.34	1.77	2.35	2.54	1.90	1.79
pH	Surface	NA	NA	NA	NA	NA	NA	NA	7.88	7.88	7.86
pH	Mid-Depth	NA	NA	NA	NA	NA	NA	NA	7.87	7.88	7.87
pH	Bottom	NA	NA	NA	NA	NA	NA	NA	7.86	7.86	7.85
Salinity (psu)	Surface	27.45	29.93	31.50	30.33	32.19	30.78	28.99	28.33	31.56	33.51
Salinity (psu)	Mid-Depth	27.50	29.90	31.67	29.51	32.11	30.77	29.15	27.94	31.53	33.54
Salinity (psu)	Bottom	27.61	29.95	31.79	30.53	32.27	30.84	29.02	28.43	31.61	33.57
Temperature ($^{\circ}\text{C}$)	Surface	27.89	28.96	26.99	28.76	26.70	25.66	28.69	28.04	30.08	27.04
Temperature ($^{\circ}\text{C}$)	Mid-Depth	27.76	28.32	26.92	28.41	26.76	25.50	28.71	28.05	29.81	27.20
Temperature ($^{\circ}\text{C}$)	Bottom	27.63	28.05	26.69	28.49	26.56	25.53	28.56	27.82	29.80	26.89
Turbidity (NTU)	Surface	19.99	15.80	13.38	18.38	12.89	9.79	10.47	11.68	9.24	7.35
Turbidity (NTU)	Mid-Depth	18.62	17.04	17.09	25.14	11.32	9.59	10.64	12.05	9.30	7.13
Turbidity (NTU)	Bottom	21.53	20.94	18.26	31.89	17.03	12.79	14.78	15.91	12.16	12.66

Table 4. Proportion of monitored estuarine resources falling into each quality category at Assateague Island National Seashore during the index periods of 2005–2022. Estuarine quality category thresholds as defined in Kopp and Neckles (2009) can be found in Table 2.

Parameter	Condition	Sampling Year									
		2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
Bottom dissolved oxygen (mg/L)	Good	89.3	70.4	89.3	82.0	93.6	98.7	98.5	92.3	89.4	98.8
Bottom dissolved oxygen (mg/L)	Fair	10.7	29.6	10.7	18.0	6.4	1.3	1.5	7.7	10.6	1.2
Bottom dissolved oxygen (mg/L)	Poor	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bottom dissolved oxygen (mg/L)	Missing	0.0	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	0.8	8.2	7.9	15.3	0.0	8.7	0.0	8.9	15.2	33.3
Chlorophyll- <i>a</i> (μg/L)	Fair	64.8	59.6	74.6	33.6	59.3	89.6	50.8	74.1	65.5	65.0
Chlorophyll- <i>a</i> (μg/L)	Poor	34.4	32.2	17.5	51.0	40.7	1.7	49.2	16.9	19.3	1.7
Chlorophyll- <i>a</i> (μg/L)	Missing	0.0	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	0.0	0.0	1.9	15.3	0.0	29.2	0.0	0.0	12.1	16.0
PAR attenuation (K_d (m ⁻¹))	Fair	4.7	10.0	32.0	13.5	12.5	23.8	20.8	13.9	16.7	42.7
PAR attenuation (K_d (m ⁻¹))	Poor	95.3	80.1	63.2	71.2	87.5	47.0	79.2	86.1	71.1	39.9
PAR attenuation (K_d (m ⁻¹))	Missing	0.0	10.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	1.5
Surface Temperature (°C)	<28	61.4	37.4	63.0	22.1	84.0	98.8	30.3	49.1	12.5	61.3
Surface Temperature (°C)	28–33	38.6	62.6	37.0	77.9	16.0	1.2	69.7	50.9	87.5	38.7
Surface Temperature (°C)	>33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature (°C)	Missing	0.0	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 concentrations ranged from 6.01 to 6.96 mg/L and were classified as being in good condition (i.e., > 5 mg/L) for every index period (Table 3). The majority of area (>70%) within the estuary was characterized as being in good condition in every year sampled (Table 4). For each index period, no area was characterized as having poor dissolved oxygen condition (i.e., < 2 mg/L).

PAR Attenuation K_d (SAV Standard)

Area-weighted average PAR attenuation was classified as being in poor condition for every index period (i.e., $K_d > 1.61 \text{ m}^{-1}$) and ranged from 1.77 to 2.85 m^{-1} (Table 3). The majority of the estuary was generally characterized as being in poor condition, with the exception of 2014 and 2022 when more than 50% of the estuary was in good or fair condition (Table 4).

pH

Area-weighted average pH ranged from 7.86 to 7.88 (Table 3). Measurements of pH began in 2018.

Salinity

Area-weighted average salinity ranged from 27.45 (surface depth in 2005) to 33.57 psu (bottom depth in 2022) (Table 3).

Temperature (Near Surface)

Area-weighted average near surface water temperature ranged from 25.66 to 30.08°C and exceeded 28°C during five index periods (Table 3). Excluding the coolest years of 2012 and 2014, temperatures in the 28–33°C range were observed in at least 37% of the estuary with highest percentages observed in 2010 (78%) and 2020 (88%) (Table 4).

Turbidity

Area-weighted average turbidity ranged from 7.13 (mid-depth in 2022) to 31.89 NTU (bottom depth in 2010) (Table 3).

GLMM Results

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

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

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

Parameter	Depth(s)	D.F.	F -value	p -value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	(9, 242)	9.31	< 0.005
Dissolved oxygen (mg/L)	Bottom	(9, 243)	2.14	0.03
PAR attenuation (K_d (m^{-1}))	Water Column	(9, 237)	2.88	< 0.005
Salinity (psu)	Surface	(9, 242)	7.79	< 0.005
Temperature ($^{\circ}\text{C}$)	Surface	(9, 242)	12.33	< 0.005
Turbidity (NTU)	Surface	(9, 242)	4.28	< 0.005

Chlorophyll-a (Near Surface)

Mean log near surface chlorophyll-a concentrations in 2012 were significantly higher than most other index periods (Figure 4). In addition, concentrations in 2022 were significantly lower than most other sample years.

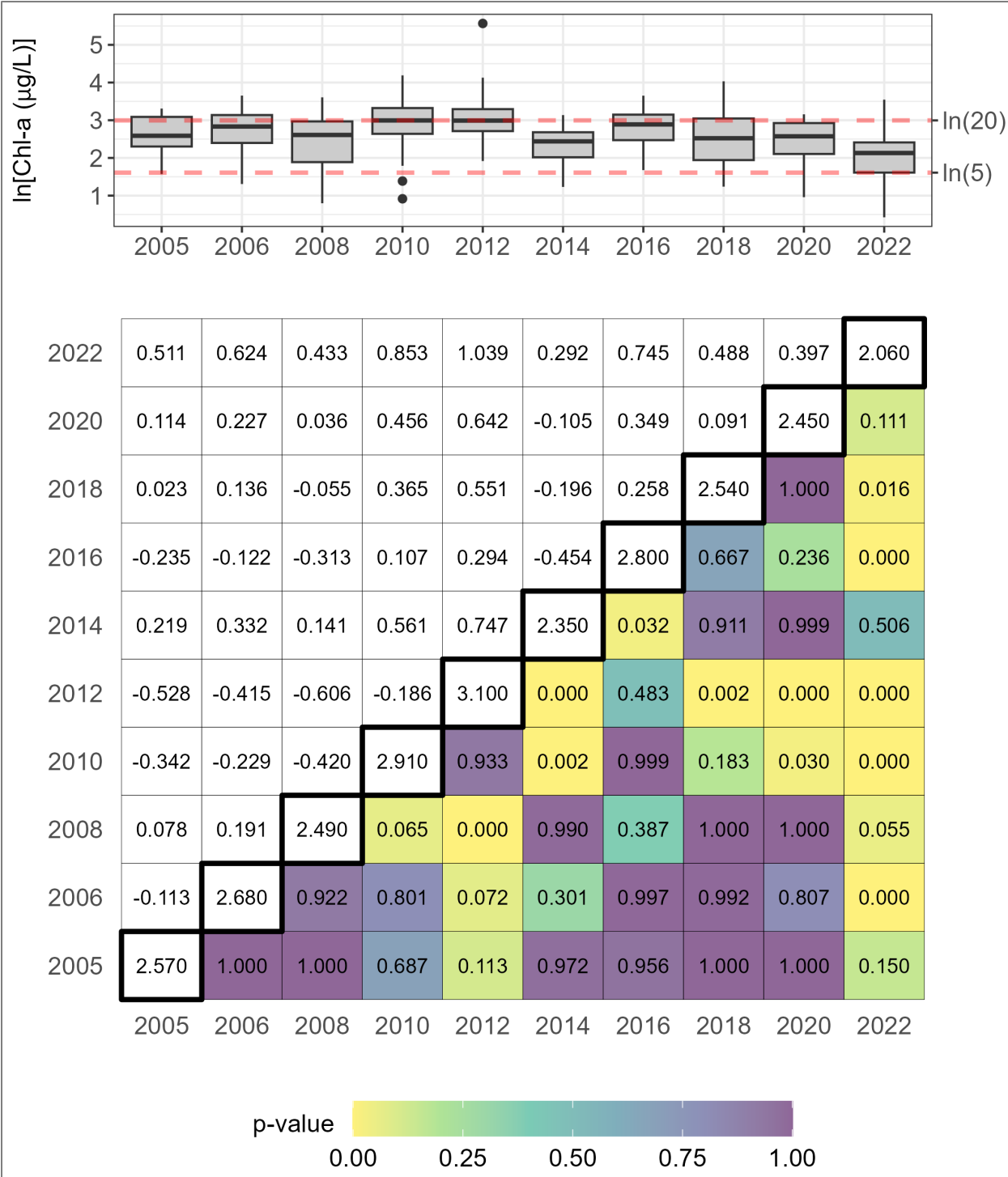


Figure 4. (Top): Boxplot of log surface chlorophyll-a concentration by year within Assateague Island National Seashore. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain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

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Dissolved Oxygen (Near Bottom)

Mean log bottom dissolved oxygen concentrations in 2014 were significantly higher compared to 2010 and 2018 (Figure 5). There was no strong evidence of statistical differences between all the other index period pairs.

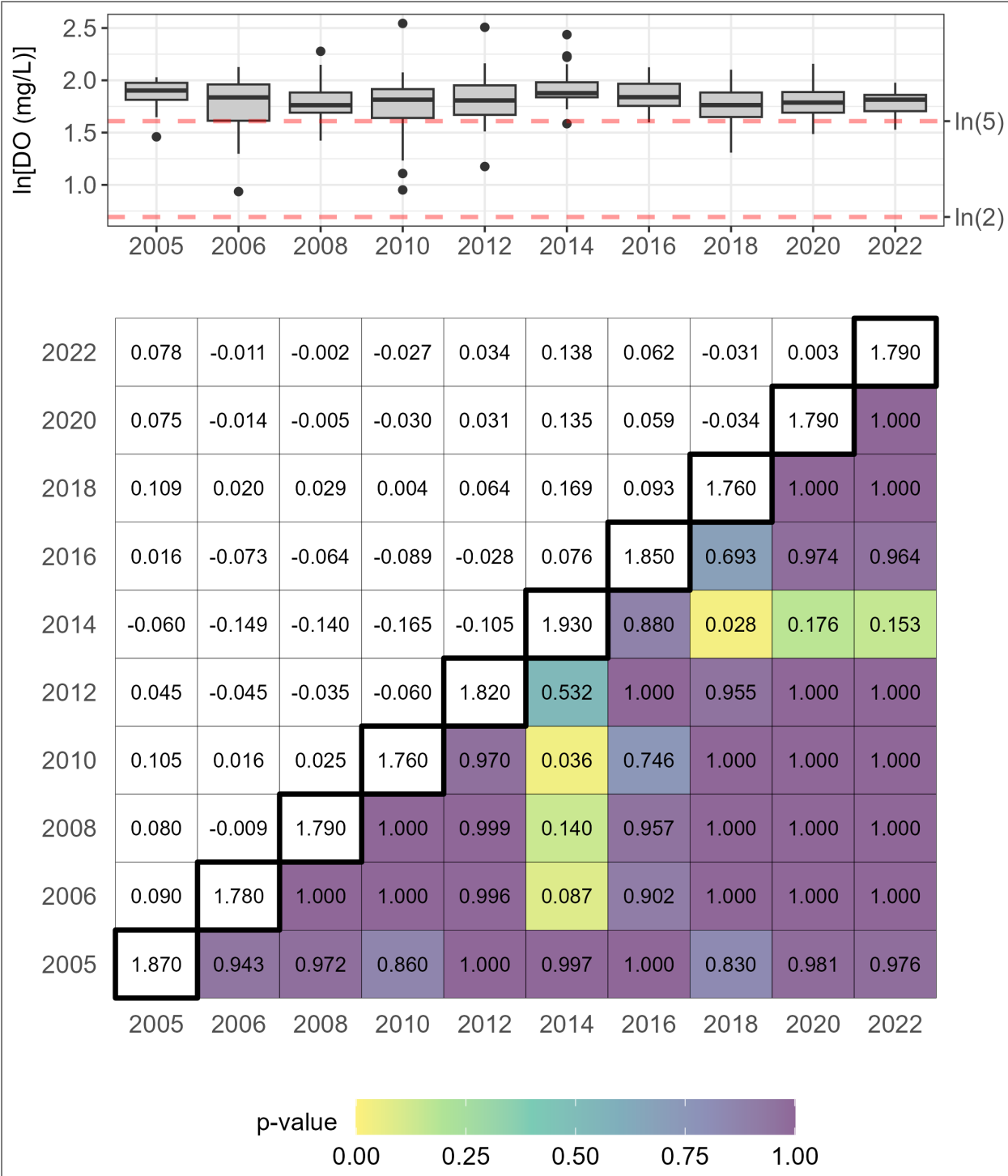


Figure 5. (Top): Boxplot of log bottom dissolved oxygen concentration by year within Assateague Island National Seashore. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain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

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PAR Attenuation K_d (SAV Standard)

Mean log PAR attenuation in 2014 was significantly lower compared to 2010 and 2018 (Figure 6). There was no strong evidence of statistical differences between the other index period pairs.

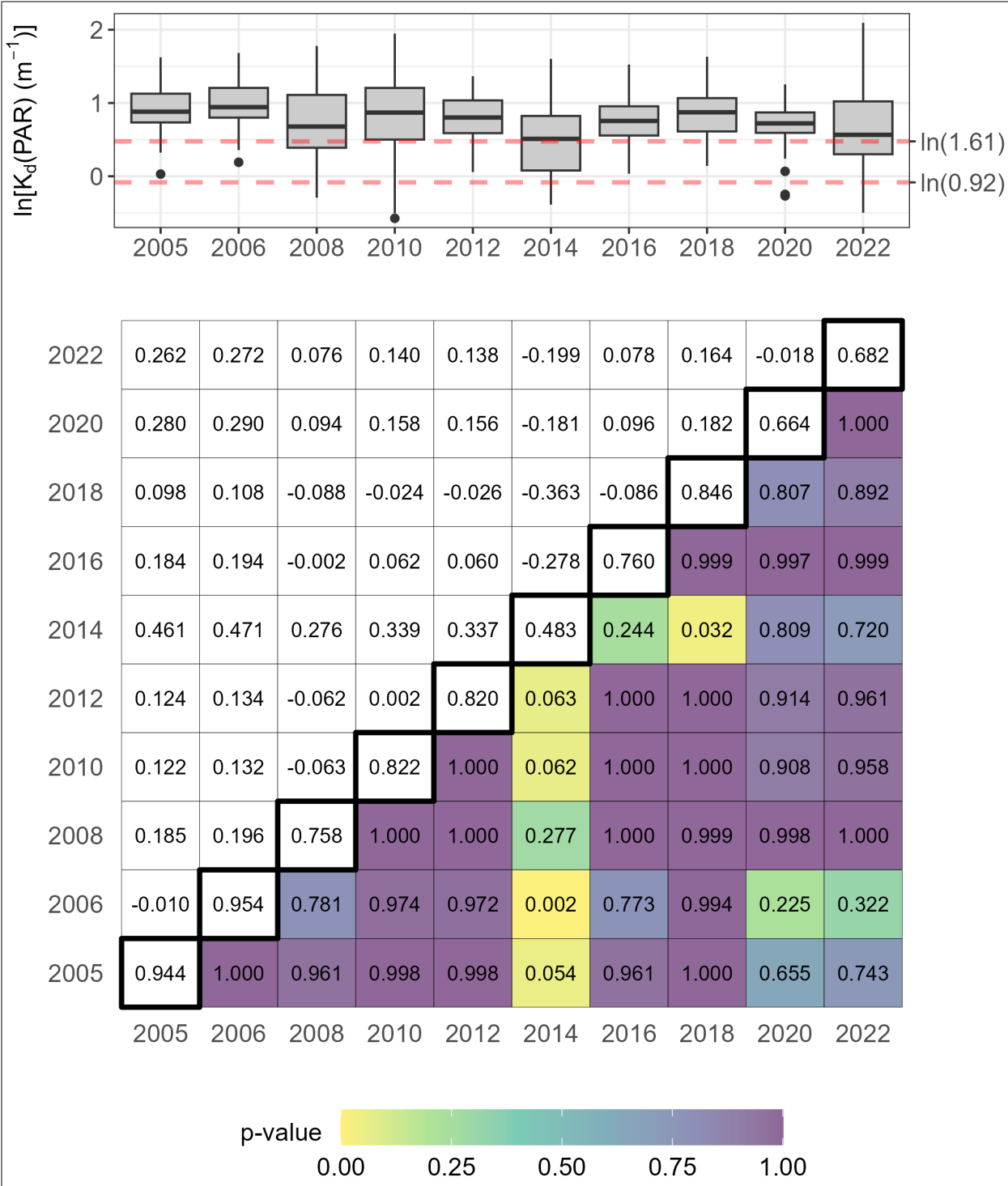


Figure 6. (Top): Boxplot of log PAR attenuation by year within Assateague Island National Seashore. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log PAR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

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Salinity (Near Surface)

Mean log surface salinity in 2022 was significantly higher than most sampling years with the exception of 2012, 2014 and 2020 (Figure 7).

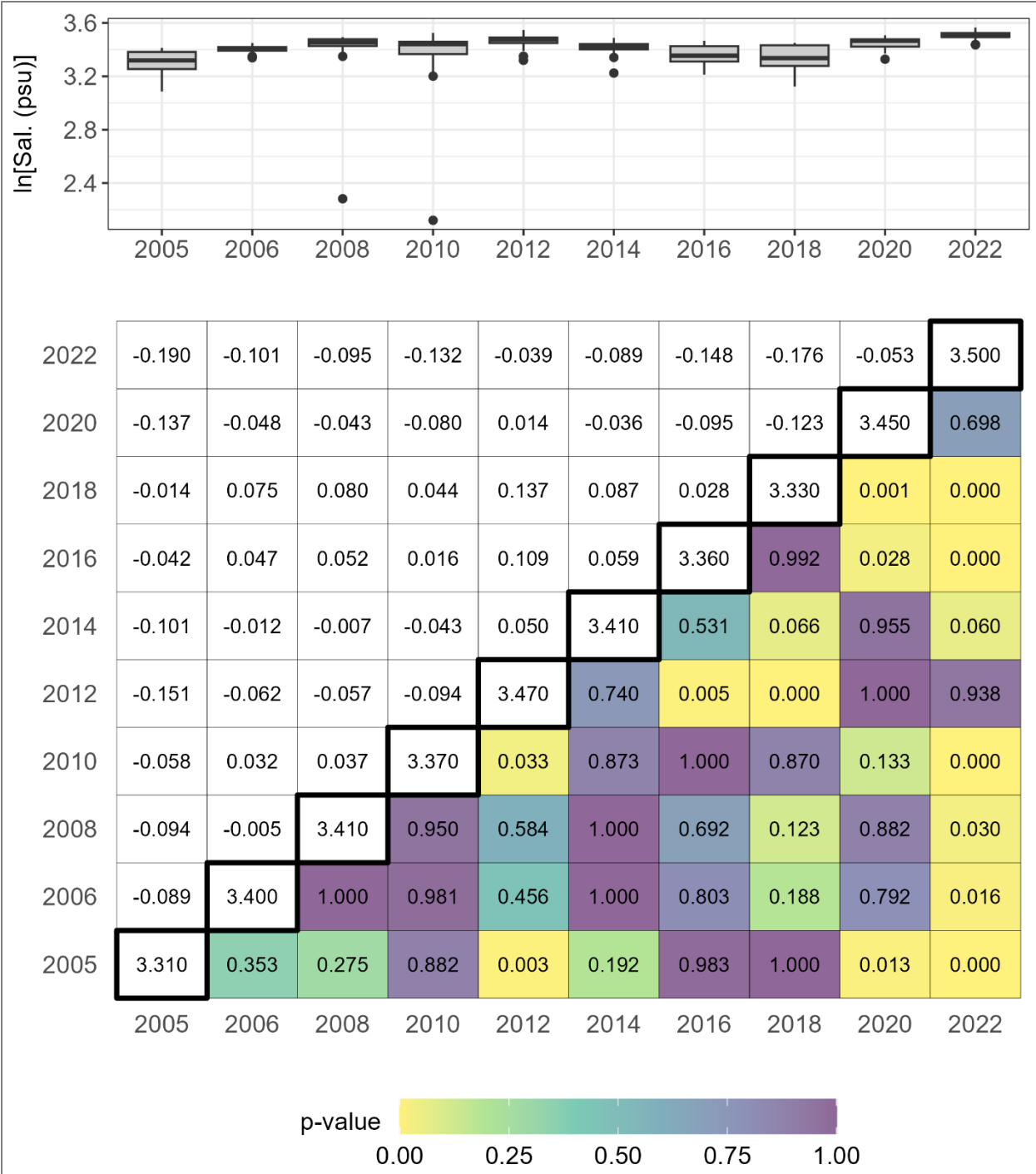


Figure 7. (Top): Boxplot of log surface salinity by year within Assateague Island National Seashore. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface salinity within each year. Upper diagonal cells contain the difference between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

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Temperature (Near Surface)

Mean log surface water temperatures in 2012 and 2014 were significantly lower than most other index periods (Figure 8). The box plots indicate that there was more year-to-year variability than within-year variability compared to the other parameters.

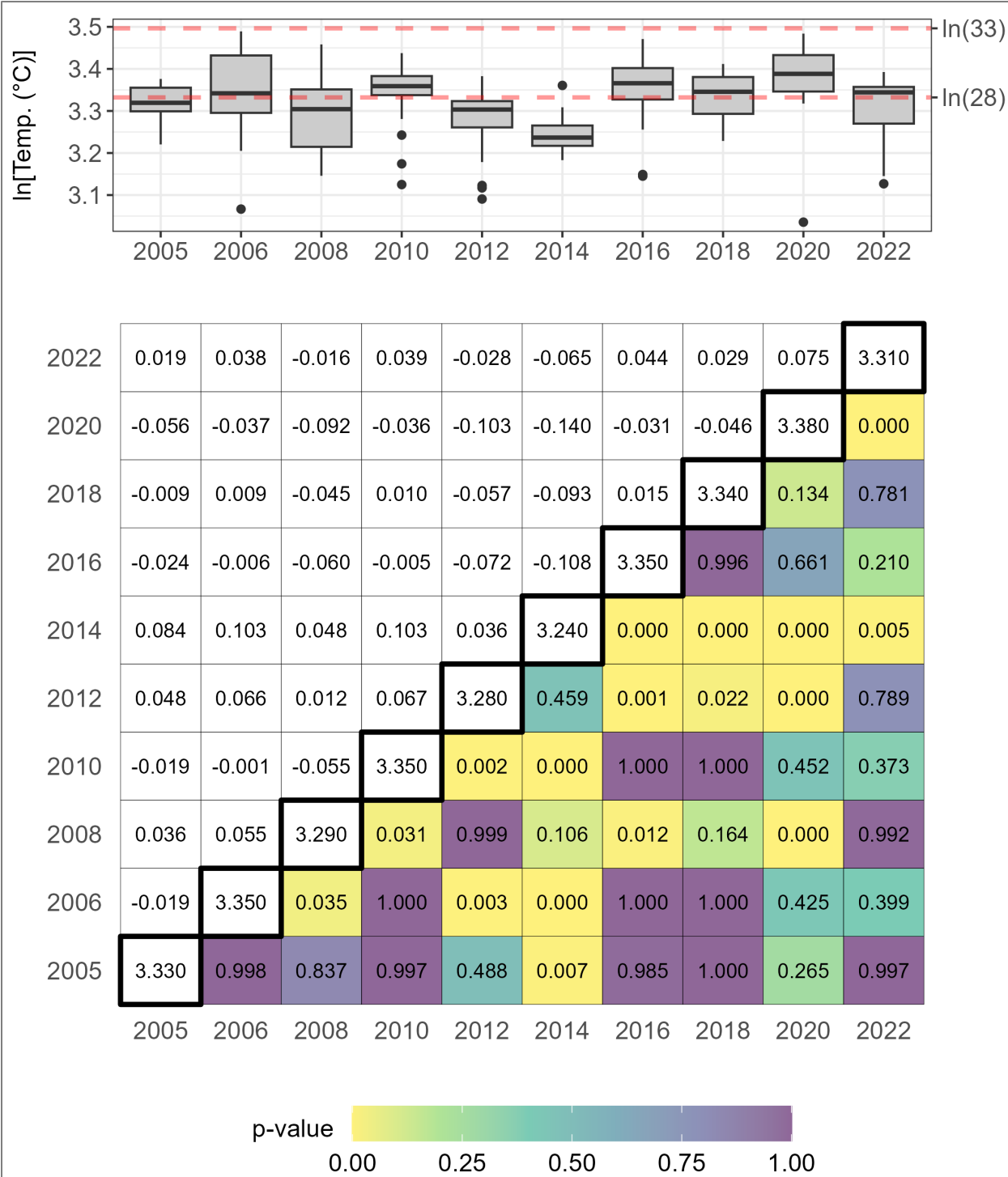


Figure 8. (Top): Boxplot of log surface temperature by year within Assateague Island National Seashore. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log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

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Turbidity (Near Surface)

Mean log surface turbidity in 2014 was significantly lower compared to 2005, 2006, 2010, and 2012 as well as in 2022 relative to 2006 (Figure 9). There was no strong evidence of statistical differences between the other index period pairs.

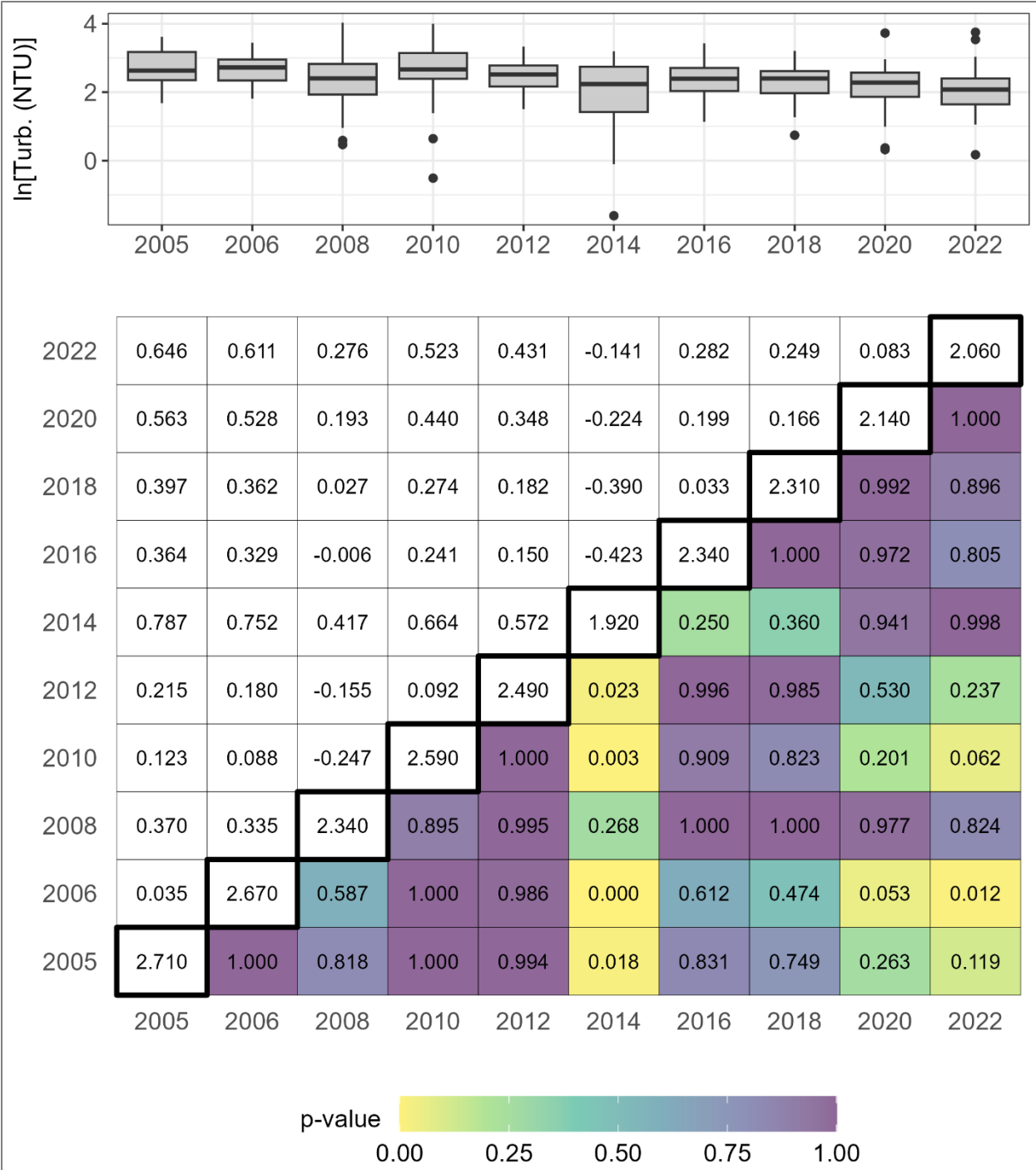


Figure 9. (Top): Boxplot of log surface turbidity by year within Assateague Island National Seashore. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface turbidity within each year. Upper diagonal cells contain the difference between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

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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 bottom dissolved oxygen, which only had a significant spatial trend (Table 6).

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

Parameter	Depth	Model Term	edf	F -value	p -value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	s(year)	7.16	7.36	< 0.001
Chlorophyll-a ($\mu\text{g/L}$)	Surface	s(long, lat)	11.20	1.82	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	1.74	0.48	0.074
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	5.54	0.35	0.003
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	1.68	0.73	0.017
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	1.94	0.67	< 0.001
Salinity (psu)	Surface	s(year)	8.33	38.46	< 0.001
Salinity (psu)	Surface	s(long, lat)	8.29	3.57	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	7.88	12.14	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	7.88	1.87	< 0.001
Turbidity (NTU)	Surface	s(year)	0.96	2.20	< 0.001
Turbidity (NTU)	Surface	s(long, lat)	5.93	0.82	< 0.001

Chlorophyll-a (Near Surface)

Chlorophyll-a concentrations exhibited a highly non-linear temporal trend with two periods of statistically significant increases from 2008–2012 and 2014–2016 and one decreasing period between 2012 and 2014 (Figure 10). Concentrations of chlorophyll-a were highest along the northwestern shore (Figure 11). Based on the fitted model, both time and location accounted for 46.9% of the variability in chlorophyll-a concentrations.

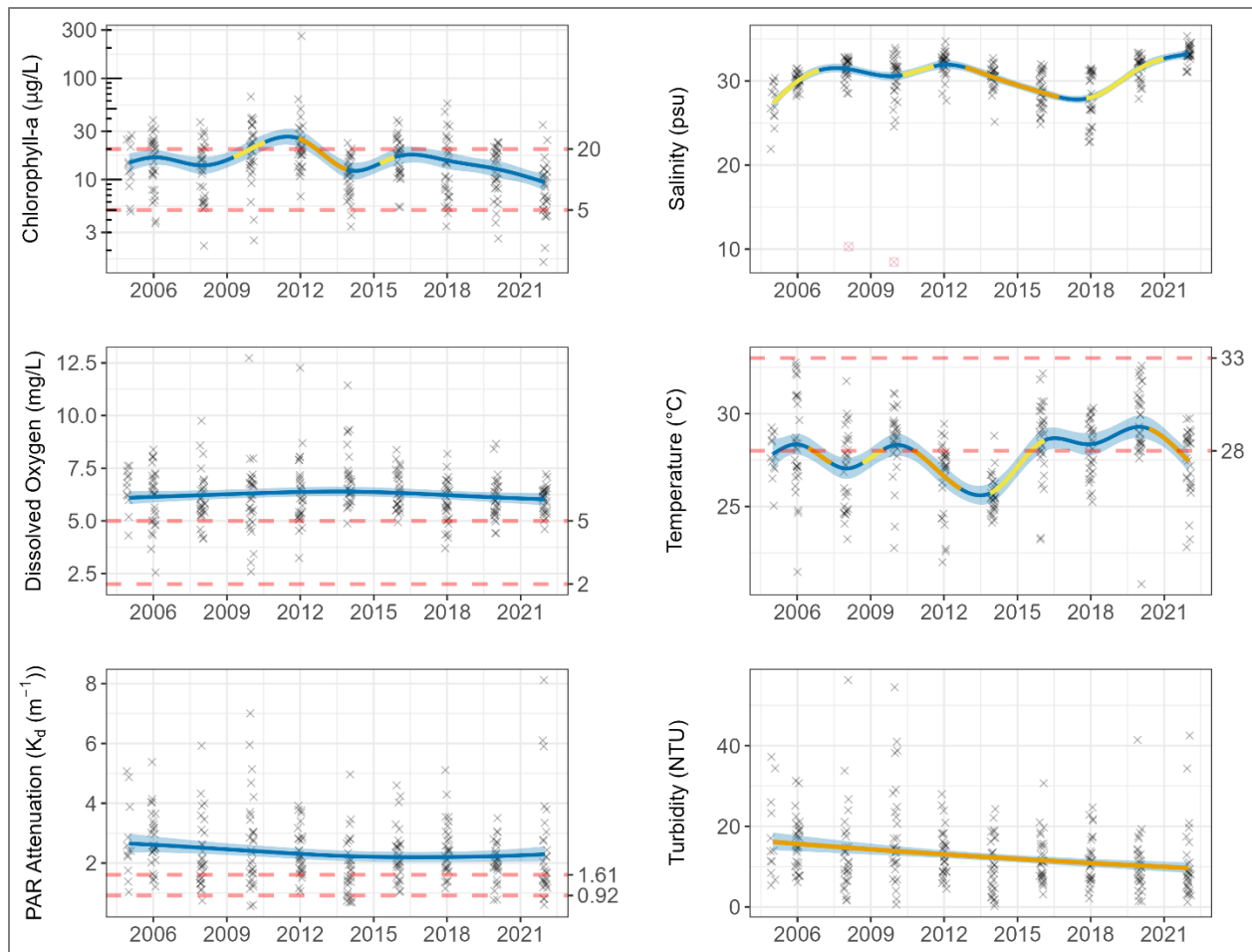


Figure 10. Trends in Assateague Island National Seashore spatial station water quality parameters based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted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

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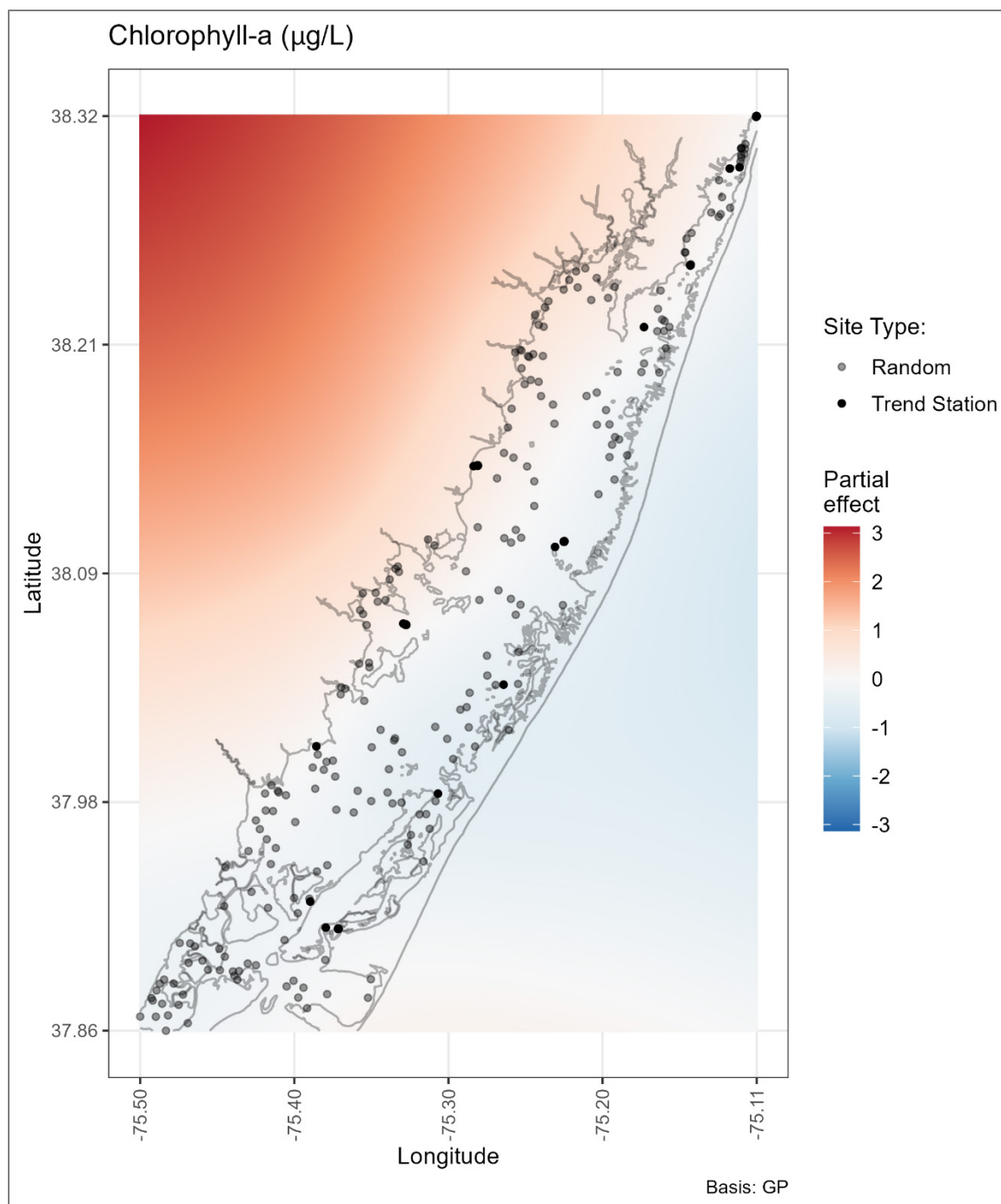


Figure 11. Mean surface for the generalized additive model latitude/longitude smooth of surface chlorophyll-a concentration ($\mu\text{g/L}$) within Assateague Island National Seashore during 2005–2022.
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Dissolved Oxygen (Near Bottom)

Although there was no statistically significant temporal trend (Figure 10), there was a significant spatial trend in bottom dissolved oxygen, with lower concentrations occurring along the northwestern

shore (Figure 12). The fitted model did very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 9.4% of the variation.

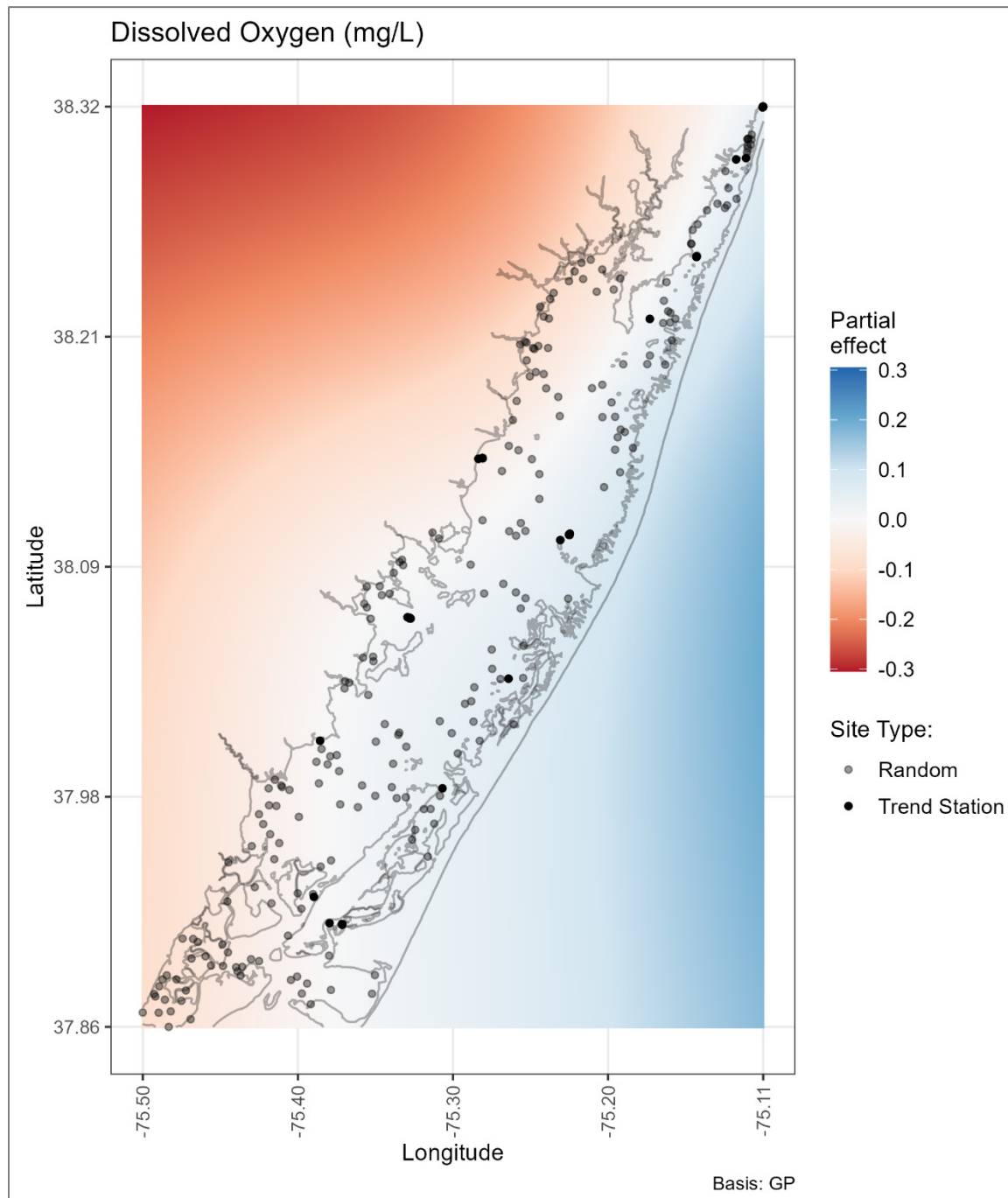


Figure 12. Mean surface for the generalized additive model latitude/longitude smooth of bottom dissolved oxygen concentration (mg/L) within Assateague Island National Seashore during 2005–2022.

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PAR Attenuation K_d (SAV Standard)

The temporal trend in PAR attenuation was slightly concave upward with the period prior to 2014 exhibiting a slight decreasing trend (Figure 10). Spatially, PAR attenuation tended to be higher on the western shore compared to the eastern shore, and more so in the northern end of the estuary (Figure 13). Based on the fitted model, both time and location accounted for only 15.1% of the variability in PAR attenuation.

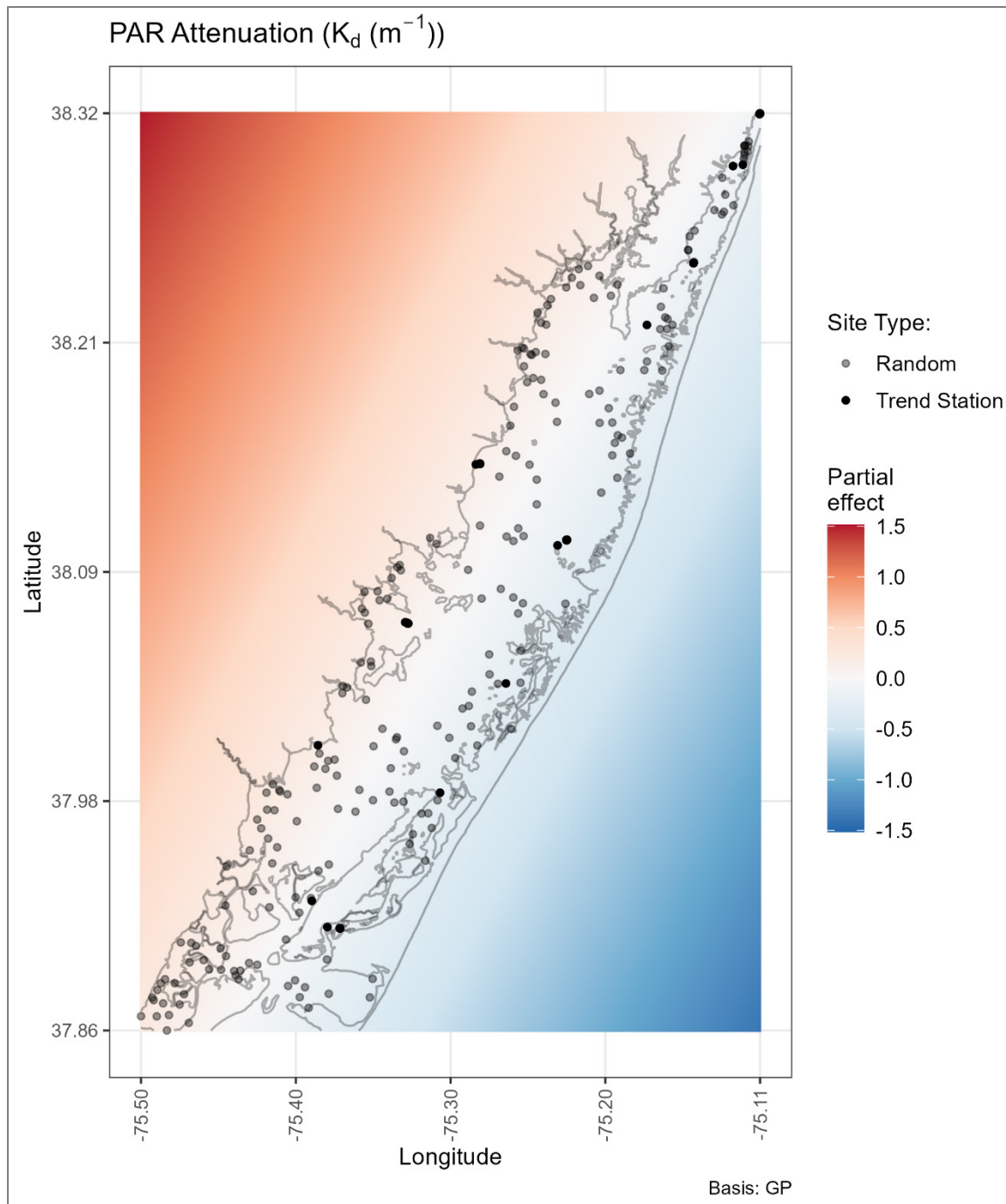


Figure 13. Mean surface for the generalized additive model latitude/longitude smooth of PAR attenuation (K_d (m^{-1})) within Assateague Island National Seashore during 2005–2022.

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Salinity (Near Surface)

Surface salinity exhibited a highly non-linear temporal trend with a significant decreasing trend during the period from 2012 to 2018 and significant increases in 2006, 2012, and 2020 (Figure 10). Spatially, salinity was lowest in the northwest region of the estuary and highest in the southern end

(Figure 14). The fitted GAM had the best fit amongst the parameters, with time and location accounting for 66.1% of the variation in salinity.

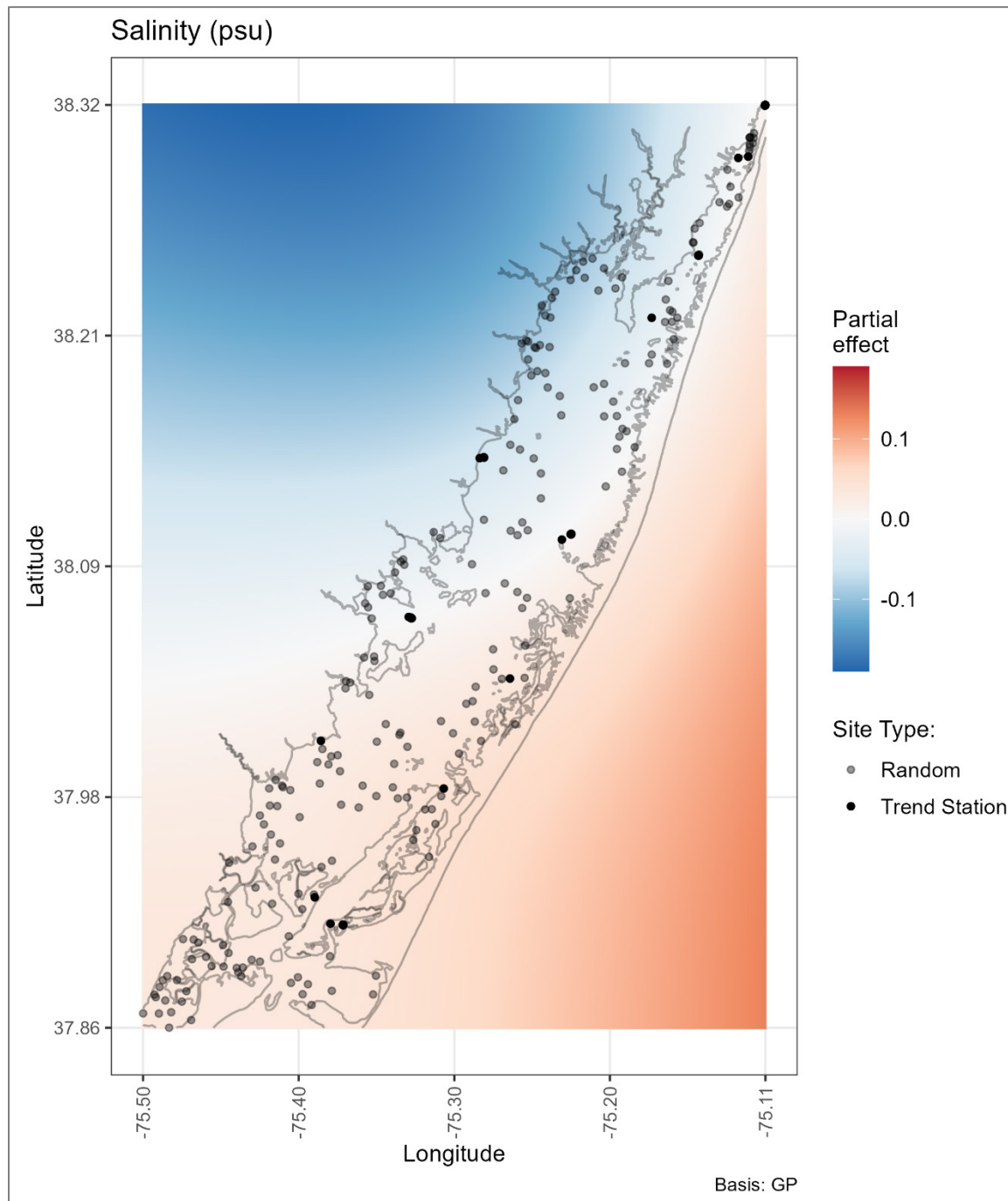


Figure 14. Mean surface for the generalized additive model latitude/longitude smooth of surface salinity (psu) within Assateague Island National Seashore during 2005–2022.

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Temperature (Near Surface)

Surface water temperature exhibited a highly non-linear temporal trend with cyclic periods of statistically significant increases and decreases (Figure 10). Temperatures exhibited two periods of significant increases since 2014. Spatially, surface temperatures were highest in the west central region of the estuary (Figure 15), with cooler temperatures observed at the northern- and southern-most extents. Based on the fitted model, both time and location account for only 44.7% of the variability in water temperature.

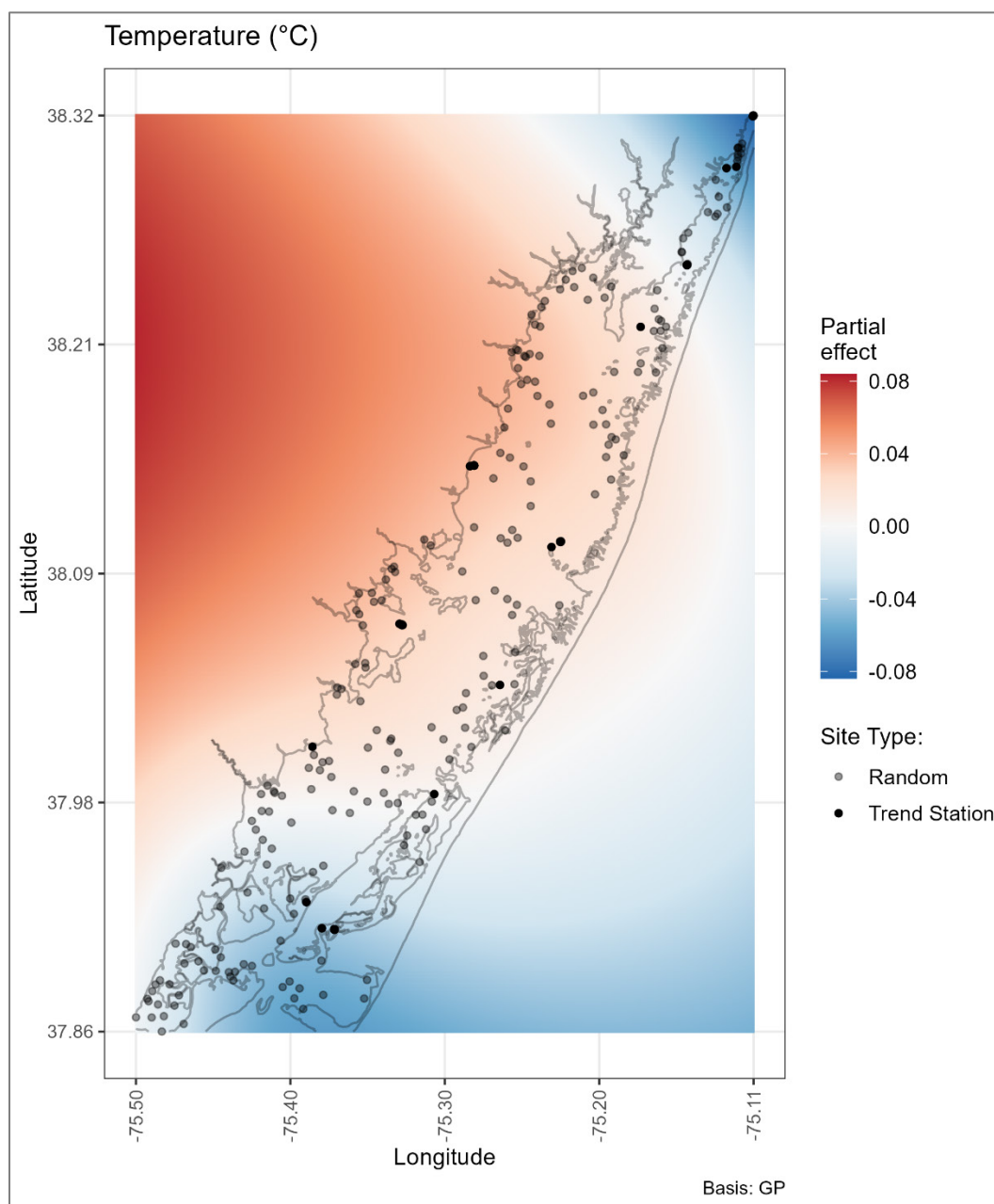


Figure 15. Mean surface for the generalized additive model latitude/longitude smooth of surface temperature (°C) within Assateague Island National Seashore during 2005–2022.

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Turbidity (Near Surface)

The temporal trend suggests a significant linear decline in surface turbidity since 2005 (Figure 10). Spatially, turbidity was higher on the western shore with the highest measurements occurring on the southwestern end of the estuary (Figure 16). Time and location accounted for only 18.9% of the variation in turbidity.

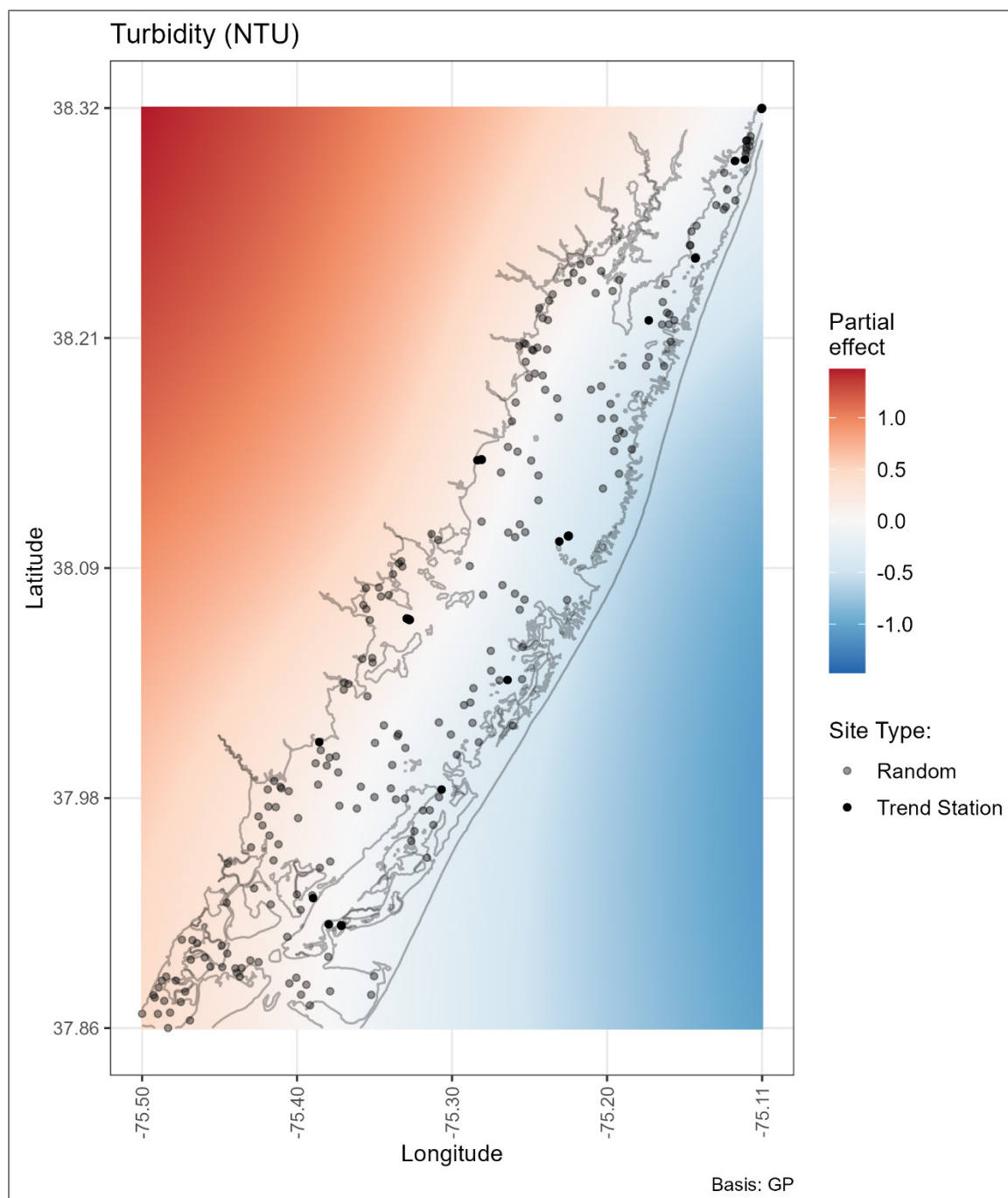


Figure 16. Mean surface for the generalized additive model latitude/longitude smooth of surface turbidity (NTU) within Assateague Island National Seashore during 2005–2022.

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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there was a statistically significant decreasing monotonic trend in surface turbidity (p -value = 0.025) and marginal statistical evidence of a

decreasing monotonic trend in PAR attenuation (p -value = 0.070) during the index periods of 2005 to 2022 (Table 7).

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

Parameter	Depth	Z_{MK}	p -value
Chlorophyll-a ($\mu\text{g/L}$)	Surface	-1.20	0.232
Dissolved oxygen (mg/L)	Bottom	0.74	0.462
PAR attenuation (K_d (m^{-1}))	Water Column	-1.81	0.070
Salinity (psu)	Surface	1.19	0.235
Temperature ($^{\circ}\text{C}$)	Surface	0.42	0.674
Turbidity (NTU)	Surface	-2.24	0.025

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} indicate that measurements tend to increase with time, whereas negative values indicate a decrease.

GAM Results

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

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

Parameter	Depth(s)	Model Term	edf (df_{ref})	F -value	p -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	s(year, hex)	46.05 (58)	5.86	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year, hex)	1.78 (58)	0.05	0.154
PAR attenuation (K_d (m^{-1}))	Water Column	s(year, hex)	10.10 (58)	1.93	< 0.001
Salinity (psu)	Surface	s(year, hex)	25.00 (58)	2.58	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year, hex)	11.13 (58)	1.75	< 0.001
Turbidity (NTU)	Surface	s(year, hex)	14.52 (58)	2.15	< 0.001

Chlorophyll-*a* (Near Surface)

Temporal trends in chlorophyll-*a* concentrations were highly non-linear and differ by station (Figure 17). The most notable trend was the sharp decrease in chlorophyll-*a* concentration at the hexagon 14 and 19 stations during the period of 2012–2014. A period of significant decline was also observed at the station within hexagon 18 between 2020 and 2022. Mean concentrations were generally classified as being in fair condition, with some stations experiencing poor conditions (i.e., > 20 $\mu\text{g/L}$) in some years.

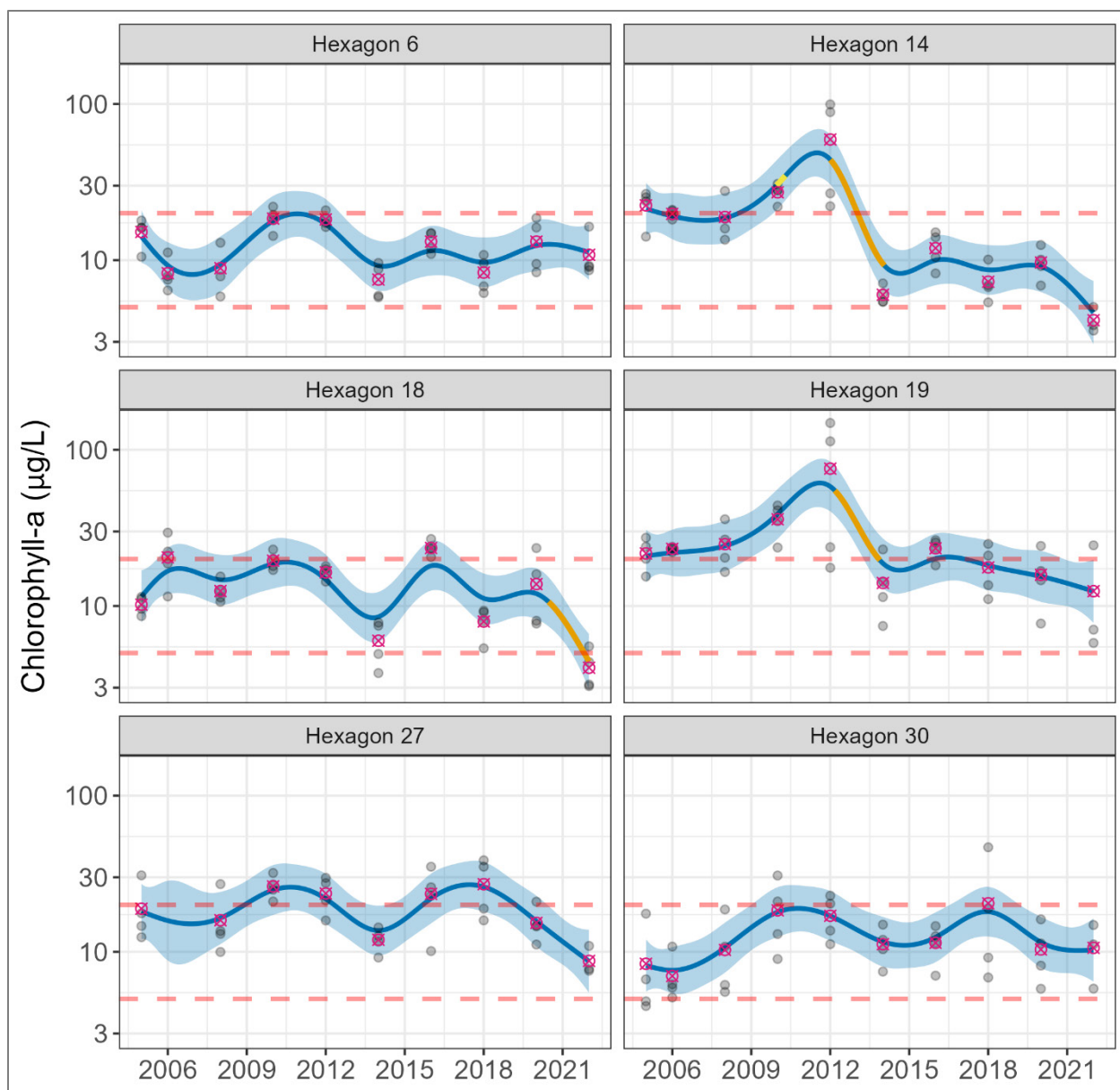


Figure 17. Mean surface chlorophyll-a concentration trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Note: the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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Dissolved Oxygen (Near Bottom)

No significant temporal trends in the bottom dissolved oxygen concentrations were observed at any trend station (Figure 18). The yearly average concentrations were all above the 5 mg/L threshold (i.e., good quality category) except for hexagon 19 in 2010.

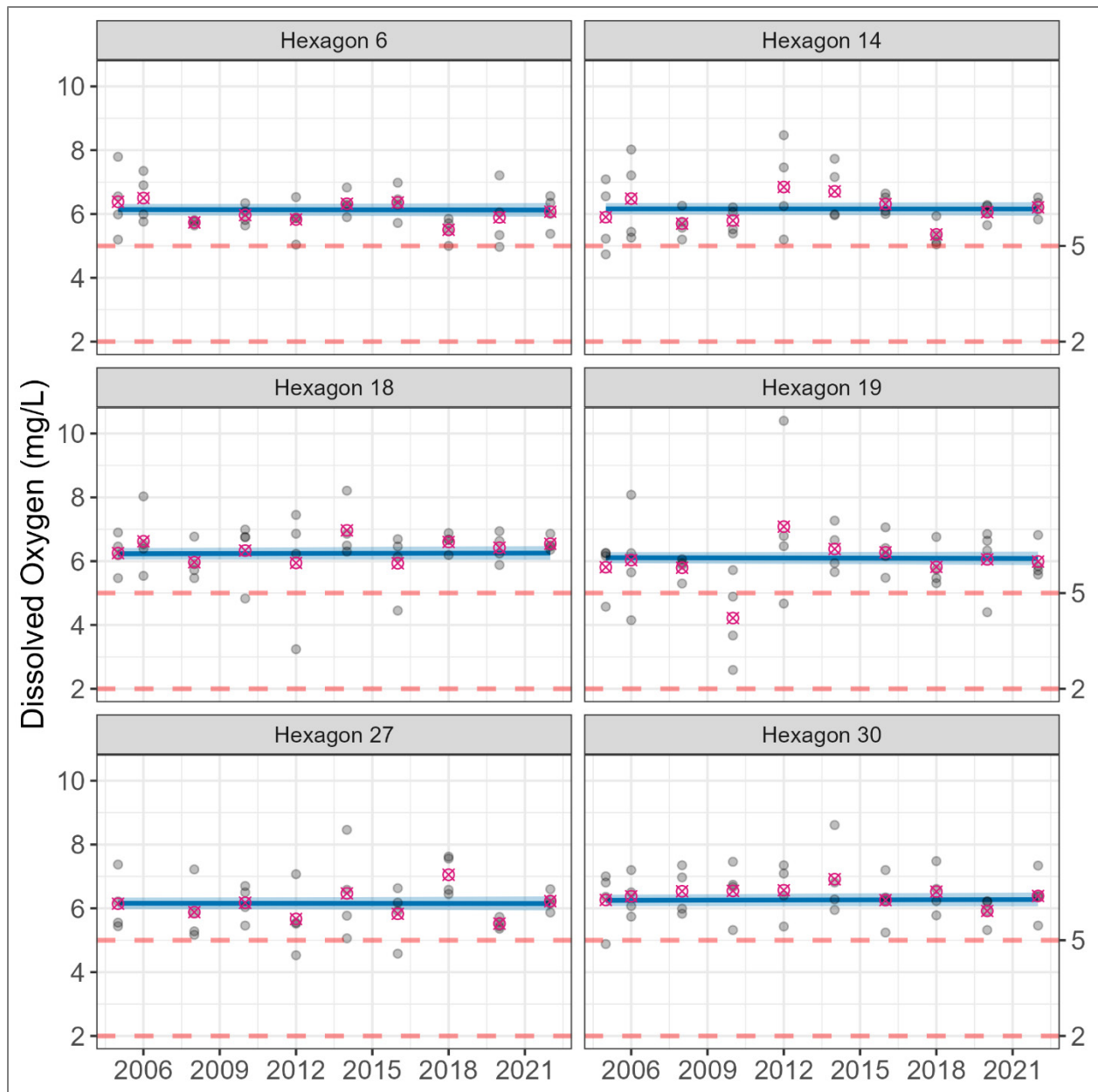


Figure 18. Mean bottom dissolved oxygen concentration trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases),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

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PAR Attenuation (K_d)

Temporal trends for the stations located within hexagons 14, 18 and 19 exhibited decreasing (improving) trends, with relatively high within year variability (Figure 19). There was a lack of any trend at the other stations and no periods of significant temporal change were identified. Mean

attenuation values were typically classified as being in poor condition (i.e., $>1.61 \text{ m}^{-1}$), with some stations experiencing fair conditions in some years.

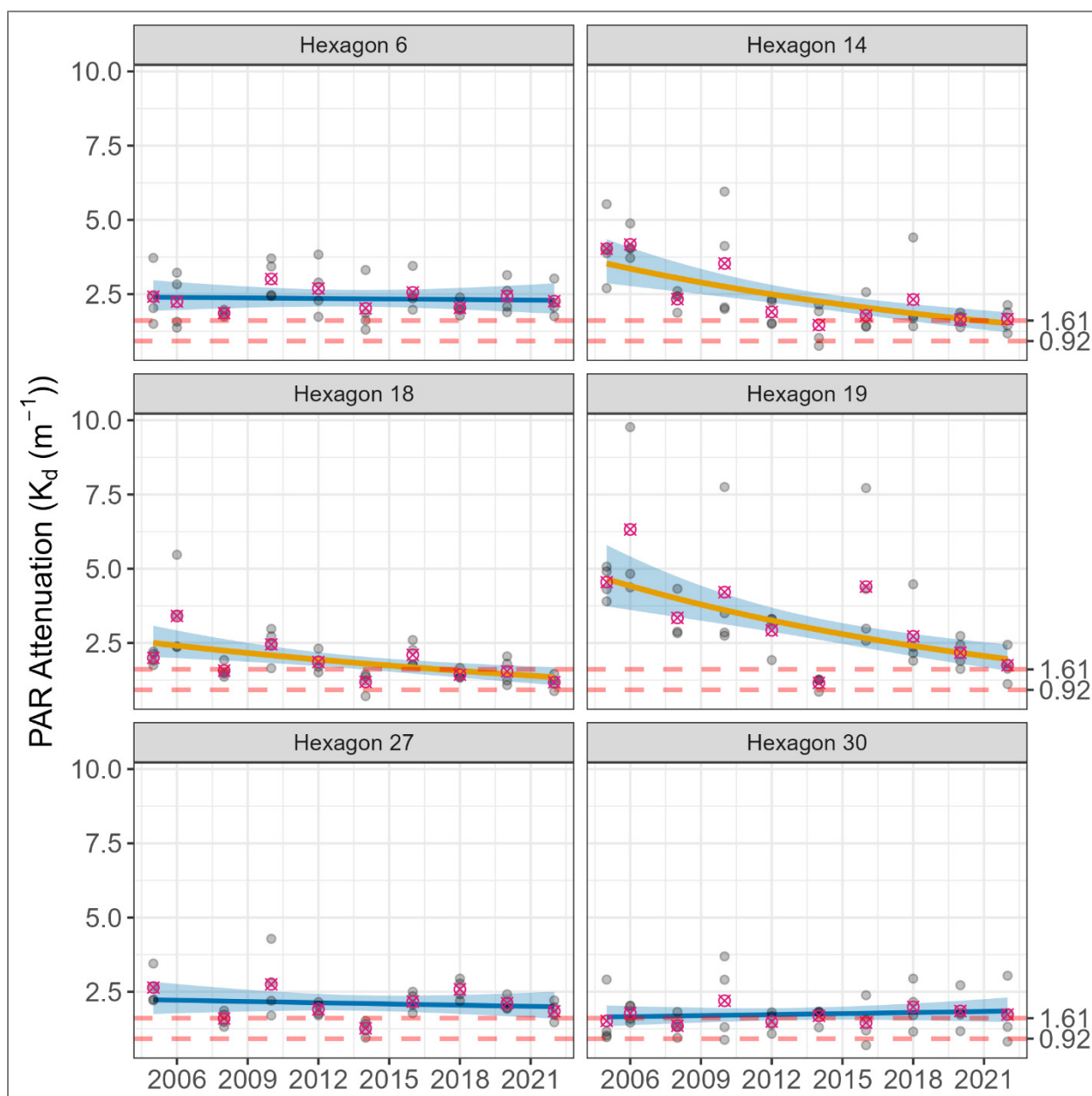


Figure 19. Mean PAR attenuation trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted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

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Salinity (Near Surface)

Temporal trends for stations within hexagons 14, 18, and 19 showed a slight increase in salinity until approximately 2012, after which salinity decreased until 2018 when it began increasing again (Figure 20). No periods of significant temporal change were identified.

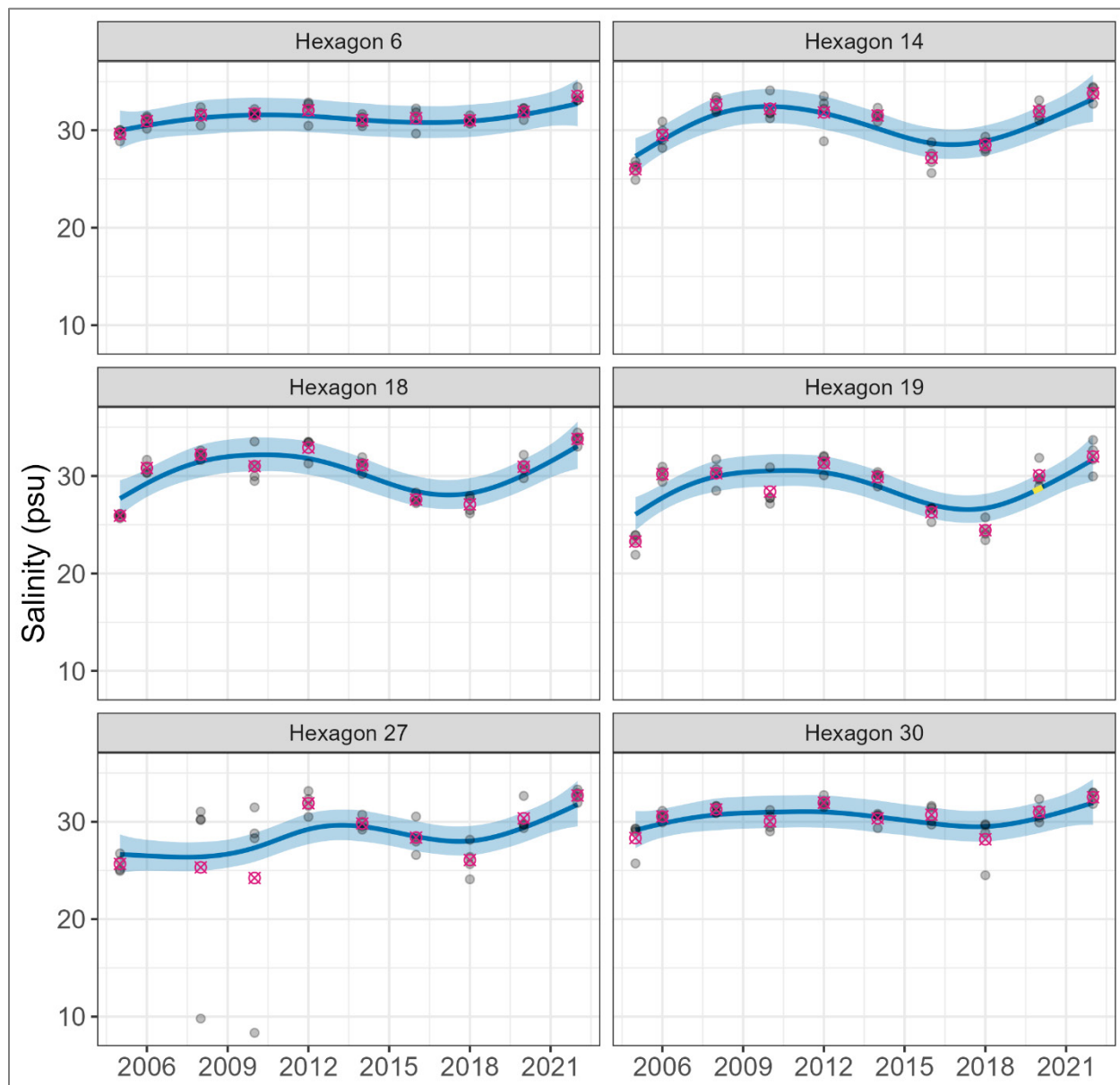


Figure 20. Mean surface salinity trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted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

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Temperature (Near Surface)

Temporal trends for stations 14, 18, 19, and 27 showed a slight decrease in surface water temperature until approximately 2014, after which temperatures have been slightly increasing (Figure 21). No periods of significant temporal change were identified. Mean temperatures exceeded 28°C in several years at all trend stations except for station 30.

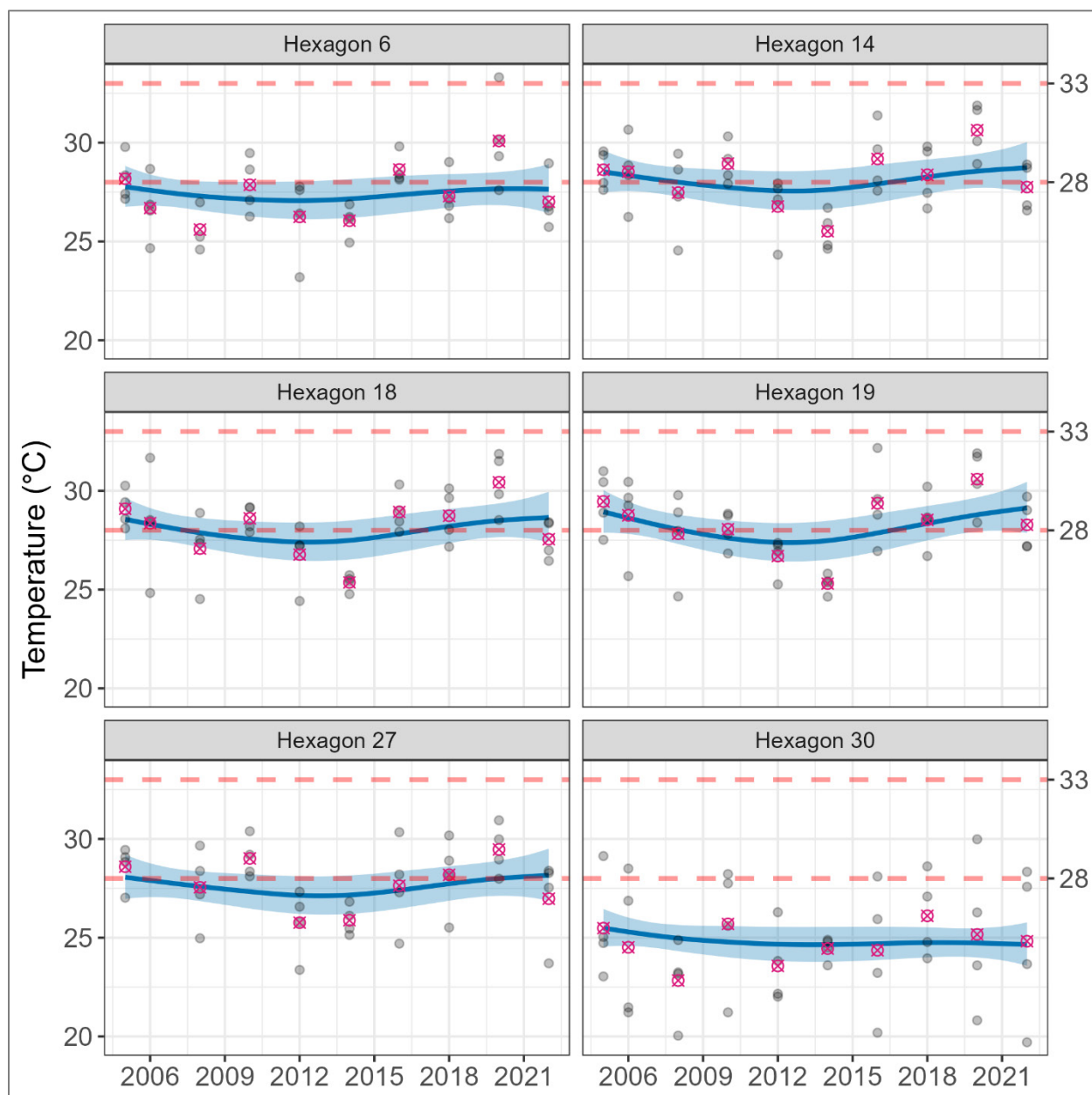


Figure 21. Mean surface temperature trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are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

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Turbidity (Near Surface)

Temporal trends for stations 14, 18, 19, and 27 showed a slight decrease in surface turbidity since sampling began (Figure 22). No periods of significant temporal change were identified.

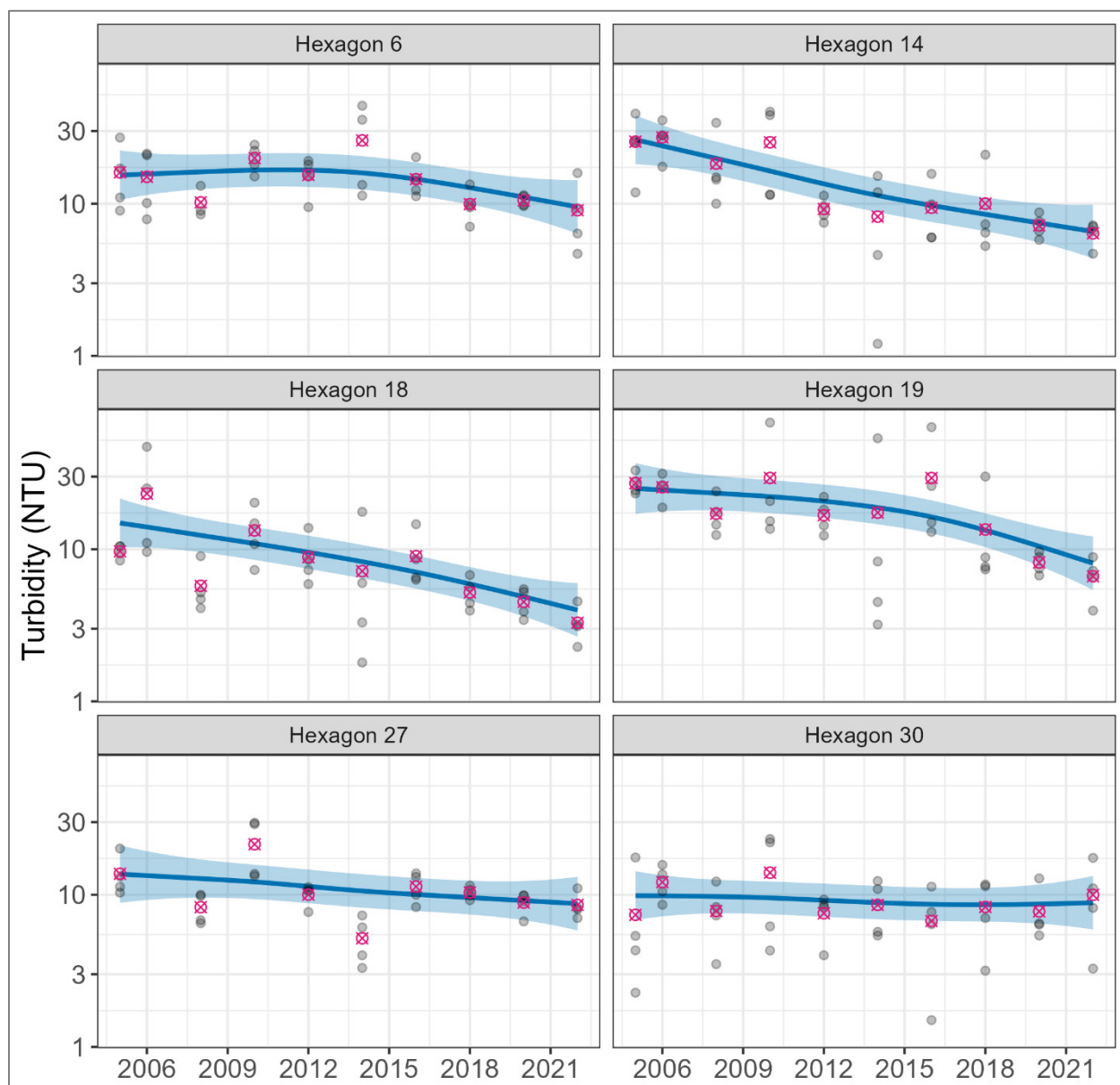


Figure 22. Mean surface turbidity trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Note: the y-axis is transformed to the log₁₀ 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 is marginal statistical evidence (assuming a significance level of 0.05) of an increasing monotonic trend in salinity ($p = 0.051$) and a marginal decreasing monotonic trend in turbidity ($p = 0.077$) measured at the trend stations during the index periods of 2005 to 2022 (Table 9).

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

Parameter	Depth	Z_{MK}	p -value
Chlorophyll- <i>a</i> ($\mu\text{g/L}$)	Surface	-0.09	0.932
Dissolved oxygen (mg/L)	Bottom	1.11	0.266
PAR attenuation (K_d (m^{-1}))	Water Column	-0.79	0.430
Salinity (psu)	Surface	1.95	0.051
Temperature ($^{\circ}\text{C}$)	Surface	0.91	0.362
Turbidity (NTU)	Surface	-1.77	0.077

Logging Station Continuous Water Quality Data

Data Analysis

Generalized Additive Model (GAM)

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

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

where μ_i is a vector of response values, β_0 is the intercept, $f_{\text{year}_i}(\text{doy})$ is a rank 20 TRPS smooth of doym for the i th year, and $f(\text{hour})$ 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 measure was observed within each estuarine quality category.

Results

An example time series plot of dissolved oxygen measurements over the course of the instrument deployment is provided in Figure 23. Yearly summary statistics for each parameter and year can be found in Table 10. Note that a new location was used starting in 2018 near to the original location, and thus, was still representative of the system. Notable observations from the fitted smooths and data summaries for each parameter are provided in the subsections below.

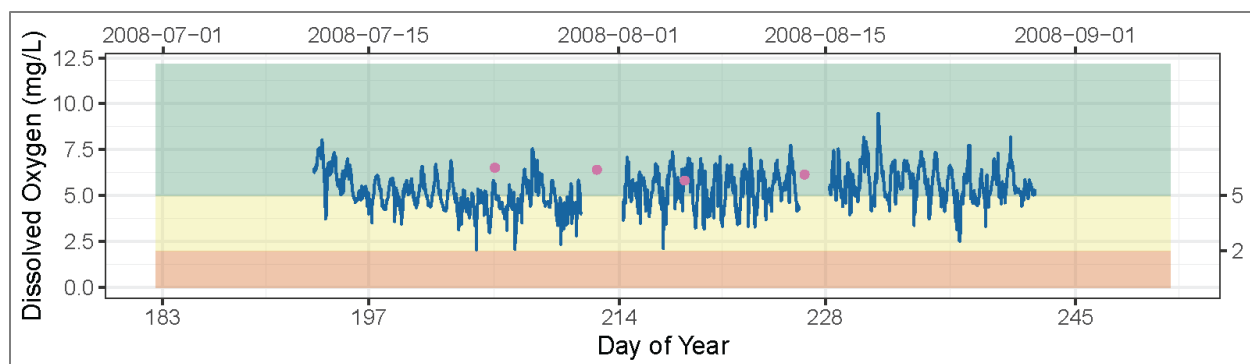


Figure 23. Example continuous dissolved oxygen readings from a data logger deployed at Assateague Island National Seashore logging station in 2008. Magenta points represent discrete grab samples collected every week for quality assurance. Estuarine quality category thresholds (Table 2) are delineated by the background color (green = good condition; yellow = fair; orange = poor).

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Table 10. Yearly summary statistics for water quality parameters collected at the Assateague Island National Seashore logging station. Note: new logging station location was used starting in 2018. [SD = standard deviation; n = number of observations; NA = not available]

Parameter	Statistic	Sampling Year									
		2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
Chlorophyll- <i>a</i> (µg/L)	Mean	18.19	29.61	7.68	19.41	34.17	4.87	22.22	16.39	9.86	8.67
Chlorophyll- <i>a</i> (µg/L)	SD	3.49	9.45	3.05	6.99	9.36	1.72	7.08	8.61	10.39	4.98
Chlorophyll- <i>a</i> (µg/L)	n	2324	1614	4044	3058	2878	3072	3346	2009	1911	2494
Dissolved oxygen (mg/L)	Mean	6.06	6.03	5.38	6.55	5.77	6.75	5.81	6.68	6.82	6.49
Dissolved oxygen (mg/L)	SD	0.97	1.30	0.97	1.08	1.53	1.58	0.87	0.75	0.69	1.00
Dissolved oxygen (mg/L)	n	2033	2955	4230	3062	2891	1735	3346	2009	1912	2494
Depth (m)	Mean	0.66	0.59	0.63	0.54	0.59	0.73	0.85	1.16	0.83	0.82
Depth (m)	SD	0.08	0.10	0.08	0.09	0.09	0.09	0.09	0.09	0.10	0.09
Depth (m)	n	2867	2955	4230	3062	2891	3076	3346	2009	1912	2494
PAR attenuation (K_d (m ⁻¹))	Mean	2.45	2.44	1.08	1.46	2.67	0.75	1.50	1.49	1.31	1.67
PAR attenuation (K_d (m ⁻¹))	SD	0.54	0.61	0.39	0.41	1.16	0.52	0.64	0.23	0.96	0.40
PAR attenuation (K_d (m ⁻¹))	n	698	546	979	181	579	480	843	516	487	543
pH	Mean	NA	NA	NA	NA	NA	NA	NA	8.25	8.13	8.00
pH	SD	NA	NA	NA	NA	NA	NA	NA	0.14	0.12	0.11
pH	n	0	0	0	0	0	0	0	2009	1912	2494
Salinity (psu)	Mean	25.46	30.83	30.34	28.87	30.49	29.71	27.84	25.48	29.85	33.44
Salinity (psu)	SD	0.38	0.88	0.53	1.37	2.92	0.56	0.81	0.90	0.66	0.70
Salinity (psu)	n	2865	2953	4224	3062	2891	3074	2466	2008	1912	2494
Temperature (°C)	Mean	28.58	28.15	26.89	28.07	26.96	25.89	29.16	28.25	29.50	28.06
Temperature (°C)	SD	1.36	2.11	1.74	1.82	1.26	1.37	1.24	1.67	1.38	1.72
Temperature (°C)	n	2867	2955	4230	3062	2891	3076	3346	2009	1912	2494
Turbidity (NTU)	Mean	20.58	16.94	6.41	8.70	22.96	0.58	14.08	8.38	8.53	7.69
Turbidity (NTU)	SD	8.39	6.73	6.40	3.43	18.30	0.84	5.08	2.07	6.41	1.93
Turbidity (NTU)	n	2415	2177	2896	3057	2879	3072	3339	2005	1912	2494

Chlorophyll-a

Mean chlorophyll-a concentrations ranged from 4.87 to 34.17 µg/L and were classified as being in poor condition (i.e., > 20 µg/L) in 2006, 2012, and 2016 (Table 10). Intra-annual mean trends in chlorophyll-a concentration were highly non-linear for most years (Figure 24), and the associated distribution of measurements tended to be highly skewed most years (Figure 25). There were several years (e.g., 2006, 2010, 2012, and 2016) where chlorophyll-a condition was poor for the majority of the hours in the day as well as most days during the sampling period (Figure 26).

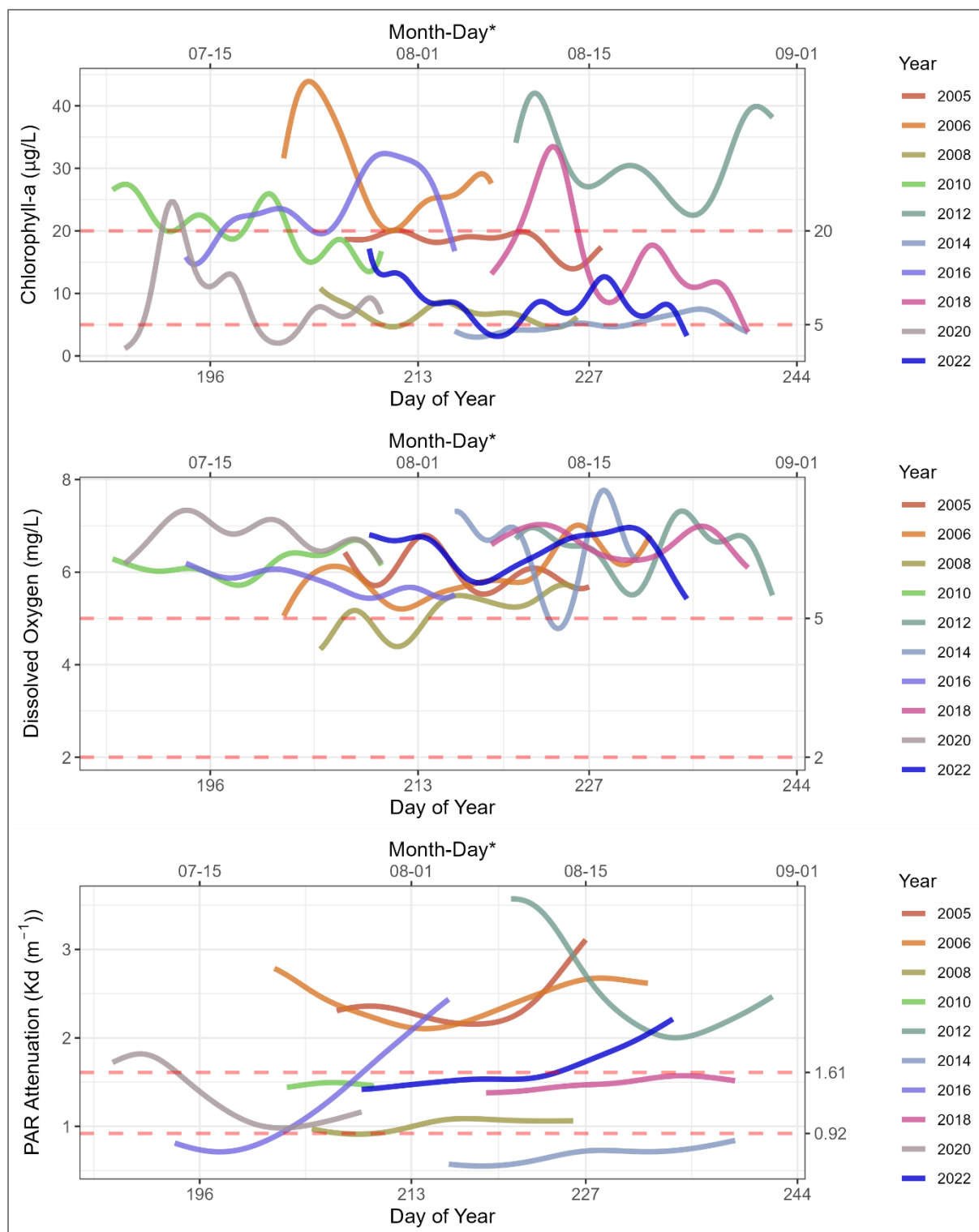


Figure 24. Intra-annual trends in surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Assateague Island National Seashore logging station based on generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: a new location was used starting in 2018.

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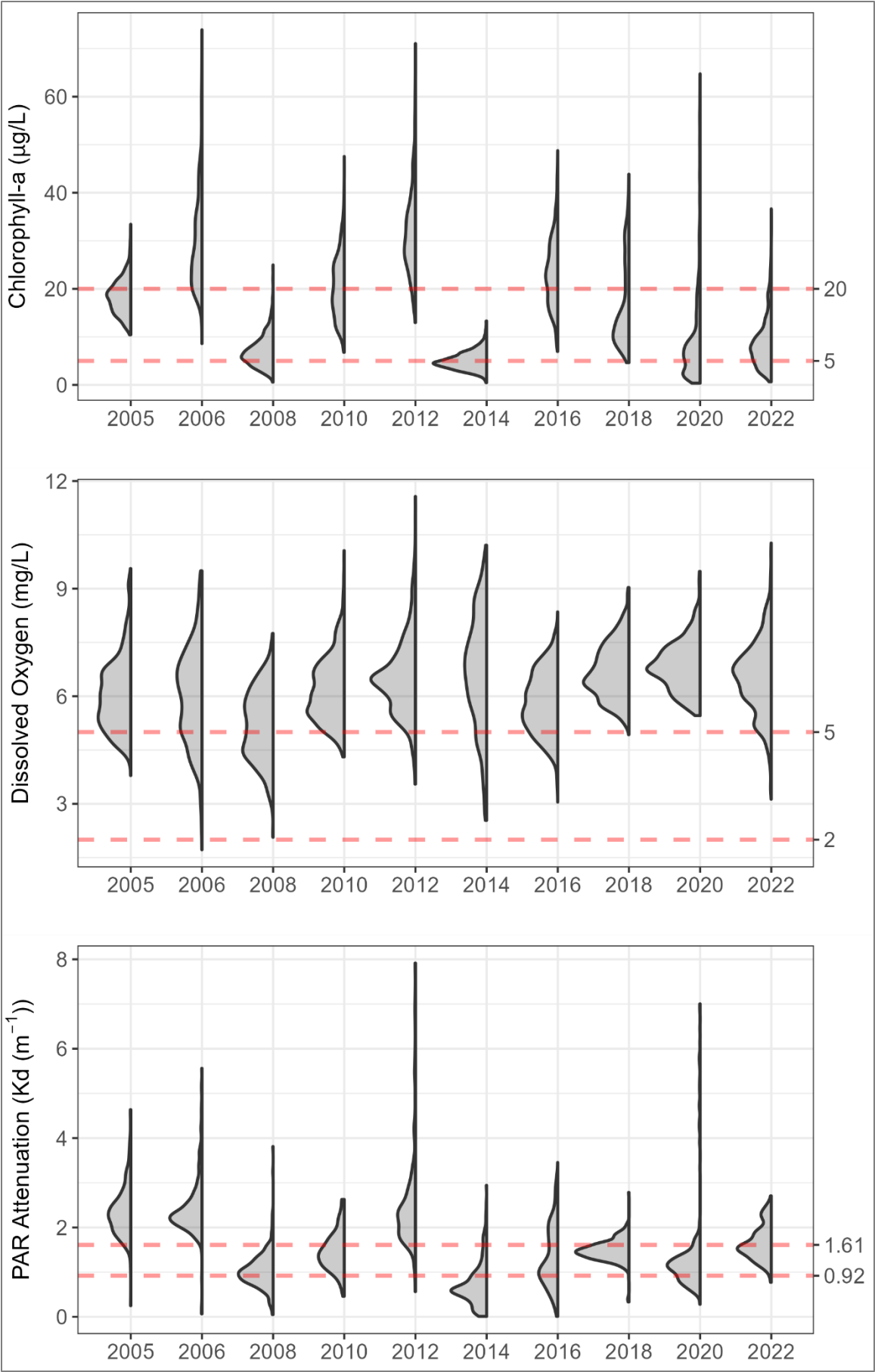


Figure 25. Distribution of index period time series values for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Assateague Island National Seashore logging station. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: a new location was used starting in 2018.

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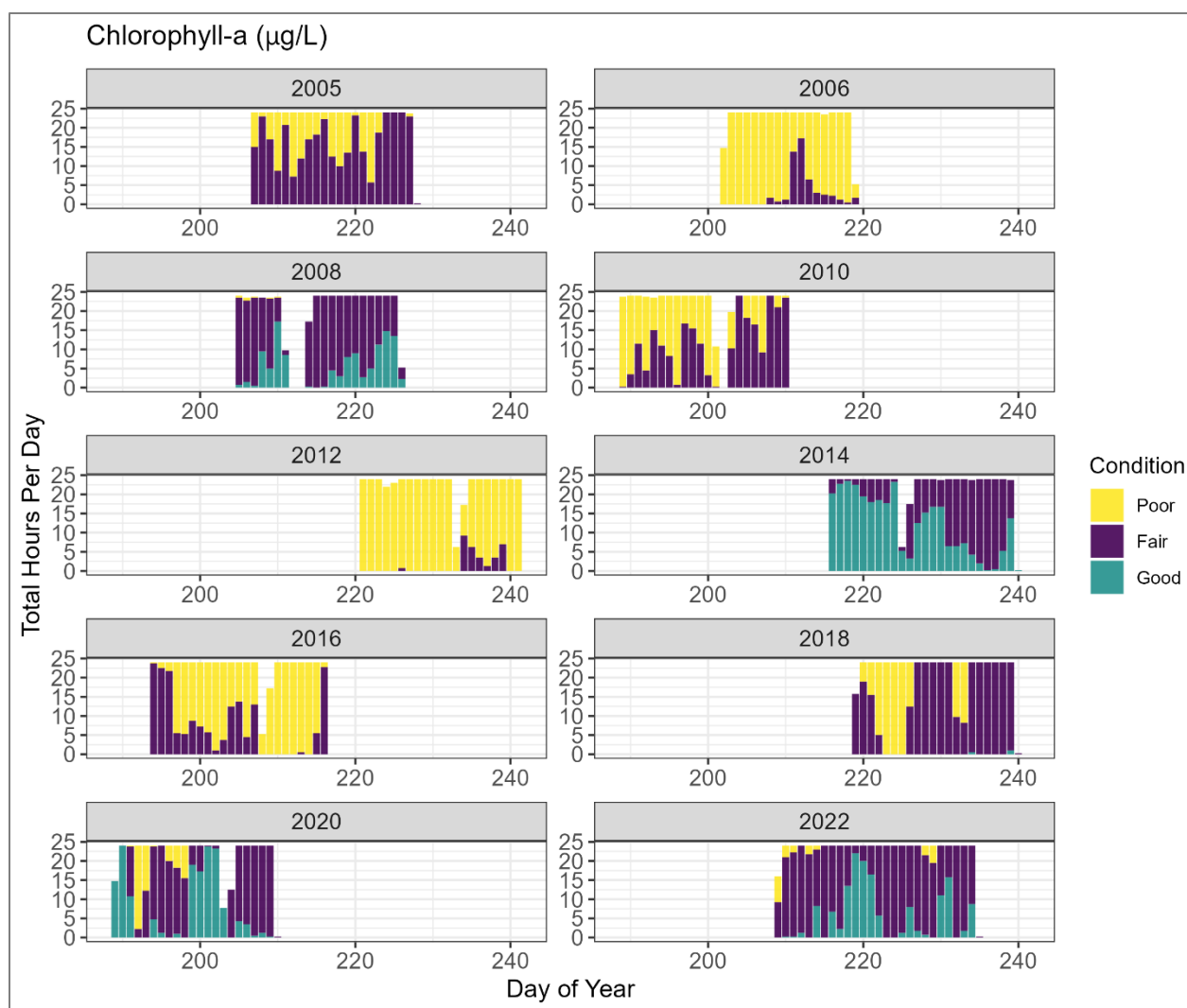


Figure 26. Total hours per day that surface chlorophyll-a concentration was observed within each condition category at the Assateague Island National Seashore logging station. Estuarine water quality condition categories are defined in Table 2. Note: a new location was used starting in 2018.

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Dissolved Oxygen

Mean dissolved oxygen concentrations ranged from 5.38 to 6.82 mg/L (Table 10). Intra-annual mean trends in dissolved oxygen were non-linear at this temporal scale and the cyclic nature was consistent across years (Figure 24). The distribution of measurements was long-tailed in many years sampled with concentrations dropping below 2 mg/L (i.e., poor condition) in 2006 and 2008 (Figure 25). Dissolved oxygen conditions were generally good across all years with some days experiencing fair conditions for part of the day (Figure 27).

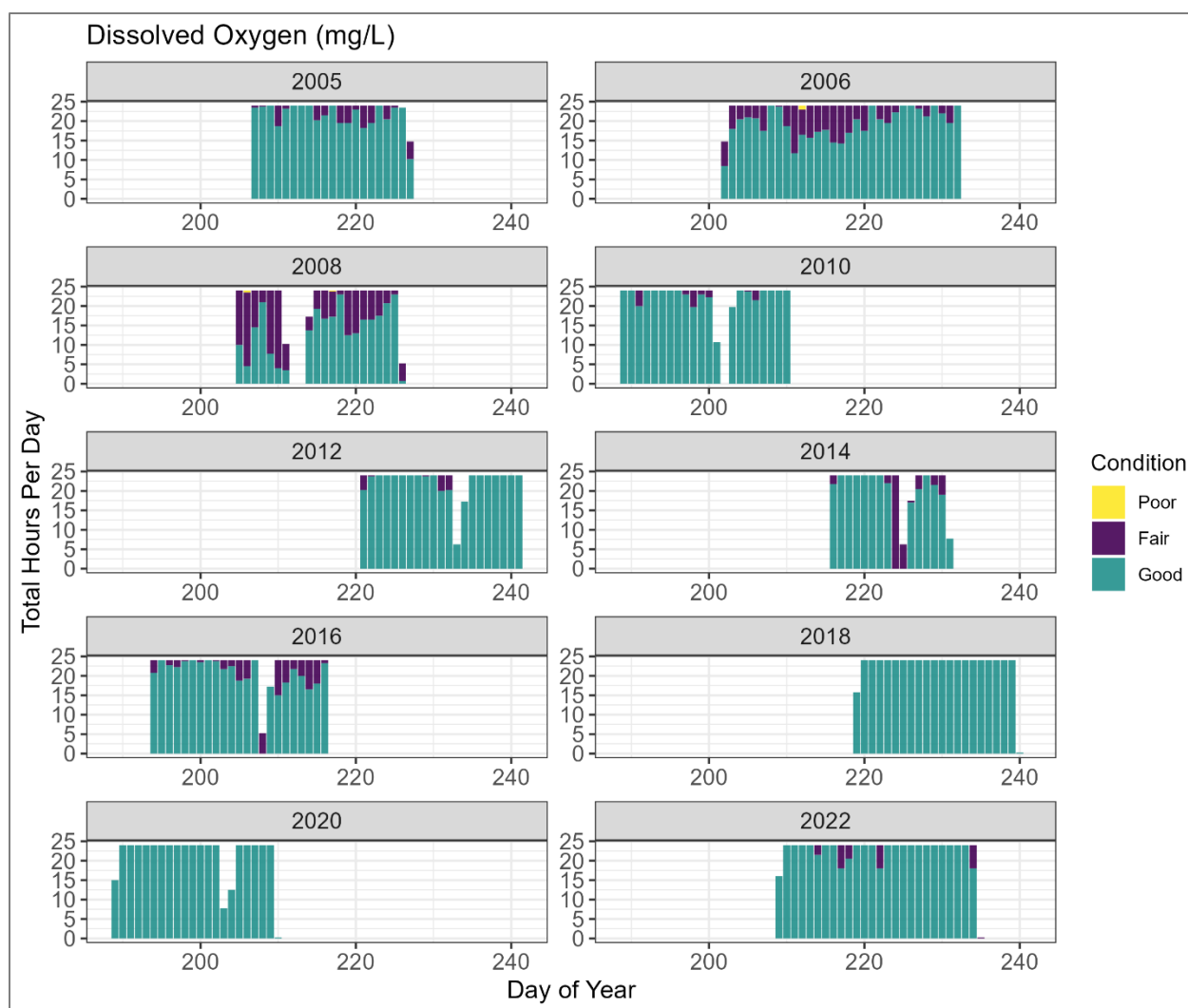


Figure 27. Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the Assateague Island National Seashore logging station. Estuarine water quality condition categories are defined in Table 2. Note: a new location was used starting in 2018.

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PAR Attenuation K_d

The highest mean PAR attenuation (2.67 m^{-1}) was observed in 2012 with the lowest observed in 2014 (0.75 m^{-1} ; Table 10). Years 2005, 2006, 2012, 2016, 2020, and 2022 exhibited more highly non-linear mean trends compared to the other years (Figure 24). The distribution of measurements in 2012 and 2020 was highly skewed compared to other years (Figure 25). For years when PAR attenuation conditions were poor (e.g., 2005, 2006 and 2012), the majority of daytime hours during which PAR attenuation could be measured were spent in poor condition (Figure 28).

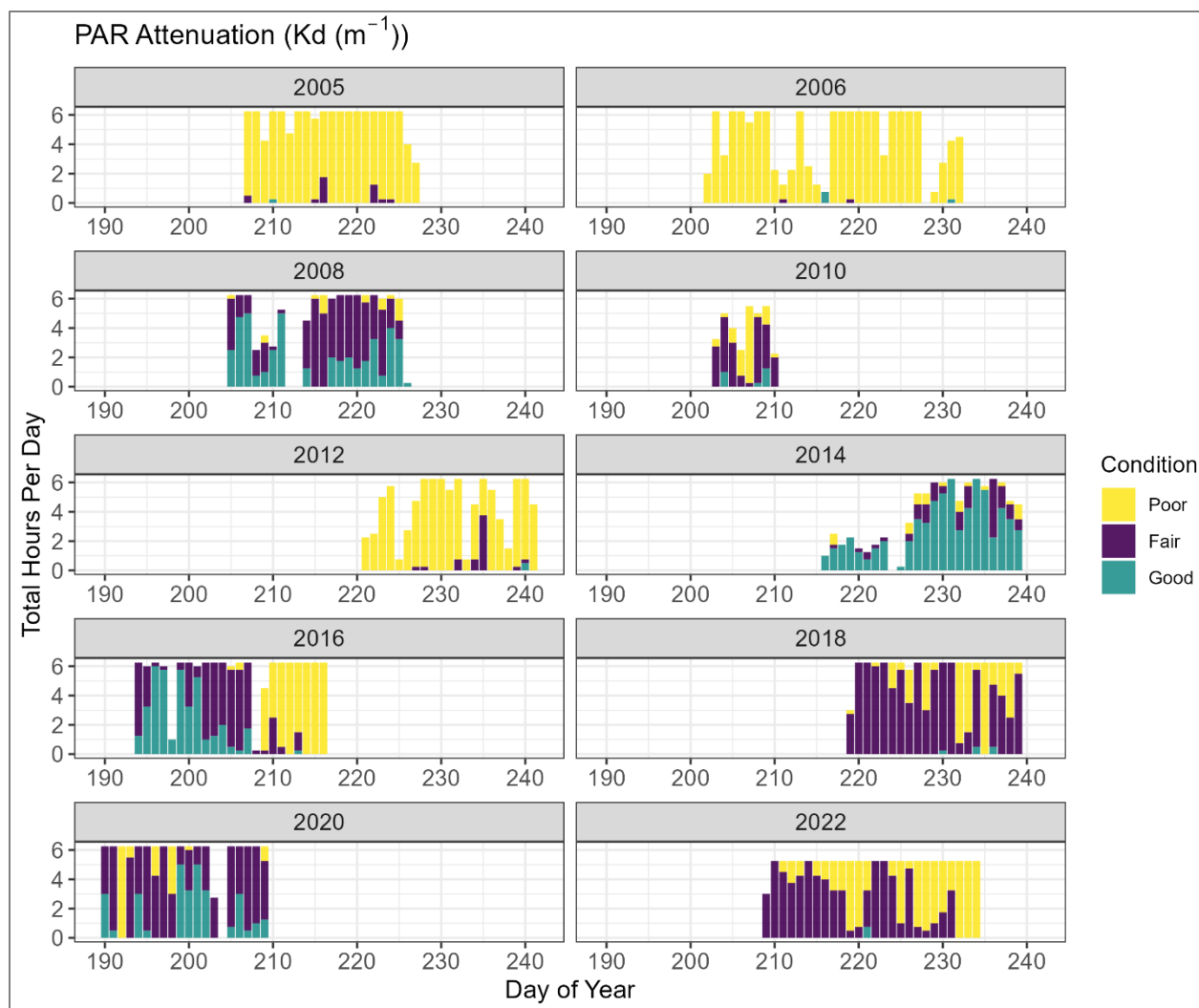


Figure 28. Total hours per day that PAR attenuation was observed within each condition category at the Assateague Island National Seashore logging station. Estuarine water quality condition categories are defined in Table 2. Note: a new location was used starting in 2018.

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Salinity

Mean salinity ranged from 25 to 33 psu (Table 10). Intra-annual mean trends in salinity were non-linear and there were a few cases of increasing (e.g., 2010, 2018, and 2022) or decreasing (e.g., 2012) trends (Figure 29). For most years, salinity measurements within each summer index period typically spanned approximately 2–4 psu (Figure 30).

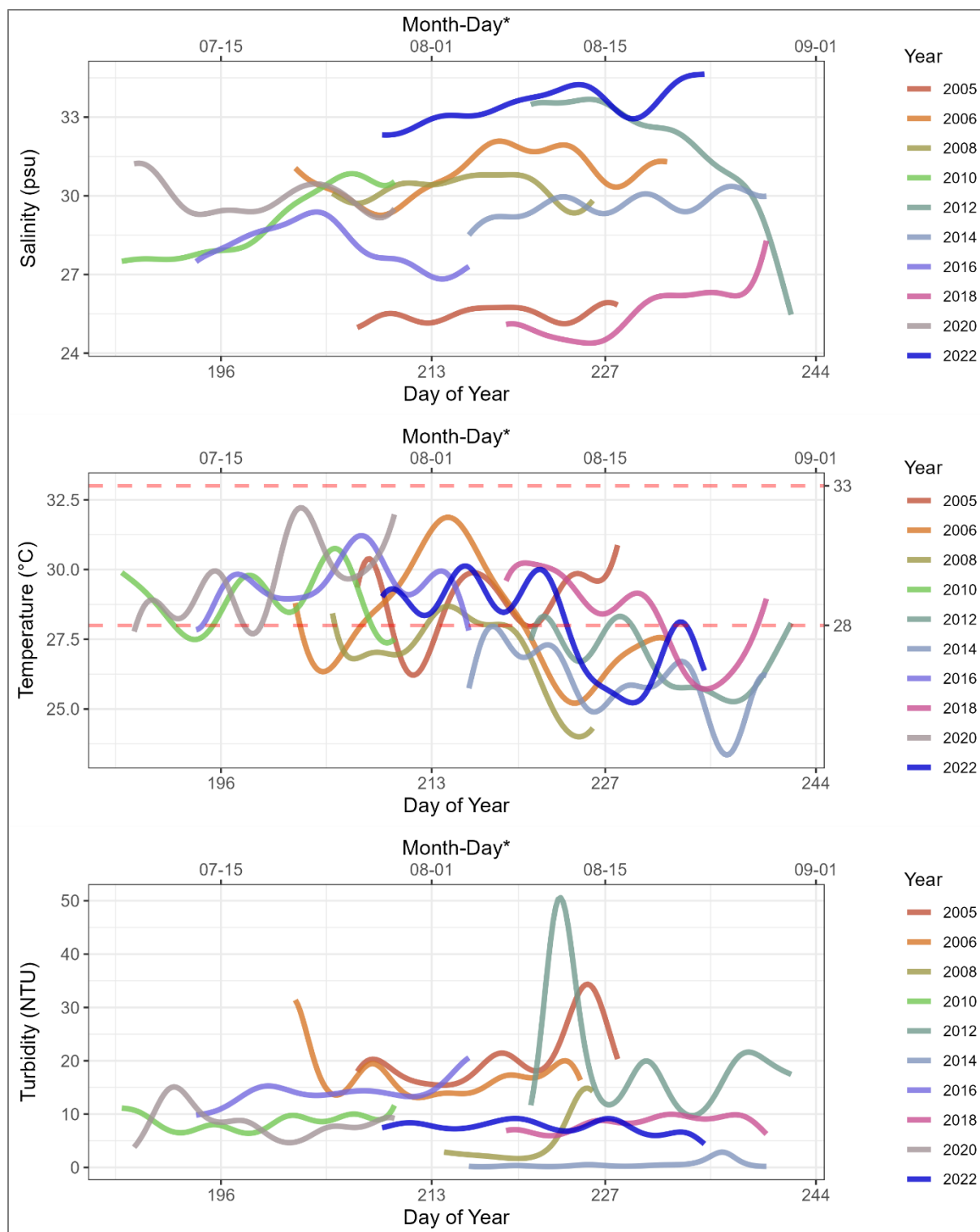


Figure 29. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Assateague Island National Seashore logging station based on generalized additive model smooths. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines. Note: a new location was used starting in 2018.

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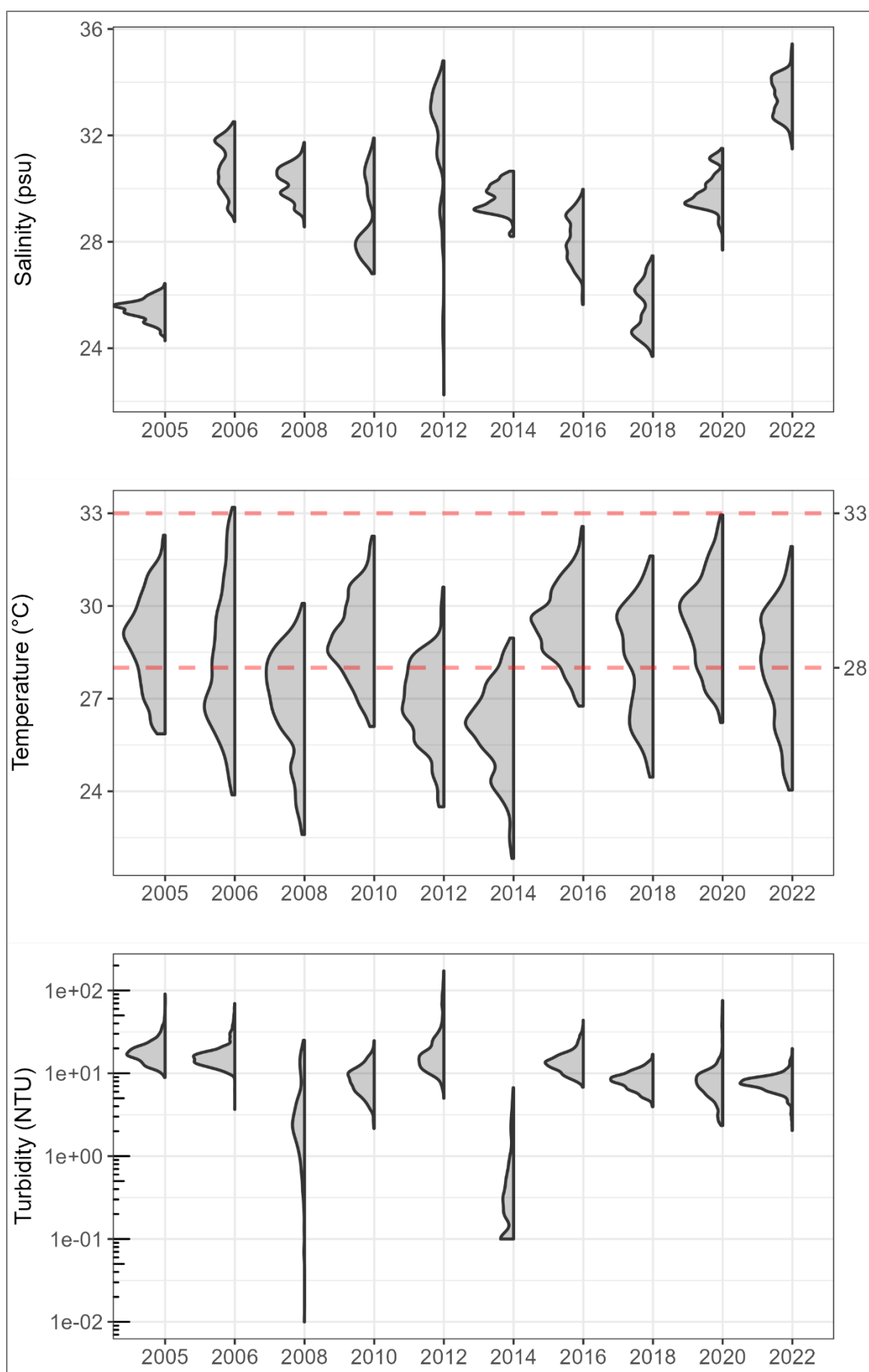


Figure 30. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Assateague Island National Seashore logging station. Note: the surface turbidity y-axis is transformed to the log₁₀ scale to better visualize the estimated distributions. Estuarine quality category thresholds (Table 2) are plotted as red dashed lines.

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Temperature

Intra-annual mean trends in water temperature were highly non-linear with an overall decreasing trend from July to August (Figure 29). Water temperature measurements within each summer index period typically spanned approximately 6–7°C (Figure 30), and temperatures exceeded 33°C on several occasions in 2006 and 2020.

Turbidity

Mean turbidity ranged from 0.58 to 22.96 NTU, with the highest values observed in 2005 and 2012 (Table 10). Intra-annual mean trends in turbidity were generally fairly smooth except for 2005, 2006, 2008, and 2012 (Figure 29). Turbidity measurements in 2008 and 2014 were more skewed than other years (Figure 30).

pH

Measurements of pH began in 2018 and mean values ranged from 8 to 8.25 (Table 10). While all years exhibited a non-linear intra-annual mean trend, trends in pH in 2020 and 2022 were much more periodic and stationary compared to 2018 (Figure 31).

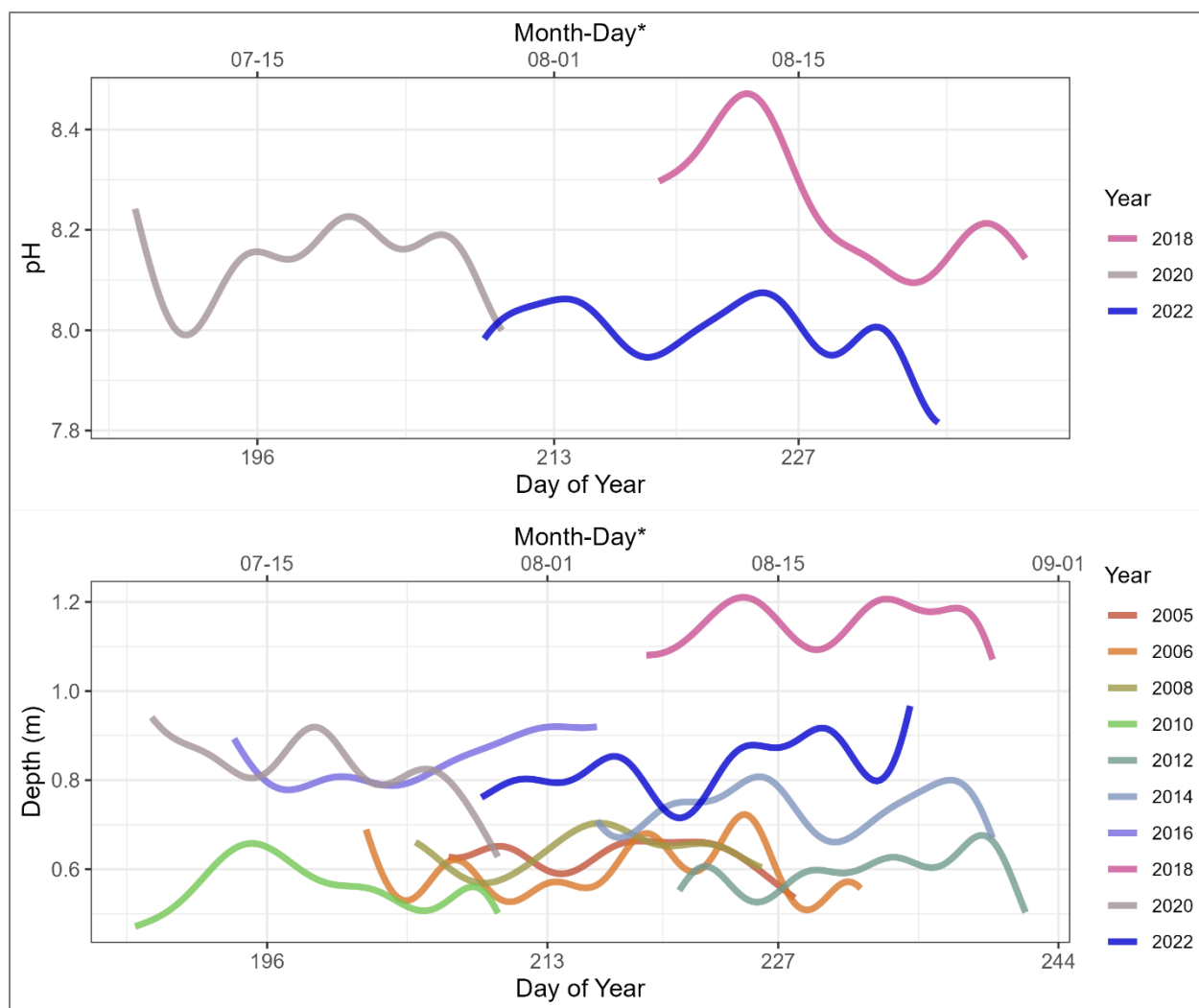


Figure 31. Intra-annual trends in pH (top) and depth (bottom) at the Assateague Island National Seashore logging station based on generalized additive model smooths. Note: a new location was used starting in 2018.

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Depth

Mean depth typically ranged from 0.5 to 0.8 m except for in 2018 when it exceeded 1.1 m (Table 10). All years exhibited a non-linear intra-annual mean trend (Figure 31). Within a given year, the depth range was generally less than 0.4 m (Figure 32).

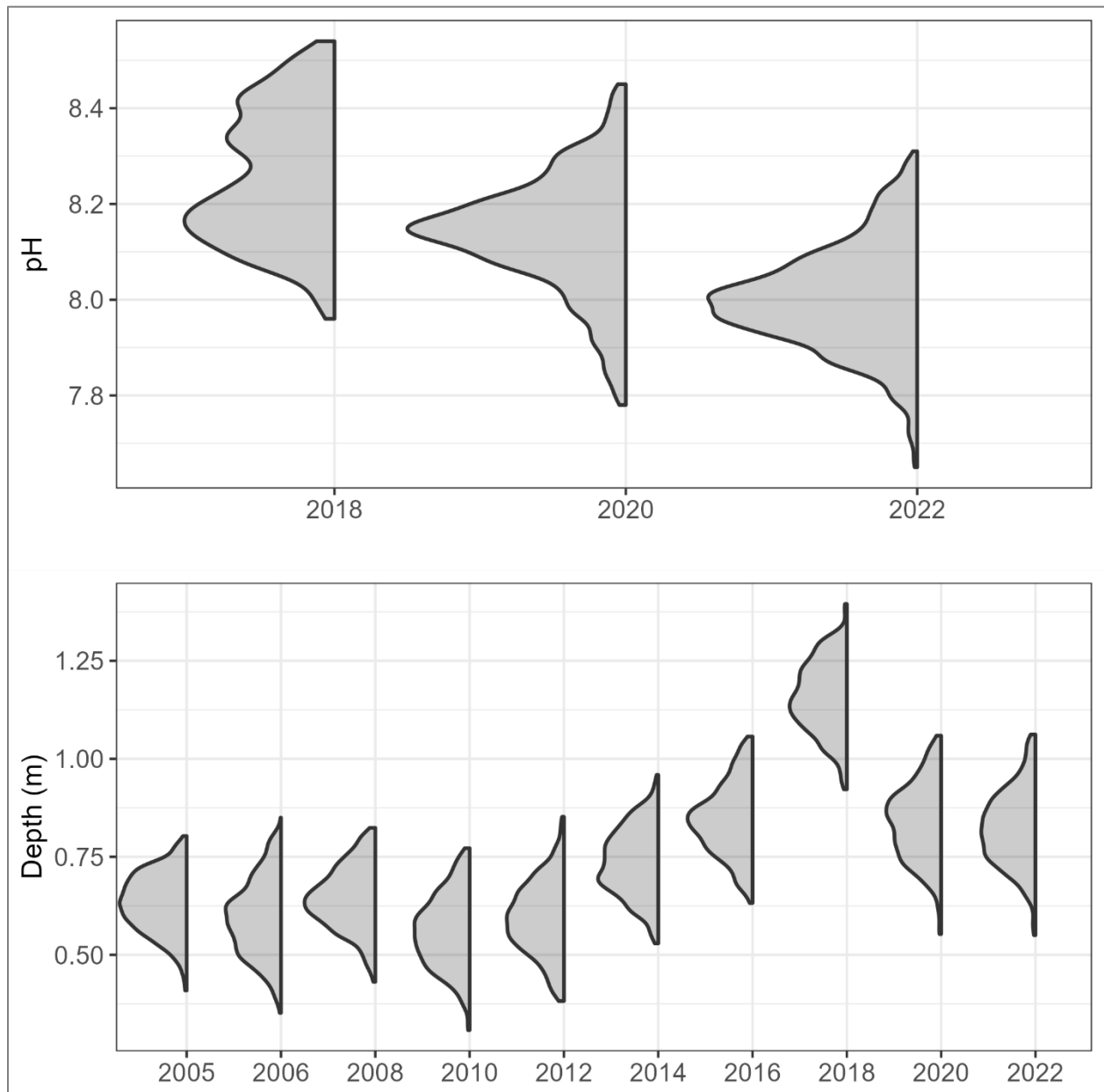


Figure 32. Distribution of index period time series values for pH (top) and depth (bottom) at the Assateague Island National Seashore logging station. Note: a new location was used starting in 2018.

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Seagrass Condition

Data Analysis

Variable Derivations

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

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

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

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

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

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

Generalized Additive Model (GAM)

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

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

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

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

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

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

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

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

Multivariate Mann-Kendall Trend Analysis

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

GAM Results

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

The generalized additive model summaries indicate that there were statistically significant temporal trends within transects for all *Zostera marina* parameters (Table 12), all *Ruppia maritima* parameters (Table 12), and ancillary sediments (Table 13).

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

Parameter	Model Term	<i>Zostera marina</i>		<i>Ruppia maritima</i>	
		edf	p -value	edf	p -value
Shoot density	s(year, transect)	27.89	< 0.001	–	–
Percent cover	s(year, transect)	25.40	< 0.001	17.15	< 0.001
Canopy height	s(year, transect)	30.08	< 0.001	8.82	< 0.001
Total biomass	s(year, transect)	28.69	< 0.001	29.25	< 0.001
Above- to belowground biomass	s(year, transect)	11.70	< 0.001	11.73	0.021

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

Parameter	Model Term	edf	p -value
Percent fine sediment	s(year, transect)	9.53	<0.001
Percent organic material	s(year, transect)	9.64	< 0.001

Shoot Density

Zostera marina shoot density was generally highest within the mid-depth transect often exceeding 250 shoots m^{-2} , and temporal trends differed between transects (Figure 33). All three transects experienced a significant decline around 2016, after which mean shoot density remained less than 50 shoots m^{-2} in the shallow transect and less than 5 shoots m^{-2} in the deep transect. Shoot density within the mid-depth transect experienced a period of brief recovery beginning in 2017.

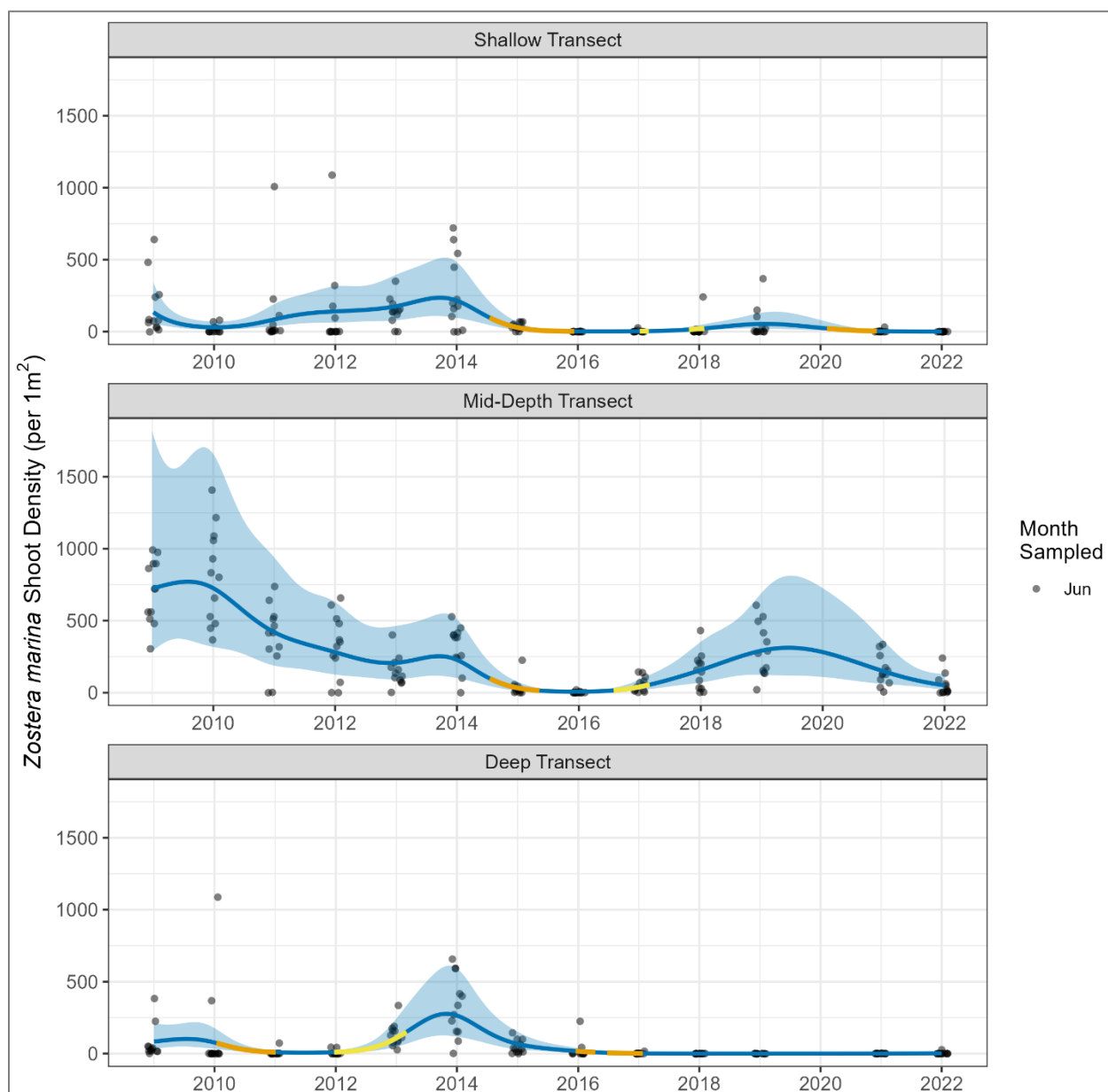


Figure 33. Trend in *Zostera marina* shoot density (shoots m^{-2}) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Percent Cover

Zostera marina experienced a significant decline in percent cover within the mid-depth transect from 2009 to 2016 followed by an increase through 2019 and a subsequent decline through 2022 (Figure 34). Despite a statistically significant increase around 2013, percent cover of eelgrass within the deep transect experienced a significant decline between 2015 and 2016 after which it did not exceed 1%. Percent cover in the shallow transect also declined around 2016 after which it did not exceed 11%.

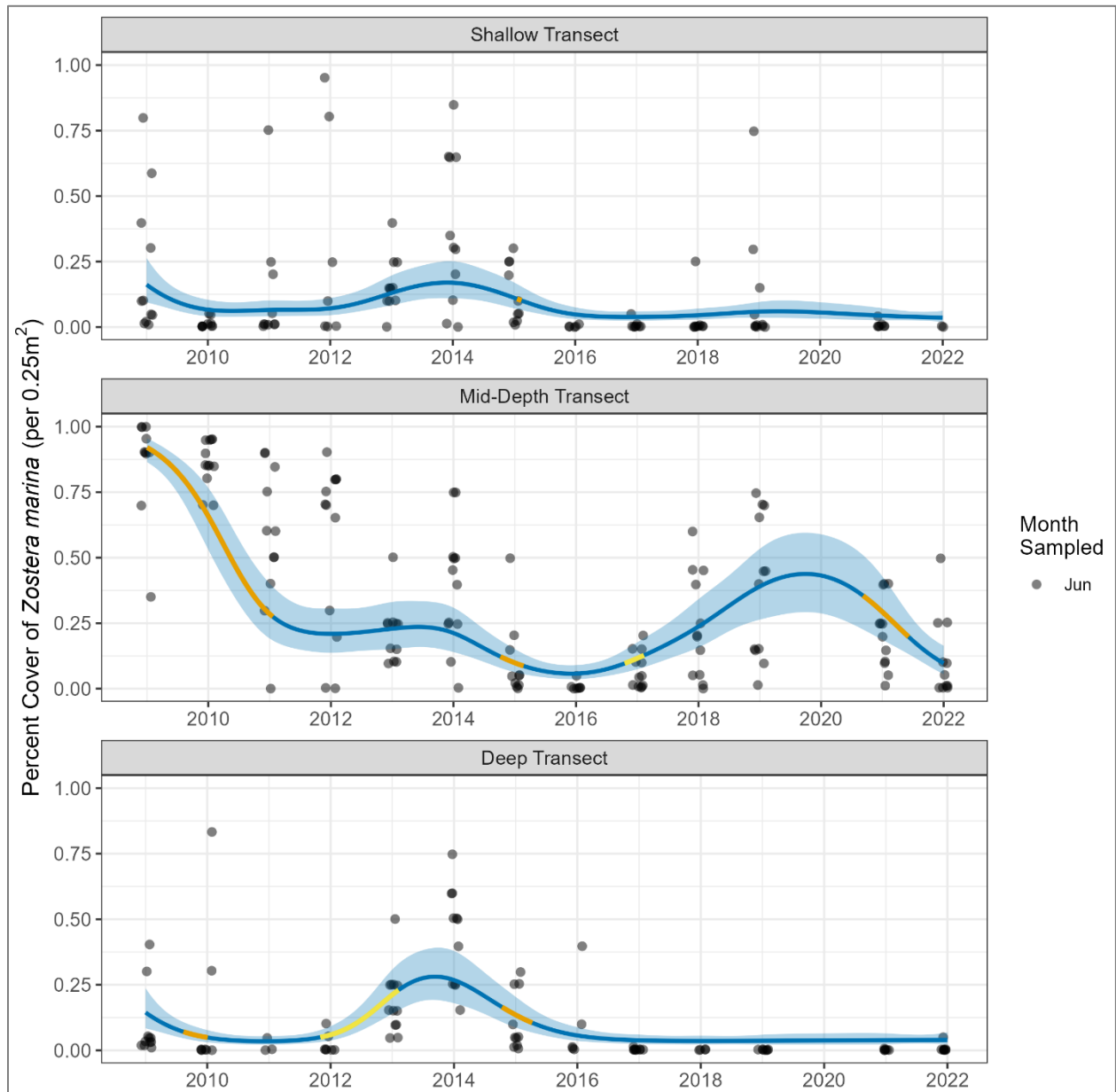


Figure 34. Trend in percent cover of *Zostera marina* (per 0.25 m²) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Percent cover of *Ruppia maritima* was generally highest within the shallow transect, where measurements were also the most variable and where there was a significant decline after 2019 (Figure 35). A significant increase in percent cover within the mid-depth transect occurred during the period of 2016–2018 before a slight decline in 2019. Percent cover in the deep transect was less than 5% in all years except 2006.

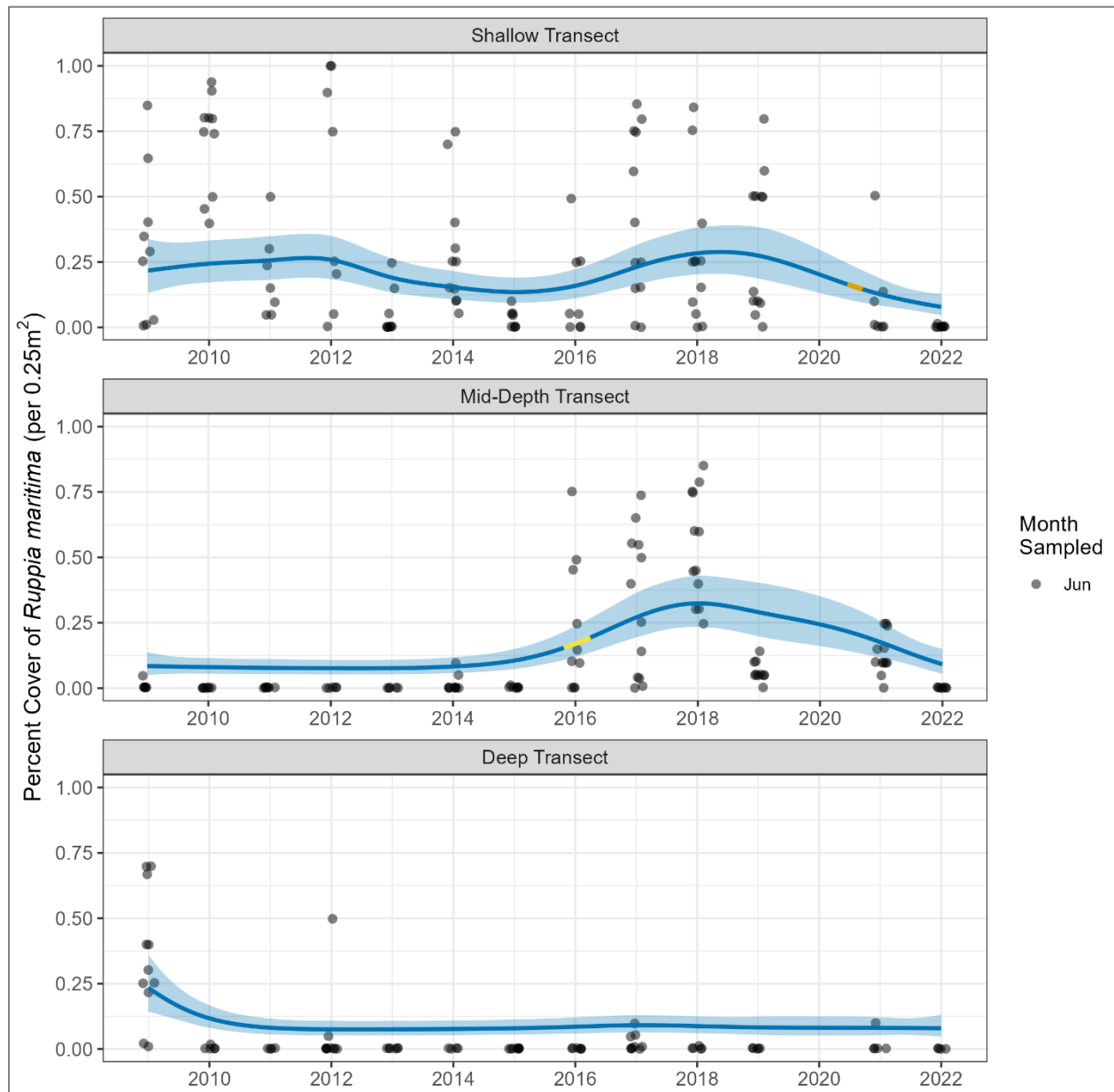


Figure 35. Trend in percent cover of *Ruppia maritima* (per 0.25 m²) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods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

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Canopy Height

Mean *Zostera marina* canopy height typically ranged from 10–20 cm and the temporal trend was cyclical in nature within all three transects (Figure 36). In the mid-depth transect, there were several periods of significant decline between 2009 and 2021 followed by a significant increase in 2022.

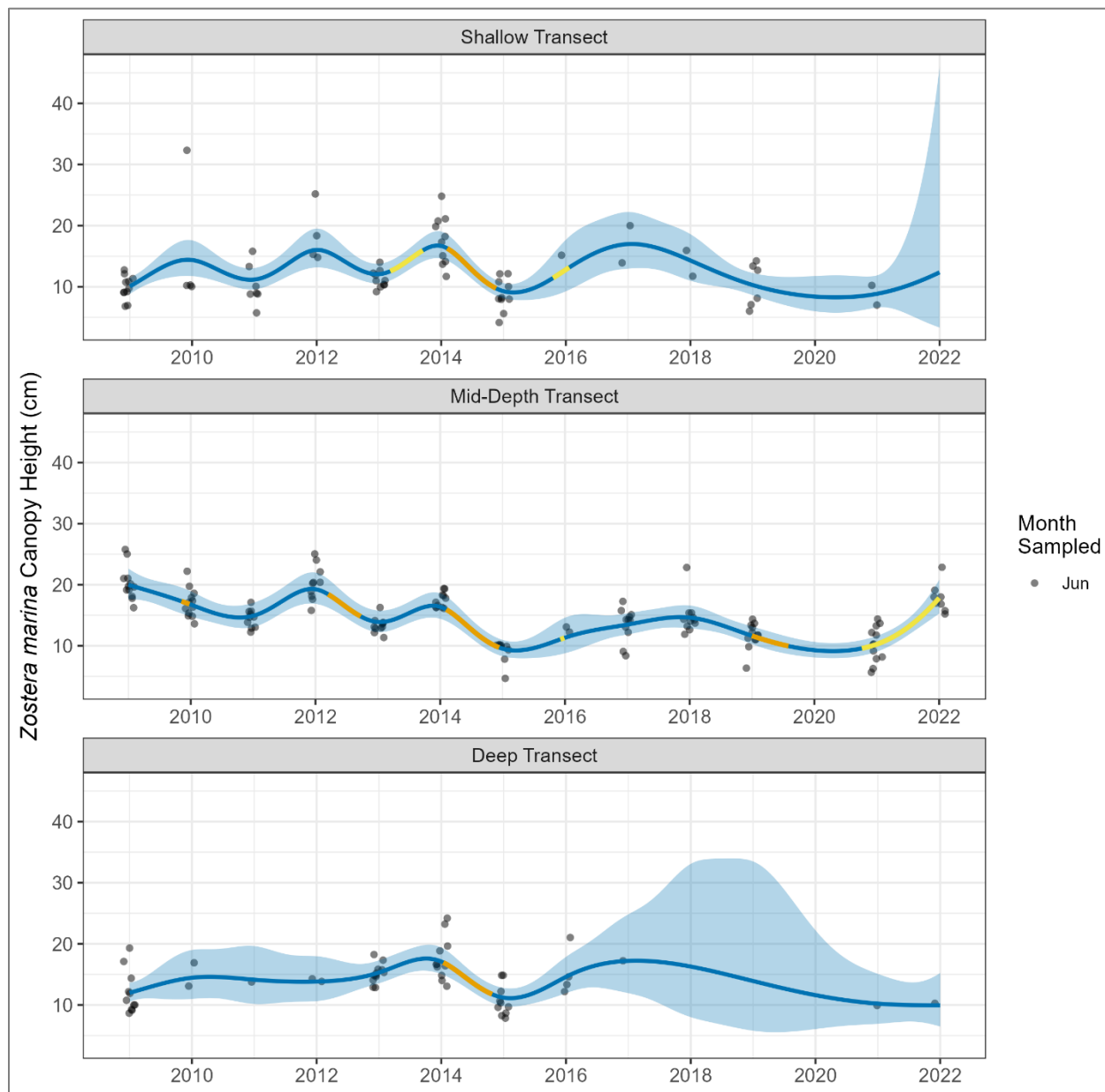


Figure 36. Trend in *Zostera marina* canopy height (cm) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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There was generally a lack of trend for *Ruppia maritima* canopy height and mean values generally ranged from 10–20 cm (Figure 37). There was a significant decline within the shallow transect during the period of 2017 to 2019.

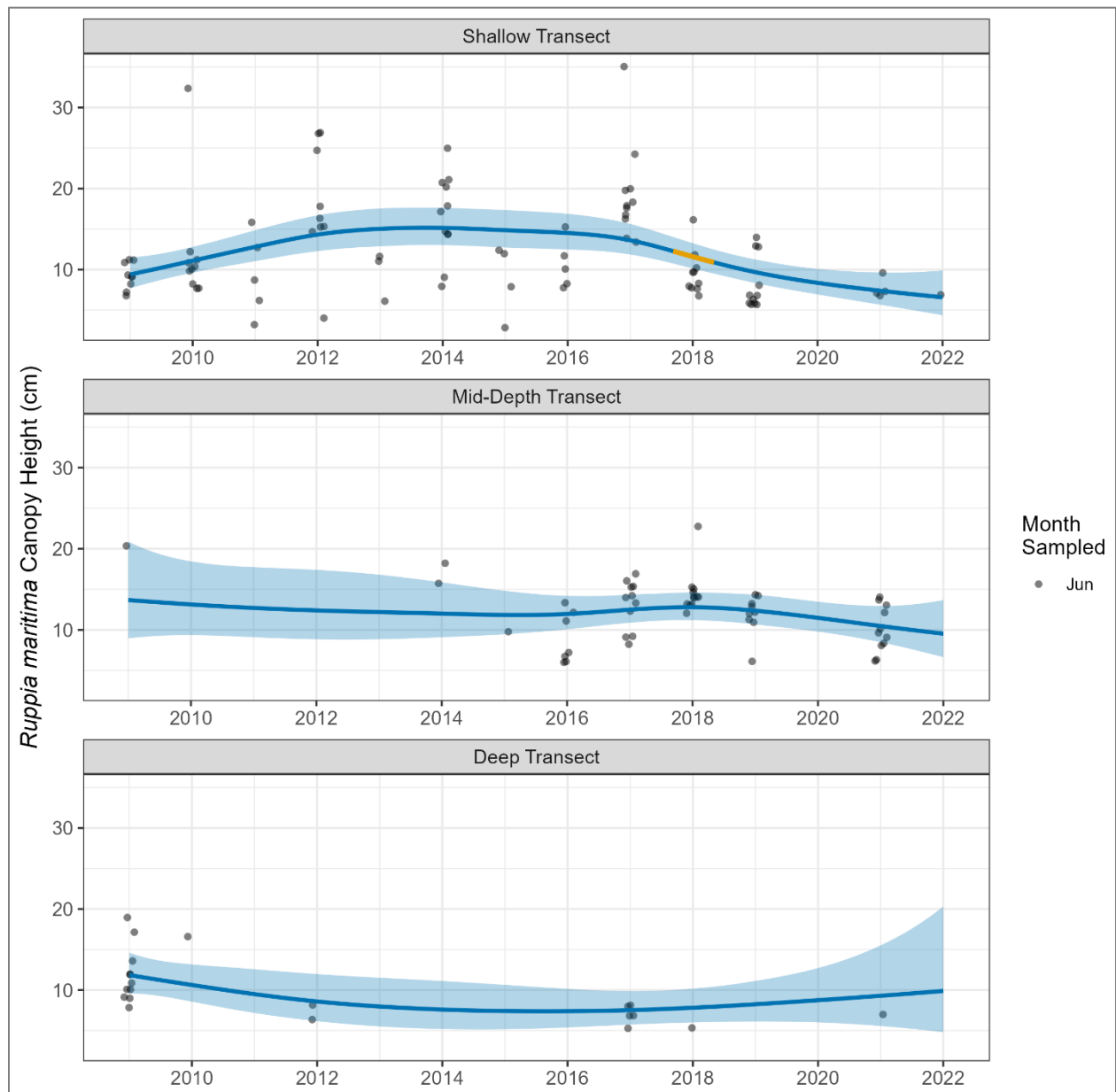


Figure 37. Trend in *Ruppia maritima* canopy height (cm) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant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

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Total Biomass

There was a significant decline in *Zostera marina* total biomass within the mid-depth transect from 2009 to 2016 followed by an increase through 2019 and a subsequent decline through 2022 (Figure 38). In 2016, mean total biomass remained below 45 g m⁻². The shallow and deep transects both experienced declines in 2015 after which mean total biomass remained below 5 g m⁻².

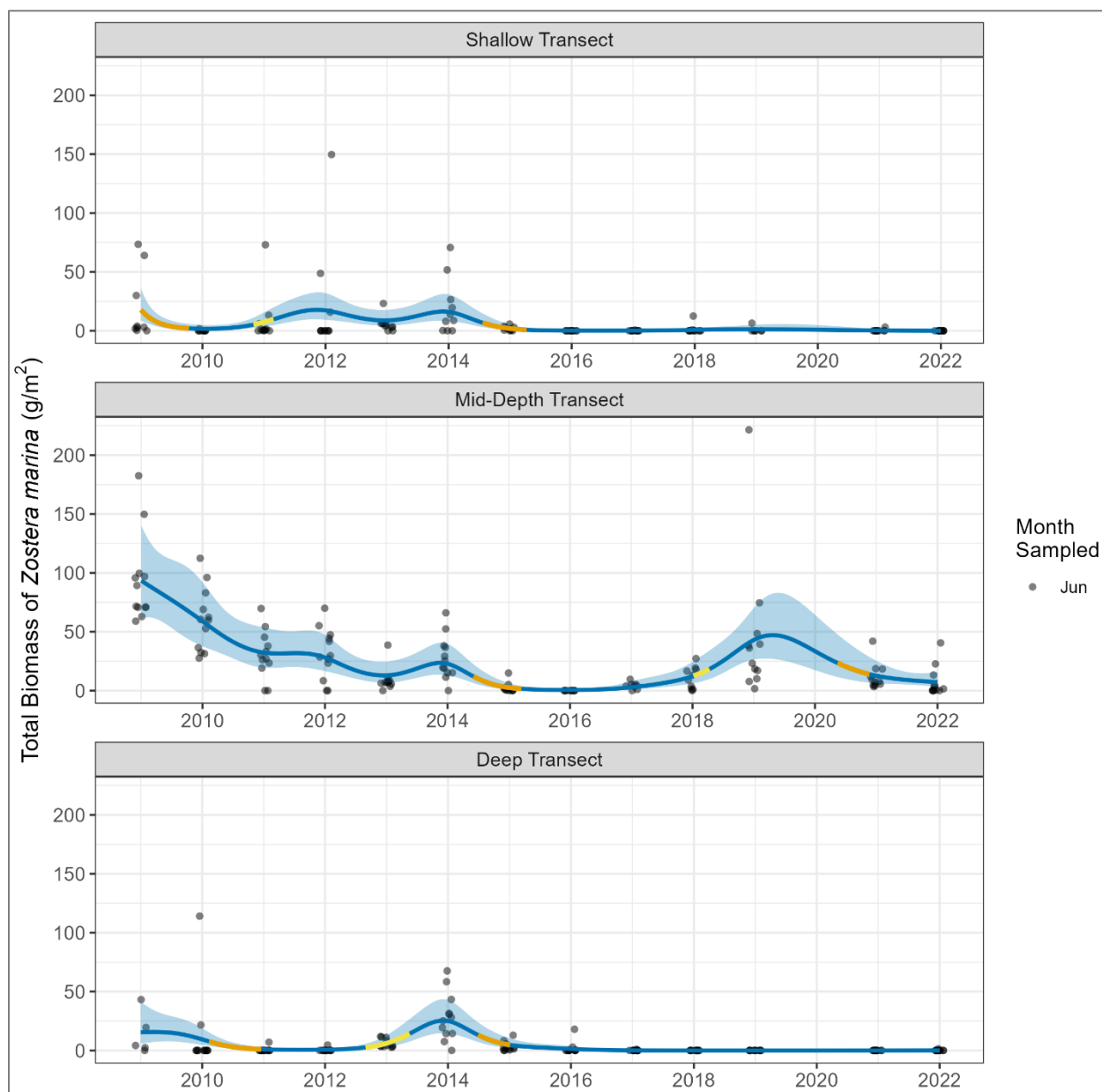


Figure 38. Trend in *Zostera marina* total biomass (g m⁻²) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Total biomass of *Ruppia maritima* was generally highest within the shallow transect where it reached over 100 g m⁻² in some years, and the trend was cyclical in nature during the period of 2009 to 2015 (Figure 39). In the mid-depth transect, total biomass increased beginning in 2015 after which it was also cyclical in nature. Biomass in the deep transect showed no temporal trends and mean values remained below 5 g m⁻² after 2013.

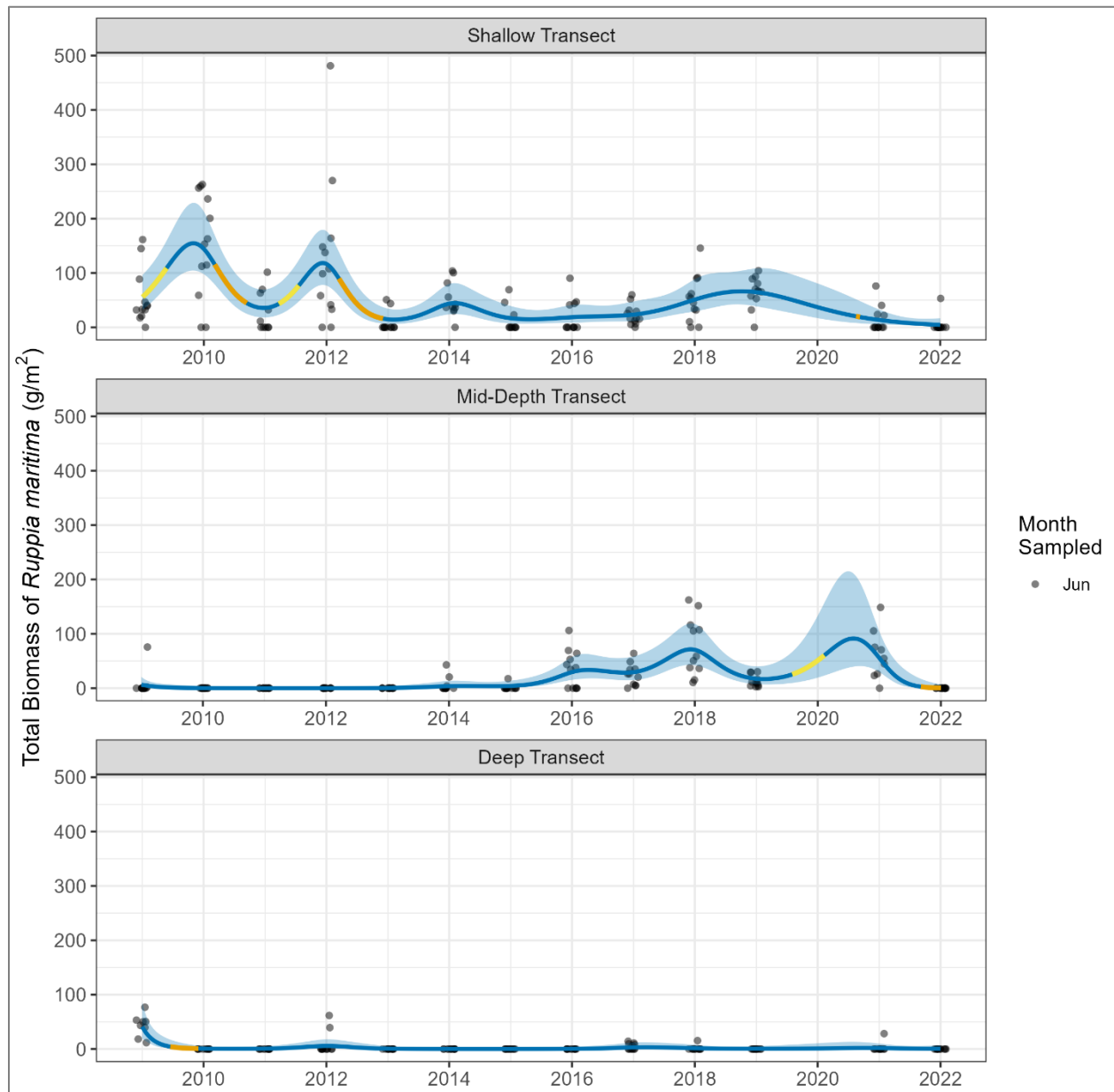


Figure 39. Trend in *Ruppia maritima* total biomass (g m⁻²) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

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Above- to Belowground Biomass Ratio

Mean above- to belowground biomass ratio for both species typically ranged from 1 to 3. Aside from a brief significant increase in the mid-depth transect between 2009 and 2011, the above- to belowground ratios for *Zostera marina* remained stable over time in all three transects (Figure 40). Similarly, there were no significant temporal trends in ratios for any transect for *Ruppia maritima* (Figure 41).

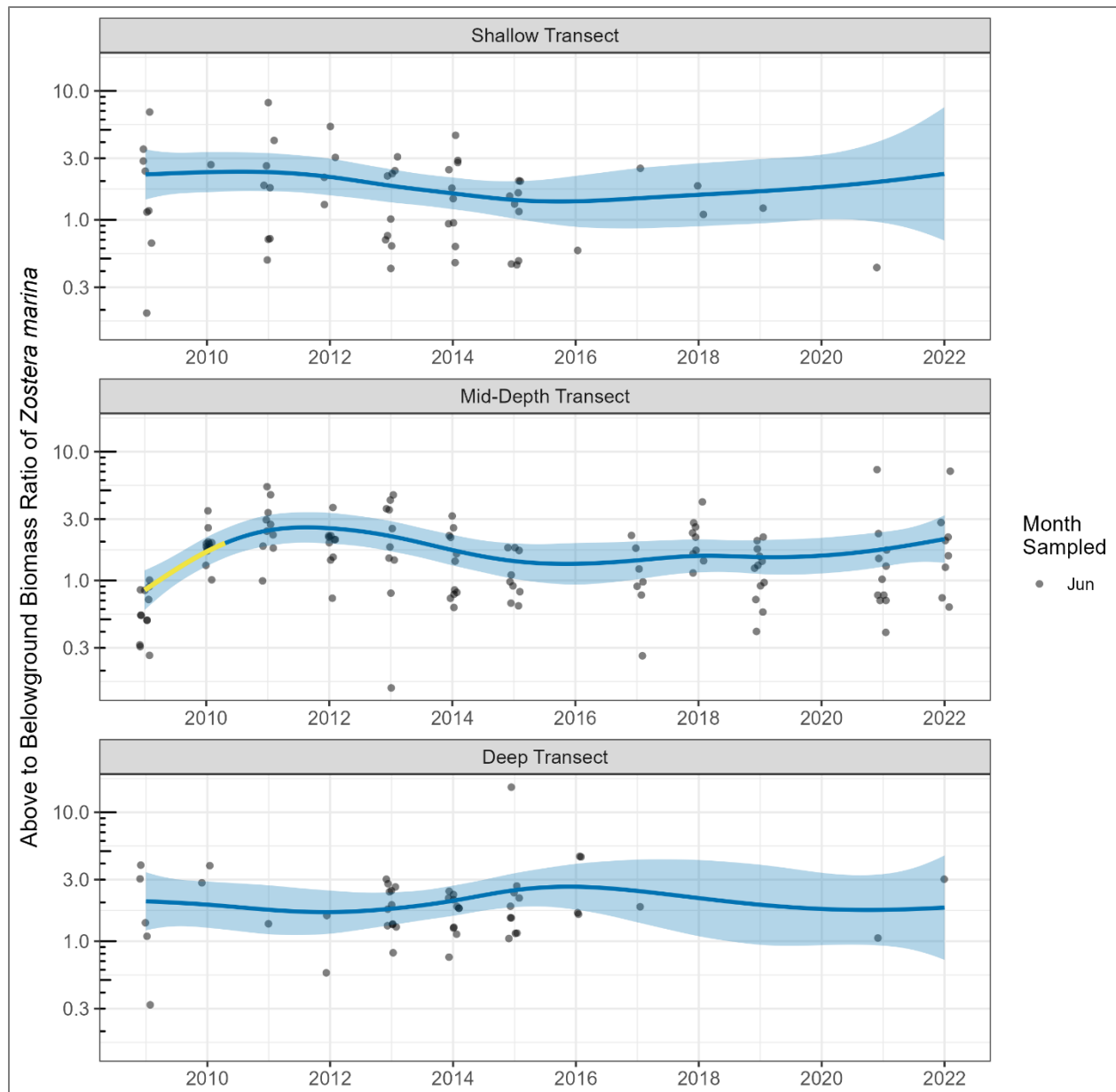


Figure 40. Trend in above- to belowground biomass ratio of *Zostera marina* by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: y-axes are transformed to the log₁₀ scale to better visualize the estimated trends.

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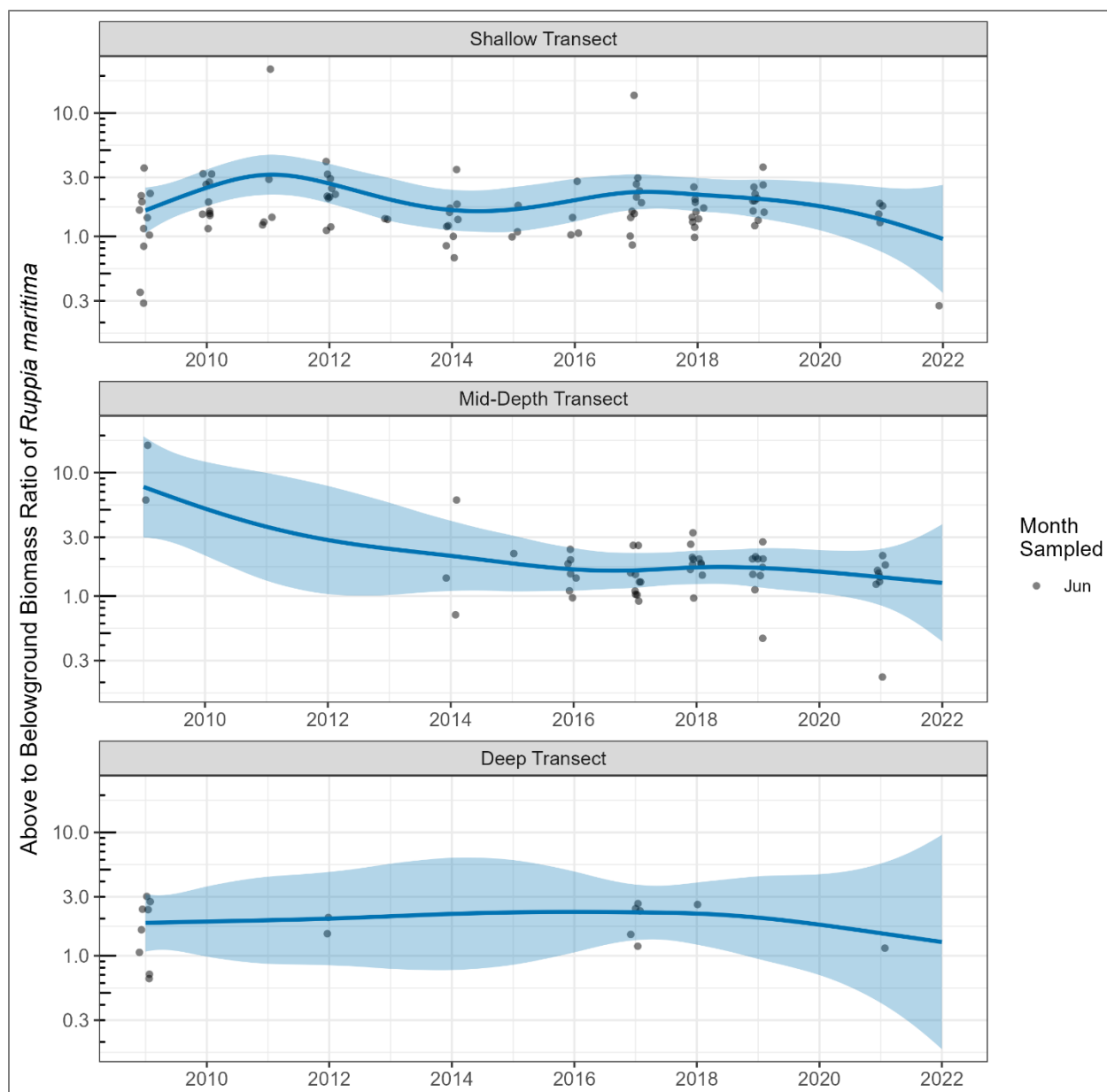


Figure 41. Trend in above- to belowground biomass ratio of *Ruppia maritima* by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: y-axes are transformed to the log₁₀ scale to better visualize the estimated trends. JESSICA NAGEL

Percent Fine Sediment

Aside from a brief significant decrease in the mid-depth transect between 2009 and 2013, the percentage of fine sediments within all three transects was stable over time and generally less than 8% (Figure 42).

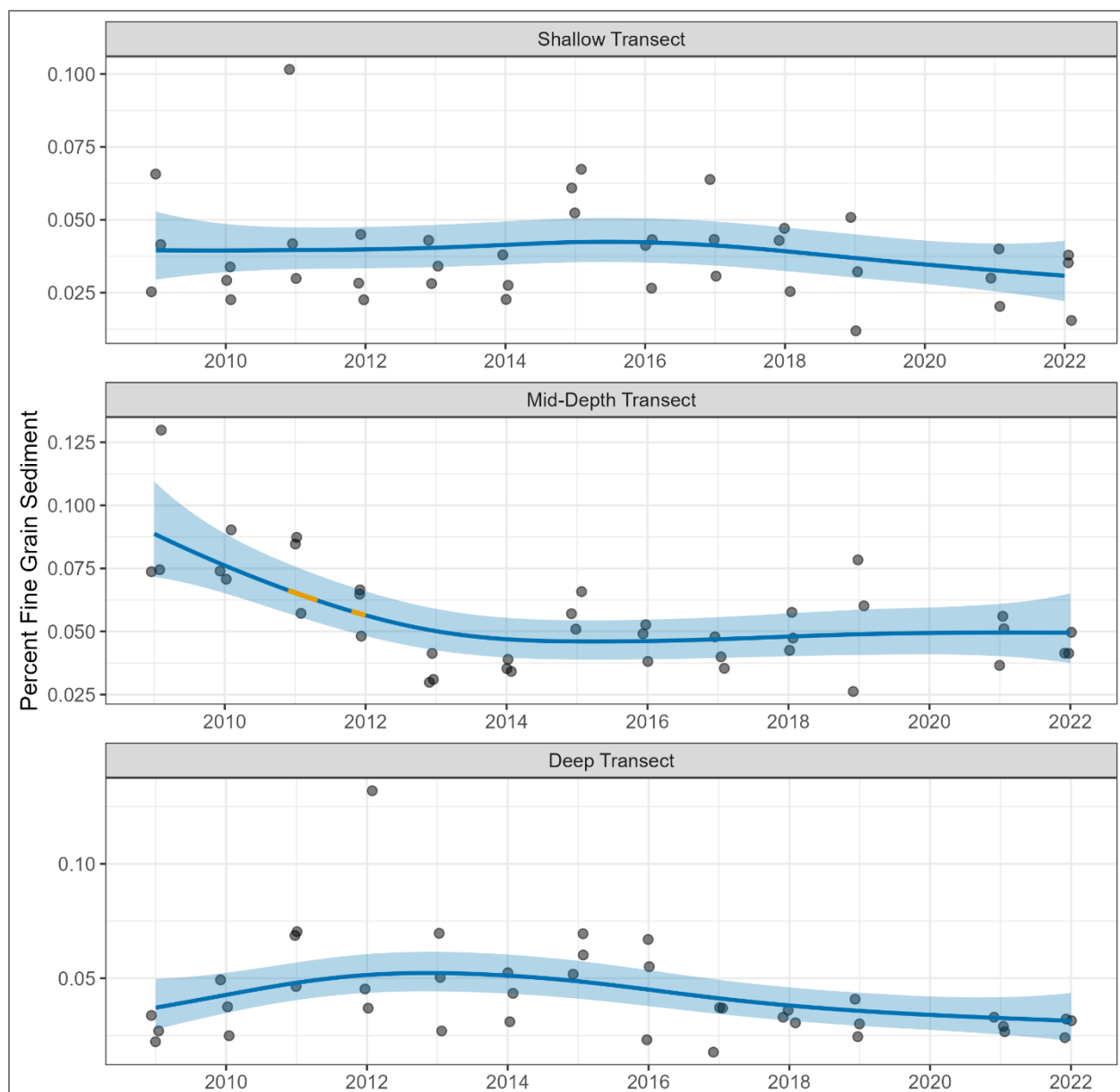


Figure 42. Trend in percent fine sediment (i.e., clay and silt) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant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

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Percent Organic Material

Percent organic material within the transects was very low (<1%) and did not exhibit significant trends over time (Figure 43).

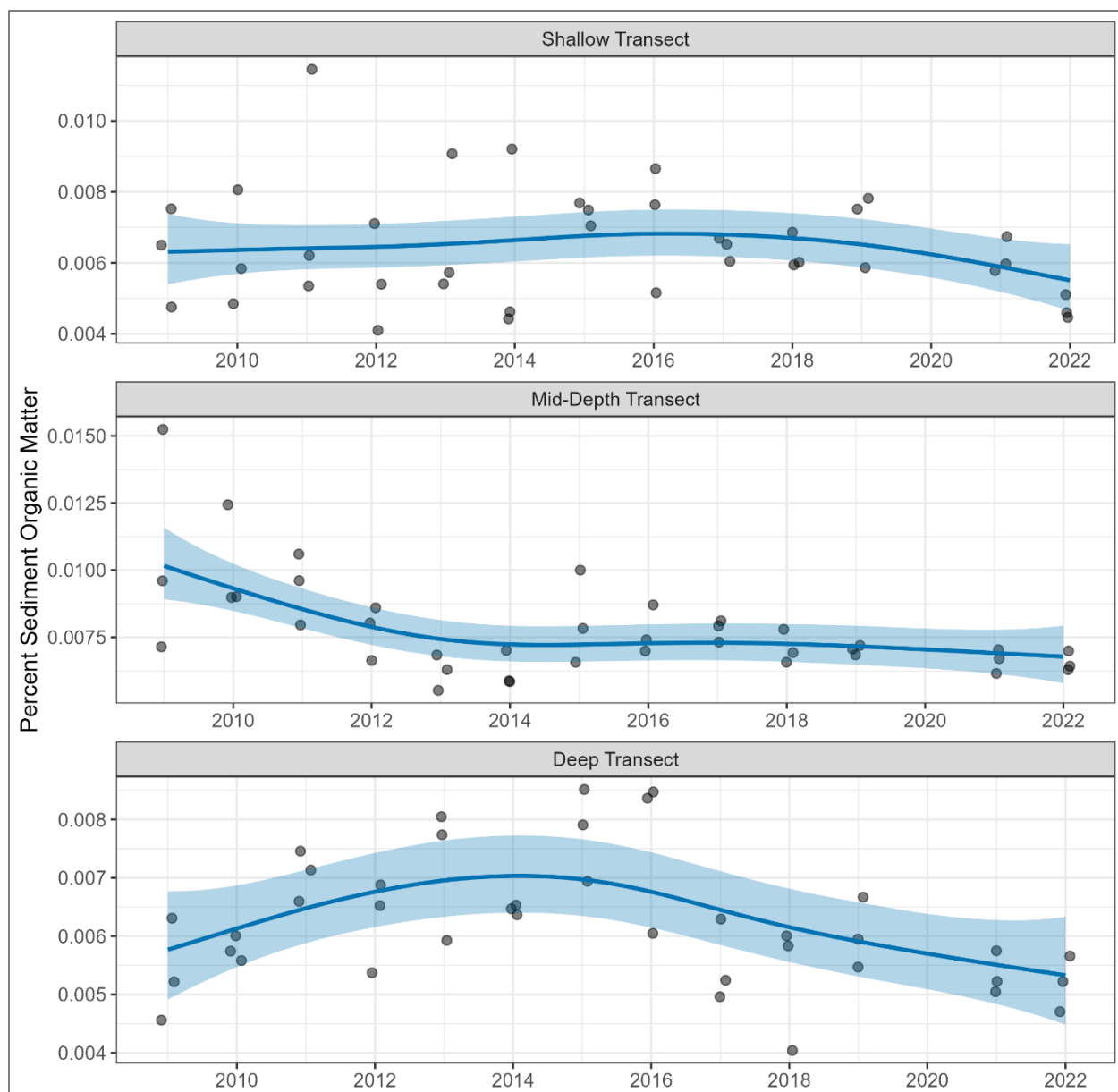


Figure 43. Trend in percent sediment organic material by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant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

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Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there is statistical evidence (assuming a significance level of 0.05) of a decreasing monotonic trend in *Zostera marina* canopy height (shallow transect), total biomass (shallow and mid-depth transects), percent cover (mid-depth transect), shoot density (shallow transect), and above- to belowground biomass ratio (shallow transect) (Table 14). Trends in *Ruppia maritima* parameters varied by transect, with the mid-depth transect exhibiting

significant increasing monotonic trends in total biomass and percent cover and a decreasing trend in the above- to belowground biomass ratio, and the deep transect exhibiting a significant decreasing trend in canopy height and an increasing trend in the above- to belowground biomass ratio.

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

Measure	Transect	<i>Zostera marina</i>		<i>Ruppia maritima</i>	
		Z_{MK}	<i>p</i> -value	Z_{MK}	<i>p</i> -value
Canopy Height (cm)	Shallow	-1.68	0.093	-1.75	0.080
Canopy Height (cm)	Mid-Depth	-2.35	0.019	-1.03	0.302
Canopy Height (cm)	Deep	-0.99	0.322	-4.18	< 0.001
Total Biomass (g/m ²)	Shallow	-2.26	0.024	-1.83	0.067
Total Biomass (g/m ²)	Mid-Depth	-2.18	0.029	2.09	0.036
Total Biomass (g/m ²)	Deep	-1.30	0.193	-1.30	0.193
Above- to Belowground Biomass Ratio	Shallow	-3.52	< 0.001	0.98	0.326
Above- to Belowground Biomass Ratio	Mid-Depth	-0.11	0.910	-2.57	0.010
Above- to Belowground Biomass Ratio	Deep	0.70	0.482	3.51	< 0.001
Percent Cover (per 0.25 m ²)	Shallow	-1.91	0.057	-1.02	0.307
Percent Cover (per 0.25 m ²)	Mid-Depth	-2.43	0.015	1.99	0.047
Percent Cover (per 0.25 m ²)	Deep	-1.60	0.110	-1.43	0.153
Shoot Density (per 1 m ²)	Shallow	-2.07	0.038	NA	NA
Shoot Density (per 1 m ²)	Mid-Depth	-1.74	0.082	NA	NA
Shoot Density (per 1 m ²)	Deep	-1.60	0.109	NA	NA

Water Temperature Summaries

Mean water temperatures within transect A (shallow) were comparable to those in transect C (deep) but had slightly higher range overall (Figure 44). Temperatures were highest in July and August, and summer temperatures exceeded 30°C in every year monitored, with some years reaching as high as 35°C (Figure 45). Days wherein the daily average temperature exceeded 28°C occurred between the months of June to September, with more days observed in the shallow transect (Table 15).

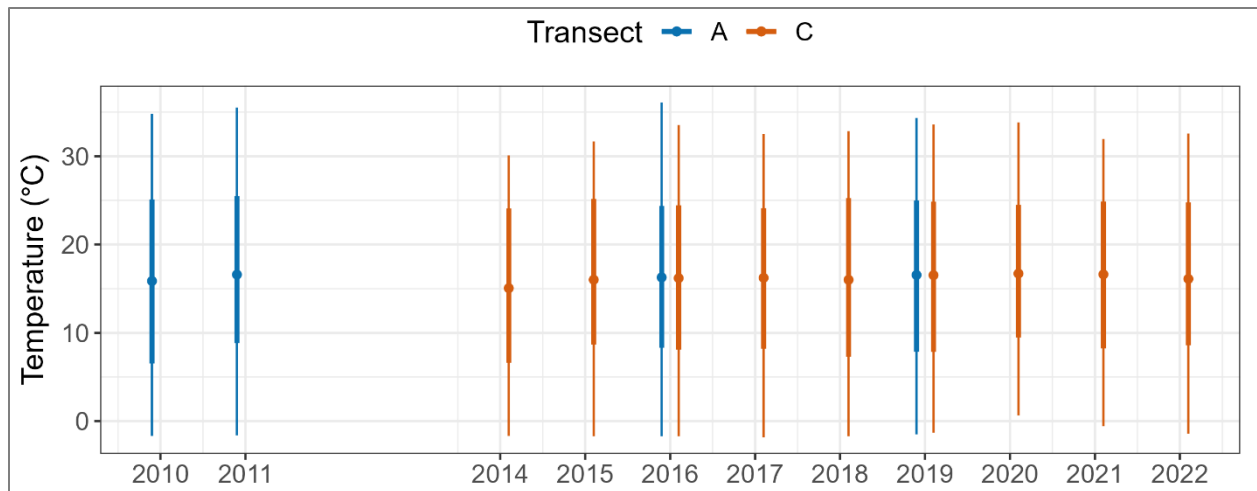


Figure 44. Dot and whisker plots depicting the mean (dot), range (thin line) and middle 50% of observed water temperatures (°C) (thick line) within the shallow (A) and deep (C) transects at the Assateague Island National Seashore Tingles Island reference seagrass bed. Only years in which complete data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

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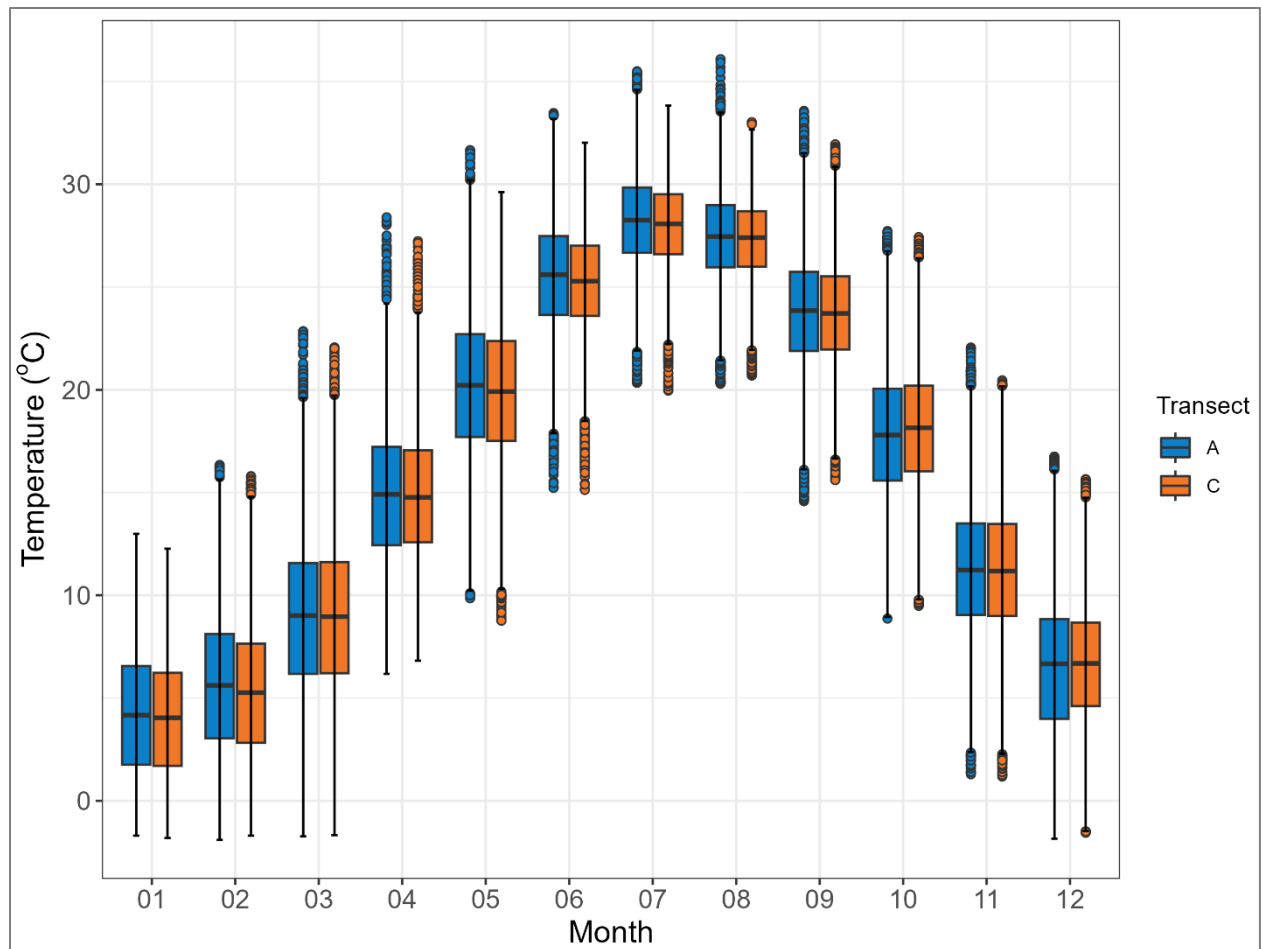


Figure 45. Box plots of mean temperature by month for the shallow (A) and deep (C) transects at the Assateague Island National Seashore Tingles Island reference seagrass bed from 2009 to 2022. Circles indicate outliers.

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Table 15. Number of days per month wherein average daily water temperature exceeded 28°C for the shallow (A) and deep (C) transects at the Assateague Island National Seashore Tingles Island 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 17 days, and blue to purple representing 8 to 28 days. [NA = not available]

Transect	Year	Number of Days per Month Daily Average Temperature > 28°C											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Shallow (A)	2022	NA	NA	NA	NA	NA	NA	16	19	2	0	0	0
	2021	NA	NA	NA	NA	0	NA	NA	NA	NA	NA	NA	NA
	2020	0	0	0	0	0	5	28	13	NA	NA	NA	NA
	2019	0	NA	0	0	0	5	23	17	0	0	0	0
	2018	0	NA	0	0	0	5	11	23	8	0	0	0
	2017	0	NA	0	0	0	1	21	7	0	0	0	0
	2016	0	0	0	0	0	0	26	25	0	0	0	0
	2015	0	NA	0	0	0	11	14	9	4	0	0	0
	2014	NA	NA	0	0	0	4	3	0	4	0	0	0
	2013	NA	NA	0	0	0	3	16	3	0	0	NA	NA
	2012	0	0	0	0	0	7	21	11	0	NA	NA	NA
	2011	0	NA	0	0	1	9	23	11	0	0	0	0
	2010	0	NA	0	0	0	12	21	15	2	0	0	0
Deep (C)	2009	NA	NA	NA	NA	NA	NA	3	23	0	0	0	0
	2022	0	NA	0	0	0	0	15	16	0	0	0	0
	2021	0	NA	0	0	0	4	16	18	1	0	0	0
	2020	0	0	0	0	0	4	27	12	2	0	0	0
	2019	0	NA	0	0	0	4	22	15	0	0	0	0
	2018	0	NA	0	0	0	4	11	20	8	0	0	0
	2017	0	NA	0	0	0	2	20	4	0	0	0	0
	2016	0	0	0	0	0	0	24	22	0	0	0	0
	2015	0	NA	0	0	0	10	16	9	3	0	0	0
	2014	0	NA	0	0	0	3	2	0	5	0	0	0
	2013	NA	NA	0	0	0	3	15	3	0	0	0	0
	2012	0	0	0	0	0	5	22	6	1	NA	NA	NA

Table 15 (continued). Number of days per month wherein average daily water temperature exceeded 28°C for the shallow (A) and deep (C) transects at the Assateague Island National Seashore Tingles Island 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 17 days, and blue to purple representing 8 to 28 days. [NA = not available]

Transect	Year	Number of Days per Month Daily Average Temperature > 28°C											
		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Deep (C) (continued)	2011	0	NA	NA	NA	0	NA	NA	NA	NA	NA	0	0
	2010	0	NA	0	0	0	11	18	13	1	0	0	0
	2009	NA	NA	NA	NA	NA	NA	1	19	0	0	0	0

Discussion

Routine long-term water quality monitoring was conducted at Assateague Island National Seashore during summer months from 2005 through 2022 as part of the NPS NCBN Vital Signs ENE monitoring program. This comprehensive program incorporates monitoring at various spatial and temporal scales in an effort to establish overall condition of the estuary as well as to identify potential trends or changes in condition over time. Analysis of the monitoring data revealed several patterns and trends with respect to water quality condition, and condition and trends at both the trend stations and logging station were generally consistent with those of the spatial stations.

The majority of the estuary was consistently classified as being in good condition with respect to bottom dissolved oxygen concentrations. Concentrations were lowest along the northwestern shoreline; however, no significant changes were observed during the monitoring timeframe. Similarly, bottom dissolved oxygen concentrations at the trend stations were generally good with no significant changes observed over time. For most years, the majority of each day at the logging station was spent in good condition, and no extensive periods of poor conditions were observed. Overall, these results are consistent with other recent studies in the Coastal Bays region (Dennison et al. 2023; MDDNR 2016) and indicate that dissolved oxygen concentrations within the park estuaries are sufficient to protect critical living estuarine resources.

For most years, the majority of the estuary was classified as being in fair condition with respect to chlorophyll-*a* concentrations. Although no significant monotonic changes were observed across the entire monitoring timeframe, there were several years when approximately 50% of the estuary was classified as being in poor condition. Chlorophyll-*a* concentrations at the trend stations were also generally characterized as being in fair condition, with some stations experiencing poor conditions in several years. Continuous monitoring at the logging station showed that in 6 of the 12 years monitored there were consecutive days in which chlorophyll-*a* conditions were poor for the majority of hours each day. Spatially, both the spatial station and trend station data indicate that conditions were worse along the northwestern shoreline. Other studies also reported fair conditions in the region in recent years and attributed the higher concentrations on the northwestern shore to higher nutrient loading compared to the rest of the monitored area (Dennison et al. 2023; MDDNR 2016).

Despite declines in turbidity over time, water clarity, as measured by PAR attenuation, was typically poor throughout the majority of the monitored area in most years sampled. While there were significant improvements in water clarity (i.e., decreasing PAR attenuation values) at some trend stations, water clarity at the trend stations was generally poor over the entire monitoring timeframe. Continuous monitoring at the logging station revealed that in 6 of the 12 years sampled there were often consecutive days when the vast majority of daylight hours during which PAR attenuation could be monitored each day were spent in poor condition. Degraded water clarity may be attributed to the high phytoplankton abundance associated with nutrient over-enrichment as well as wind-driven sediment resuspension typical in this shallow, coastal lagoon (Ganju et al 2020).

While there was no statistical evidence of significantly increasing water temperature over time, summertime temperatures at the logging station, most trend stations, and in a large percentage of the estuary exceeded 28°C in several years. Temperatures above 28°C have been shown to be detrimental to the survival of eelgrass (Shields et al. 2019) and juvenile blue crab populations (Bauer and Miller 2010a,b), and rising temperatures may have significant impacts on marine life by leading to changes in population dynamics, species composition and diversity, and timing of ecosystem-level events and processes (Doney et al. 2012). In addition, higher temperatures have been shown to offset improvements in bottom dissolved oxygen concentrations following reductions in nutrient loading to Chesapeake Bay (Ni et al. 2020). Considering that regional temperatures are projected to rise in the coming decades (IPCC 2022) and that increasing temperatures may negatively influence estuarine water quality and key resources, continued monitoring of temperature and water quality parameters will be extremely valuable for supporting future management efforts in this system.

Trends in seagrass condition within the park's reference bed varied by depth and species. In the shallow transect, widgeon grass (*Ruppia maritima*) remained relatively stable over time whereas eelgrass (*Zostera marina*) experienced a significant decline with very low percent cover (< 10%) and biomass (< 5 g m⁻²) persisting after 2015. Eelgrass biomass, density, and percent cover were the highest in the mid-depth transect. However, there was a significant decline in eelgrass biomass along with a significant increase in widgeon grass biomass and percent cover in the mid-depth transect since monitoring began in 2009. In the deep transect, widgeon grass presence was generally very low across the monitoring timeframe while eelgrass experienced a brief recovery between 2012 and 2015 after which time both biomass and percent cover remained extremely low. Other recent studies have also reported declines in seagrass distribution and abundance within Chincoteague and the Coastal Bays (Dennison et al. 2023; MDDNR 2016). Possible causes of eelgrass decline in the park may be related to chronically poor water clarity limiting growth at depth and heat stress from prolonged exposure to summertime temperatures greater than 28°C limiting growth in shallow areas. Unusually warm temperatures have been shown to contribute to eelgrass loss across the northeastern US (Plaisted et al. 2022), and even short-term exposure to excessive temperatures can lead to significant die-off events (Moore et al. 2014; Shields et al. 2019). The relative stability of widgeon grass in the shallow transect and expansion within the mid-depth transect following eelgrass decline is not surprising as it has been shown to have a higher heat tolerance (Evans et al. 1986) and a better ability to rapidly recolonize areas after dieback events (Shields et al. 2019). While widgeon grass may provide valuable ecosystem services, widgeon grass-dominated beds are characterized by higher seasonal and interannual variability as well as lower biomass and productivity compared to eelgrass beds, which ultimately may affect local food webs (Cho et al. 2009). Management efforts to prevent further loss of eelgrass in this system should focus on improvements in water clarity and possibly reseeding or transplanting with more heat-tolerant genotypes.

Conclusions

Although some aspects of water quality were generally classified as being in fair to good condition, water clarity was consistently poor at Assateague Island National Seashore over the timeframe of 2005 to 2022. Significant declines in eelgrass in the park's reference seagrass bed since 2015 suggest that conditions in the shallow and deep extremes are becoming less conducive for supporting eelgrass growth. The continued monitoring of estuarine nutrient enrichment vital signs and seagrass condition will be essential for managers to make informed decisions, develop effective mitigation measures, reduce management costs, and provide a means of measuring progress towards goals.

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Appendix A: Spatial Station Water Quality Data

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

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

Contrast	Estimate	SE	t_{242}	<i>p</i> -value	95% CI
2005–2006	-0.113	0.183	-0.618	1.000	(-0.696, 0.470)
2005–2008	0.078	0.183	0.427	1.000	(-0.505, 0.661)
2005–2010	-0.342	0.183	-1.866	0.688	(-0.925, 0.241)
2005–2012	-0.528	0.183	-2.884	0.113	(-1.111, 0.055)
2005–2014	0.219	0.183	1.196	0.972	(-0.364, 0.802)
2005–2016	-0.235	0.183	-1.281	0.956	(-0.818, 0.348)
2005–2018	0.023	0.183	0.126	1.000	(-0.560, 0.606)
2005–2020	0.114	0.183	0.623	1.000	(-0.469, 0.697)
2005–2022	0.511	0.184	2.772	0.149	(-0.076, 1.098)
2006–2008	0.191	0.136	1.408	0.922	(-0.241, 0.624)
2006–2010	-0.229	0.136	-1.682	0.801	(-0.661, 0.204)
2006–2012	-0.415	0.136	-3.053	0.073	(-0.848, 0.018)
2006–2014	0.332	0.136	2.445	0.300	(-0.101, 0.765)
2006–2016	-0.121	0.136	-0.894	0.996	(-0.554, 0.311)
2006–2018	0.136	0.136	1.002	0.992	(-0.297, 0.569)
2006–2020	0.227	0.136	1.673	0.806	(-0.205, 0.660)
2006–2022	0.624	0.137	4.549	0.000	(0.187, 1.061)
2008–2010	-0.420	0.136	-3.090	0.066	(-0.853, 0.013)
2008–2012	-0.606	0.136	-4.462	0.000	(-1.039, -0.174)
2008–2014	0.141	0.136	1.036	0.989	(-0.292, 0.574)
2008–2016	-0.313	0.136	-2.302	0.387	(-0.746, 0.120)
2008–2018	-0.055	0.136	-0.406	1.000	(-0.488, 0.378)
2008–2020	0.036	0.136	0.264	1.000	(-0.397, 0.469)
2008–2022	0.433	0.137	3.154	0.055	(-0.004, 0.869)
2010–2012	-0.186	0.136	-1.371	0.933	(-0.619, 0.246)
2010–2014	0.561	0.136	4.127	0.002	(0.128, 0.994)
2010–2016	0.107	0.136	0.788	0.999	(-0.326, 0.540)
2010–2018	0.365	0.136	2.684	0.183	(-0.068, 0.798)
2010–2020	0.456	0.136	3.355	0.030	(0.023, 0.889)
2010–2022	0.853	0.137	6.216	0.000	(0.416, 1.289)

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

Contrast	Estimate	SE	t_{242}	<i>p</i> -value	95% CI
2012–2014	0.747	0.136	5.498	0.000	(0.314, 1.180)
2012–2016	0.293	0.136	2.160	0.483	(-0.139, 0.726)
2012–2018	0.551	0.136	4.056	0.003	(0.118, 0.984)
2012–2020	0.642	0.136	4.726	0.000	(0.210, 1.075)
2012–2022	1.039	0.137	7.574	0.000	(0.602, 1.476)
2014–2016	-0.454	0.136	-3.338	0.032	(-0.886, -0.021)
2014–2018	-0.196	0.136	-1.442	0.911	(-0.629, 0.237)
2014–2020	-0.105	0.136	-0.772	0.999	(-0.538, 0.328)
2014–2022	0.292	0.137	2.127	0.505	(-0.145, 0.729)
2016–2018	0.258	0.136	1.896	0.668	(-0.175, 0.690)
2016–2020	0.349	0.136	2.567	0.235	(-0.084, 0.782)
2016–2022	0.745	0.137	5.435	0.000	(0.309, 1.182)
2018–2020	0.091	0.136	0.670	1.000	(-0.342, 0.524)
2018–2022	0.488	0.137	3.556	0.016	(0.051, 0.925)

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

Contrast	Estimate	SE	t_{243}	<i>p</i> -value	95% CI
2005–2006	0.090	0.067	1.337	0.943	(-0.124, 0.303)
2005–2008	0.080	0.067	1.197	0.972	(-0.133, 0.294)
2005–2010	0.105	0.067	1.569	0.859	(-0.108, 0.318)
2005–2012	0.045	0.067	0.667	1.000	(-0.169, 0.258)
2005–2014	-0.060	0.067	-0.894	0.996	(-0.273, 0.154)
2005–2016	0.016	0.067	0.242	1.000	(-0.197, 0.230)
2005–2018	0.109	0.067	1.630	0.830	(-0.104, 0.323)
2005–2020	0.075	0.067	1.124	0.981	(-0.138, 0.289)
2005–2022	0.078	0.067	1.170	0.976	(-0.135, 0.292)
2006–2008	-0.009	0.050	-0.187	1.000	(-0.169, 0.150)
2006–2010	0.016	0.050	0.310	1.000	(-0.144, 0.175)
2006–2012	-0.045	0.050	-0.897	0.996	(-0.204, 0.115)
2006–2014	-0.149	0.050	-2.987	0.087	(-0.309, 0.010)

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

Contrast	Estimate	SE	t_{243}	p -value	95% CI
2006–2016	-0.073	0.050	-1.466	0.902	(-0.233, 0.086)
2006–2018	0.020	0.050	0.392	1.000	(-0.140, 0.179)
2006–2020	-0.014	0.050	-0.285	1.000	(-0.174, 0.145)
2006–2022	-0.011	0.050	-0.224	1.000	(-0.171, 0.148)
2008–2010	0.025	0.050	0.497	1.000	(-0.135, 0.184)
2008–2012	-0.035	0.050	-0.709	0.999	(-0.195, 0.124)
2008–2014	-0.140	0.050	-2.799	0.140	(-0.299, 0.019)
2008–2016	-0.064	0.050	-1.278	0.957	(-0.223, 0.095)
2008–2018	0.029	0.050	0.579	1.000	(-0.130, 0.188)
2008–2020	-0.005	0.050	-0.098	1.000	(-0.164, 0.155)
2008–2022	-0.002	0.050	-0.037	1.000	(-0.161, 0.158)
2010–2012	-0.060	0.050	-1.207	0.970	(-0.220, 0.099)
2010–2014	-0.165	0.050	-3.297	0.036	(-0.324, -0.005)
2010–2016	-0.089	0.050	-1.776	0.746	(-0.248, 0.071)
2010–2018	0.004	0.050	0.082	1.000	(-0.155, 0.164)
2010–2020	-0.030	0.050	-0.595	1.000	(-0.189, 0.130)
2010–2022	-0.027	0.050	-0.534	1.000	(-0.186, 0.133)
2012–2014	-0.105	0.050	-2.090	0.532	(-0.264, 0.055)
2012–2016	-0.028	0.050	-0.569	1.000	(-0.188, 0.131)
2012–2018	0.064	0.050	1.288	0.955	(-0.095, 0.224)
2012–2020	0.031	0.050	0.611	1.000	(-0.129, 0.190)
2012–2022	0.034	0.050	0.672	1.000	(-0.126, 0.193)
2014–2016	0.076	0.050	1.521	0.881	(-0.083, 0.236)
2014–2018	0.169	0.050	3.378	0.028	(0.010, 0.328)
2014–2020	0.135	0.050	2.701	0.176	(-0.024, 0.295)
2014–2022	0.138	0.050	2.762	0.153	(-0.021, 0.298)
2016–2018	0.093	0.050	1.857	0.694	(-0.067, 0.252)
2016–2020	0.059	0.050	1.180	0.974	(-0.100, 0.218)
2016–2022	0.062	0.050	1.241	0.964	(-0.097, 0.222)
2018–2020	-0.034	0.050	-0.677	1.000	(-0.193, 0.126)
2018–2022	-0.031	0.050	-0.616	1.000	(-0.190, 0.129)

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

Contrast	Estimate	SE	t_{237}	p-value	95% CI
2005–2006	-0.010	0.149	-0.069	1.000	(-0.484, 0.463)
2005–2008	0.185	0.147	1.258	0.961	(-0.284, 0.655)
2005–2010	0.122	0.146	0.835	0.998	(-0.343, 0.587)
2005–2012	0.124	0.146	0.847	0.998	(-0.342, 0.589)
2005–2014	0.461	0.146	3.157	0.054	(-0.004, 0.926)
2005–2016	0.184	0.146	1.257	0.961	(-0.282, 0.649)
2005–2018	0.098	0.146	0.670	1.000	(-0.367, 0.563)
2005–2020	0.280	0.146	1.915	0.655	(-0.186, 0.745)
2005–2022	0.262	0.147	1.781	0.743	(-0.206, 0.730)
2006–2008	0.196	0.114	1.717	0.781	(-0.167, 0.559)
2006–2010	0.132	0.112	1.182	0.974	(-0.224, 0.489)
2006–2012	0.134	0.112	1.197	0.972	(-0.223, 0.491)
2006–2014	0.471	0.112	4.211	0.002	(0.115, 0.828)
2006–2016	0.194	0.112	1.731	0.773	(-0.163, 0.550)
2006–2018	0.108	0.112	0.965	0.994	(-0.249, 0.465)
2006–2020	0.290	0.112	2.590	0.225	(-0.067, 0.646)
2006–2022	0.272	0.113	2.409	0.321	(-0.088, 0.632)
2008–2010	-0.063	0.111	-0.573	1.000	(-0.416, 0.290)
2008–2012	-0.062	0.111	-0.557	1.000	(-0.415, 0.291)
2008–2014	0.276	0.111	2.487	0.277	(-0.077, 0.629)
2008–2016	-0.002	0.111	-0.018	1.000	(-0.355, 0.351)
2008–2018	-0.088	0.111	-0.791	0.999	(-0.441, 0.265)
2008–2020	0.094	0.111	0.850	0.998	(-0.259, 0.447)
2008–2022	0.076	0.112	0.682	1.000	(-0.280, 0.432)
2010–2012	0.002	0.109	0.016	1.000	(-0.345, 0.348)
2010–2014	0.339	0.109	3.118	0.061	(-0.007, 0.685)
2010–2016	0.062	0.109	0.566	1.000	(-0.285, 0.408)
2010–2018	-0.024	0.109	-0.223	1.000	(-0.371, 0.322)
2010–2020	0.158	0.109	1.450	0.908	(-0.189, 0.504)
2010–2022	0.140	0.110	1.273	0.958	(-0.210, 0.489)
2012–2014	0.337	0.109	3.102	0.064	(-0.009, 0.684)
2012–2016	0.060	0.109	0.550	1.000	(-0.287, 0.406)
2012–2018	-0.026	0.109	-0.239	1.000	(-0.372, 0.320)
2012–2020	0.156	0.109	1.434	0.914	(-0.191, 0.502)
2012–2022	0.138	0.110	1.257	0.961	(-0.212, 0.488)

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

Contrast	Estimate	SE	t_{237}	p-value	95% CI
2014–2016	-0.278	0.109	-2.552	0.244	(-0.624, 0.069)
2014–2018	-0.363	0.109	-3.341	0.031	(-0.710, -0.017)
2014–2020	-0.181	0.109	-1.669	0.809	(-0.528, 0.165)
2014–2022	-0.199	0.110	-1.817	0.720	(-0.549, 0.150)
2016–2018	-0.086	0.109	-0.788	0.999	(-0.432, 0.261)
2016–2020	0.096	0.109	0.884	0.997	(-0.250, 0.442)
2016–2022	0.078	0.110	0.712	0.999	(-0.271, 0.428)
2018–2020	0.182	0.109	1.672	0.807	(-0.165, 0.528)
2018–2022	0.164	0.110	1.494	0.892	(-0.186, 0.513)
2020–2022	-0.018	0.110	-0.163	1.000	(-0.367, 0.332)

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

Contrast	Estimate	SE	t_{242}	p-value	95% CI
2005–2006	-0.089	0.038	-2.356	0.353	(-0.210, 0.032)
2005–2008	-0.094	0.038	-2.491	0.275	(-0.215, 0.026)
2005–2010	-0.058	0.038	-1.518	0.882	(-0.178, 0.063)
2005–2012	-0.151	0.038	-3.992	0.003	(-0.272, -0.030)
2005–2014	-0.101	0.038	-2.663	0.192	(-0.222, 0.020)
2005–2016	-0.042	0.038	-1.107	0.983	(-0.163, 0.079)
2005–2018	-0.014	0.038	-0.368	1.000	(-0.135, 0.107)
2005–2020	-0.137	0.038	-3.619	0.013	(-0.258, -0.016)
2005–2022	-0.190	0.038	-4.978	0.000	(-0.311, -0.068)
2006–2008	-0.005	0.028	-0.182	1.000	(-0.095, 0.085)
2006–2010	0.032	0.028	1.126	0.981	(-0.058, 0.122)
2006–2012	-0.062	0.028	-2.199	0.456	(-0.152, 0.028)
2006–2014	-0.012	0.028	-0.414	1.000	(-0.102, 0.078)
2006–2016	0.047	0.028	1.678	0.804	(-0.043, 0.137)
2006–2018	0.075	0.028	2.672	0.188	(-0.015, 0.165)
2006–2020	-0.048	0.028	-1.699	0.792	(-0.138, 0.042)
2006–2022	-0.101	0.028	-3.535	0.017	(-0.191, -0.010)
2008–2010	0.037	0.028	1.308	0.950	(-0.053, 0.127)
2008–2012	-0.057	0.028	-2.017	0.583	(-0.147, 0.033)

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

Contrast	Estimate	SE	t_{242}	p -value	95% CI
2008–2014	-0.007	0.028	-0.232	1.000	(-0.096, 0.083)
2008–2016	0.052	0.028	1.860	0.691	(-0.037, 0.142)
2008–2018	0.080	0.028	2.854	0.123	(-0.009, 0.170)
2008–2020	-0.043	0.028	-1.517	0.882	(-0.133, 0.047)
2008–2022	-0.095	0.028	-3.354	0.030	(-0.186, -0.005)
2010–2012	-0.094	0.028	-3.325	0.033	(-0.184, -0.004)
2010–2014	-0.043	0.028	-1.540	0.872	(-0.133, 0.046)
2010–2016	0.016	0.028	0.552	1.000	(-0.074, 0.105)
2010–2018	0.044	0.028	1.546	0.870	(-0.046, 0.133)
2010–2020	-0.080	0.028	-2.825	0.132	(-0.169, 0.010)
2010–2022	-0.132	0.028	-4.650	0.000	(-0.223, -0.042)
2012–2014	0.050	0.028	1.786	0.740	(-0.040, 0.140)
2012–2016	0.109	0.028	3.877	0.005	(0.019, 0.199)
2012–2018	0.137	0.028	4.871	0.000	(0.047, 0.227)
2012–2020	0.014	0.028	0.501	1.000	(-0.076, 0.104)
2012–2022	-0.039	0.028	-1.355	0.938	(-0.129, 0.052)
2014–2016	0.059	0.028	2.092	0.530	(-0.031, 0.149)
2014–2018	0.087	0.028	3.086	0.066	(-0.003, 0.177)
2014–2020	-0.036	0.028	-1.285	0.955	(-0.126, 0.054)
2014–2022	-0.089	0.028	-3.125	0.060	(-0.180, 0.002)
2016–2018	0.028	0.028	0.994	0.992	(-0.062, 0.118)
2016–2020	-0.095	0.028	-3.377	0.028	(-0.185, -0.005)
2016–2022	-0.148	0.028	-5.197	0.000	(-0.239, -0.057)
2018–2020	-0.123	0.028	-4.371	0.001	(-0.213, -0.033)
2018–2022	-0.176	0.028	-6.182	0.000	(-0.267, -0.085)
2020–2022	-0.053	0.028	-1.851	0.698	(-0.143, 0.038)

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

Contrast	Estimate	SE	t_{242}	p -value	95% CI
2005–2006	-0.019	0.022	-0.841	0.998	(-0.089, 0.052)
2005–2008	0.036	0.022	1.616	0.837	(-0.035, 0.107)
2005–2010	-0.019	0.022	-0.871	0.997	(-0.090, 0.051)

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

Contrast	Estimate	SE	t_{242}	p-value	95% CI
2005–2012	0.048	0.022	2.151	0.489	(-0.023, 0.118)
2005–2014	0.084	0.022	3.782	0.007	(0.013, 0.155)
2005–2016	-0.024	0.022	-1.094	0.985	(-0.095, 0.046)
2005–2018	-0.009	0.022	-0.416	1.000	(-0.080, 0.061)
2005–2020	-0.056	0.022	-2.510	0.265	(-0.126, 0.015)
2005–2022	0.019	0.022	0.867	0.997	(-0.052, 0.091)
2006–2008	0.055	0.016	3.305	0.036	(0.002, 0.107)
2006–2010	-0.001	0.016	-0.039	1.000	(-0.053, 0.052)
2006–2012	0.066	0.016	4.026	0.003	(0.014, 0.119)
2006–2014	0.103	0.016	6.220	0.000	(0.050, 0.155)
2006–2016	-0.006	0.016	-0.340	1.000	(-0.058, 0.047)
2006–2018	0.009	0.016	0.572	1.000	(-0.043, 0.062)
2006–2020	-0.037	0.016	-2.245	0.424	(-0.090, 0.016)
2006–2022	0.038	0.017	2.284	0.398	(-0.015, 0.091)
2008–2010	-0.055	0.016	-3.345	0.031	(-0.108, -0.003)
2008–2012	0.012	0.016	0.720	0.999	(-0.041, 0.064)
2008–2014	0.048	0.016	2.915	0.105	(-0.004, 0.101)
2008–2016	-0.060	0.016	-3.645	0.012	(-0.113, -0.008)
2008–2018	-0.045	0.016	-2.733	0.164	(-0.098, 0.007)
2008–2020	-0.092	0.016	-5.550	0.000	(-0.144, -0.039)
2008–2022	-0.016	0.017	-0.991	0.992	(-0.070, 0.037)
2010–2012	0.067	0.016	4.065	0.003	(0.015, 0.120)
2010–2014	0.103	0.016	6.260	0.000	(0.051, 0.156)
2010–2016	-0.005	0.016	-0.300	1.000	(-0.058, 0.048)
2010–2018	0.010	0.016	0.612	1.000	(-0.042, 0.063)
2010–2020	-0.036	0.016	-2.206	0.451	(-0.089, 0.016)
2010–2022	0.039	0.017	2.323	0.372	(-0.014, 0.092)
2012–2014	0.036	0.016	2.194	0.458	(-0.016, 0.089)
2012–2016	-0.072	0.016	-4.366	0.001	(-0.125, -0.019)
2012–2018	-0.057	0.016	-3.453	0.022	(-0.110, -0.004)
2012–2020	-0.103	0.016	-6.271	0.000	(-0.156, -0.051)
2012–2022	-0.028	0.017	-1.704	0.789	(-0.081, 0.025)
2014–2016	-0.108	0.016	-6.560	0.000	(-0.161, -0.056)
2014–2018	-0.093	0.016	-5.648	0.000	(-0.146, -0.041)
2014–2020	-0.140	0.016	-8.465	0.000	(-0.192, -0.087)

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

Contrast	Estimate	SE	t_{242}	p -value	95% CI
2014–2022	-0.065	0.017	-3.879	0.005	(-0.118, -0.012)
2016–2018	0.015	0.016	0.912	0.996	(-0.037, 0.068)
2016–2020	-0.031	0.016	-1.905	0.660	(-0.084, 0.021)
2016–2022	0.044	0.017	2.621	0.211	(-0.009, 0.097)
2018–2020	-0.046	0.016	-2.817	0.134	(-0.099, 0.006)
2018–2022	0.029	0.017	1.717	0.782	(-0.024, 0.082)
2020–2022	0.075	0.017	4.509	0.000	(0.022, 0.128)

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

Contrast	Estimate	SE	t_{242}	p -value	95% CI
2005–2006	0.035	0.224	0.157	1.000	(-0.678, 0.749)
2005–2008	0.370	0.224	1.652	0.818	(-0.343, 1.084)
2005–2010	0.123	0.224	0.549	1.000	(-0.590, 0.837)
2005–2012	0.215	0.224	0.958	0.994	(-0.499, 0.928)
2005–2014	0.787	0.224	3.514	0.018	(0.074, 1.501)
2005–2016	0.364	0.224	1.626	0.832	(-0.349, 1.078)
2005–2018	0.397	0.224	1.771	0.749	(-0.317, 1.110)
2005–2020	0.563	0.224	2.514	0.262	(-0.150, 1.277)
2005–2022	0.646	0.225	2.866	0.119	(-0.072, 1.364)
2006–2008	0.335	0.167	2.011	0.588	(-0.196, 0.865)
2006–2010	0.088	0.167	0.528	1.000	(-0.443, 0.618)
2006–2012	0.180	0.167	1.078	0.986	(-0.351, 0.710)
2006–2014	0.752	0.167	4.516	0.000	(0.221, 1.283)
2006–2016	0.329	0.167	1.976	0.613	(-0.201, 0.860)
2006–2018	0.362	0.167	2.171	0.475	(-0.169, 0.892)
2006–2020	0.528	0.167	3.171	0.052	(-0.002, 1.059)
2006–2022	0.611	0.168	3.634	0.012	(0.075, 1.146)
2008–2010	-0.247	0.167	-1.483	0.896	(-0.778, 0.284)
2008–2012	-0.155	0.167	-0.933	0.995	(-0.686, 0.375)
2008–2014	0.417	0.167	2.504	0.268	(-0.113, 0.948)
2008–2016	-0.006	0.167	-0.035	1.000	(-0.536, 0.525)
2008–2018	0.027	0.167	0.160	1.000	(-0.504, 0.557)

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

Contrast	Estimate	SE	t_{242}	p-value	95% CI
2008–2020	0.193	0.167	1.159	0.977	(-0.337, 0.724)
2008–2022	0.276	0.168	1.641	0.824	(-0.260, 0.811)
2010–2012	0.092	0.167	0.550	1.000	(-0.439, 0.622)
2010–2014	0.664	0.167	3.988	0.003	(0.134, 1.195)
2010–2016	0.241	0.167	1.448	0.909	(-0.289, 0.772)
2010–2018	0.274	0.167	1.643	0.823	(-0.257, 0.804)
2010–2020	0.440	0.167	2.643	0.201	(-0.090, 0.971)
2010–2022	0.523	0.168	3.111	0.062	(-0.013, 1.058)
2012–2014	0.572	0.167	3.437	0.023	(0.042, 1.103)
2012–2016	0.150	0.167	0.898	0.996	(-0.381, 0.680)
2012–2018	0.182	0.167	1.093	0.985	(-0.349, 0.713)
2012–2020	0.348	0.167	2.093	0.530	(-0.182, 0.879)
2012–2022	0.431	0.168	2.566	0.236	(-0.104, 0.967)
2014–2016	-0.423	0.167	-2.540	0.249	(-0.953, 0.108)
2014–2018	-0.390	0.167	-2.344	0.360	(-0.921, 0.140)
2014–2020	-0.224	0.167	-1.345	0.941	(-0.755, 0.307)
2014–2022	-0.141	0.168	-0.840	0.998	(-0.677, 0.394)
2016–2018	0.033	0.167	0.195	1.000	(-0.498, 0.563)
2016–2020	0.199	0.167	1.195	0.972	(-0.332, 0.730)
2016–2022	0.282	0.168	1.676	0.805	(-0.254, 0.817)
2018–2020	0.166	0.167	1.000	0.992	(-0.364, 0.697)
2018–2022	0.249	0.168	1.483	0.896	(-0.286, 0.785)
2020–2022	0.083	0.168	0.492	1.000	(-0.453, 0.618)

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

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

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

Year	Mean Log Surface Chlorophyll-a Concentration (µg/L)									
	2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
2022	0.511	0.624	0.433	0.853	1.039	0.292	0.745	0.488	0.397	2.060
2020	0.114	0.227	0.036	0.456	0.642	-0.105	0.349	0.091	2.450	0.111
2018	0.023	0.136	-0.055	0.365	0.551	-0.196	0.258	2.540	1.000	0.016
2016	-0.235	-0.122	-0.313	0.107	0.294	-0.454	2.800	0.667	0.236	0.000
2014	0.219	0.332	0.141	0.561	0.747	2.350	0.032	0.911	0.999	0.506
2012	-0.528	-0.415	-0.606	-0.186	3.100	0.000	0.483	0.002	0.000	0.000
2010	-0.342	-0.229	-0.420	2.910	0.933	0.002	0.999	0.183	0.030	0.000
2008	0.078	0.191	2.490	0.065	0.000	0.990	0.387	1.000	1.000	0.055
2006	-0.113	2.680	0.922	0.801	0.072	0.301	0.997	0.992	0.807	0.000
2005	2.570	1.000	1.000	0.687	0.113	0.972	0.956	1.000	1.000	0.150

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

Year	Mean Log Bottom Dissolved Oxygen Concentration (mg/L)									
	2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
2022	0.078	-0.011	-0.002	-0.027	0.034	0.138	0.062	-0.031	0.003	1.790
2020	0.075	-0.014	-0.005	-0.030	0.031	0.135	0.059	-0.034	1.790	1.000
2018	0.109	0.020	0.029	0.004	0.064	0.169	0.093	1.760	1.000	1.000
2016	0.016	0.016	-0.073	-0.064	-0.089	-0.028	1.850	0.693	0.974	0.964
2014	-0.060	-0.149	-0.140	-0.165	-0.105	1.930	0.880	0.028	0.176	0.153
2012	0.045	-0.045	-0.035	-0.060	1.820	0.532	1.000	0.955	1.000	1.000
2010	0.105	0.016	0.025	1.760	0.970	0.036	0.746	1.000	1.000	1.000
2008	0.080	-0.009	1.790	1.000	0.999	0.140	0.957	1.000	1.000	1.000
2006	0.090	1.780	1.000	1.000	0.996	0.087	0.902	1.000	1.000	1.000
2005	1.870	0.943	0.972	0.860	1.000	0.997	1.000	0.830	0.981	0.976

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

Year	Mean log PAR Attenuation (K_d (m^{-1}))									
	2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
2022	0.262	0.272	0.076	0.140	0.138	-0.199	0.078	0.164	-0.018	0.682
2020	0.280	0.290	0.094	0.158	0.156	-0.181	0.096	0.182	0.664	1.000
2018	0.098	0.108	-0.088	-0.024	-0.026	-0.363	-0.086	0.846	0.807	0.892
2016	0.184	0.194	-0.002	0.062	0.060	-0.278	0.760	0.999	0.997	0.999
2014	0.461	0.471	0.276	0.339	0.337	0.483	0.244	0.032	0.809	0.720
2012	0.124	0.134	-0.062	0.002	0.820	0.063	1.000	1.000	0.914	0.961
2010	0.122	0.132	-0.063	0.822	1.000	0.062	1.000	1.000	0.908	0.958
2008	0.185	0.196	0.758	1.000	1.000	0.277	1.000	0.999	0.998	1.000
2006	-0.010	0.954	0.781	0.974	0.972	0.002	0.773	0.994	0.225	0.322
2005	0.944	1.000	0.961	0.998	0.998	0.054	0.961	1.000	0.655	0.743

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

Year	Mean log Surface Salinity (psu)									
	2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
2022	-0.190	-0.101	-0.095	-0.132	-0.039	-0.089	-0.148	-0.176	-0.053	3.500
2020	-0.137	-0.048	-0.043	-0.080	0.014	-0.036	-0.095	-0.123	3.450	0.698
2018	-0.014	0.075	0.080	0.044	0.137	0.087	0.028	3.330	0.001	0.000
2016	-0.042	0.047	0.052	0.016	0.109	0.059	3.360	0.992	0.028	0.000
2014	-0.101	-0.012	-0.007	-0.043	0.050	3.410	0.531	0.066	0.955	0.060
2012	-0.151	-0.062	-0.057	-0.094	3.470	0.740	0.005	0.000	1.000	0.938
2010	-0.058	0.032	0.037	3.370	0.033	0.873	1.000	0.870	0.133	0.000
2008	-0.094	-0.005	3.410	0.950	0.584	1.000	0.692	0.123	0.882	0.030
2006	-0.089	3.400	1.000	0.981	0.456	1.000	0.803	0.188	0.792	0.016
2005	3.310	0.353	0.275	0.882	0.003	0.192	0.983	1.000	0.013	0.000

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

Year	Mean log Surface Temperature (°C)									
	2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
2022	0.019	0.038	-0.016	0.039	-0.028	-0.065	0.044	0.029	0.075	3.310
2020	-0.056	-0.037	-0.092	-0.036	-0.103	-0.140	-0.031	-0.046	3.380	0.000
2018	-0.009	0.009	-0.045	0.010	-0.057	-0.093	0.015	3.340	0.134	0.781
2016	-0.024	-0.006	-0.060	-0.005	-0.072	-0.108	3.350	0.996	0.000	0.210
2014	0.084	0.103	0.048	0.103	0.036	3.240	0.000	0.000	0.000	0.005
2012	0.048	0.066	0.012	0.067	3.280	0.459	0.001	0.022	0.000	0.789
2010	-0.019	-0.001	-0.055	3.350	0.002	0.000	1.000	1.000	0.452	0.373
2008	0.036	0.055	3.290	0.031	0.999	0.106	0.012	0.164	0.000	0.992
2006	-0.019	3.350	0.035	1.000	0.003	0.000	1.000	1.000	0.425	0.399
2005	3.330	0.998	0.837	0.997	0.488	0.007	0.985	1.000	0.265	0.997

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

Year	Mean log Surface Turbidity (NTU)									
	2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
2022	0.646	0.611	0.276	0.523	0.431	-0.141	0.282	0.249	0.083	2.060
2020	0.563	0.528	0.193	0.440	0.348	-0.224	0.199	0.166	2.140	1.000
2018	0.397	0.362	0.027	0.274	0.182	-0.390	0.033	2.310	0.992	0.896
2016	0.364	0.329	-0.006	0.241	0.150	-0.423	2.340	1.000	0.972	0.805
2014	0.787	0.752	0.417	0.664	0.572	1.920	0.250	0.360	0.941	0.998
2012	0.215	0.180	-0.155	0.092	2.490	0.023	0.996	0.985	0.530	0.237
2010	0.123	0.088	-0.247	2.590	1.000	0.003	0.909	0.823	0.201	0.062
2008	0.370	0.335	2.340	0.895	0.995	0.268	1.000	1.000	0.977	0.824
2006	0.035	2.670	0.587	1.000	0.986	0.000	0.612	0.474	0.053	0.012
2005	2.710	1.000	0.818	1.000	0.994	0.018	0.831	0.740	0.263	0.119

Appendix C: Trend Station Water Quality Data Summaries

This appendix contains yearly summary statistics for water quality parameters for each trend station within Assateague Island National Seashore between 2005 and 2022 (Tables 28–33).

Table 28. Yearly summary statistics for surface chlorophyll-*a* concentration ($\mu\text{g/L}$) at Assateague Island National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available]

Station	Statistic	Sampling Year									
		2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
6	Mean	15.17	8.25	8.88	18.45	18.25	7.51	13.16	8.33	13.16	10.81
6	SD	3.22	2.07	3.65	3.22	1.96	1.95	2.02	2.21	5.02	3.73
6	n	4	4	3	4	4	4	4	4	4	4
14	Mean	22.43	19.80	18.91	27.20	59.30	6.00	11.94	7.27	9.66	4.13
14	SD	5.64	1.30	6.22	3.71	40.51	0.79	3.17	2.00	2.32	0.78
14	n	4	4	4	4	4	4	4	4	4	3
18	Mean	10.19	20.50	12.46	19.50	16.42	5.99	23.53	7.95	13.81	4.03
18	SD	1.32	7.49	2.13	2.65	1.59	1.99	2.57	1.82	7.51	1.16
18	n	4	4	4	4	4	4	4	4	4	4
19	Mean	21.71	23.25	24.87	35.92	75.86	14.04	23.40	17.67	15.83	12.44
19	SD	5.14	0.79	8.48	8.97	65.35	6.61	3.67	6.45	6.80	10.44
19	n	4	4	4	4	4	4	4	4	4	3
27	Mean	18.90	NA	15.94	26.25	23.64	11.94	23.52	27.11	15.34	8.75
27	SD	8.28	NA	7.64	4.57	6.29	2.14	10.32	11.37	4.08	1.88
27	n	4	NA	4	4	4	4	4	4	4	3
30	Mean	8.39	7.00	10.29	18.45	17.03	11.18	11.42	20.44	10.36	10.60
30	SD	6.19	2.58	6.06	9.63	5.50	3.11	3.20	18.29	4.47	4.54
30	n	4	4	4	4	4	4	4	4	4	3

Table 29. Yearly summary statistics for bottom dissolved oxygen concentration (mg/L) at Assateague Island National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available]

Station	Statistic	Sampling Year									
		2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
6	Mean	6.38	6.50	5.74	5.97	5.83	6.32	6.36	5.50	5.89	6.07
6	SD	1.09	0.75	0.09	0.31	0.61	0.38	0.52	0.37	0.99	0.52
6	n	4	4	3	4	4	4	4	4	4	4
14	Mean	5.90	6.48	5.70	5.80	6.85	6.71	6.31	5.36	6.06	6.21
14	SD	1.10	1.35	0.44	0.40	1.42	0.88	0.31	0.40	0.29	0.30
14	n	4	4	4	4	4	4	4	4	4	4
18	Mean	6.25	6.62	5.97	6.33	5.94	6.96	5.94	6.60	6.42	6.54
18	SD	0.60	1.04	0.56	1.01	1.87	0.86	1.02	0.29	0.46	0.22
18	n	4	4	4	4	4	4	4	4	4	4
19	Mean	5.81	6.03	5.80	4.22	7.08	6.38	6.28	5.82	6.06	5.99
19	SD	0.83	1.63	0.34	1.37	2.40	0.73	0.65	0.65	1.12	0.57
19	n	4	4	4	4	4	4	4	4	4	4
27	Mean	6.15	NA	5.88	6.18	5.67	6.47	5.83	7.05	5.52	6.22
27	SD	0.89	NA	0.94	0.55	1.05	1.47	0.88	0.62	0.16	0.30
27	n	4	NA	4	4	4	4	4	4	4	4
30	Mean	6.26	6.38	6.54	6.55	6.57	6.91	6.26	6.53	5.92	6.39
30	SD	0.96	0.63	0.74	0.89	0.86	1.19	0.80	0.72	0.42	0.77
30	n	4	4	4	4	4	4	4	4	4	4

Table 30. Yearly summary statistics for PAR attenuation (K_d (m^{-1})) at Assateague Island National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available]

Station	Statistic	Sampling Year									
		2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
6	Mean	2.42	2.25	1.86	3.01	2.69	2.02	2.56	2.04	2.43	2.26
6	SD	0.95	0.92	0.12	0.65	0.90	0.89	0.63	0.26	0.56	0.54
6	n	4	4	3	4	4	4	4	4	4	4
14	Mean	4.03	4.18	2.33	3.53	1.90	1.46	1.78	2.32	1.64	1.66
14	SD	1.16	0.50	0.32	1.89	0.45	0.67	0.55	1.40	0.22	0.43
14	n	4	4	4	4	4	4	4	4	4	4
18	Mean	2.00	3.41	1.57	2.45	1.86	1.19	2.10	1.43	1.54	1.18
18	SD	0.21	1.46	0.25	0.58	0.34	0.33	0.41	0.15	0.46	0.24
18	n	4	4	4	4	4	4	4	4	4	4
19	Mean	4.55	6.32	3.34	4.21	2.93	1.16	4.39	2.72	2.17	1.75
19	SD	0.54	2.99	0.85	2.38	0.67	0.20	2.34	1.18	0.50	0.55
19	n	4	3	3	4	4	4	4	4	4	4
27	Mean	2.64	NA	1.60	2.75	1.91	1.27	2.17	2.58	2.12	1.84
27	SD	0.58	NA	0.24	1.12	0.21	0.25	0.32	0.34	0.22	0.32
27	n	4	NA	4	4	4	4	4	4	4	4
30	Mean	1.52	1.77	1.36	2.20	1.49	1.69	1.46	1.99	1.85	1.73
30	SD	0.93	0.29	0.36	1.32	0.32	0.26	0.71	0.76	0.64	0.95
30	n	4	4	4	4	4	4	4	4	4	4

Table 31. Yearly summary statistics for surface salinity (psu) at Assateague Island National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available]

Station	Statistic	Sampling Year									
		2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
6	Mean	29.63	30.93	31.54	31.72	32.05	31.04	31.24	31.02	31.90	33.50
6	SD	0.54	0.57	0.96	0.36	1.09	0.57	1.13	0.36	0.58	0.65
6	n	4	4	3	4	4	4	4	4	4	4
14	Mean	26.00	29.52	32.63	32.20	31.83	31.51	27.18	28.50	31.94	33.79
14	SD	0.81	1.17	0.75	1.28	2.04	0.59	1.34	0.70	0.90	0.79
14	n	4	4	4	4	4	4	4	4	4	4
18	Mean	25.92	30.82	32.18	31.00	32.92	31.12	27.59	27.08	30.94	33.81
18	SD	0.22	0.63	0.41	1.81	1.09	0.72	0.49	0.88	1.00	0.59
18	n	4	4	4	4	4	4	4	4	4	4
19	Mean	23.28	30.19	30.28	28.39	31.33	29.88	26.30	24.44	30.06	32.00
19	SD	0.95	0.67	1.35	1.69	0.92	0.66	0.69	0.98	1.26	1.58
19	n	4	4	4	4	4	4	4	4	4	4
27	Mean	25.68	NA	25.31	24.23	31.90	29.82	28.38	26.07	30.36	32.69
27	SD	0.84	NA	10.35	10.68	1.12	0.66	1.63	1.69	1.54	0.58
27	n	4	NA	4	4	4	4	4	4	4	4
30	Mean	28.32	30.53	31.26	30.06	31.95	30.36	30.71	28.20	30.98	32.52
30	SD	1.74	0.48	0.40	1.00	0.54	0.68	0.96	2.49	1.05	0.56
30	n	4	4	4	4	4	4	4	4	4	4

Table 32. Yearly summary statistics for surface temperature (°C) at Assateague Island National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available]

Station	Statistic	Sampling Year									
		2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
6	Mean	28.17	26.69	25.60	27.87	26.25	26.05	28.64	27.29	30.09	27.01
6	SD	1.19	1.64	1.24	1.46	2.13	0.81	0.79	1.22	2.39	1.37
6	n	4	4	3	4	4	4	4	4	4	4
14	Mean	28.63	28.53	27.47	28.94	26.77	25.52	29.18	28.37	30.63	27.75
14	SD	0.98	1.82	2.15	1.06	1.66	0.98	1.72	1.55	1.39	1.23
14	n	4	4	4	4	4	4	4	4	4	4
18	Mean	29.09	28.36	27.07	28.60	26.77	25.36	28.93	28.74	30.43	27.55
18	SD	0.95	2.80	1.83	0.65	1.63	0.42	1.03	1.38	1.55	0.98
18	n	4	4	4	4	4	4	4	4	4	4
19	Mean	29.46	28.76	27.83	28.06	26.70	25.30	29.37	28.53	30.59	28.28
19	SD	1.57	2.11	2.24	0.94	0.97	0.49	2.17	1.44	1.62	1.28
19	n	4	4	4	4	4	4	4	4	4	4
27	Mean	28.60	NA	27.55	29.01	25.76	25.88	27.63	28.18	29.47	26.98
27	SD	1.08	NA	1.99	1.03	1.72	0.74	2.34	1.97	1.28	2.22
27	n	4	NA	4	4	4	4	4	4	4	4
30	Mean	25.49	24.52	22.83	25.70	23.57	24.45	24.36	26.11	25.17	24.82
30	SD	2.59	3.72	2.02	3.20	1.99	0.59	3.42	2.13	3.91	3.98
30	n	4	4	4	4	4	4	4	4	4	4

Table 33. Yearly summary statistics for surface turbidity (NTU) at Assateague Island National Seashore trend stations. [SD = standard deviation; n = number of observations; NA = not available]

Station	Statistic	Sampling Year									
		2005	2006	2008	2010	2012	2014	2016	2018	2020	2022
6	Mean	16.05	15.03	10.20	19.95	15.45	26.05	14.50	9.94	10.51	9.07
6	SD	8.17	7.02	2.52	4.19	4.32	16.26	4.01	2.61	0.91	4.94
6	n	4	4	3	4	4	4	4	4	4	4
14	Mean	25.55	27.25	18.32	25.33	9.22	8.22	9.40	10.01	7.20	6.38
14	SD	11.10	7.33	10.68	16.04	1.65	6.45	4.58	7.36	1.29	1.16
14	n	4	4	4	4	4	4	4	4	4	4
18	Mean	9.68	23.20	5.75	13.28	8.88	7.18	9.00	5.20	4.51	3.29
18	SD	0.98	17.40	2.21	5.54	3.45	7.16	3.88	1.27	1.00	0.93
18	n	4	4	4	4	4	4	4	4	4	4
19	Mean	27.16	25.50	17.12	29.38	16.73	17.40	29.35	13.47	8.18	6.64
19	SD	4.38	6.30	5.06	25.86	4.34	24.23	23.41	11.05	1.33	2.05
19	n	4	3	4	4	4	4	4	4	4	4
27	Mean	13.73	NA	8.28	21.45	10.03	5.18	11.30	10.33	8.88	8.57
27	SD	4.42	NA	1.88	9.18	1.58	1.85	2.59	0.99	1.52	1.71
27	n	4	NA	4	4	4	4	4	4	4	4
30	Mean	7.38	12.10	7.82	13.95	7.55	8.58	6.73	8.31	7.76	9.98
30	SD	6.91	3.16	3.58	10.09	2.40	3.54	4.05	4.03	3.39	5.92
30	n	4	4	4	4	4	4	4	4	4	4

Appendix D: Seagrass Data Summaries

This appendix contains seasonal summary statistics for seagrass condition parameters by species (where available) in the Tingles Island reference bed at Assateague Island National Seashore from 2009 through 2022 (Tables 34–42).

Table 34. Summary statistics for *Zostera marina* shoot density (shoots m⁻²) at Assateague Island National Seashore. [SD = standard deviation; n = number of observations]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2009–06	165.7	204.2	12	706.7	222.6	12	72.7	114.3	12
2009–10	19.3	24.6	12	291.0	126.3	12	28.0	82.4	12
2010–01	27.0	34.2	12	355.7	93.7	12	65.3	172.6	12
2010–04	30.3	46.0	12	560.0	159.3	12	67.7	169.6	12
2010–06	16.7	28.7	12	817.3	332.0	12	121.3	322.3	12
2010–10	4.7	11.0	12	143.0	127.5	12	3.0	10.4	12
2011–04	25.3	51.1	12	464.0	267.3	12	11.7	36.8	12
2011–06	120.0	287.7	12	382.7	225.0	12	6.0	20.8	12
2011–10	35.0	109.3	12	173.7	143.8	12	0.0	0.0	12
2012–04	141.0	290.2	12	275.3	202.0	12	6.7	11.6	12
2012–06	140.0	315.0	12	322.0	221.2	12	7.3	17.1	12
2012–10	0.3	1.2	12	9.7	15.1	12	0.0	0.0	12
2013–04	21.3	21.8	12	69.7	52.0	12	27.3	11.7	12
2013–06	141.3	94.8	12	147.3	103.3	12	132.0	81.4	12
2013–10	175.7	192.6	12	221.3	204.2	12	259.3	235.5	12
2014–04	249.7	276.9	12	272.7	184.7	12	242.3	185.1	12
2014–06	268.3	255.2	12	316.7	152.8	12	324.0	212.9	12
2014–10	21.3	34.0	12	54.7	57.2	12	95.7	84.2	12
2015–04	33.3	33.0	12	35.7	38.2	12	53.3	42.7	12
2015–06	36.3	23.7	12	37.7	61.6	12	45.7	46.6	12
2015–10	0.0	0.0	12	1.7	3.2	12	7.7	18.7	12
2016–04	0.0	0.0	12	3.7	8.9	12	28.3	47.1	12
2016–06	0.3	1.2	12	2.3	6.0	12	23.7	64.3	12
2016–10	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2017–04	1.3	4.6	12	22.7	33.0	12	3.3	5.9	12
2017–06	3.0	8.2	12	56.7	51.8	12	1.3	4.6	12
2017–10	2.7	9.2	12	42.7	46.8	12	0.0	0.0	12
2018–04	12.3	35.6	12	150.7	176.4	12	0.0	0.0	12

Table 34 (continued). Summary statistics for *Zostera marina* shoot density (shoots m⁻²) at Assateague Island National Seashore. [SD = standard deviation; n = number of observations]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2018-06	21.3	69.0	12	147.3	127.6	12	0.0	0.0	12
2018-10	29.7	101.5	12	168.3	126.9	12	0.0	0.0	12
2019-04	55.7	140.1	12	396.3	283.2	12	1.0	3.5	12
2019-06	57.0	109.2	12	298.0	184.1	12	0.0	0.0	12
2019-10	19.7	43.1	12	101.7	62.1	12	0.0	0.0	12
2021-04	1.7	2.7	12	179.7	167.8	12	1.7	2.7	12
2021-06	3.0	9.2	12	151.7	104.9	12	0.3	1.2	12
2022-06	0.0	0.0	12	50.7	73.5	12	2.3	8.1	12

Table 35. Summary statistics for percent cover (per 0.25 m²) of *Ruppia maritima* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2009-06	23.7	28.7	12	0.4	1.4	12	32.7	25.8	12
2009-10	9.0	19.5	12	0.0	0.0	12	0.0	0.0	12
2010-01	5.8	8.1	12	0.0	0.0	12	0.0	0.0	12
2010-04	19.8	24.6	12	0.0	0.0	12	0.0	0.0	12
2010-06	59.0	32.5	12	0.0	0.0	12	0.2	0.6	12
2010-10	0.7	2.3	12	0.0	0.0	12	0.0	0.0	12
2011-04	2.4	6.9	12	0.0	0.0	12	0.0	0.0	12
2011-06	11.6	15.8	12	0.0	0.0	12	0.0	0.0	12
2011-10	14.9	16.8	12	0.0	0.0	12	0.0	0.0	12
2012-04	44.6	41.6	12	0.0	0.0	12	0.2	0.9	12
2012-06	59.6	44.9	12	0.0	0.0	12	4.6	14.4	12
2012-10	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2013-04	0.2	0.4	12	0.0	0.0	12	0.0	0.0	12
2013-06	3.8	8.0	12	0.0	0.0	12	0.0	0.0	12
2013-10	4.2	7.0	12	0.0	0.0	12	0.0	0.0	12
2014-04	15.9	21.8	12	0.4	1.4	12	0.0	0.0	12
2014-06	26.7	24.2	12	1.2	3.1	12	0.0	0.0	12
2014-10	1.1	2.9	12	0.0	0.0	12	0.0	0.0	12
2015-04	0.8	2.6	12	0.0	0.0	12	0.0	0.0	12
2015-06	2.1	3.3	12	0.1	0.3	12	0.0	0.0	12
2015-10	0.2	0.4	12	0.1	0.3	12	0.0	0.0	12

Table 35 (continued). Summary statistics for percent cover (per 0.25 m²) of *Ruppia maritima* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2016-04	1.8	4.4	12	1.4	2.0	12	0.0	0.0	12
2016-06	9.1	15.7	12	19.1	24.7	12	0.0	0.0	12
2016-10	19.8	26.7	12	22.7	26.8	12	0.1	0.3	12
2017-04	27.8	23.4	12	21.8	25.8	12	1.5	2.0	12
2017-06	41.3	32.0	12	32.2	27.3	12	1.8	3.2	12
2017-10	14.6	14.4	12	62.2	23.3	12	0.4	0.5	12
2018-04	11.8	15.9	12	35.8	14.6	12	0.0	0.0	12
2018-06	27.4	27.2	12	54.1	21.1	12	0.1	0.3	12
2018-10	43.7	33.5	12	19.2	11.2	12	0.0	0.0	12
2019-04	32.5	28.5	12	8.4	5.6	12	0.2	0.5	12
2019-06	32.3	26.9	12	5.3	4.3	12	0.0	0.0	12
2019-10	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2021-04	5.8	11.8	12	5.8	5.1	12	1.2	3.1	12
2021-06	6.2	14.5	12	13.2	7.9	12	0.8	2.9	12
2022-06	0.1	0.3	12	0.0	0.0	12	0.0	0.0	12

Table 36. Summary statistics for percent cover (per 0.25 m²) of *Zostera marina* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2009-06	20.2	26.5	12	88.3	18.9	12	8.2	12.8	12
2009-10	2.3	3.2	12	35.0	14.9	12	3.2	8.6	12
2010-01	3.5	5.0	12	29.2	10.8	12	3.6	8.8	12
2010-04	4.8	7.7	12	72.5	11.6	12	7.7	18.6	12
2010-06	1.0	1.9	12	85.8	9.0	12	9.4	24.7	12
2010-10	0.6	1.5	12	19.6	14.7	12	0.4	1.4	12
2011-04	1.8	4.2	12	42.1	25.9	12	1.3	4.3	12
2011-06	10.8	21.9	12	52.5	31.2	12	0.4	1.4	12
2011-10	2.2	7.2	12	24.4	25.8	12	0.0	0.0	12
2012-04	15.1	33.0	12	48.3	35.6	12	0.8	1.5	12
2012-06	17.5	33.7	12	55.0	33.0	12	1.2	3.1	12
2012-10	0.1	0.3	12	1.0	1.3	12	0.0	0.0	12
2013-04	1.8	1.8	12	9.4	8.7	12	2.3	1.3	12
2013-06	15.0	11.1	12	19.6	12.7	12	18.8	12.5	12

Table 36 (continued). Summary statistics for percent cover (per 0.25 m²) of *Zostera marina* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2013–10	16.6	15.6	12	20.1	15.4	12	20.8	16.4	12
2014–04	15.8	15.1	12	19.3	13.9	12	13.3	8.9	12
2014–06	33.8	29.7	12	39.2	23.2	12	39.6	21.8	12
2014–10	3.2	4.7	12	5.5	5.7	12	8.5	7.3	12
2015–04	3.8	5.9	12	5.2	7.7	12	8.1	7.6	12
2015–06	10.4	11.3	12	8.7	14.5	12	9.1	11.0	12
2015–10	0.0	0.0	12	0.2	0.5	12	0.7	1.5	12
2016–04	0.0	0.0	12	0.5	1.4	12	4.3	7.2	12
2016–06	0.1	0.3	12	0.5	1.4	12	4.3	11.6	12
2016–10	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2017–04	0.1	0.3	12	2.8	3.8	12	0.4	0.5	12
2017–06	0.5	1.4	12	6.9	6.9	12	0.1	0.3	12
2017–10	0.4	1.4	12	7.0	8.1	12	0.0	0.0	12
2018–04	1.8	4.4	12	16.3	13.7	12	0.0	0.0	12
2018–06	2.2	7.2	12	23.4	19.9	12	0.0	0.0	12
2018–10	3.4	11.5	12	17.9	11.8	12	0.0	0.0	12
2019–04	7.1	20.1	12	35.8	23.7	12	0.1	0.3	12
2019–06	10.6	22.2	12	38.8	26.9	12	0.0	0.0	12
2019–10	2.2	5	12	12.5	8.7	12	0.0	0.0	12
2021–04	0.3	0.5	12	18.3	14.7	12	0.3	0.5	12
2021–06	0.4	1.2	12	21.3	13.7	12	0.1	0.3	12
2022–06	0.0	0.0	12	10.6	15.5	12	0.4	1.4	12

Table 37. Summary statistics for *Ruppia maritima* canopy height (cm) at Assateague Island National Seashore. [SD = standard deviation; n = number of observations; – = not applicable].

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2009–06	9.1	1.6	9	20.0	–	1	11.9	3.5	11
2009–10	12.0	4.7	6	–	–	0	–	–	0
2010–01	11.5	5.8	8	–	–	0	–	–	0
2010–04	8.4	5.3	9	–	–	0	–	–	0
2010–06	12.0	7.2	10	–	–	0	17.0	–	1
2010–10	13.0	–	1	–	–	0	–	–	0

Table 37 (continued). Summary statistics for *Ruppia maritima* canopy height (cm) at Assateague Island National Seashore. [SD = standard deviation; n = number of observations; – = not applicable].

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2011-04	9.5	0.7	2	–	–	0	–	–	0
2011-06	9.4	5.2	5	–	–	0	–	–	0
2011-10	8.9	1.7	8	–	–	0	–	–	0
2012-04	10.5	5.2	10	–	–	0	9.0	–	1
2012-06	18.0	7.4	9	–	–	0	7.0	1.4	2
2012-10	–	–	0	–	–	0	–	–	0
2013-04	6.0	1.4	2	–	–	0	–	–	0
2013-06	9.7	3.2	3	–	–	0	–	–	0
2013-10	19.4	4.0	7	–	–	0	–	–	0
2014-04	9.6	2.4	8	14.0	–	1	–	–	0
2014-06	16.5	5.2	11	17.0	1.4	2	–	–	0
2014-10	20.3	0.6	3	–	–	0	–	–	0
2015-04	5.0	–	1	–	–	0	–	–	0
2015-06	8.8	4.3	4	10.0	–	1	–	–	0
2015-10	9.0	0.0	2	10.0	–	1	–	–	0
2016-04	5.3	0.6	3	6.7	5.6	6	–	–	0
2016-06	10.6	3.0	5	8.9	3.0	7	–	–	0
2016-10	15.6	5.6	10	13.8	3.0	8	10.0	–	1
2017-04	5.7	0.7	10	9.6	3.8	7	5.0	1.3	7
2017-06	19.4	6	11	12.9	3.0	11	7.0	1.2	5
2017-10	13.7	4.0	11	16.8	3.4	12	7.6	3.2	5
2018-04	7.4	2.8	11	9.8	1.8	12	–	–	0
2018-06	9.7	2.7	10	14.6	2.8	12	5.0	–	1
2018-10	12.3	2.3	11	13.8	1.7	12	–	–	0
2019-04	7.5	2.8	11	10.0	2.4	11	6.3	1.5	3
2019-06	8.4	3.3	11	11.8	2.4	9	–	–	0
2019-10	–	–	0	–	–	0	–	–	0
2021-04	5.5	1.3	4	10.0	2.3	8	6.0	0.0	2
2021-06	7.8	1.5	4	10.0	2.9	11	7.0	–	1
2022-06	7.0	–	1	–	–	0.0	–	–	0.0

Table 38. Summary statistics for *Zostera marina* canopy height (cm) at Assateague Island National Seashore. [SD = standard deviation; n = number of observations; – = not applicable].

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2009–06	9.9	1.9	11	20.2	2.8	12	12.0	3.4	11
2009–10	12.4	4.4	7	13.8	3.7	12	12.8	5.6	5
2010–01	14.9	3.2	7	9.6	1.6	12	10.2	0.4	5
2010–04	11.8	7.3	6	15.6	3.3	12	14.3	2.1	3
2010–06	15.5	11.0	4	17.0	2.4	12	15.0	2.8	2
2010–10	11.5	2.1	2	18.8	2.3	10	13.0	–	1
2011–04	9.4	2.1	8	13.3	1.3	11	9.5	4.9	2
2011–06	10.3	3.3	7	14.6	1.6	10	14.0	–	1
2011–10	11.0	1.4	2	12.9	2.0	10	–	–	0
2012–04	14.2	4.9	5	15.1	2.6	10	13.8	3.9	4
2012–06	18.2	4.7	4	20.2	2.8	10	14.0	0.0	2
2012–10	5.0	–	1	6.8	1.8	8	–	–	0
2013–04	7.9	2.0	10	12.3	2.7	11	10.1	3.6	12
2013–06	11.2	1.5	10	13.4	1.3	11	15.2	1.5	12
2013–10	18.7	4.3	11	22.0	4.0	11	20.9	3.8	11
2014–04	9.0	3.4	11	14.6	0.7	11	11.4	3.9	12
2014–06	17.7	4.1	10	17.3	1.2	11	17.6	3.5	11
2014–10	17.7	4.6	7	10.6	1.9	8	12.4	2.6	9
2015–04	6.6	1.5	9	7.7	2.4	10	11.4	3.2	11
2015–06	8.7	2.6	10	9.1	1.7	9	10.8	2.5	10
2015–10	–	–	0	8.3	1.5	3	11.0	3.6	3
2016–04	–	–	0	15.5	3.5	2	13.4	2.6	7
2016–06	15.0	–	1	12.5	0.7	2	15.2	4.0	4
2016–10	–	–	0	–	–	0	–	–	0
2017–04	6.0	–	1	10.3	2.9	7	6.8	1.8	5
2017–06	17.0	4.2	2	13.4	2.8	11	17.0	–	1
2017–10	18.0	–	1	17.3	2.9	10	–	–	0
2018–04	10.7	3.8	3	10.2	1.5	10	–	–	0
2018–06	14.0	2.8	2	14.7	2.9	11	–	–	0
2018–10	14.0	2.8	2	13.8	1.7	12	–	–	0
2019–04	10.7	4.0	3	10.5	1.8	11	12.0	–	1
2019–06	10.2	3.5	6	11.6	2.2	12	–	–	0
2019–10	8.3	0.6	3	8.5	1.4	11	–	–	0
2021–04	10.0	2.2	4	10.3	2.0	12	10.0	1.4	4

Table 38 (continued). Summary statistics for *Zostera marina* canopy height (cm) at Assateague Island National Seashore. [SD = standard deviation; n = number of observations; – = not applicable].

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2021-06	8.5	2.1	2	10.2	2.9	12	10.0	–	1
2022-06	–	–	0.0	17.9	2.4	8	10.0	–	1

Table 39. Summary statistics for total biomass (g m⁻²) of *Ruppia maritima* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2009-06	54.7	50.6	12	6.5	21.8	12	43.0	20.6	8
2009-10	20.1	28.6	12	0.0	0.0	12	0.0	0.0	12
2010-01	6.4	8.1	7	0.0	0.0	12	0.0	0.0	12
2010-04	20.3	21.9	11	0.0	0.0	12	0.0	0.0	12
2010-06	151.5	96.4	12	0.0	0.0	12	0.0	0.0	11
2010-10	0.0	0.0	11	0.0	0.0	12	0.0	0.0	12
2011-04	1.8	4.1	11	0.0	0.0	12	0.0	0.0	12
2011-06	27.8	37.4	10	0.0	0.0	12	0.0	0.0	12
2011-10	72.0	86.0	12	0.0	0.0	12	0.0	0.0	12
2012-04	33.4	30	11	0.1	0.4	12	0.0	0.0	11
2012-06	128.3	135.5	12	0.0	0.0	12	8.4	20.3	12
2012-10	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2013-04	0.8	2.6	11	0.0	0.0	12	0.0	0.0	12
2013-06	8.6	19.2	11	0.0	0.0	12	0.0	0.0	12
2013-10	29.6	39.3	9	6.8	22.9	12	0.0	0.0	12
2014-04	20.7	27.4	9	8.5	20.2	12	0.0	0.0	12
2014-06	50.6	32.0	11	5.6	13.1	12	0.0	0.0	12
2014-10	1.2	3.7	10	4.8	11.6	12	0.0	0.0	12
2015-04	0.8	2.6	12	0.0	0.0	12	0.0	0.0	12
2015-06	13.8	24.7	10	1.5	5.1	12	0.0	0.0	12
2015-10	0.2	0.7	11	0.0	0.0	11	0.0	0.0	12
2016-04	7.4	13.6	12	8	15.1	8	0.0	0.0	12
2016-06	20.2	30.8	11	34	35.2	12	0.0	0.0	12
2016-10	25.8	24.2	12	14.5	14.5	12	0.5	1.8	12
2017-04	30.2	21.0	12	15	15.4	12	3.5	3.5	12
2017-06	22.5	18.3	12	24.7	20.1	11	4.1	5.4	12

Table 39 (continued). Summary statistics for total biomass (g m^{-2}) of *Ruppia maritima* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2017-10	12.7	11.3	12	47.3	20.7	12	0.5	1.2	9
2018-04	22.3	13.0	11	44.2	23.5	11	0.0	0.0	12
2018-06	51.7	42.5	12	77.5	53.5	11	1.3	4.5	12
2018-10	35.8	25.7	12	16.8	8.1	12	0.0	0.0	12
2019-04	34.2	20.8	11	6.4	4.6	5	0.6	1.4	11
2019-06	64.9	28.2	12	13.7	11.0	11	0.0	0.0	12
2019-10	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2021-04	5.9	12.7	12	6.6	8.5	10	2.0	5.5	12
2021-06	13.5	23.9	12	61.0	45.6	9	2.4	8.2	12
2022-06	4.4	15.3	12	0.0	0.0	12	0.0	0.0	12

Table 40. Summary statistics for total biomass (g m^{-2}) of *Zostera marina* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2009-06	19.9	29.3	9	93.3	37.3	12	13.8	18.1	5
2009-10	1.5	2.1	9	18.1	9.7	12	1.1	2.7	12
2010-01	0.1	0.2	6	7.8	4.9	11	1.8	4.2	9
2010-04	4.8	8.4	10	27.4	10.6	12	2.9	7.3	12
2010-06	0.2	0.6	9	60.3	26.8	12	11.3	33	12
2010-10	0.2	0.5	11	4.7	3.8	11	0.1	0.3	12
2011-04	0.2	0.2	9	15.7	9.6	10	0.2	0.7	11
2011-06	8.8	21.7	11	30.6	20.1	12	0.6	2.0	12
2011-10	1.3	3.8	12	8.7	8.4	12	0.0	0.0	12
2012-04	9.5	18.5	11	17.9	14.6	12	0.3	0.6	12
2012-06	19.5	45.7	11	31.3	21.7	12	0.4	1.4	11
2012-10	0.0	0.0	11	0.0	0.0	4	0.0	0.0	12
2013-04	0.3	0.3	12	2.7	3.0	11	0.8	0.4	12
2013-06	5.8	6.2	11	9.4	10.1	11	6.1	3.6	12
2013-10	9.2	10.6	12	15.0	12.7	11	19.2	19.2	12
2014-04	9.7	11.0	10	15.4	10.7	11	12.9	15.2	12
2014-06	19.9	23.8	10	27.4	18.5	12	28.3	20.0	12
2014-10	1.1	1.9	12	3.4	4.7	11	4.3	3.4	12

Table 40 (continued). Summary statistics for total biomass (g m⁻²) of *Zostera marina* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2015-04	0.8	0.8	8	1.5	1.8	12	2.0	2.5	12
2015-06	1.9	1.8	11	2.4	4.2	12	3.2	3.9	12
2015-10	0.0	0.0	12	0.0	0.1	10	0.3	0.7	12
2016-04	0.0	0.0	12	0.2	0.6	12	1.5	3.0	11
2016-06	0.0	0.0	11	0.0	0.0	10	1.8	5.2	12
2016-10	0.0	0.0	12	0.0	0.0	12	0.0	0.0	12
2017-04	0.0	0.0	11	0.4	0.7	8	0.1	0.1	11
2017-06	0.1	0.2	11	4.2	2.9	8	0.1	0.3	12
2017-10	0.0	0.0	11	3.7	3.5	5	0.0	0.0	12
2018-04	0.4	1.2	11	10.5	15.4	10	0.0	0.0	12
2018-06	1.1	3.6	12	10.9	9.4	10	0.0	0.0	12
2018-10	0.0	0.0	10	7.3	5.7	9	0.0	0.0	12
2019-04	4.6	12.3	11	33.7	40.7	12	0.0	0.0	11
2019-06	0.9	2.5	7	44.7	59.3	12	0.0	0.0	12
2019-10	0.4	1.0	11	4.7	3.7	12	0.0	0.0	12
2021-04	0.1	0.1	12	6.2	4.6	12	0.0	0.1	11
2021-06	0.3	0.9	11	12.1	11.2	11	0.0	0.0	12
2022-06	0.0	0.0	12	7.3	12.6	12	0.1	0.4	12

Table 41. Summary statistics for ratio of above- to belowground biomass of *Ruppia maritima* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations; – = not applicable].

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2009-06	1.5	1.0	11	11.3	7.5	2	1.8	0.9	8
2009-10	1.2	0.4	9	–	–	0	–	–	0
2010-01	–	–	0	–	–	0	–	–	0
2010-04	1.1	0.2	7	–	–	0	–	–	0
2010-06	2.1	0.8	10	–	–	0	–	–	0
2010-10	–	–	0	–	–	0	–	–	0
2011-04	1.6	0.7	2	–	–	0	–	–	0
2011-06	5.9	9.4	5	–	–	0	–	–	0
2011-10	1.5	0.8	8	–	–	0	–	–	0
2012-04	1.2	0.5	9	1.5	–	1	–	–	0

Table 41 (continued). Summary statistics for ratio of above- to belowground biomass of *Ruppia maritima* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations; – = not applicable].

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2012–06	2.3	0.9	10	–	–	0	1.8	0.4	2
2012–10	–	–	0	–	–	0	–	–	0
2013–04	0.5	–	1	–	–	0	–	–	0
2013–06	1.4	0.0	2	–	–	0	–	–	0
2013–10	1.8	0.8	4	1.2	0.2	2	–	–	0
2014–04	1.2	0.2	5	0.7	0.3	2	–	–	0
2014–06	1.5	0.8	10	2.7	2.9	3	–	–	0
2014–10	1.3	–	1	1.3	1.2	2	–	–	0
2015–04	–	–	0	–	–	0	–	–	0
2015–06	1.3	0.4	3	2.2	–	1	–	–	0
2015–10	1.1	–	1	–	–	0	–	–	0
2016–04	0.9	0.4	3	1.7	0.2	2	–	–	0
2016–06	1.6	0.8	4	1.6	0.5	7	–	–	0
2016–10	1.4	0.7	10	1.1	0.3	8	2.4	–	1
2017–04	0.7	0.2	10	0.8	0.1	7	1.4	0.7	7
2017–06	2.9	3.7	11	1.5	0.6	10	2.0	0.6	5
2017–10	2.5	4.8	11	1.4	0.6	12	1.1	0.7	2
2018–04	1.1	0.3	10	1.1	0.5	11	–	–	0
2018–06	1.6	0.4	10	2.0	0.6	11	2.6	–	1
2018–10	1.2	0.7	11	1.7	1.5	12	–	–	0
2019–04	1.2	0.5	10	1.1	1.0	5	0.7	0.5	2
2019–06	2.1	0.7	11	1.7	0.6	10	–	–	0
2019–10	–	–	0	–	–	0	–	–	0
2021–04	1.2	0.2	4	1.1	1.1	6	1.4	0.3	2
2021–06	1.6	0.3	4	1.4	0.6	8	1.2	–	1
2022–06	0.3	–	1	–	–	0.0	–	–	0.0

Table 42. Summary statistics for ratio of above- to belowground biomass of *Zostera marina* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations; – = not applicable].

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2009–06	2.4	2.1	8	0.6	0.3	12	1.9	1.5	5
2009–10	2.9	2.1	4	1.0	0.3	12	1.3	0.3	5
2010–01	0.4	–	1	0.8	0.5	11	0.6	0.2	2
2010–04	2.2	0.4	4	2.8	1.6	12	1.3	0.3	3
2010–06	2.7	–	1	1.9	0.6	12	3.3	0.7	2
2010–10	3.9	–	1	1.5	0.4	9	0.4	–	1
2011–04	1.8	0.3	5	2.6	1.8	9	2.2	–	1
2011–06	2.5	2.6	8	2.8	1.3	10	1.4	–	1
2011–10	2.4	1.1	3	1.6	1.4	10	–	–	0
2012–04	5.4	4.8	4	2.6	1.4	10	2.5	0.6	4
2012–06	2.9	1.7	4	2.0	0.8	10	1.1	0.7	2
2012–10	–	–	0	–	–	0	–	–	0
2013–04	2.6	1.3	10	3.4	2.1	10	2.9	1	11
2013–06	1.5	1.0	9	2.4	1.5	10	1.9	0.7	12
2013–10	3.4	2.9	11	2.9	2.7	10	2.3	0.9	11
2014–04	1.7	1.3	9	3.5	3.9	10	1.7	1.9	12
2014–06	1.9	1.3	10	1.5	0.9	11	1.7	0.5	11
2014–10	1.2	0.6	7	0.9	0.5	7	0.9	0.8	9
2015–04	1.6	1.1	6	1.9	1.6	10	2.2	1.3	11
2015–06	1.2	0.6	9	1.2	0.5	9	3.1	4.4	10
2015–10	–	–	0	2.7	–	1	0.7	0.0	3
2016–04	–	–	0	1.8	1.2	6	1.2	0.4	6
2016–06	0.6	–	1	–	–	0	3.1	1.7	4
2016–10	–	–	0	–	–	0	–	–	0
2017–04	–	–	0	1.8	0.4	3	1.9	0.8	4
2017–06	2.5	–	1	1.2	0.7	7	1.9	–	1
2017–10	–	–	0	2.9	3.4	3	11.7	–	1
2018–04	1.2	0.9	3	2.8	1.8	8	–	–	0
2018–06	1.5	0.5	2	2.2	0.9	9	–	–	0
2018–10	–	–	0	3.3	4.5	10	–	–	0
2019–04	3.3	2.3	4	2.1	2.2	12	–	–	0
2019–06	1.2	–	1	1.3	0.6	12	–	–	0
2019–10	1.3	0.7	2	1.1	0.6	11	–	–	0
2021–04	1.3	0.4	4	1.2	0.6	12	0.8	0.3	3

Table 42 (continued). Summary statistics for ratio of above- to belowground biomass of *Zostera marina* at Assateague Island National Seashore. [SD = standard deviation; n = number of observations; – = not applicable].

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2021-06	0.4	–	1	1.7	1.9	11	1.1	–	1
2022-06	–	–	0.0	2.3	2.1	8	3.0	–	1

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1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525