



Estuarine Nutrient Enrichment Monitoring: Data Summary and Trend Analysis for Cape Cod National Seashore

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Acronyms and Abbreviations

CACO	Cape Cod National Seashore
ENE	Estuarine nutrient enrichment
GAM	Generalized additive model
NCBN	Northeast Coastal and Barrier Network
NTU	Nephelometric turbidity units
PAR	Photosynthetically active radiation
Psu	Practical salinity units
SAV	Submerged aquatic vegetation

1. Background Information

Six parks within the Northeast Coastal and Barrier Network (NCBN) contain critical estuarine habitat (Figure 1-1). 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 is one of the highest priority issues identified by park managers (Stevens et al. 2005). In response, B. S. Kopp and Neckles (2009) developed a regional protocol for monitoring estuarine nutrient enrichment (ENE) that was fully implemented in NCBN parks beginning in 2007. The vital signs selected for monitoring include: estuarine water chemistry, estuarine water quality, estuarine water clarity, seagrass distribution, and seagrass condition. Previous reports by Blaine S Kopp et al. (2009) and Caldwell et al. (2015) summarized water quality condition and trends during 2003-2006 and 2006-2011, respectively. The current report summarizes conditions and trends for both water quality and seagrass data collected in Fire Island National Seashore to date (Table 1-1).

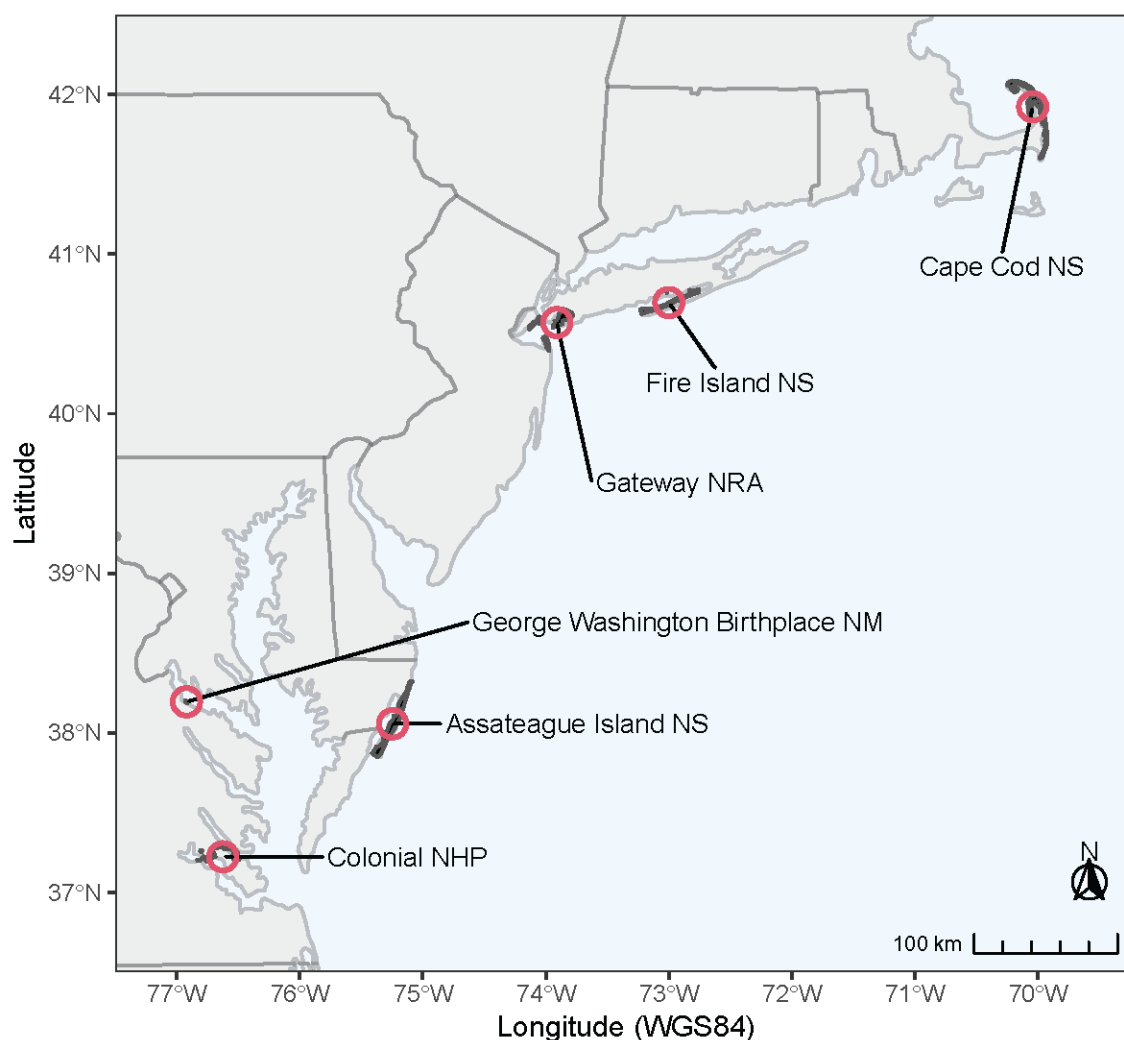


Figure 1-1. Locations of Northeast Coastal and Barrier Inventory & Monitoring (I&M) Network parks monitored for estuarine nutrient enrichment.

Table 1-1. Sampling years for water quality and seagrass monitoring within Cape Cod National Seashore.

Year	Water Quality	Seagrass
2003	not sampled	sampled
2004	not sampled	sampled
2005	not sampled	sampled
2006	not sampled	sampled
2007	sampled	sampled
2008	sampled	sampled
2009	sampled	sampled
2010	sampled	sampled
2011	sampled	sampled
2012	sampled	sampled
2013	sampled	sampled
2014	sampled	sampled
2015	not sampled	sampled
2016	sampled	sampled
2017	not sampled	sampled
2018	sampled	sampled
2019	sampled	sampled

2. Spatial-Station Water Quality Data

2.1 Methods

2.1.1 Area-Weighted Condition

Water quality within each estuary is characterized by the area-weighted mean of each measure. For estuaries containing multiple strata, summaries are computed for each stratum and on a park-wide basis. The area-weighted mean ($\bar{y}$) is computed 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. The area-weighted mean is computed separately for each measured depth, as applicable. Measurements from the first successful sampling event are used for hexagons containing trend stations. Despite several parks having existing monitoring programs prior to the implementation of the protocol, no hexagons contained multiple trend stations in the provided data set.

Condition is also characterized by the percent of estuarine area within quality categories for a subset of measures. Thresholds for chlorophyll-*a*, dissolved oxygen, and water clarity are defined in B. S. Kopp and Neckles (2009) and temperature thresholds are based on eelgrass (25 °C: Greve, Borum, and Pedersen (2003; Reusch et al. 2005); 28 °C: Shields, Parrish, and Moore (2019)) and hard clam (25 °C: Pratt and Campbell (1956; Grizzle and Lutz 1905)) tolerance (Table 2-1). The proportion of estuarine area in quality category j (p_j) is 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. The proportion of estuarine area containing missing observations is also provided. All computations were carried out using the R Statistical Computing Environment (R Core Team 2020).

Table 2-1. Threshold values associated with each measure quality category.

Measure	Quality Category*		
	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)	< 25 °C	25-28 °C	> 28 °C

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

2.1.2 General Linear Mixed Model (GLMM)

Consistent with the previous report by Caldwell et al. (2015), a general linear mixed model is used to determine whether there are differences in water quality measures among index periods. Year is treated as a categorical fixed effect and individual hexagons are included as random intercepts. The fitted model is used to test the hypothesis: H_0 : the mean measure value is the same across years versus H_1 : at least one of the year's means is different. If the null hypothesis is rejected at the 5% significance level (i.e., p -value < 0.05), then a multiple comparison test (MCT) is performed to determine which pairs of years have statistically different means based on Tukey-adjusted p -values¹.

Residual analysis indicated that the homogeneity of variance assumption is oftentimes violated. Therefore, each measure is log-transformed prior to fitting the model and the results of the MCT are presented on the log scale. Interpretation of the MCTs on the original scale should be reported as follows: it is estimated that the median for year t_0 is $\exp(\bar{Z}_0 - \bar{Z}_1)$ times as large as the median for year t_1 , where $\bar{Z}_0$ and $\bar{Z}_1$ represent the means of the log-transformed values for years t_0 and t_1 , respectively (Ramsey and Schafer 2012 Chapter 3.5).

For example, consider the comparison between years 2007 and 2013 for PAR attenuation within CACO (Figure 2-6). In this matrix, the values for $\bar{Z}_t$ are provided on the diagonal and the differences ($\bar{Z}_i - \bar{Z}_j$, $i \neq j$) are located on the upper diagonal entries. Note: a more detailed summary of the test statistics and confidence intervals associated with Figure 2-6 are provided in Table 2-24. For this comparison we would state: it is estimated that the median PAR attenuation in CACO during 2007 is $\exp(0.623) \approx 1.86$ times the median during 2013 (95% CI equal to $(1.23, 2.82)^2$). Stated another way: with 95% confidence, it is estimated that the median PAR attenuation in CACO during 2007 is between 1.23 and 2.82 times the median in 2013.

Analyses were carried out using the R Statistical Computing Environment (R Core Team 2020). The nlme package (Pinheiro et al. 2020) is used to fit the models and multiple comparison tests are carried out using the emmeans package (Lenth 2020).

2.1.3 Generalized Additive Model (GAM)

Based on initial exploratory analyses, several measures display potential nonlinear trends over time. Generalized additive models (GAMs; (Wood 2017)) are used to estimate trends in water quality measures as smooth functions over time. We refer the reader to Appendix A for a short primer on GAMs if desired.

Each water quality measure is 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 that we are modeling the

¹ See Appendix A for additional discussion of MCT family-wise error rate and p -value adjustments.

² The confidence intervals given in Table 2-24 are on the log scale. Therefore, we need to take the exponential of the upper and lower bound to put it on the response scale.

mean of the measure 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 (as opposed to the geometric mean³). Additionally, the log link has the added benefit of ensuring that simulated values used in power simulations will be non-negative.

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

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

where $i = 1, \dots, n$ indexes the respective 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 is modeled in the mean structure (i.e., first-order model specification⁴) 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 measures. For measures that did exhibit significant temporal autocorrelation, the lag-1 autocorrelation was generally less than 0.4.

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% 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 2020). Each model is fit using the *mgcv* package (Wood 2011) and results were summarized/visualized using the *gratia* package (Simpson 2020).

³ The geometric mean is defined as the n th root of the product of n numbers. For example, the geometric mean of the numbers 2, 5, and 7 is equal to $(2 \cdot 5 \cdot 7)^{1/3} = 70^{1/3} \approx 4.12$.

⁴ See Hefley et al. (2017) for additional discussion of first-order and second-order model specifications for modeling autocorrelation in ecological and environmental data.

2.1.4 Multivariate Mann-Kendall Trend Analysis

Despite several measures exhibiting non-linear trends over time, it is still of interest to quantify whether measures are increasing/decreasing over time. The multivariate Mann-Kendall test (trend R package; (Pohlert 2020)) is used to determine whether there exists a monotonically⁵ increasing or decreasing trend in values for all sites within the estuary over time (Libiseller and Grimvall 2002). Positive (negative) values of the test statistic Z_{MK} indicate that measurements tend to increase (decrease) with time. For example, based on the summary of tests provided in Table 2-14, we'd conclude that there is evidence of decreasing measurements over time for bottom dissolved oxygen concentration ($Z_{MK} = -2.16$; p -value = 0.030) and increasing measurements for surface salinity ($Z_{MK} = 2.00$; p -value = 0.045).

2.2 Pleasant Bay Stratum Results

2.2.1 Area-Weighted Condition Results

Sampling start and end dates for each index period are provided in Table 2-4. Area-weighted condition summaries for each measure are as follows:

Chlorophyll-*a* (near surface)

Area-weighted average near surface chlorophyll-*a* in the Pleasant Bay stratum ranged from 2.55 to 7.88 $\mu\text{g/L}$ and has been of good condition quality (i.e., $< 5 \mu\text{g/L}$) since 2014. Fair area-weighted average condition was observed from 2008 to 2013. The proportion of the estuary categorized as fair condition ranged from 5.8 to 71.3%.

Dissolved Oxygen (near bottom)

Area-weighted average near bottom dissolved oxygen concentration in the Pleasant Bay stratum was good (i.e., $> 5 \text{ mg/L}$) for every index period and ranged from 6.66 to 8.59 mg/L . The majority of area ($>80\%$) within the Pleasant Bay stratum was characterized as in good condition.

PAR Attenuation K_d (SAV standard)

Area-weighted average PAR attenuation was good in all sampled years except 2010 and ranged from 0.55 to 1.47 m^{-1} (Table 2-2). The majority of area ($>75\%$) within the Pleasant Bay stratum was characterized as being good condition since 2011 (Table 2-3).

pH

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

Salinity

Area-weighted average salinity ranged from 30.14 (bottom depth in 2011) to 33.04 psu (mid-depth in 2012).

⁵ A monotonically increasing function $f(x)$ is a function that is never decreasing for all values of x (e.g., $f(x) = 2x$, $f(x) = \log(x)$, $f(x) = e^x$, etc.), and vice versa for monotonically decreasing functions. Note that these functions can be either linear or non-linear.

Temperature (near surface)

Area-weighted average near surface water temperature ranged from 19.13 to 23.23 °C. Excluding the 2012, temperatures less than 25 °C were observed in at least 75% of Pleasant Bay stratum.

Turbidity

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

Table 2-2. Area-weighted average water quality condition at Pleasant Bay stratum of Cape Cod National Seashore during the index periods of 2007-2019.

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

Table 2-3. Proportion of monitored estuarine resources falling into each quality category at Cape Cod National Seashore during the index periods of 2007-2019.

Measure	Condition	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019
Bottom dissolved oxygen (mg/L)	Good	94.6	80.3	87.0	100.0	100.0	100.0	99.9	100.0	99.9	100.0	100.0
Bottom dissolved oxygen (mg/L)	Fair	5.4	19.7	13.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Bottom dissolved oxygen (mg/L)	Poor	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	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	0.0
Chlorophyll a ($\mu\text{g/L}$)	Good	70.3	71.9	28.7	41.8	59.7	45.0	70.4	66.2	90.2	83.6	94.2
Chlorophyll a ($\mu\text{g/L}$)	Fair	29.7	28.1	71.3	57.5	34.6	49.3	29.6	33.8	5.8	16.3	5.8
Chlorophyll a ($\mu\text{g/L}$)	Poor	0.0	0.0	0.0	0.8	5.8	5.6	0.0	0.0	4.0	0.1	0.0
Chlorophyll a ($\mu\text{g/L}$)	Missing	0.0	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	24.2	44.4	63.5	27.1	75.6	94.2	83.7	77.1	99.9	94.2	94.2
PAR attenuation (K_d (m^{-1}))	Fair	14.5	14.8	4.3	33.8	19.2	5.8	16.3	22.9	0.1	5.7	5.8
PAR attenuation (K_d (m^{-1}))	Poor	0.0	0.0	7.8	17.2	5.2	0.0	0.0	0.0	0.0	0.1	0.0
PAR attenuation (K_d (m^{-1}))	Missing	61.3	40.8	24.4	21.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature ($^{\circ}\text{C}$)	<25	93.2	90.1	89.8	76.4	94.2	64.2	87.7	94.2	94.7	84.7	77.5
Surface Temperature ($^{\circ}\text{C}$)	25-28	0.0	9.9	10.2	23.6	5.8	30.1	11.8	5.8	5.3	12.3	21.9
Surface Temperature ($^{\circ}\text{C}$)	>28	0.0	0.0	0.0	0.0	0.0	5.8	0.5	0.0	0.0	3.1	0.6
Surface Temperature ($^{\circ}\text{C}$)	Missing	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2-4. Sampling start and end dates for each index period within Cape Cod National Seashore Pleasant Bay stratum.

Stratum	Year	Start	End
Pleasant Bay	2007	2007-07-25	2007-08-15
Pleasant Bay	2008	2008-07-08	2008-07-24
Pleasant Bay	2009	2009-07-29	2009-08-11
Pleasant Bay	2010	2010-07-07	2010-07-22
Pleasant Bay	2011	2011-07-12	2011-08-03
Pleasant Bay	2012	2012-07-17	2012-08-08
Pleasant Bay	2013	2013-07-09	2013-07-30
Pleasant Bay	2014	2014-07-02	2014-07-22
Pleasant Bay	2016	2016-07-06	2016-07-29
Pleasant Bay	2018	2018-07-19	2018-08-07
Pleasant Bay	2019	2019-07-15	2019-08-05

2.2.2 GAM Results

The generalized additive model summaries indicate that there exists statistically significant (assuming a 0.05 significance level) spatial and temporal trends within the Pleasant Bay stratum for several water quality measures (Table 2-5). Notable observations from the fitted smooths for each measure are as follows:

Chlorophyll-*a* (near surface)

Chlorophyll-*a* exhibited a slightly concave down trend with no periods of statistically significant change (Figure 2-1). Based on the fitted model, both time and location account for 60.5% of the variability in chlorophyll-*a* concentrations within Pleasant Bay stratum (Table 2-6).

Dissolved Oxygen (near bottom)

Bottom dissolved oxygen exhibited a slightly concave up trend with no periods of statistically significant change (Figure 2-1). The fitted model does very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 11.6% of the variation within Pleasant Bay stratum (Table 2-6).

PAR Attenuation *K_d* (SAV standard)

The temporal trend in PAR attenuation is slightly decreasing with no periods of statistically significant change (Figure 2-1). Based on the fitted model, both time and location account for only 33.1% of the variability in PAR attenuation within Pleasant Bay stratum (Table 2-6).

Salinity (near surface)

Surface salinity exhibited a non-linear temporal trend (edf = 4.00) with no periods of statistically significant change (Figure 2-1). Based on the fitted model, both time and location account for 58.1% of the variability in salinity within Pleasant Bay stratum (Table 2-6).

Temperature (near surface)

Surface water temperature within the Pleasant Bay stratum exhibited a non-linear temporal trend that has been increasing over time (Figure 2-1). Based on the fitted model, both time and location account for 70% of the variability in water temperature within Pleasant Bay stratum (Table 2-6).

Turbidity (near surface)

No temporal trend exists in surface turbidity and the mean trend is estimated to be constant from 2007 to 2019 (Figure 2-1). Time and location account for 50% of the variation in turbidity within Pleasant Bay stratum (Table 2-6).

Table 2-5. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Pleasant Bay 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]

Measure	Depth	Model Term	edf	F-value	p-value
Chlorophyll <i>a</i> ($\mu\text{g/L}$)	Surface	s(year)	2.05	1.66	< 0.001
Chlorophyll <i>a</i> ($\mu\text{g/L}$)	Surface	s(long, lat)	8.38	3.39	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	1.29	0.46	0.028
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	2.36	0.34	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	1.43	0.37	0.071
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	4.64	0.88	< 0.001
Salinity (psu)	Surface	s(year)	4.00	1.67	0.007
Salinity (psu)	Surface	s(long, lat)	8.43	2.96	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	3.69	1.57	0.002
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	10.98	5.51	< 0.001
Turbidity (NTU)	Surface	s(year)	0.00	0.00	0.361
Turbidity (NTU)	Surface	s(long, lat)	6.88	2.34	< 0.001

Table 2-6. Proportion of null deviance explained by the explanatory variables for each Cape Cod National Seashore Pleasant Bay model.

Measure	Deviance Explained
Chlorophyll <i>a</i> ($\mu\text{g/L}$)	60.5%
Dissolved oxygen (mg/L)	11.6%
PAR attenuation (K_d (m^{-1}))	33.1%
Salinity (psu)	58.1%
Temperature ($^{\circ}\text{C}$)	70.0%
Turbidity (NTU)	50.0%

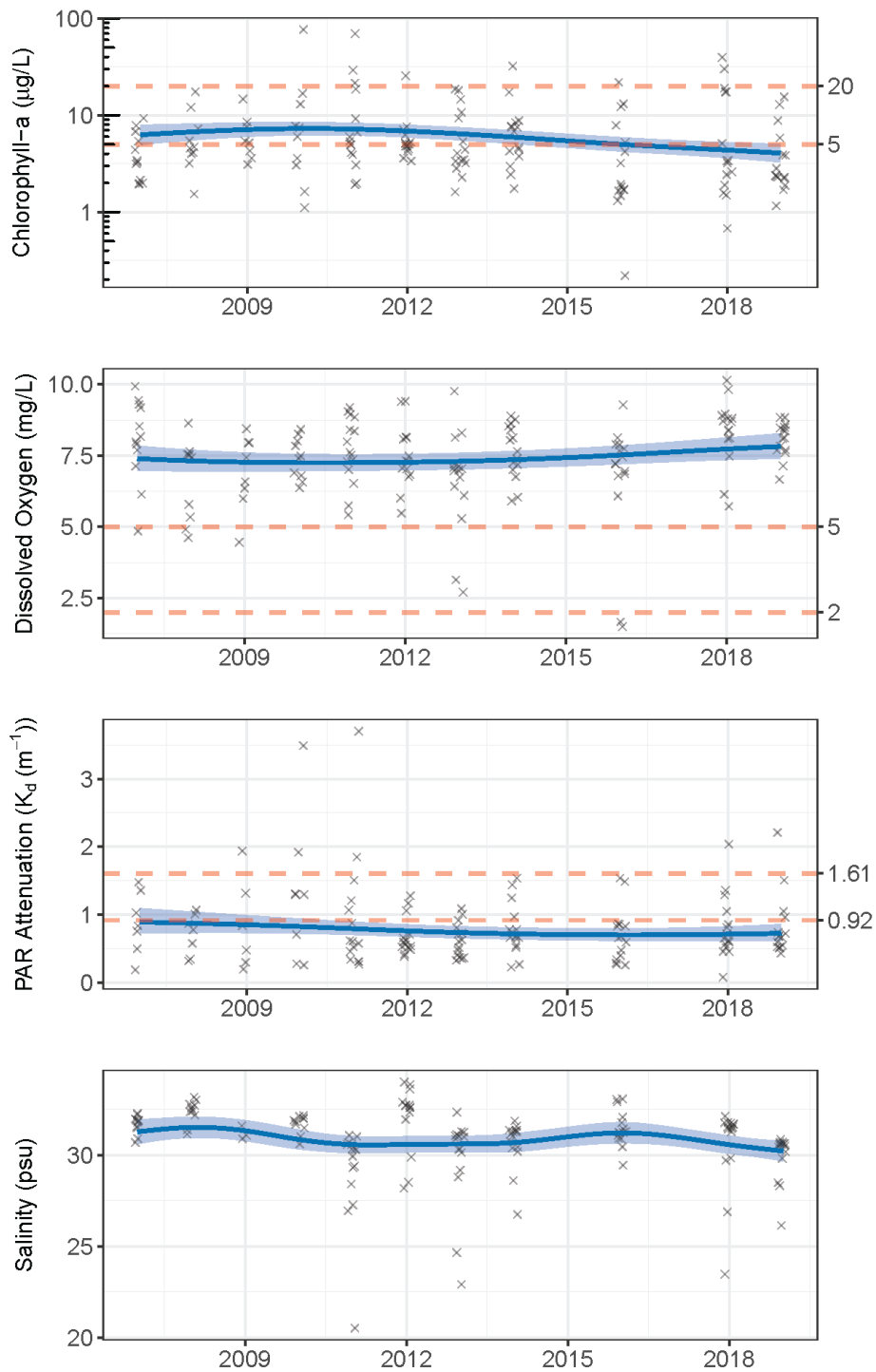


Figure 2-1. Trends in Cape Cod National Seashore Pleasant Bay water quality measures based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted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

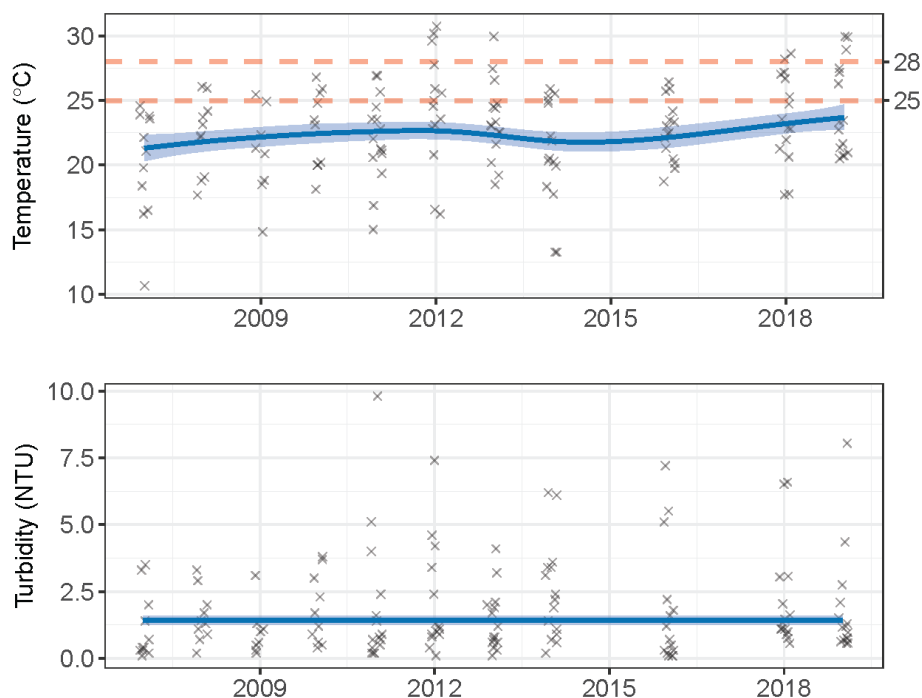


Figure 2-1 (continued). Trends in Cape Cod National Seashore Pleasant Bay water quality measures based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present,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

2.2.3 Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate that there is a statistically significant decreasing monotonic trend in chlorophyll- (p -value = 0.047) and increasing monotonic trend in surface temperature (p -value = 0.037) within the Pleasant Bay stratum during the period of 2007 to 2020 (Table 2-7).

Table 2-7. Summary of multivariate Mann-Kendall test for monotonic trend for each Cape Cod National Seashore Pleasant Bay measure: 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.

Measure	Depth	Z_{MK}	p -value
Chlorophyll <i>a</i> ($\mu\text{g/L}$)	Surface	-1.99	0.047
Dissolved oxygen (mg/L)	Bottom	1.57	0.115
PAR attenuation (K_d (m^{-1}))	Water Column	1.24	0.214
Salinity (psu)	Surface	-0.74	0.460
Temperature ($^{\circ}\text{C}$)	Surface	2.08	0.037
Turbidity (NTU)	Surface	1.66	0.096

2.3 Nauset Harbor Stratum Results

2.3.1 Area-Weighted Condition Results

Sampling start and end dates for each index period are provided in Table 2-10. Area-weighted condition summaries for each measure are as follows:

Chlorophyll-*a* (near surface)

Area-weighted average near surface chlorophyll-*a* ranged from 4.08 to 10.08 $\mu\text{g/L}$ and was near the good/fair threshold for a majority of the index periods. The proportion of Nauset Harbor stratum categorized as fair condition ranged from 41 to 95%. At most 12% of the stratum was in poor condition during 2007 to 2013. The maximum observed proportion of area in good condition (i.e., < 5 $\mu\text{g/L}$) was 70.9% and it occurred in 2018.

Dissolved Oxygen (near bottom)

Area-weighted average near bottom dissolved oxygen concentration was good (i.e., > 5 mg/L) for every index period and ranged from 6.82 to 8.50 mg/L. The majority of area (>85%) within the Nauset Harbor stratum was characterized as in good condition. Approximately 5% of the stratum was characterized as having poor dissolved oxygen condition (i.e., < 2 mg/L) in years 2010, 2011, 2018, and 2019.

PAR Attenuation K_d (SAV standard)

Area-weighted average PAR attenuation within Nauset Harbor ranged from 0.52 to 1.82 m^{-1} (Table 2-8). Since 2010, a majority of the stratum was characterized as being in either fair or good condition (Table 2-9).

pH

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

Salinity

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

Temperature (near surface)

Area-weighted average near surface water temperature ranged from 20.01 to 24.42 °C. Excluding 2019 (which was the hottest), temperatures less than 25 °C were observed in at least 80% of the Nauset Harbor stratum.

Turbidity

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

Table 2-8. Area-weighted average water quality condition at Nauset Harbor stratum of Cape Cod National Seashore during the index periods of 2007-2019.

Measure	Depth	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019
Chlorophyll <i>a</i> (µg/L)	Surface	8.14	10.08	9.97	10.79	8.72	9.37	9.26	9.96	4.65	4.08	7.84
Dissolved oxygen (% saturation)	Surface	104.30	94.82	97.59	107.23	105.56	100.65	120.02	103.93	107.78	111.75	116.92
Dissolved oxygen (% saturation)	Mid-Depth	103.51	89.96	94.69	102.25	106.54	97.33	129.60	98.83	114.33	108.33	97.03
Dissolved oxygen (% saturation)	Bottom	100.24	91.20	93.18	99.82	100.65	99.43	119.73	102.59	105.38	105.72	108.26
Dissolved oxygen (mg/L)	Surface	7.78	7.18	7.06	8.10	7.88	7.26	8.44	7.72	7.84	8.10	8.18
Dissolved oxygen (mg/L)	Mid-Depth	7.81	6.86	6.92	7.73	7.86	7.02	8.98	7.51	8.23	8.08	7.16
Dissolved oxygen (mg/L)	Bottom	7.55	6.99	6.82	7.65	7.58	7.23	8.50	7.65	7.72	7.72	7.62
PAR attenuation (K_d (m ⁻¹))	Water Column	1.69	1.20	1.82	0.55	0.63	0.76	0.52	0.88	0.64	0.69	0.93
pH	Surface	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.50	7.94
pH	Mid-Depth	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.58	7.88
pH	Bottom	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.48	7.90
Salinity (psu)	Surface	31.60	31.51	31.23	31.31	29.71	32.39	30.49	31.29	32.22	31.88	30.48
Salinity (psu)	Mid-Depth	31.77	31.69	31.32	31.64	30.08	32.46	30.57	31.11	32.43	32.04	30.68
Salinity (psu)	Bottom	31.79	31.50	31.40	31.52	29.97	32.60	30.82	31.36	32.29	31.92	30.58
Temperature (°C)	Surface	21.17	20.03	21.28	20.01	21.34	22.58	24.01	21.10	21.89	22.16	24.42
Temperature (°C)	Mid-Depth	20.56	19.72	20.58	20.08	21.83	22.55	25.02	20.08	22.43	20.64	21.92
Temperature (°C)	Bottom	20.20	19.51	20.26	19.24	20.66	22.10	23.42	20.87	21.51	21.80	24.10
Turbidity (NTU)	Surface	1.95	1.92	2.47	3.09	2.20	2.47	1.70	3.55	2.99	1.76	2.38
Turbidity (NTU)	Mid-Depth	1.77	1.55	2.41	3.91	1.61	4.28	1.66	2.79	3.22	0.81	1.42
Turbidity (NTU)	Bottom	9.91	3.15	3.13	9.76	2.19	2.42	1.89	4.23	2.98	2.09	3.09

Table 2-9. Proportion of monitored estuarine resources falling into each quality category at Nauset Harbor stratum of Cape Cod National Seashore during the index periods of 2007-2019.

Measure	Condition	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019
Bottom dissolved oxygen (mg/L)	Good	89.4	85.8	94.2	94.2	95.4	92.0	100.0	95.4	94.4	95.4	89.9
Bottom dissolved oxygen (mg/L)	Fair	10.6	14.2	5.8	0.0	0.0	8.0	0.0	4.6	5.6	0.0	5.6
Bottom dissolved oxygen (mg/L)	Poor	0.0	0.0	0.0	5.8	4.6	0.0	0.0	0.0	0.0	4.6	4.6
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	0.0
Chlorophyll a ($\mu\text{g/L}$)	Good	20.0	16.5	37.7	12.9	41.9	41.0	30.1	4.9	59.2	70.9	31.6
Chlorophyll a ($\mu\text{g/L}$)	Fair	74.2	77.9	55.6	81.9	53.6	47.8	60.7	95.1	40.8	29.1	68.4
Chlorophyll a ($\mu\text{g/L}$)	Poor	5.8	5.6	6.7	5.2	4.6	11.3	9.3	0.0	0.0	0.0	0.0
Chlorophyll a ($\mu\text{g/L}$)	Missing	0.0	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	24.5	27.7	38.6	59.5	73.8	73.5	94.1	44.9	81.6	57.5	47.5
PAR attenuation (K_d (m^{-1}))	Fair	56.1	41.1	0.0	3.2	26.2	26.5	0.0	49.2	18.4	37.2	51.7
PAR attenuation (K_d (m^{-1}))	Poor	11.3	10.5	45.3	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.7
PAR attenuation (K_d (m^{-1}))	Missing	8.1	20.6	16.1	36.0	0.0	0.0	5.9	5.9	0.0	5.3	0.0
Surface Temperature ($^{\circ}\text{C}$)	<25	93.8	92.8	93.0	100.0	100.0	81.0	74.8	100.0	80.3	79.5	43.2
Surface Temperature ($^{\circ}\text{C}$)	25-28	0.0	0.0	7.0	0.0	0.0	19.0	11.0	0.0	19.7	20.5	47.2
Surface Temperature ($^{\circ}\text{C}$)	>28	0.0	0.0	0.0	0.0	0.0	0.0	14.2	0.0	0.0	0.0	9.6
Surface Temperature ($^{\circ}\text{C}$)	Missing	6.2	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2-10. Sampling start and end dates for each index period within Cape Cod National Seashore Nauset Harbor stratum.

Stratum	Year	Start	End
Nauset Harbor	2007	2007-08-02	2007-08-22
Nauset Harbor	2008	2008-07-10	2008-07-28
Nauset Harbor	2009	2009-07-15	2009-08-17
Nauset Harbor	2010	2010-07-26	2010-08-17
Nauset Harbor	2011	2011-07-06	2011-07-25
Nauset Harbor	2012	2012-07-09	2012-07-30
Nauset Harbor	2013	2013-07-08	2013-07-29
Nauset Harbor	2014	2014-07-01	2014-07-23
Nauset Harbor	2016	2016-07-12	2016-08-03
Nauset Harbor	2018	2018-08-27	2018-08-29
Nauset Harbor	2019	2019-07-31	2019-08-16

2.3.2 GAM Results

The generalized additive model summaries indicate that there exists statistically significant (assuming a 0.05 significance level) spatial and temporal trends within the Nauset Harbor stratum for several water quality measures (Table 2-11). Notable observations from the fitted smooths for each measure are as follows:

Chlorophyll-*a* (near surface)

Chlorophyll-*a* exhibited a non-linear temporal trend with a statistically significant decrease occurring between 2014 and 2016 (Figure 2-2). Based on the fitted model, both time and location account for 55.1% of the variability in chlorophyll-*a* concentrations within the Nauset Harbor stratum (Table 2-12).

Dissolved Oxygen (near bottom)

No temporal trend exists in bottom dissolved oxygen and the mean trend is estimated to be constant from 2007 to 2019 (Figure 2-2). The fitted model does very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 5.7% of the variation within the Nauset Harbor stratum (Table 2-12).

PAR Attenuation K_d (SAV standard)

The temporal trend in PAR attenuation is slightly concave upward ($\text{edf} = 2.68$) with a statistically significant decrease occurring between 2009 and 2010 (Figure 2-2). Based on the fitted model, both time and location account for only 20.8% of the variability in PAR attenuation within the Nauset Harbor stratum (Table 2-12).

Salinity (near surface)

Surface salinity exhibited a non-linear temporal trend ($\text{edf} = 6.15$) with a statistically significant increase in 2014 followed by a decrease around 2018 (Figure 2-2). The mean trend is near the 25 °C threshold in 2012, 2014, and 2019. Based on the fitted model, both time and location account for only 32.1% of the variation in salinity within the Nauset Harbor stratum (Table 2-12).

Temperature (near surface)

Surface water temperature exhibited a non-linear increasing temporal trend (Figure 2-2 (continued)). Based on the fitted model, both time and location account for 62.8% of the variability in water temperature within the Nauset Harbor stratum (Table 2-12).

Turbidity (near surface)

The temporal trend in surface turbidity indicates measurements have remained relatively constant with no periods of statistically significant change (Figure 2-2 (continued)). Time and location account for only 10.3% of the variation in turbidity within the Nauset Harbor stratum (Table 2-12).

Table 2-11. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Nauset Harbor 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]

Measure	Depth	Model Term	edf	F -value	p -value
Chlorophyll a ($\mu\text{g/L}$)	Surface	s(year)	5.49	5.10	< 0.001
Chlorophyll a ($\mu\text{g/L}$)	Surface	s(long, lat)	4.54	2.32	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	0.00	0.00	0.334
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	1.85	0.43	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	2.68	2.39	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	0.00	0.00	0.732
Salinity (psu)	Surface	s(year)	6.15	5.33	< 0.001
Salinity (psu)	Surface	s(long, lat)	2.71	0.34	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	5.48	6.44	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	7.68	3.74	< 0.001
Turbidity (NTU)	Surface	s(year)	1.23	0.15	0.297
Turbidity (NTU)	Surface	s(long, lat)	1.80	0.19	0.007

Table 2-12. Proportion of null deviance explained by the explanatory variables for each Cape Cod National Seashore Nauset Harbor model.

Measure	Deviance Explained
Chlorophyll a ($\mu\text{g/L}$)	55.1%
Dissolved oxygen (mg/L)	5.7%
PAR attenuation (K_d (m^{-1}))	20.8%
Salinity (psu)	32.1%
Temperature ($^{\circ}\text{C}$)	62.8%
Turbidity (NTU)	10.3%

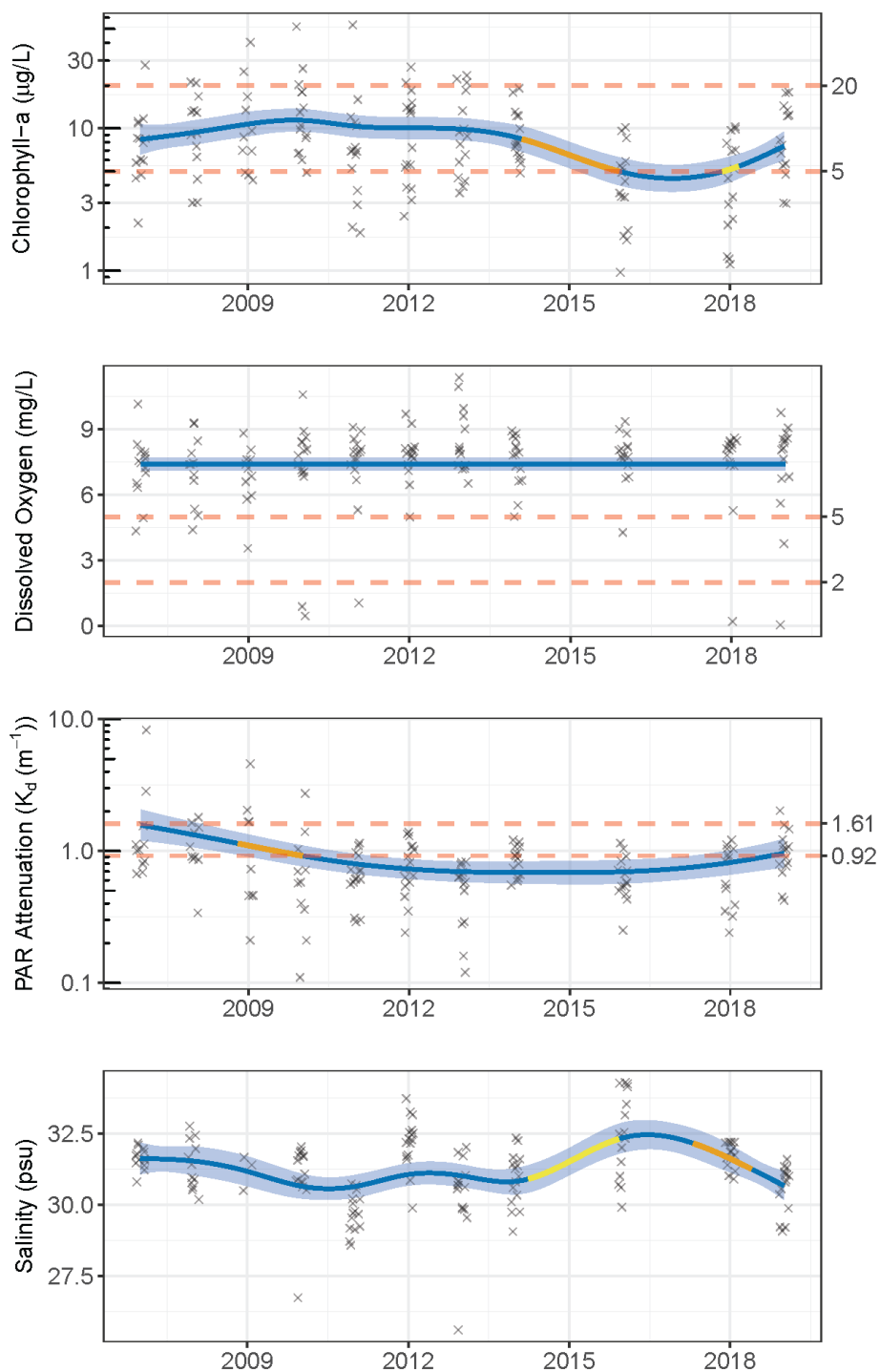


Figure 2-2. Trends in Cape Cod National Seashore Nauset Harbor water quality measures based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: in some instances, the y-axis is transformed to the log₁₀ scale to better visualize the estimated trend.

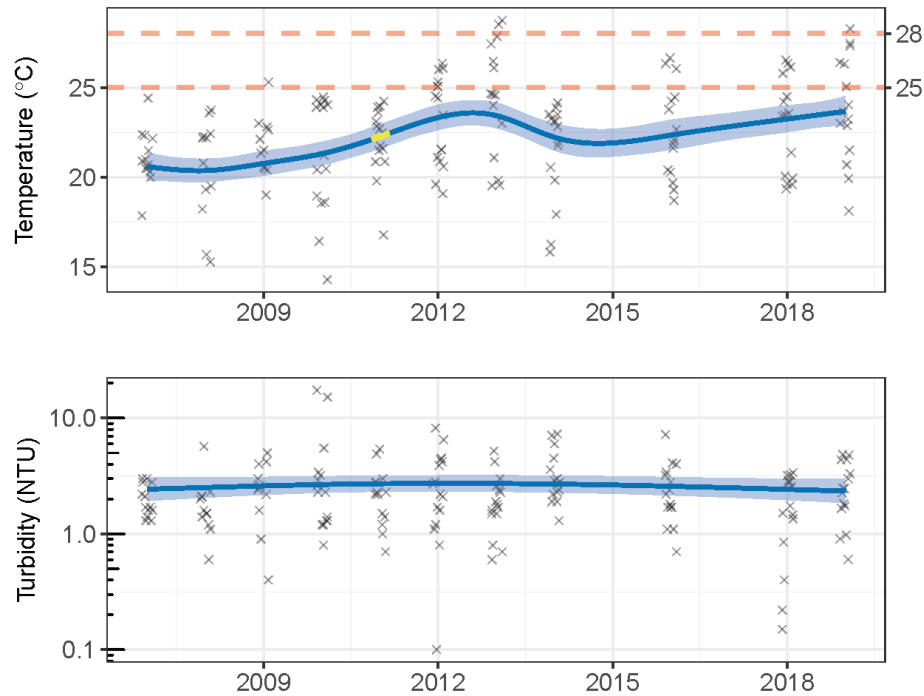


Figure 2-2 (continued). Trends in Cape Cod National Seashore Nauset Harbor water quality measures based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present,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

2.3.3 Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there is a statistically significant monotonic increase in both bottom dissolved oxygen (p -value = 0.001) and surface temperature (p -value = 0.008) within the Nauset Harbor stratum during 2007 to 2019 (Table 2-13).

Table 2-13. Summary of multivariate Mann-Kendall test for monotonic trend for each Cape Cod National Seashore Nauset Harbor measure: 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.

Measure	Depth	Z_{MK}	p -value
Chlorophyll <i>a</i> ($\mu\text{g/L}$)	Surface	-1.46	0.146
Dissolved oxygen (mg/L)	Bottom	3.46	0.001
PAR attenuation (K_d (m^{-1}))	Water Column	0.20	0.838
Salinity (psu)	Surface	-0.01	0.989
Temperature ($^{\circ}\text{C}$)	Surface	2.67	0.008
Turbidity (NTU)	Surface	1.56	0.119

2.4 Salt Pond Stratum Results

2.4.1 Area-Weighted Condition Results

Sampling start and end dates for each index period are provided in Table 2-16. Area-weighted condition summaries for each measure are as follows:

Chlorophyll-*a* (near surface)

Area-weighted average near surface chlorophyll-*a* ranged from 8.23 to 29.53 $\mu\text{g/L}$ and was fair (i.e., 5-20 $\mu\text{g/L}$) for every sampled year. Since 2012, the proportion of the Salt Pond stratum categorized as fair condition has ranged from 68 to 92%. Approximately 30% of the stratum was in poor condition during 2007 and 2011. The maximum observed proportion of area in good condition (i.e., < 5 $\mu\text{g/L}$) during the index periods was 42.7% which occurred in 2010.

Dissolved Oxygen (near bottom)

Area-weighted average near bottom dissolved oxygen concentration was good (i.e., > 5 mg/L) for every index period except 2009 and ranged from 4.07 to 6.65 mg/L. Except for 2009, the majority of area (>68%) within the stratum was characterized as in good condition.

PAR Attenuation K_d (SAV standard)

Area-weighted average PAR attenuation ranged from 0.65 to 3.53 m^{-1} (Table 2-14). Since 2011, >60% of the Salt Pond stratum was characterized as being in good condition (Table 2-15).

pH

Area-weighted average pH ranged from 7.81 to 7.94. Measurements of pH began in 2018.

Salinity

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

Temperature (near surface)

Area-weighted average near surface water temperature ranged from 22.54 to 26.01 °C. Temperatures in the 25-28 °C range were observed in at most 35% of Salt Pond stratum.

Turbidity

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

Table 2-14. Area-weighted average water quality condition at Salt Pond stratum of Cape Cod National Seashore during the index periods of 2007-2019.

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

Table 2-15. Proportion of monitored estuarine resources falling into each quality category at Salt Pond stratum of Cape Cod National Seashore during the index periods of 2007-2019.

Measure	Condition	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019
Bottom dissolved oxygen (mg/L)	Good	73.4	85.3	41.7	74.8	74.3	85.8	87.1	78.1	90.4	67.6	79.9
Bottom dissolved oxygen (mg/L)	Fair	16.5	14.7	23.5	25.2	25.7	14.2	3.3	12.3	0.0	32.4	15.4
Bottom dissolved oxygen (mg/L)	Poor	10.1	0.0	34.9	0.0	0.0	0.0	9.6	9.6	9.6	0.0	4.7
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	0.0
Chlorophyll a ($\mu\text{g/L}$)	Good	35.2	0.0	0.0	42.7	0.0	0.0	5.0	21.6	26.7	21.6	17.9
Chlorophyll a ($\mu\text{g/L}$)	Fair	34.3	95.2	7.2	37.9	64.8	88.1	91.7	77.0	70.0	75.1	67.9
Chlorophyll a ($\mu\text{g/L}$)	Poor	30.5	4.8	20.3	19.4	35.2	11.9	3.3	1.4	3.3	3.3	14.2
Chlorophyll a ($\mu\text{g/L}$)	Missing	0.0	0.0	72.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m^{-1}))	Good	13.1	50.0	33.4	48.7	59.5	64.9	89.0	75.2	94.7	82.9	66.5
PAR attenuation (K_d (m^{-1}))	Fair	22.5	19.5	54.3	6.4	40.5	25.8	11.0	23.4	2.0	17.1	30.2
PAR attenuation (K_d (m^{-1}))	Poor	28.6	9.3	1.4	34.0	0.0	9.3	0.0	1.4	3.3	0.0	3.3
PAR attenuation (K_d (m^{-1}))	Missing	35.8	21.2	10.9	10.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surface Temperature ($^{\circ}\text{C}$)	<25	100.0	85.3	19.5	79.2	82.0	66.0	46.6	95.3	95.3	82.0	78.6
Surface Temperature ($^{\circ}\text{C}$)	25-28	0.0	14.7	7.9	20.8	18.0	34.0	35.4	4.7	4.7	18.0	21.4
Surface Temperature ($^{\circ}\text{C}$)	>28	0.0	0.0	0.0	0.0	0.0	0.0	18.0	0.0	0.0	0.0	0.0
Surface Temperature ($^{\circ}\text{C}$)	Missing	0.0	0.0	72.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2-16. Sampling start and end dates for each index period within Cape Cod National Seashore Salt Pond stratum.

Stratum	Year	Start	End
Salt Pond	2007	2007-08-10	2007-08-13
Salt Pond	2008	2008-07-01	2008-07-02
Salt Pond	2009	2009-07-29	2009-08-18
Salt Pond	2010	2010-07-19	2010-08-17
Salt Pond	2011	2011-07-19	2011-07-26
Salt Pond	2012	2012-07-16	2012-07-20
Salt Pond	2013	2013-07-17	2013-07-29
Salt Pond	2014	2014-07-08	2014-07-17
Salt Pond	2016	2016-07-12	2016-07-20
Salt Pond	2018	2018-08-16	2018-08-23
Salt Pond	2019	2019-08-15	2019-08-19

2.4.2 GAM Results

The generalized additive model summaries indicate that there exists statistically significant (assuming a 0.05 significance level) spatial and temporal trends within the Salt Pond stratum for surface chlorophyll-*a* concentration, surface temperature, and surface turbidity (Table 2-17). Notable observations from the fitted smooths for each measure are as follows:

Chlorophyll-*a* (near surface)

Chlorophyll-*a* exhibited a slightly decreasing temporal trend with no periods of statistically significant change (Figure 2-3). Based on the fitted model, both time and location account for 42.4% of the variability in chlorophyll-*a* concentrations within the Salt Pond stratum (Table 2-18).

Dissolved Oxygen (near bottom)

No temporal trend exists in bottom dissolved oxygen and the mean trend is estimated to be constant from 2007 to 2019 (Figure 2-3). The fitted model does very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 4.3% of the variation within the Salt Pond stratum (Table 2-18).

PAR Attenuation K_d (SAV standard)

The temporal trend in PAR attenuation is slightly decreasing over time and the most recent mean is within the good condition category (Figure 2-3). No periods of statistically significant change were identified. The fitted model does very poorly explaining variation in PAR attenuation, with time and location accounting for only 4.7% of the variability within the Salt Pond stratum (Table 2-18).

Salinity (near surface)

Surface salinity exhibited a slightly concave up temporal trend with no periods of statistically significant change (Figure 2-3). The fitted model does very poorly explaining variation in surface salinity, with time and location accounting for only 3.5% of the variation within the Salt Pond stratum (Table 2-18).

Temperature (near surface)

Surface water temperature exhibited a highly non-linear temporal trend (edf = 8.47) with a few periods of statistically significant increases and decreases (Figure 2-3 (continued)). Temperatures were increasing from 2007 to 2013 before dropping back down to pre-2009 mean values. Based on the fitted model, both time and location account for 67.9% of the variability in water temperature within the Salt Pond stratum (Table 2-18).

Turbidity (near surface)

The temporal trend in surface turbidity is slightly decreasing with no periods of statistically significant change (Figure 2-2 (continued)). Time and location account for 44.9% of the variation in turbidity within the Salt Pond stratum (Table 2-18).

Table 2-17. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Salt Pond 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]

Measure	Depth	Model Term	edf	<i>F</i> -value	<i>p</i> -value
Chlorophyll <i>a</i> (µg/L)	Surface	s(year)	1.45	0.57	0.019
Chlorophyll <i>a</i> (µg/L)	Surface	s(long, lat)	7.91	1.25	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	0.00	0.00	0.292
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	1.62	0.13	0.015
PAR attenuation (K_d (m ⁻¹))	Water Column	s(year)	1.33	0.20	0.211
PAR attenuation (K_d (m ⁻¹))	Water Column	s(long, lat)	0.00	0.00	0.595
Salinity (psu)	Surface	s(year)	1.38	0.39	0.104
Salinity (psu)	Surface	s(long, lat)	0.00	0.00	0.412
Temperature (°C)	Surface	s(year)	8.47	9.90	< 0.001
Temperature (°C)	Surface	s(long, lat)	7.13	2.51	< 0.001
Turbidity (NTU)	Surface	s(year)	2.05	1.17	0.002
Turbidity (NTU)	Surface	s(long, lat)	9.51	0.48	0.008

Table 2-18. Proportion of null deviance explained by the explanatory variables for each Cape Cod National Seashore Salt Pond model.

Measure	Deviance Explained
Chlorophyll <i>a</i> (µg/L)	42.4%
Dissolved oxygen (mg/L)	4.3%
PAR attenuation (K_d (m ⁻¹))	4.7%
Salinity (psu)	3.5%
Temperature (°C)	67.9%
Turbidity (NTU)	44.9%

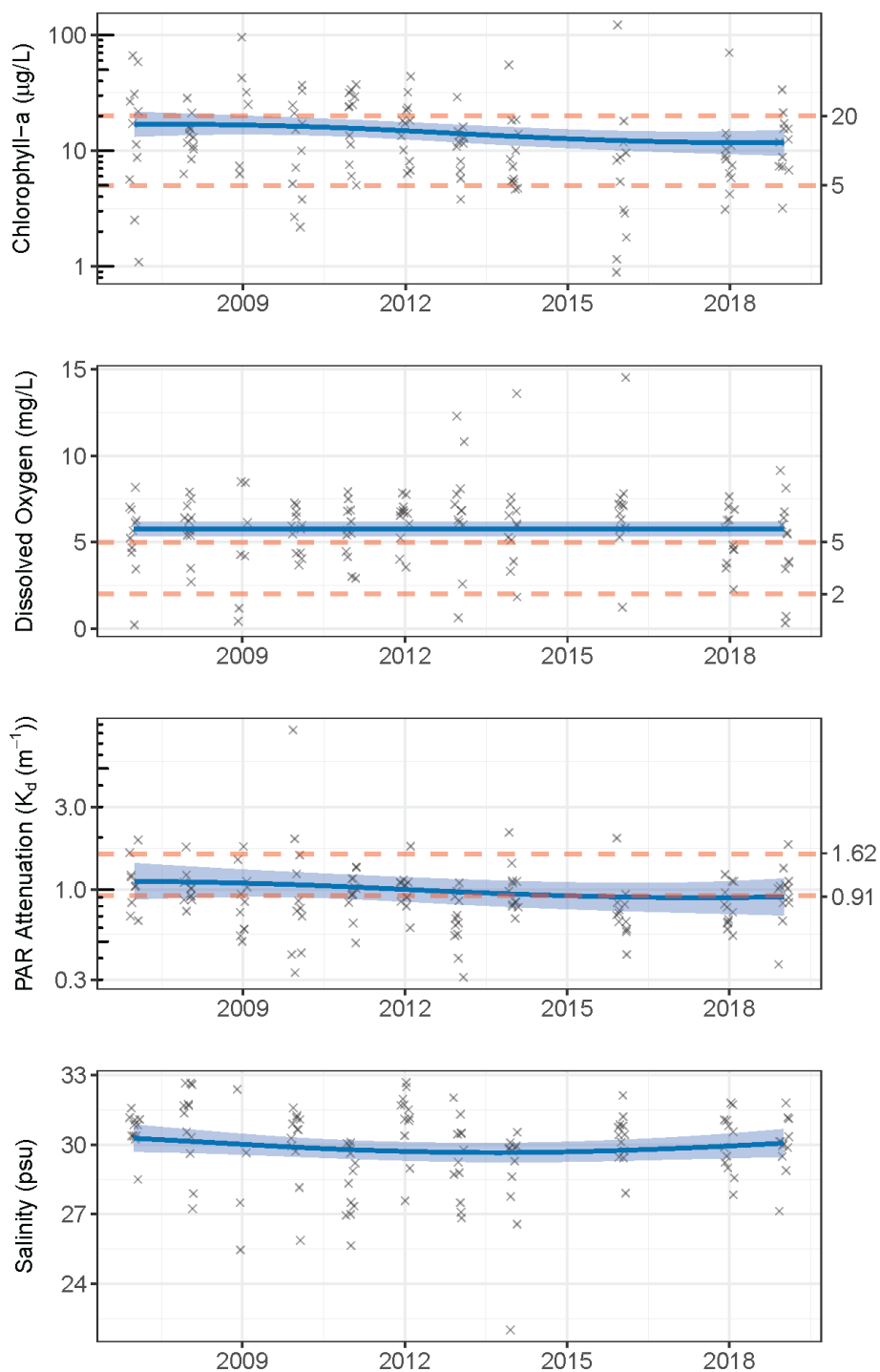


Figure 2-3. Trends in Cape Cod National Seashore Salt Pond water quality measures based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: in some instances, the y-axis is transformed to the log₁₀ scale to better visualize the estimated trend.

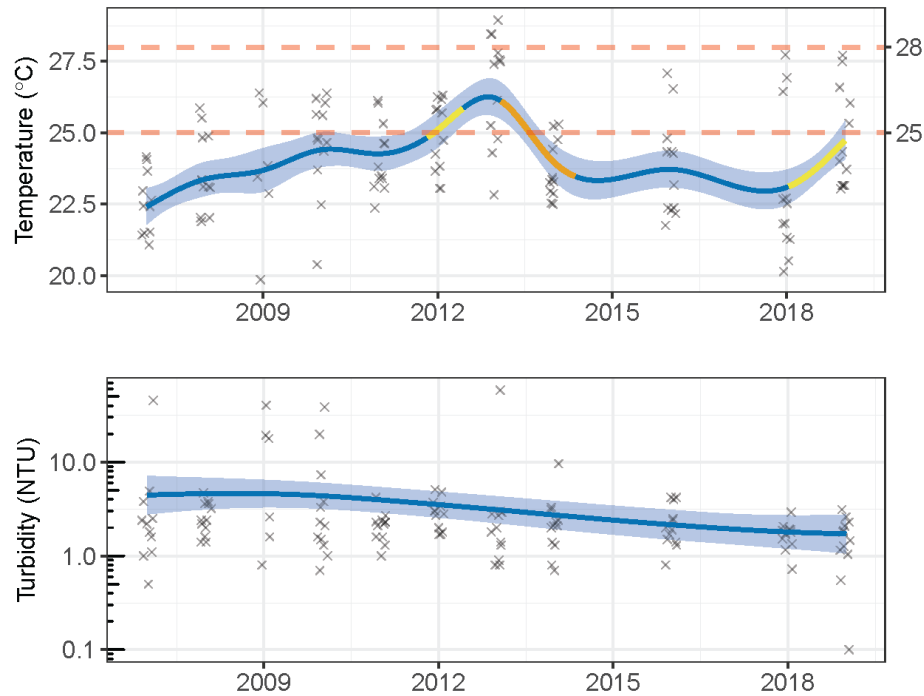


Figure 2-3 (continued). Trends in Cape Cod National Seashore Salt Pond water quality measures based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: in some instances, the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend.

2.4.3 Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there is a statistically significant monotonic increase in both bottom dissolved oxygen (p -value = 0.001) and surface temperature (p -value = 0.008) within the Nauset Harbor stratum during 2007 to 2019 (Table 2-13).

Table 2-19. Summary of multivariate Mann-Kendall test for monotonic trend for each Cape Cod National Seashore Salt Pond measure: 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.

Measure	Depth	Z_{MK}	p -value
Chlorophyll <i>a</i> ($\mu\text{g/L}$)	Surface	-1.99	0.046
Dissolved oxygen (mg/L)	Bottom	1.33	0.184
PAR attenuation (K_d (m^{-1}))	Water Column	-0.68	0.496
Salinity (psu)	Surface	-0.35	0.729
Temperature ($^{\circ}\text{C}$)	Surface	1.29	0.198
Turbidity (NTU)	Surface	-1.27	0.203

2.5 All Strata Results

2.5.1 Area-Weighted Condition Results

Area-weighted condition summaries for each measure are as follows:

Chlorophyll-*a* (near surface)

Area-weighted average near surface chlorophyll-*a* ranged from 3.71 to 8.75 $\mu\text{g/L}$ and was fair (i.e., 5-20 $\mu\text{g/L}$) for a majority of the index periods. Good area-weighted average condition ($< 5 \mu\text{g/L}$) has been observed since 2016. The proportion of the estuary categorized as fair condition ranged from 15 to 63%. Approximately 7% of the estuary was in poor condition during 2011 and 2012. The maximum observed proportion of area in good condition (i.e., $< 5 \mu\text{g/L}$) during the index periods was 81.7% which occurred in 2016.

Dissolved Oxygen (near bottom)

Area-weighted average near bottom dissolved oxygen concentration was good (i.e., $> 5 \text{ mg/L}$) for every index period and ranged from 6.62 to 8.30 mg/L . The majority of area ($>80\%$) within the estuary was characterized as in good condition.

PAR Attenuation K_d (SAV standard)

Area-weighted average PAR ranged from 0.55 to 1.46 m^{-1} (Table 2-20). Since 2011, the majority (i.e., $>70\%$) of the estuary was characterized as being in good quality condition (Table 2-21).

pH

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

Salinity

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

Temperature (near surface)

Area-weighted average near surface water temperature ranged from 19.68 to 23.39 $^{\circ}\text{C}$. Temperatures in the 25-28 $^{\circ}\text{C}$ range were observed in at most 27.6% of the estuary, which occurred in 2012.

Turbidity

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

Table 2-20. Area-weighted average water quality condition at Cape Cod National Seashore (all strata) during the index periods of 2007-2019.

Measure	Depth	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019
Chlorophyll <i>a</i> (µg/L)	Surface	5.22	6.66	7.69	8.75	6.81	7.01	6.79	5.82	3.71	4.38	3.88
Dissolved oxygen (% saturation)	Surface	107.01	94.92	93.00	103.30	103.94	100.87	105.74	99.36	103.16	115.35	110.83
Dissolved oxygen (% saturation)	Mid-Depth	109.02	94.15	89.87	102.40	100.39	99.44	100.91	97.22	100.57	115.72	106.49
Dissolved oxygen (% saturation)	Bottom	107.31	92.85	89.91	101.02	102.79	100.07	103.94	98.46	102.22	113.76	108.96
Dissolved oxygen (mg/L)	Surface	8.13	6.98	6.80	7.49	7.79	7.21	7.64	7.59	7.48	8.30	7.92
Dissolved oxygen (mg/L)	Mid-Depth	8.23	6.87	6.51	7.42	7.55	7.14	7.27	7.51	7.39	8.62	7.87
Dissolved oxygen (mg/L)	Bottom	8.11	6.88	6.62	7.43	7.76	7.19	7.59	7.57	7.48	8.30	7.95
PAR attenuation (K_d (m ⁻¹))	Water Column	1.17	0.84	0.96	1.46	0.70	0.64	0.55	0.74	0.57	0.64	0.69
pH	Surface	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.01	7.90
pH	Mid-Depth	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.08	7.91
pH	Bottom	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.02	7.93
Salinity (psu)	Surface	31.76	32.14	30.36	31.63	30.04	32.77	30.88	31.15	31.57	31.53	30.51
Salinity (psu)	Mid-Depth	31.82	32.20	31.30	31.78	30.28	32.86	31.04	31.22	31.71	31.46	30.65
Salinity (psu)	Bottom	31.84	32.17	31.32	31.78	30.08	32.89	31.12	31.29	31.69	31.59	30.64
Temperature (°C)	Surface	19.91	21.53	21.19	22.19	21.14	23.14	22.64	19.68	22.17	22.67	23.39
Temperature (°C)	Mid-Depth	20.13	21.97	21.43	22.26	20.79	22.83	22.87	19.06	21.38	20.80	21.55
Temperature (°C)	Bottom	19.79	21.64	20.46	21.29	21.18	22.81	22.01	19.31	21.58	21.88	22.20
Turbidity (NTU)	Surface	1.01	1.63	1.79	2.09	1.11	1.51	1.18	2.38	1.27	1.33	1.30
Turbidity (NTU)	Mid-Depth	1.03	1.46	1.94	2.21	1.27	1.61	1.41	2.52	1.22	1.01	1.10
Turbidity (NTU)	Bottom	2.84	3.11	2.91	4.13	1.78	1.69	1.63	4.60	1.80	1.64	2.00

Table 2-21. Proportion of monitored estuarine resources falling into each quality condition at Cape Cod National Seashore (all strata) during the index periods of 2007-2019.

Measure	Condition	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019
Bottom dissolved oxygen (mg/L)	Good	92.7	81.8	87.4	96.9	98.0	97.6	99.3	98.1	98.5	97.6	97.2
Bottom dissolved oxygen (mg/L)	Fair	6.8	18.2	11.5	1.8	1.2	2.4	0.2	1.4	1.0	1.6	1.7
Bottom dissolved oxygen (mg/L)	Poor	0.5	0.0	1.1	1.4	0.8	0.0	0.5	0.5	0.5	0.8	1.0
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	0.0
Chlorophyll a ($\mu\text{g/L}$)	Good	59.9	55.4	28.7	35.1	53.6	41.9	60.2	53.3	81.7	78.4	79.5
Chlorophyll a ($\mu\text{g/L}$)	Fair	37.6	43.1	62.7	61.7	39.4	50.8	38.0	46.6	15.0	21.4	19.8
Chlorophyll a ($\mu\text{g/L}$)	Poor	2.5	1.5	3.1	3.1	7.0	7.3	1.8	0.1	3.3	0.2	0.7
Chlorophyll a ($\mu\text{g/L}$)	Missing	0.0	0.0	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PAR attenuation (K_d (m^{-1}))	Good	23.7	41.2	55.0	36.2	74.5	87.9	85.8	71.3	96.4	87.2	84.7
PAR attenuation (K_d (m^{-1}))	Fair	22.1	20.8	7.4	24.8	21.5	11.7	13.2	27.6	3.4	11.8	15.0
PAR attenuation (K_d (m^{-1}))	Poor	3.3	2.8	16.2	14.6	4.0	0.5	0.0	0.1	0.2	0.1	0.3
PAR attenuation (K_d (m^{-1}))	Missing	50.9	35.2	21.3	24.4	0.0	0.0	1.0	1.0	0.0	0.9	0.0
Surface Temperature ($^{\circ}\text{C}$)	<25	93.6	90.4	85.3	82.0	94.7	68.3	83.4	95.3	92.2	83.6	71.5
Surface Temperature ($^{\circ}\text{C}$)	25-28	0.0	8.1	9.3	18.0	5.3	27.6	12.8	4.7	7.8	14.0	26.3
Surface Temperature ($^{\circ}\text{C}$)	>28	0.0	0.0	0.0	0.0	0.0	4.1	3.7	0.0	0.0	2.4	2.1
Surface Temperature ($^{\circ}\text{C}$)	Missing	6.4	1.5	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

2.5.2 GLMM Results

For all measures except bottom dissolved oxygen and surface turbidity, the analysis of variance based on the fitted GLMM indicates that there is at least one year that is statistically different from the others assuming a significance level equal to 0.05 (Table 2-22). Notable observations from the multiple comparison tests (MCT) for each measure are as follows:

Chlorophyll-*a* (near surface)

The MCT results indicate that mean log near surface chlorophyll-*a* concentrations in 2016 and 2018 were statistically different from most other index periods (Figure 2-4; Table 2-23).

Dissolved Oxygen (near bottom)

The GLMM results indicate that there is insufficient evidence to conclude that there are differences in mean log bottom dissolved oxygen among the sampled years. Boxplots of mean log bottom dissolved oxygen indicate measurements are relatively constant with some low outliers (Figure 2-5).

PAR Attenuation K_d (SAV standard)

The MCT results indicate that mean log PAR attenuation in 2007 and 2013 are statistically different compared to several other years (Figure 2-6; Table 2-24). There is no strong evidence of statistical differences between the other index period pairs.

Salinity (near surface)

The MCT results indicate that mean log surface salinity is statistically different for several pairs of years due to the cyclic nature of the measurements (Figure 2-7; Table 2-25).

Temperature (near surface)

The MCT results indicate that mean log surface water temperature in 2007, 2012, 2013, and 2019 are statistically different from most other index periods (Figure 2-8; Table 2-26).

Turbidity (near surface)

The GLMM results indicate that there is insufficient evidence to conclude that there are differences in mean log surface turbidity among the sampled years. Boxplots of log surface turbidity indicate that within-year variability has also remained relatively constant over time (Figure 2-9).

Table 2-22. Analysis of variance for the general linear mixed model fit to log-transformed water quality measurements collected within Cape Cod National Seashore (all strata). Each respective F-statistic and p-value corresponds to the test of the hypotheses: H_0 : the mean of the log-transformed measure values are the same in each year versus H_1 : at least one of the year's means is different. Hyperlinked references will re-direct to the results of the multiple comparison tests (MCT), if applicable. [D.F. = degrees of freedom.]

Measure	Depth	DF	F-value	p-value	MCT Results
Chlorophyll <i>a</i> ($\mu\text{g/L}$)	Surface	(10, 373)	7.10	< 0.005	Figure 2-4
Dissolved oxygen (mg/L)	Bottom	(10, 372)	0.92	0.52	Figure 2-5
PAR attenuation (K_d (m^{-1}))	Water Column	(10, 345)	3.66	< 0.005	Figure 2-6
Salinity (psu)	Surface	(10, 355)	18.66	< 0.005	Figure 2-7
Temperature ($^{\circ}\text{C}$)	Surface	(10, 370)	12.62	< 0.005	Figure 2-8
Turbidity (NTU)	Surface	(10, 369)	1.85	0.05	Figure 2-9

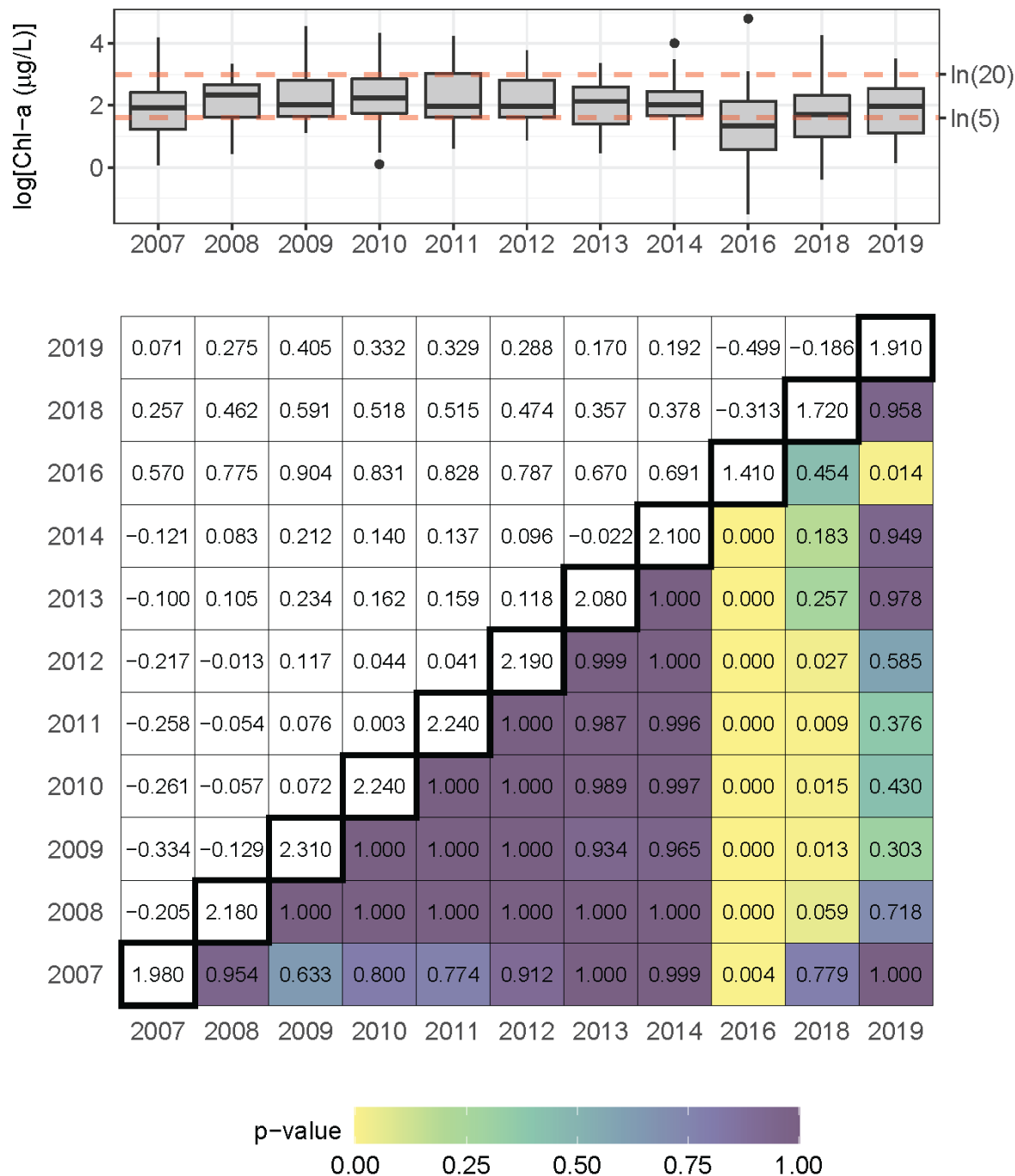


Figure 2-4. (Top): Boxplot of log surface chlorophyll-a concentration by year within Cape Cod National Seashore (all strata). Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements 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 latter). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test that the means of the years indicated by the row and column names are equal (i.e., $H_0: \mu_1 = \mu_2$ versus $H_1: \mu_1 \neq \mu_2$). A more detailed summary of the test statistics and confidence intervals is provided in Table 2-23.

Table 2-23. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-a concentration within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval]

Contrast	Estimate	SE	T_{374}	p-value	95% CI
2007 - 2008	-0.205	0.149	-1.371	0.954	(-0.688, 0.279)
2007 - 2009	-0.334	0.165	-2.021	0.632	(-0.868, 0.201)
2007 - 2010	-0.261	0.148	-1.762	0.800	(-0.741, 0.219)
2007 - 2011	-0.258	0.143	-1.808	0.773	(-0.721, 0.204)
2007 - 2012	-0.217	0.143	-1.519	0.912	(-0.680, 0.245)
2007 - 2013	-0.100	0.143	-0.697	1.000	(-0.562, 0.363)
2007 - 2014	-0.121	0.143	-0.849	0.999	(-0.584, 0.341)
2007 - 2016	0.570	0.143	3.989	0.004	(0.107, 1.032)
2007 - 2018	0.257	0.143	1.799	0.779	(-0.205, 0.720)
2007 - 2019	0.071	0.143	0.495	1.000	(-0.392, 0.533)
2008 - 2009	-0.129	0.167	-0.775	1.000	(-0.669, 0.411)
2008 - 2010	-0.057	0.150	-0.377	1.000	(-0.544, 0.430)
2008 - 2011	-0.054	0.145	-0.370	1.000	(-0.524, 0.416)
2008 - 2012	-0.013	0.145	-0.086	1.000	(-0.483, 0.458)
2008 - 2013	0.105	0.145	0.723	1.000	(-0.365, 0.575)
2008 - 2014	0.083	0.145	0.573	1.000	(-0.387, 0.553)
2008 - 2016	0.775	0.145	5.333	0.000	(0.304, 1.245)
2008 - 2018	0.462	0.145	3.179	0.059	(-0.008, 0.932)
2008 - 2019	0.275	0.145	1.896	0.718	(-0.195, 0.745)
2009 - 2010	0.072	0.166	0.437	1.000	(-0.465, 0.610)
2009 - 2011	0.076	0.161	0.468	1.000	(-0.447, 0.598)
2009 - 2012	0.117	0.161	0.723	1.000	(-0.406, 0.639)
2009 - 2013	0.234	0.161	1.451	0.934	(-0.288, 0.757)
2009 - 2014	0.212	0.161	1.317	0.965	(-0.310, 0.735)
2009 - 2016	0.904	0.161	5.600	0.000	(0.381, 1.426)
2009 - 2018	0.591	0.161	3.661	0.012	(0.068, 1.113)
2009 - 2019	0.405	0.161	2.507	0.303	(-0.118, 0.927)
2010 - 2011	0.003	0.144	0.021	1.000	(-0.463, 0.469)
2010 - 2012	0.044	0.144	0.307	1.000	(-0.422, 0.510)
2010 - 2013	0.162	0.144	1.123	0.989	(-0.304, 0.628)
2010 - 2014	0.140	0.144	0.972	0.997	(-0.326, 0.606)
2010 - 2016	0.831	0.144	5.772	0.000	(0.365, 1.297)
2010 - 2018	0.518	0.144	3.600	0.016	(0.052, 0.985)
2010 - 2019	0.332	0.144	2.306	0.431	(-0.134, 0.798)
2011 - 2012	0.041	0.138	0.299	1.000	(-0.405, 0.487)
2011 - 2013	0.159	0.138	1.152	0.987	(-0.287, 0.605)
2011 - 2014	0.137	0.138	0.994	0.996	(-0.309, 0.583)
2011 - 2016	0.828	0.138	6.011	0.000	(0.382, 1.274)
2011 - 2018	0.515	0.138	3.740	0.010	(0.069, 0.961)
2011 - 2019	0.329	0.138	2.388	0.374	(-0.117, 0.775)
2012 - 2013	0.118	0.138	0.852	0.999	(-0.329, 0.564)

Contrast	Estimate	SE	T_{374}	p -value	95% CI
2012 - 2014	0.096	0.138	0.695	1.000	(-0.350, 0.542)
2012 - 2016	0.787	0.138	5.709	0.000	(0.341, 1.233)
2012 - 2018	0.474	0.138	3.439	0.026	(0.028, 0.920)
2012 - 2019	0.288	0.138	2.088	0.585	(-0.158, 0.734)
2013 - 2014	-0.022	0.138	-0.158	1.000	(-0.468, 0.424)
2013 - 2016	0.670	0.138	4.859	0.000	(0.224, 1.116)
2013 - 2018	0.357	0.138	2.589	0.257	(-0.089, 0.803)
2013 - 2019	0.170	0.138	1.237	0.978	(-0.276, 0.616)
2014 - 2016	0.691	0.138	5.017	0.000	(0.245, 1.137)
2014 - 2018	0.378	0.138	2.746	0.182	(-0.068, 0.824)
2014 - 2019	0.192	0.138	1.394	0.949	(-0.254, 0.638)
2016 - 2018	-0.313	0.138	-2.271	0.455	(-0.759, 0.133)
2016 - 2019	-0.499	0.138	-3.622	0.014	(-0.945, -0.053)
2018 - 2019	-0.186	0.138	-1.352	0.958	(-0.632, 0.260)

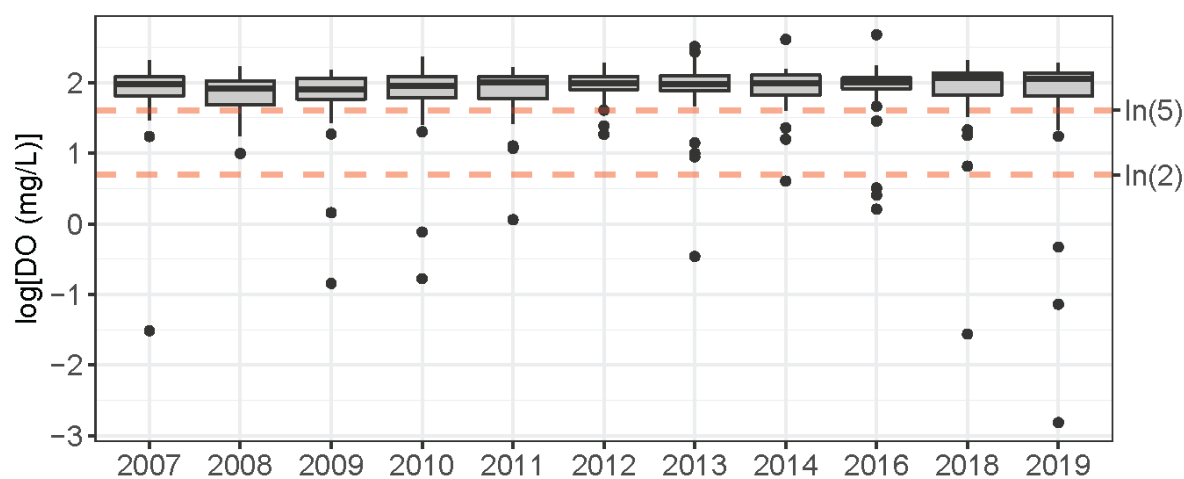
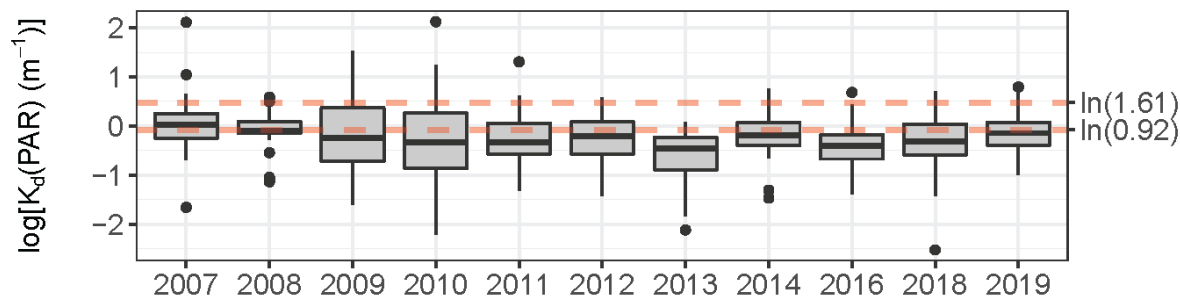


Figure 2-5. Boxplot of log bottom dissolved oxygen concentration by year within Cape Cod National Seashore (all strata). Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines.



2019	0.178	0.035	-0.123	-0.122	-0.162	-0.122	-0.437	-0.043	-0.294	-0.220	-0.134
2018	0.398	0.254	0.097	0.097	0.057	0.097	-0.218	0.176	-0.074	-0.354	0.684
2016	0.472	0.329	0.171	0.172	0.132	0.172	-0.143	0.251	-0.429	1.000	0.231
2014	0.221	0.078	-0.079	-0.079	-0.119	-0.079	-0.394	-0.178	0.477	0.899	1.000
2013	0.616	0.472	0.315	0.315	0.275	0.315	-0.572	0.022	0.972	0.703	0.005
2012	0.300	0.157	-0.000	-0.000	-0.040	-0.257	0.157	1.000	0.903	0.999	0.991
2011	0.340	0.197	0.040	0.040	-0.297	1.000	0.333	0.993	0.984	1.000	0.932
2010	0.301	0.157	-0.000	-0.257	1.000	1.000	0.291	1.000	0.951	1.000	0.996
2009	0.301	0.157	-0.257	1.000	1.000	1.000	0.343	1.000	0.962	1.000	0.997
2008	0.144	-0.100	0.990	0.988	0.900	0.978	0.011	1.000	0.256	0.659	1.000
2007	0.044	0.995	0.553	0.517	0.210	0.388	0.000	0.814	0.010	0.075	0.946
2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019	

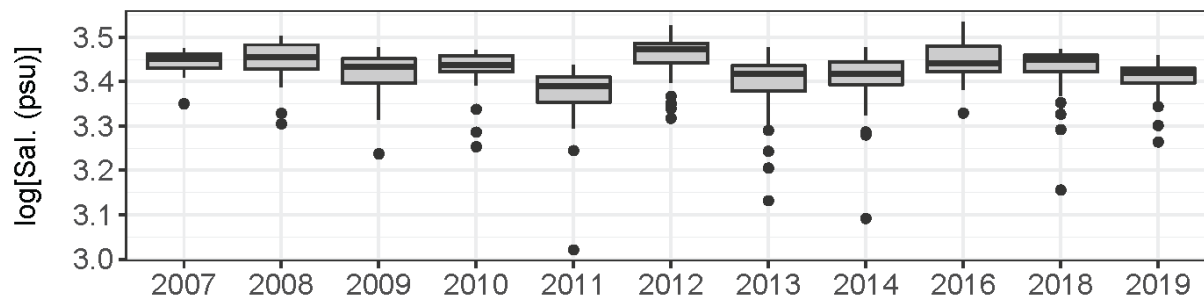


Figure 2-6. (Top): Boxplot of log PAR attenuation by year within Cape Cod National Seashore (all strata). Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. [Bottom]: Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log 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 latter). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test that the means of the years indicated by the row and column names are equal (i.e., $H_0: \mu^1 = \mu^2$ versus $H_1: \mu^1 \neq \mu^2$). A more detailed summary of the test statistics and confidence intervals is provided in Table 2-24

Table 2-24. Summary of the multiple comparison test results for all possible yearly contrasts of mean log PAR attenuation within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval]

Contrast	Estimate	SE	T_{346}	p-value	95% CI
2007 - 2008	0.144	0.140	1.027	0.995	(-0.308, 0.595)
2007 - 2009	0.301	0.141	2.130	0.553	(-0.156, 0.757)
2007 - 2010	0.301	0.138	2.181	0.517	(-0.145, 0.746)
2007 - 2011	0.340	0.127	2.682	0.211	(-0.070, 0.751)
2007 - 2012	0.300	0.127	2.368	0.388	(-0.110, 0.711)
2007 - 2013	0.616	0.127	4.830	0.000	(0.204, 1.028)
2007 - 2014	0.221	0.127	1.736	0.813	(-0.191, 0.633)
2007 - 2016	0.472	0.127	3.721	0.010	(0.062, 0.882)
2007 - 2018	0.398	0.128	3.100	0.074	(-0.017, 0.813)
2007 - 2019	0.178	0.127	1.404	0.946	(-0.232, 0.588)
2008 - 2009	0.157	0.141	1.113	0.990	(-0.299, 0.614)
2008 - 2010	0.157	0.138	1.140	0.988	(-0.288, 0.602)
2008 - 2011	0.197	0.127	1.550	0.900	(-0.214, 0.607)
2008 - 2012	0.157	0.127	1.236	0.978	(-0.253, 0.567)
2008 - 2013	0.472	0.128	3.699	0.011	(0.060, 0.885)
2008 - 2014	0.078	0.128	0.609	1.000	(-0.335, 0.490)
2008 - 2016	0.329	0.127	2.589	0.256	(-0.082, 0.739)
2008 - 2018	0.254	0.128	1.981	0.660	(-0.161, 0.669)
2008 - 2019	0.035	0.127	0.272	1.000	(-0.376, 0.445)
2009 - 2010	-0.000	0.139	-0.002	1.000	(-0.449, 0.449)
2009 - 2011	0.040	0.129	0.308	1.000	(-0.376, 0.455)
2009 - 2012	-0.000	0.128	-0.003	1.000	(-0.416, 0.415)
2009 - 2013	0.315	0.129	2.437	0.344	(-0.103, 0.733)
2009 - 2014	-0.079	0.129	-0.615	1.000	(-0.497, 0.338)
2009 - 2016	0.171	0.129	1.334	0.962	(-0.244, 0.587)
2009 - 2018	0.097	0.130	0.746	1.000	(-0.323, 0.517)
2009 - 2019	-0.123	0.129	-0.954	0.997	(-0.538, 0.293)
2010 - 2011	0.040	0.124	0.321	1.000	(-0.361, 0.441)
2010 - 2012	-0.000	0.124	-0.001	1.000	(-0.401, 0.401)
2010 - 2013	0.315	0.125	2.526	0.291	(-0.088, 0.718)
2010 - 2014	-0.079	0.125	-0.635	1.000	(-0.483, 0.324)
2010 - 2016	0.172	0.124	1.384	0.951	(-0.229, 0.573)
2010 - 2018	0.097	0.125	0.776	0.999	(-0.308, 0.503)
2010 - 2019	-0.122	0.124	-0.986	0.996	(-0.523, 0.279)
2011 - 2012	-0.040	0.111	-0.359	1.000	(-0.400, 0.320)
2011 - 2013	0.275	0.112	2.454	0.333	(-0.087, 0.638)
2011 - 2014	-0.119	0.112	-1.061	0.993	(-0.482, 0.244)
2011 - 2016	0.132	0.111	1.183	0.984	(-0.228, 0.492)
2011 - 2018	0.057	0.113	0.508	1.000	(-0.308, 0.422)
2011 - 2019	-0.162	0.111	-1.455	0.932	(-0.522, 0.198)
2012 - 2013	0.315	0.112	2.810	0.156	(-0.047, 0.678)
2012 - 2014	-0.079	0.112	-0.705	1.000	(-0.442, 0.284)

Contrast	Estimate	SE	T_{346}	p-value	95% CI
2012 - 2016	0.172	0.111	1.542	0.903	(−0.188, 0.532)
2012 - 2018	0.097	0.113	0.862	0.999	(−0.268, 0.463)
2012 - 2019	−0.122	0.111	−1.097	0.991	(−0.483, 0.238)
2013 - 2014	−0.394	0.113	−3.496	0.022	(−0.759, −0.030)
2013 - 2016	−0.143	0.112	−1.279	0.971	(−0.506, 0.219)
2013 - 2018	−0.218	0.114	−1.918	0.702	(−0.585, 0.149)
2013 - 2019	−0.437	0.112	−3.900	0.005	(−0.800, −0.075)
2014 - 2016	0.251	0.112	2.237	0.477	(−0.112, 0.613)
2014 - 2018	0.176	0.114	1.553	0.899	(−0.191, 0.544)
2014 - 2019	−0.043	0.112	−0.385	1.000	(−0.406, 0.319)
2016 - 2018	−0.074	0.113	−0.659	1.000	(−0.439, 0.291)
2016 - 2019	−0.294	0.111	−2.639	0.230	(−0.654, 0.066)
2018 - 2019	−0.220	0.113	−1.945	0.684	(−0.585, 0.145)



2019	0.034	0.039	0.005	0.020	-0.037	0.052	-0.012	-0.002	0.042	0.020	3.405
2018	0.013	0.019	-0.015	-0.001	-0.058	0.031	-0.033	-0.023	0.021	3.426	0.372
2016	-0.008	-0.002	-0.037	-0.022	-0.079	0.010	-0.054	-0.044	3.447	0.319	0.000
2014	0.036	0.042	0.007	0.022	-0.035	0.054	-0.010	3.403	0.000	0.231	1.000
2013	0.046	0.052	0.017	0.032	-0.025	0.064	3.393	0.985	0.000	0.008	0.942
2012	-0.018	-0.012	-0.047	-0.032	-0.089	3.457	0.000	0.000	0.985	0.014	0.000
2011	0.071	0.077	0.042	0.057	3.368	0.000	0.108	0.002	0.000	0.000	0.001
2010	0.014	0.020	-0.014	3.425	0.000	0.016	0.019	0.355	0.320	1.000	0.515
2009	0.029	0.034	3.410	0.995	0.098	0.043	0.981	1.000	0.261	0.991	1.000
2008	-0.006	3.445	0.387	0.564	0.000	0.959	0.000	0.000	1.000	0.584	0.001
2007	3.439	1.000	0.656	0.909	0.000	0.655	0.000	0.004	0.999	0.925	0.010
	2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019



Figure 2-7. (Top): Boxplot of log surface salinity by year within Cape Cod National Seashore (all strata). (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface salinity within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus latter). Lower diagonals contain the Tukey-adjusted p-value from a two-sided test that the means of the years indicated by the row and column names are equal (i.e., $H_0: \mu^1 = \mu^2$ versus $H_1: \mu^1 \neq \mu^2$). A more detailed summary of the test statistics and confidence intervals is provided in Table 2-26.

Table 2-25. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface salinity within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval]

Contrast	Estimate	SE	T_{356}	p-value	95% CI
2007 - 2008	-0.006	0.010	-0.595	1.000	(-0.036, 0.025)
2007 - 2009	0.029	0.015	1.977	0.656	(-0.018, 0.076)
2007 - 2010	0.014	0.009	1.519	0.909	(-0.016, 0.045)
2007 - 2011	0.071	0.009	7.873	0.000	(0.042, 0.100)
2007 - 2012	-0.018	0.009	-1.980	0.655	(-0.047, 0.011)
2007 - 2013	0.046	0.009	5.074	0.000	(0.017, 0.075)
2007 - 2014	0.036	0.009	3.967	0.004	(0.007, 0.065)
2007 - 2016	-0.008	0.009	-0.871	0.999	(-0.037, 0.021)
2007 - 2018	0.013	0.009	1.472	0.925	(-0.016, 0.043)
2007 - 2019	0.034	0.009	3.732	0.010	(0.005, 0.063)
2008 - 2009	0.034	0.015	2.361	0.386	(-0.013, 0.081)
2008 - 2010	0.020	0.009	2.108	0.563	(-0.011, 0.050)
2008 - 2011	0.077	0.009	8.425	0.000	(0.047, 0.106)
2008 - 2012	-0.012	0.009	-1.342	0.959	(-0.042, 0.017)
2008 - 2013	0.052	0.009	5.650	0.000	(0.022, 0.081)
2008 - 2014	0.042	0.009	4.553	0.000	(0.012, 0.071)
2008 - 2016	-0.002	0.009	-0.242	1.000	(-0.032, 0.027)
2008 - 2018	0.019	0.009	2.079	0.584	(-0.010, 0.048)
2008 - 2019	0.039	0.009	4.320	0.001	(0.010, 0.069)
2009 - 2010	-0.014	0.014	-1.003	0.995	(-0.061, 0.032)
2009 - 2011	0.042	0.014	2.985	0.098	(-0.003, 0.088)
2009 - 2012	-0.047	0.014	-3.275	0.043	(-0.093, -0.001)
2009 - 2013	0.017	0.014	1.207	0.981	(-0.029, 0.063)
2009 - 2014	0.007	0.014	0.503	1.000	(-0.039, 0.053)
2009 - 2016	-0.037	0.014	-2.570	0.262	(-0.083, 0.009)
2009 - 2018	-0.015	0.014	-1.082	0.991	(-0.061, 0.031)
2009 - 2019	0.005	0.014	0.354	1.000	(-0.041, 0.051)
2010 - 2011	0.057	0.009	6.350	0.000	(0.028, 0.086)
2010 - 2012	-0.032	0.009	-3.584	0.016	(-0.061, -0.003)
2010 - 2013	0.032	0.009	3.527	0.020	(0.003, 0.061)
2010 - 2014	0.022	0.009	2.411	0.354	(-0.007, 0.051)
2010 - 2016	-0.022	0.009	-2.466	0.319	(-0.051, 0.007)
2010 - 2018	-0.001	0.009	-0.105	1.000	(-0.030, 0.028)
2010 - 2019	0.020	0.009	2.175	0.516	(-0.009, 0.048)
2011 - 2012	-0.089	0.009	-10.378	0.000	(-0.117, -0.061)
2011 - 2013	-0.025	0.009	-2.951	0.107	(-0.053, 0.002)
2011 - 2014	-0.035	0.009	-4.118	0.002	(-0.063, -0.008)
2011 - 2016	-0.079	0.009	-9.216	0.000	(-0.107, -0.051)
2011 - 2018	-0.058	0.009	-6.747	0.000	(-0.086, -0.030)
2011 - 2019	-0.037	0.009	-4.365	0.001	(-0.065, -0.010)
2012 - 2013	0.064	0.009	7.430	0.000	(0.036, 0.092)
2012 - 2014	0.054	0.009	6.264	0.000	(0.026, 0.082)

Contrast	Estimate	SE	T_{356}	p-value	95% CI
2012 - 2016	0.010	0.009	1.169	0.985	(−0.018, 0.038)
2012 - 2018	0.031	0.009	3.636	0.013	(0.003, 0.059)
2012 - 2019	0.052	0.009	6.017	0.000	(0.024, 0.079)
2013 - 2014	−0.010	0.009	−1.167	0.985	(−0.038, 0.018)
2013 - 2016	−0.054	0.009	−6.265	0.000	(−0.081, −0.026)
2013 - 2018	−0.033	0.009	−3.797	0.007	(−0.060, −0.005)
2013 - 2019	−0.012	0.009	−1.414	0.942	(−0.040, 0.016)
2014 - 2016	−0.044	0.009	−5.098	0.000	(−0.071, −0.016)
2014 - 2018	−0.023	0.009	−2.630	0.230	(−0.050, 0.005)
2014 - 2019	−0.002	0.009	−0.247	1.000	(−0.030, 0.026)
2016 - 2018	0.021	0.009	2.468	0.319	(−0.007, 0.049)
2016 - 2019	0.042	0.009	4.851	0.000	(0.014, 0.069)
2018 - 2019	0.020	0.009	2.383	0.372	(−0.007, 0.048)

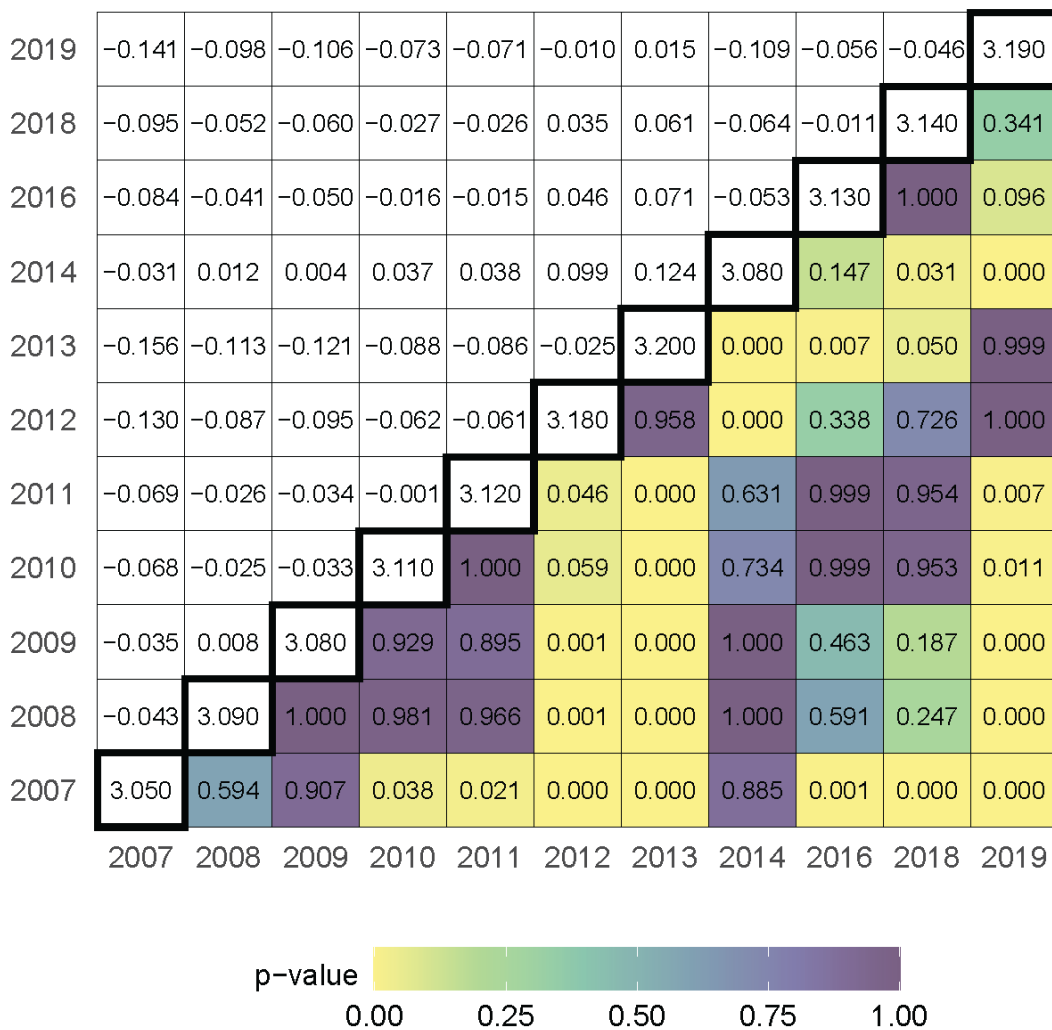
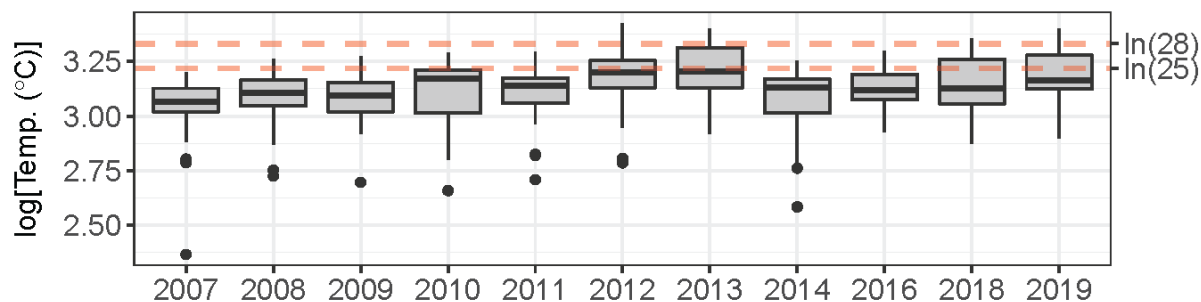


Figure 2-8. (Top): Boxplot of log surface temperature by year within Cape Cod National Seashore (all strata). Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean 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 latter). Lower diagonals contain the Tukey-adjusted p -value from a two-sided test that the means of the years indicated by the row and column names are equal (i.e., $H_0: \mu_1 = \mu_2$ versus $H_1: \mu_1 \neq \mu_2$). A more detailed summary of the test statistics and confidence intervals is provided in Table 2-26.

Table 2-26. Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature within Cape Cod National Seashore (all strata). Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error, CI = confidence interval]

Contrast	Estimate	SE	T_{371}	p-value	95% CI
2007 - 2008	-0.043	0.021	-2.075	0.594	(-0.110, 0.024)
2007 - 2009	-0.035	0.023	-1.534	0.907	(-0.108, 0.039)
2007 - 2010	-0.068	0.020	-3.323	0.039	(-0.134, -0.002)
2007 - 2011	-0.069	0.020	-3.510	0.020	(-0.133, -0.005)
2007 - 2012	-0.130	0.020	-6.599	0.000	(-0.194, -0.066)
2007 - 2013	-0.156	0.020	-7.891	0.000	(-0.219, -0.092)
2007 - 2014	-0.031	0.020	-1.591	0.885	(-0.095, 0.032)
2007 - 2016	-0.084	0.020	-4.281	0.001	(-0.148, -0.021)
2007 - 2018	-0.095	0.020	-4.813	0.000	(-0.159, -0.031)
2007 - 2019	-0.141	0.020	-7.131	0.000	(-0.204, -0.077)
2008 - 2009	0.008	0.023	0.358	1.000	(-0.066, 0.082)
2008 - 2010	-0.025	0.021	-1.210	0.981	(-0.091, 0.042)
2008 - 2011	-0.026	0.020	-1.315	0.966	(-0.090, 0.038)
2008 - 2012	-0.087	0.020	-4.378	0.001	(-0.152, -0.023)
2008 - 2013	-0.113	0.020	-5.657	0.000	(-0.177, -0.048)
2008 - 2014	0.012	0.020	0.587	1.000	(-0.053, 0.076)
2008 - 2016	-0.041	0.020	-2.079	0.591	(-0.106, 0.023)
2008 - 2018	-0.052	0.020	-2.607	0.248	(-0.116, 0.012)
2008 - 2019	-0.098	0.020	-4.904	0.000	(-0.162, -0.033)
2009 - 2010	-0.033	0.023	-1.468	0.929	(-0.106, 0.040)
2009 - 2011	-0.034	0.022	-1.566	0.895	(-0.105, 0.037)
2009 - 2012	-0.095	0.022	-4.345	0.001	(-0.166, -0.024)
2009 - 2013	-0.121	0.022	-5.505	0.000	(-0.192, -0.050)
2009 - 2014	0.004	0.022	0.160	1.000	(-0.067, 0.074)
2009 - 2016	-0.050	0.022	-2.259	0.463	(-0.120, 0.021)
2009 - 2018	-0.060	0.022	-2.738	0.186	(-0.131, 0.011)
2009 - 2019	-0.106	0.022	-4.821	0.000	(-0.177, -0.035)
2010 - 2011	-0.001	0.020	-0.064	1.000	(-0.064, 0.062)
2010 - 2012	-0.062	0.020	-3.181	0.059	(-0.126, 0.001)
2010 - 2013	-0.088	0.020	-4.480	0.001	(-0.151, -0.024)
2010 - 2014	0.037	0.020	1.872	0.734	(-0.027, 0.100)
2010 - 2016	-0.016	0.020	-0.840	0.999	(-0.080, 0.047)
2010 - 2018	-0.027	0.020	-1.377	0.953	(-0.090, 0.036)
2010 - 2019	-0.073	0.020	-3.714	0.011	(-0.136, -0.009)
2011 - 2012	-0.061	0.019	-3.258	0.047	(-0.122, -0.000)
2011 - 2013	-0.086	0.019	-4.618	0.000	(-0.147, -0.026)
2011 - 2014	0.038	0.019	2.023	0.632	(-0.023, 0.098)
2011 - 2016	-0.015	0.019	-0.812	0.999	(-0.076, 0.045)
2011 - 2018	-0.026	0.019	-1.374	0.954	(-0.086, 0.035)
2011 - 2019	-0.071	0.019	-3.817	0.007	(-0.132, -0.011)
2012 - 2013	-0.025	0.019	-1.355	0.958	(-0.086, 0.035)
2012 - 2014	0.099	0.019	5.279	0.000	(0.038, 0.159)

Contrast	Estimate	SE	T_{371}	p -value	95% CI
2012 - 2016	0.046	0.019	2.446	0.339	(-0.015, 0.106)
2012 - 2018	0.035	0.019	1.885	0.725	(-0.025, 0.096)
2012 - 2019	-0.010	0.019	-0.555	1.000	(-0.071, 0.050)
2013 - 2014	0.124	0.019	6.641	0.000	(0.064, 0.185)
2013 - 2016	0.071	0.019	3.805	0.007	(0.011, 0.132)
2013 - 2018	0.061	0.019	3.244	0.049	(0.000, 0.121)
2013 - 2019	0.015	0.019	0.801	0.999	(-0.046, 0.075)
2014 - 2016	-0.053	0.019	-2.835	0.149	(-0.114, 0.007)
2014 - 2018	-0.064	0.019	-3.397	0.031	(-0.124, -0.003)
2014 - 2019	-0.109	0.019	-5.840	0.000	(-0.170, -0.049)
2016 - 2018	-0.011	0.019	-0.561	1.000	(-0.071, 0.050)
2016 - 2019	-0.056	0.019	-3.004	0.096	(-0.117, 0.004)
2018 - 2019	-0.046	0.019	-2.443	0.340	(-0.106, 0.015)

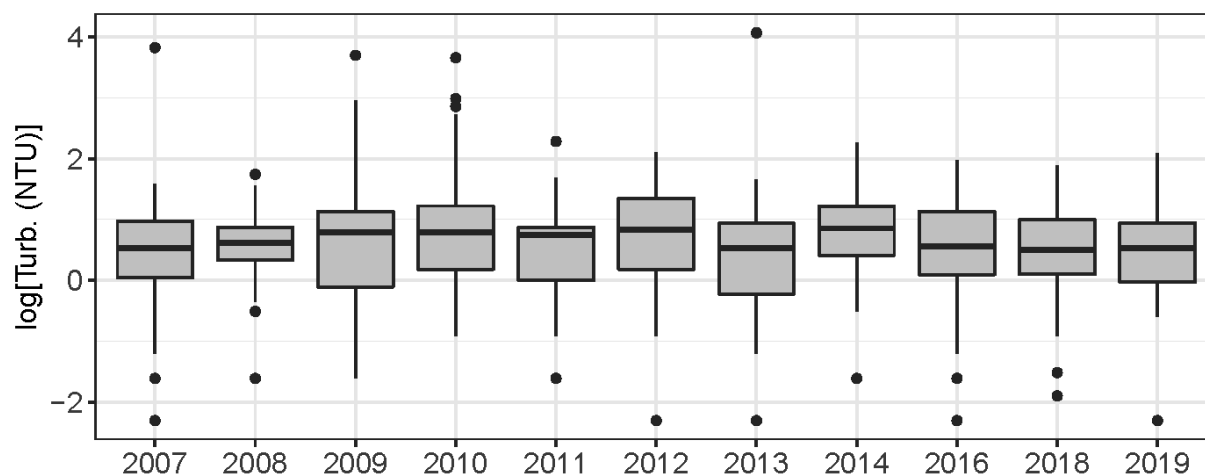


Figure 2-9. Boxplot of log surface turbidity by year within Cape Cod National Seashore (all strata).

2.5.3 GAM Results

The generalized additive model summaries indicate that there exists statistically significant (assuming a 0.05 significance level) spatial and temporal trends in all water quality measures except bottom dissolved oxygen (Table 2-27). Notable observations from the fitted smooths for each measure are as follows:

Chlorophyll-*a* (near surface)

Chlorophyll-*a* exhibited a non-linear temporal trend (edf = 4.17) with a period of statistically significant decline around 2014 (Figure 2-10). High concentrations of chlorophyll-*a* are spatially concentrated along the western shores of Pleasant Bay, the shores of East Orleans and Nauset Heights, and Town Cove (Figure 2-11). Based on the fitted model, both time and location account for 57.8% of the variability in chlorophyll-*a* concentrations (Table 2-28).

Dissolved Oxygen (near bottom)

Although there is no statistically significant temporal trend, there is a significant spatial trend in bottom dissolved oxygen, with lower concentrations occurring near South/East Orleans and Town Cove (Figure 2-12). The fitted model does very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 7.9% of the variation (Table 2-28).

PAR Attenuation K_d (SAV standard)

The temporal trend in PAR attenuation is slightly concave upward (edf = 2.68) with no periods of statistically significant change (Figure 2-10). Spatially, PAR attenuation tends to be higher on the eastern shore compared to the western shore, except for the southern end of Pleasant Bay (Figure 2-13). Based on the fitted model, both time and location account for only 20.8% of the variability in PAR attenuation (Table 2-28).

Salinity (near surface)

Surface salinity exhibited a highly non-linear temporal trend (edf = 6.40) with cyclic periods of statistically significant increases and decreases (Figure 2-10). Spatially, salinity is lowest along the shores near Orleans and around Pochet Island (Figure 2-14). Based on the fitted model, both time and location account for 48% of the variation in salinity (Table 2-28).

Temperature (near surface)

Surface water temperature exhibited a non-linear temporal trend with a few periods of statistically significant increases and decreases (Figure 2-10 (continued)). Temperatures were increasing from 2007 to 2013 before dropping back down to pre-2009 mean values. Spatially, surface temperatures are the highest along the shores near Orleans and around Pochet Island, and cooler temperatures observed on the eastern shores of Nauset Harbor and near Chatham Harbor (Figure 2-15). Based on the fitted model, both time and location account for 68.2% of the variability in water temperature (Table 2-28).

Turbidity (near surface)

The temporal trend in surface turbidity is slightly decreasing with no periods of statistically significant change (Figure 2-10 (continued)). Spatially, turbidity is higher the inland shores of the estuary (Figure 2-16). Time and location account for 41.9% of the variation in turbidity (Table 2-28).

Table 2-27. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore (all strata) 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]

Measure	Depth	Model Term	edf	F -value	p -value
Chlorophyll a ($\mu\text{g/L}$)	Surface	s(year)	4.17	5.31	< 0.001
Chlorophyll a ($\mu\text{g/L}$)	Surface	s(long, lat)	22.50	8.98	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year)	0.31	0.07	0.105
Dissolved oxygen (mg/L)	Bottom	s(long, lat)	5.38	1.23	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year)	2.68	2.34	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(long, lat)	10.71	0.67	< 0.001
Salinity (psu)	Surface	s(year)	6.40	8.18	< 0.001
Salinity (psu)	Surface	s(long, lat)	24.50	5.49	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(year)	8.37	12.33	< 0.001
Temperature ($^{\circ}\text{C}$)	Surface	s(long, lat)	22.89	14.89	< 0.001
Turbidity (NTU)	Surface	s(year)	1.77	0.49	0.052
Turbidity (NTU)	Surface	s(long, lat)	23.17	2.74	< 0.001

Table 2-28. Proportion of null deviance explained by the explanatory variables for each Cape Cod National Seashore (all strata) model.

Measure	Deviance Explained
Chlorophyll a ($\mu\text{g/L}$)	57.8%
Dissolved oxygen (mg/L)	7.9%
PAR attenuation (K_d (m^{-1}))	20.8%
Salinity (psu)	48.0%
Temperature ($^{\circ}\text{C}$)	68.2%
Turbidity (NTU)	41.9%

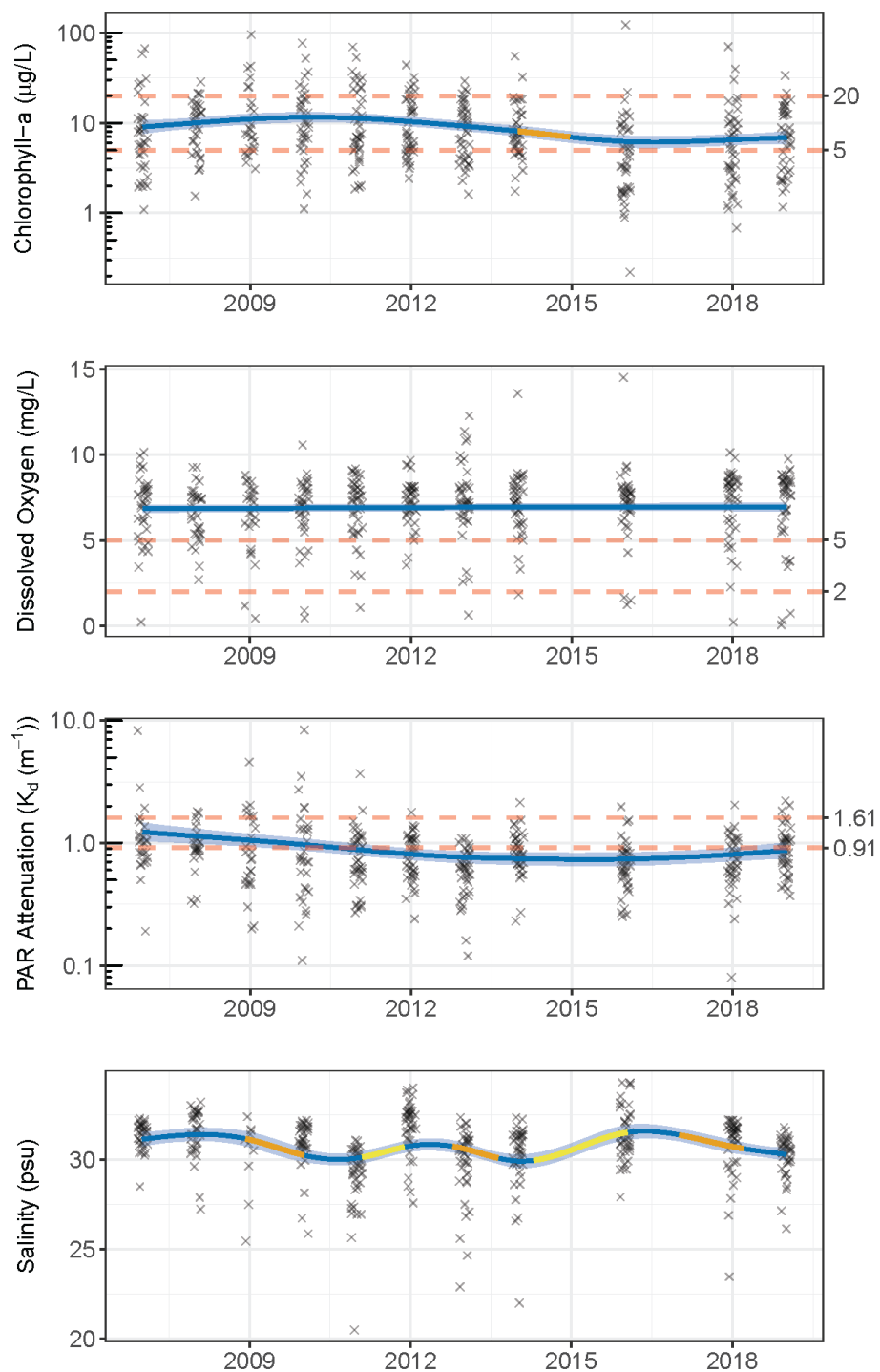


Figure 2-10. Trends in Cape Cod National Seashore (all strata) water quality measures based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2-1) are plotted as red dashed lines. Note: (1) in some instances, the y-axis is transformed to the log₁₀ scale to better visualize the estimated trend.

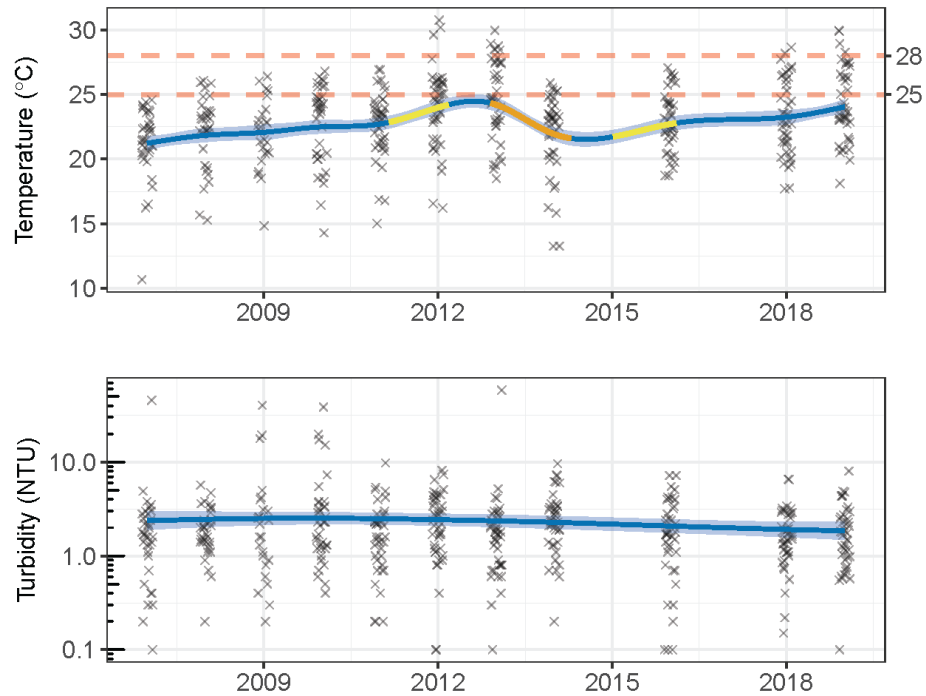


Figure 2-10 (continued). Trends in Cape Cod National Seashore (all strata) water quality measures based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2-1) 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.

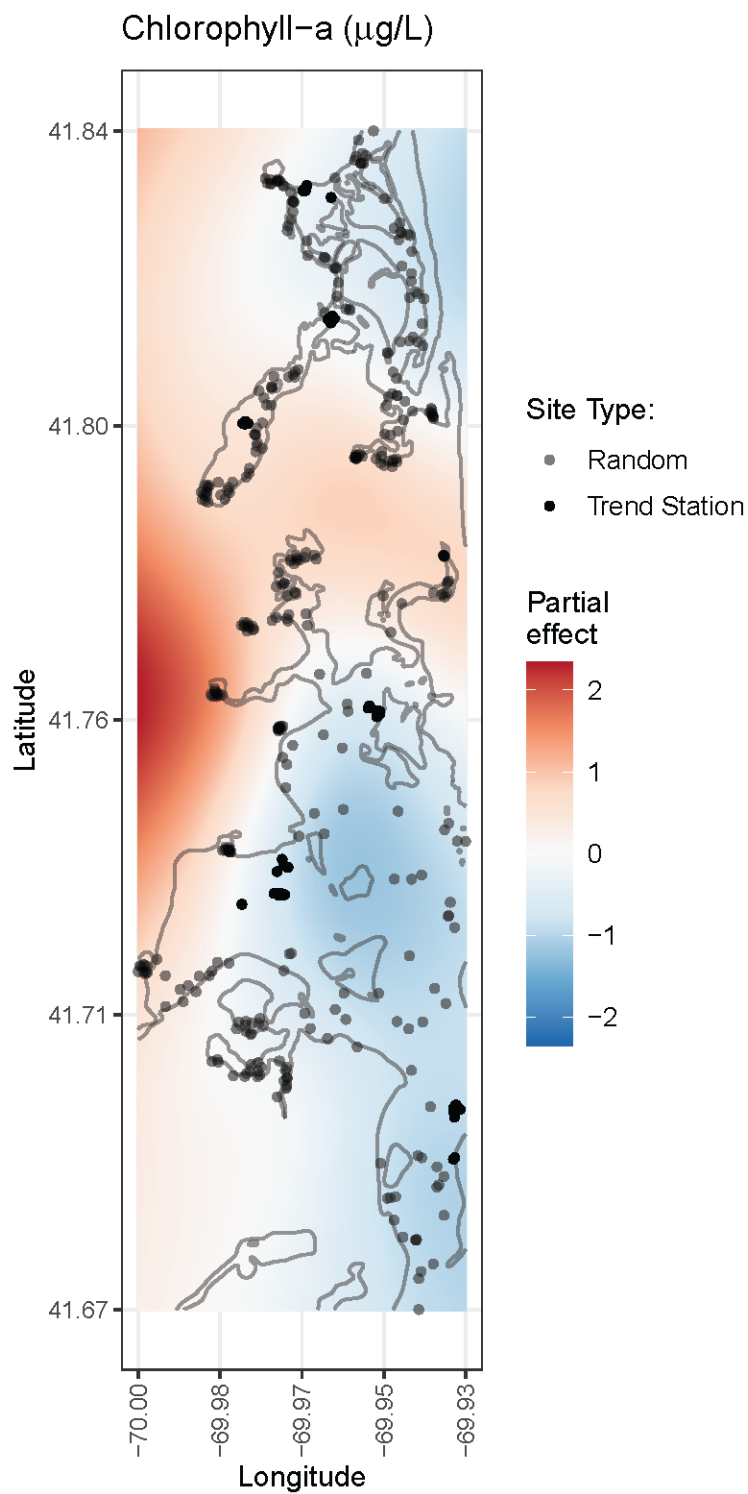


Figure 2-11. Mean surface for the generalized additive model latitude/longitude smooth of surface chlorophyll-a concentration within Cape Cod National Seashore (all strata) during 2007-2019.

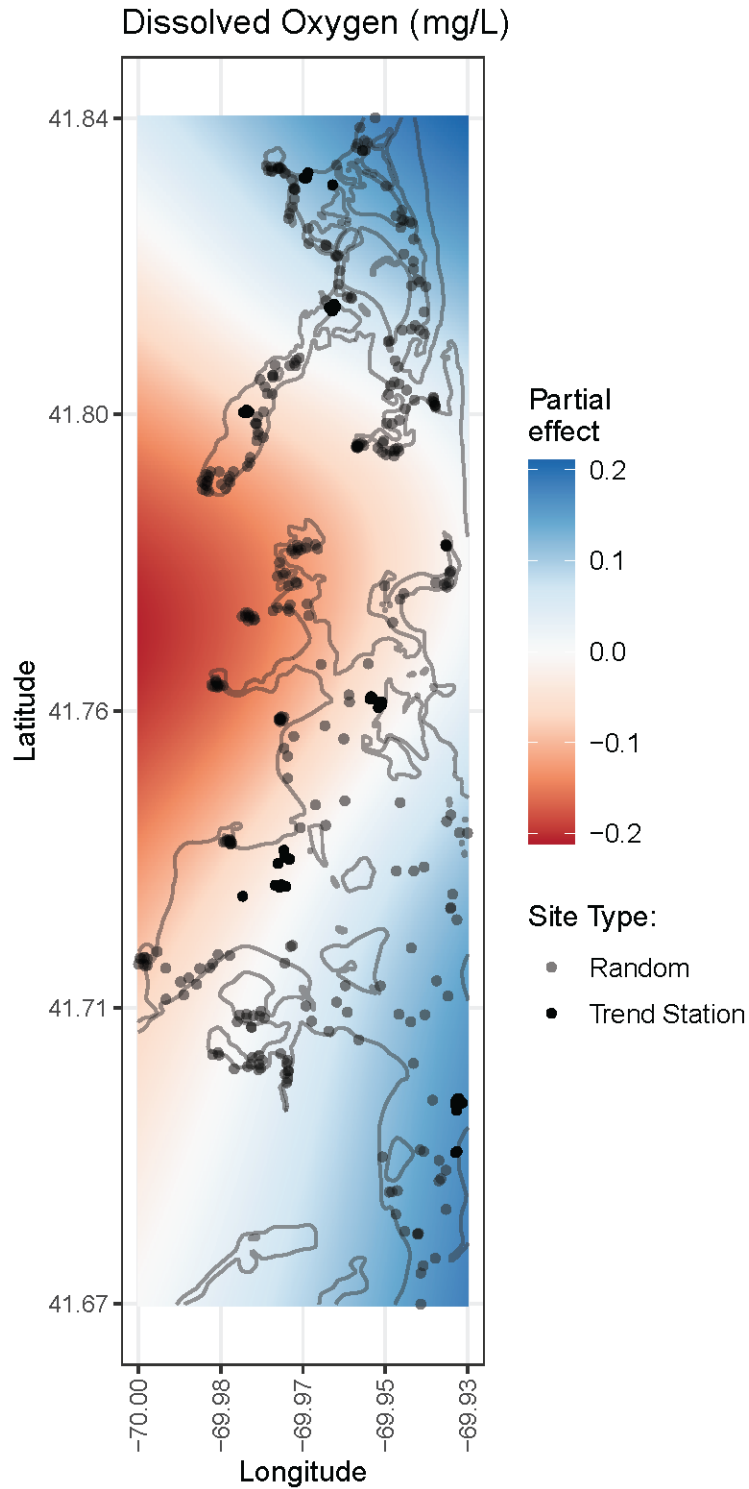


Figure 2-12. Mean surface for the generalized additive model latitude/longitude smooth of bottom dissolved oxygen concentration within Cape Cod National Seashore (all strata) during 2007-2019.

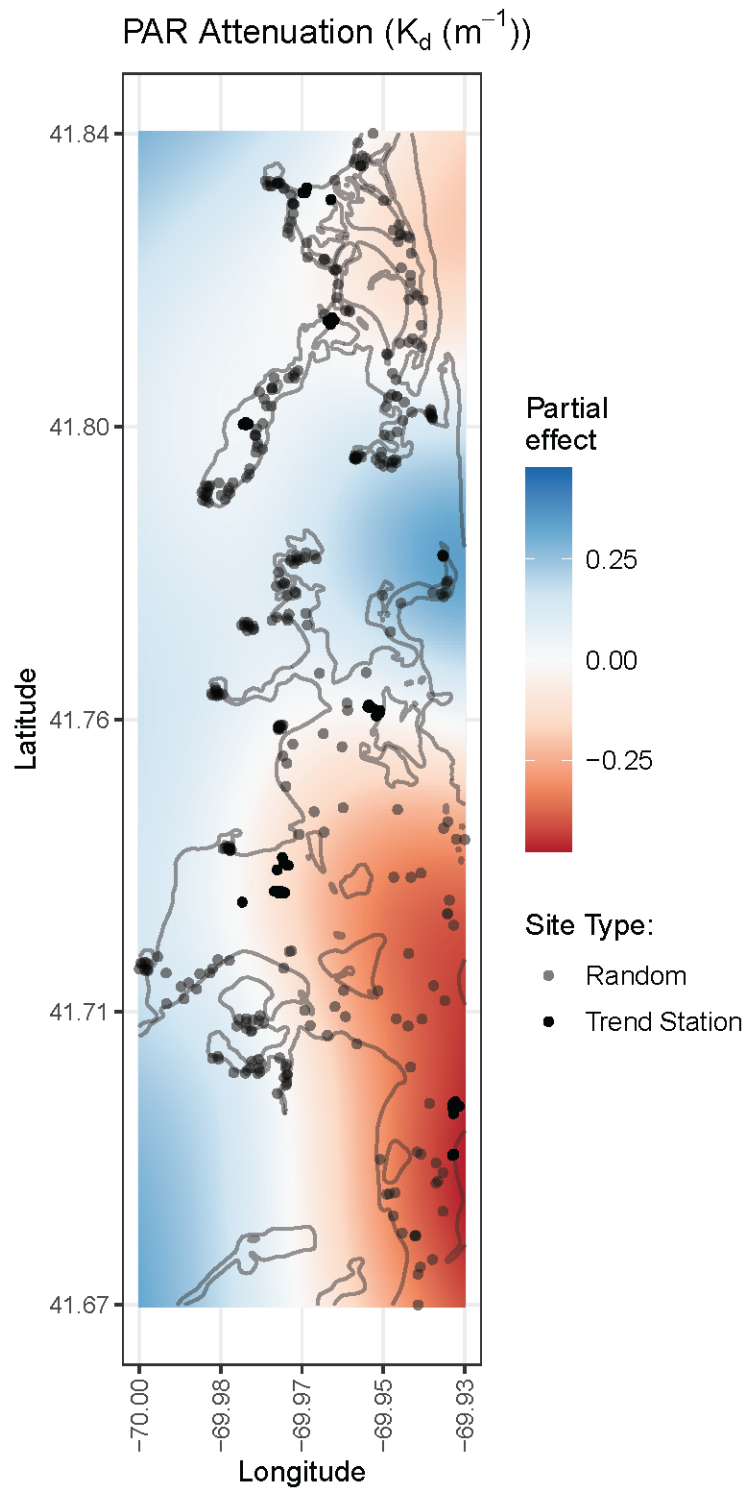


Figure 2-13. Mean surface for the generalized additive model latitude/longitude smooth of PAR attenuation within Cape Cod National Seashore (all strata) during 2007-2019.

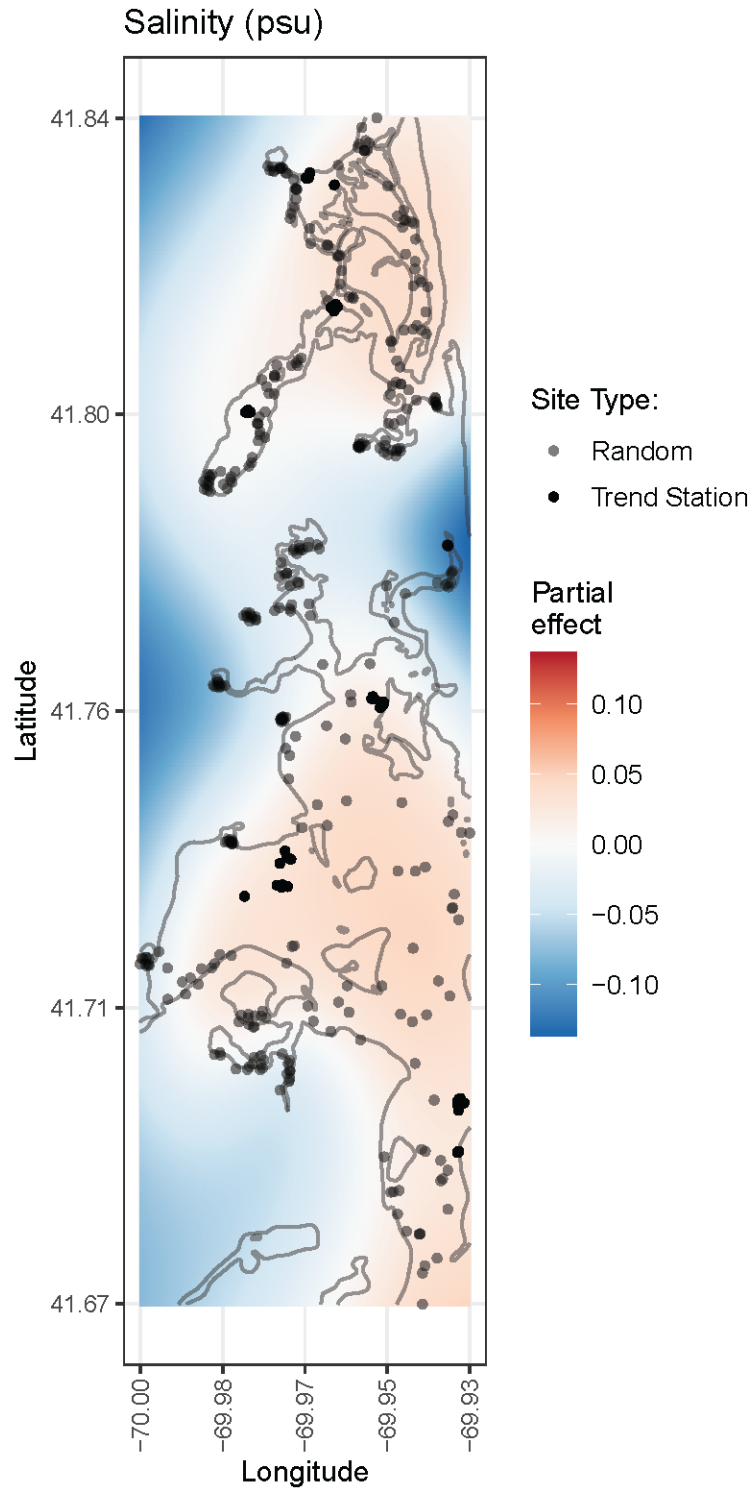


Figure 2-14. Mean surface for the generalized additive model latitude/longitude smooth of surface salinity within Cape Cod National Seashore (all strata) during 2007-2019.

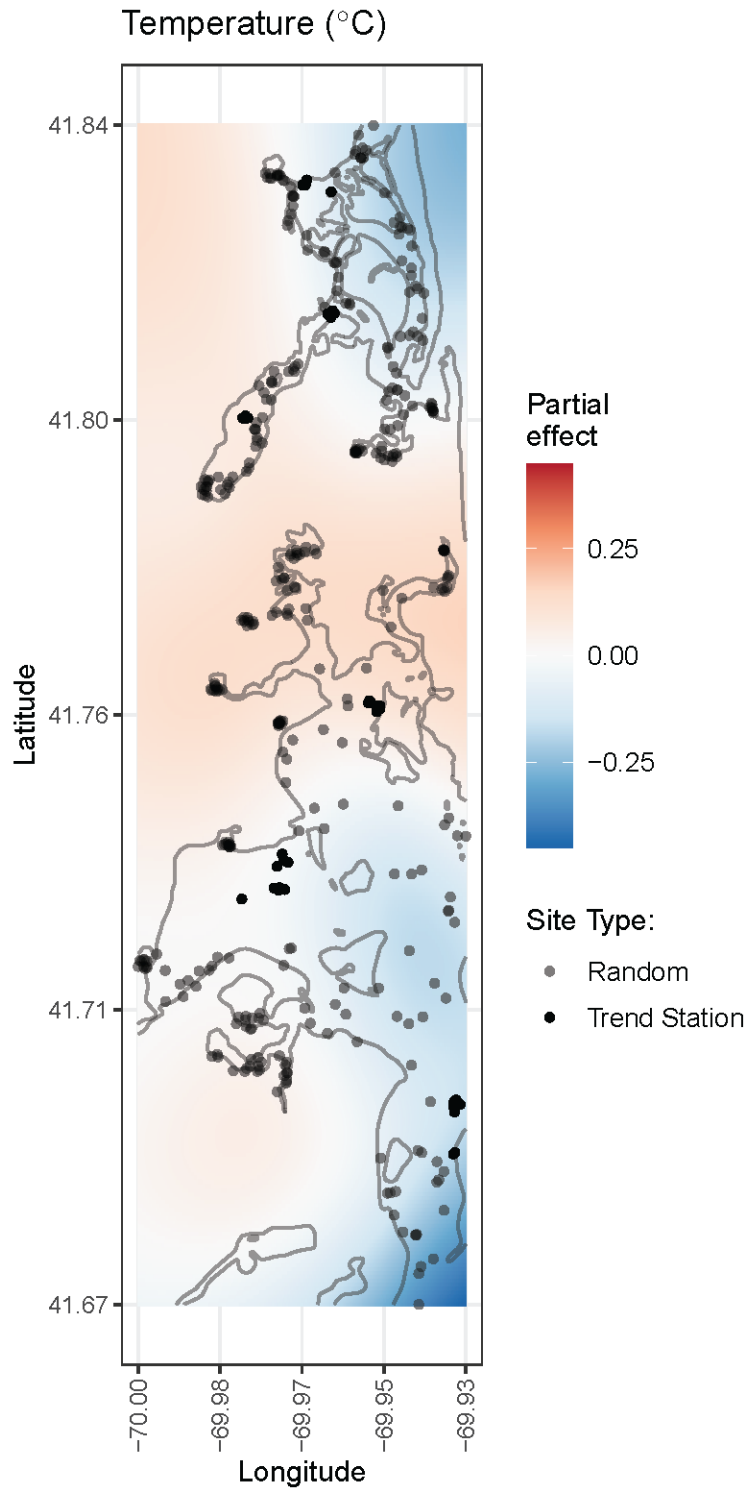


Figure 2-15. Mean surface for the generalized additive model latitude/longitude smooth of surface temperature within Cape Cod National Seashore (all strata) during 2007-2019.

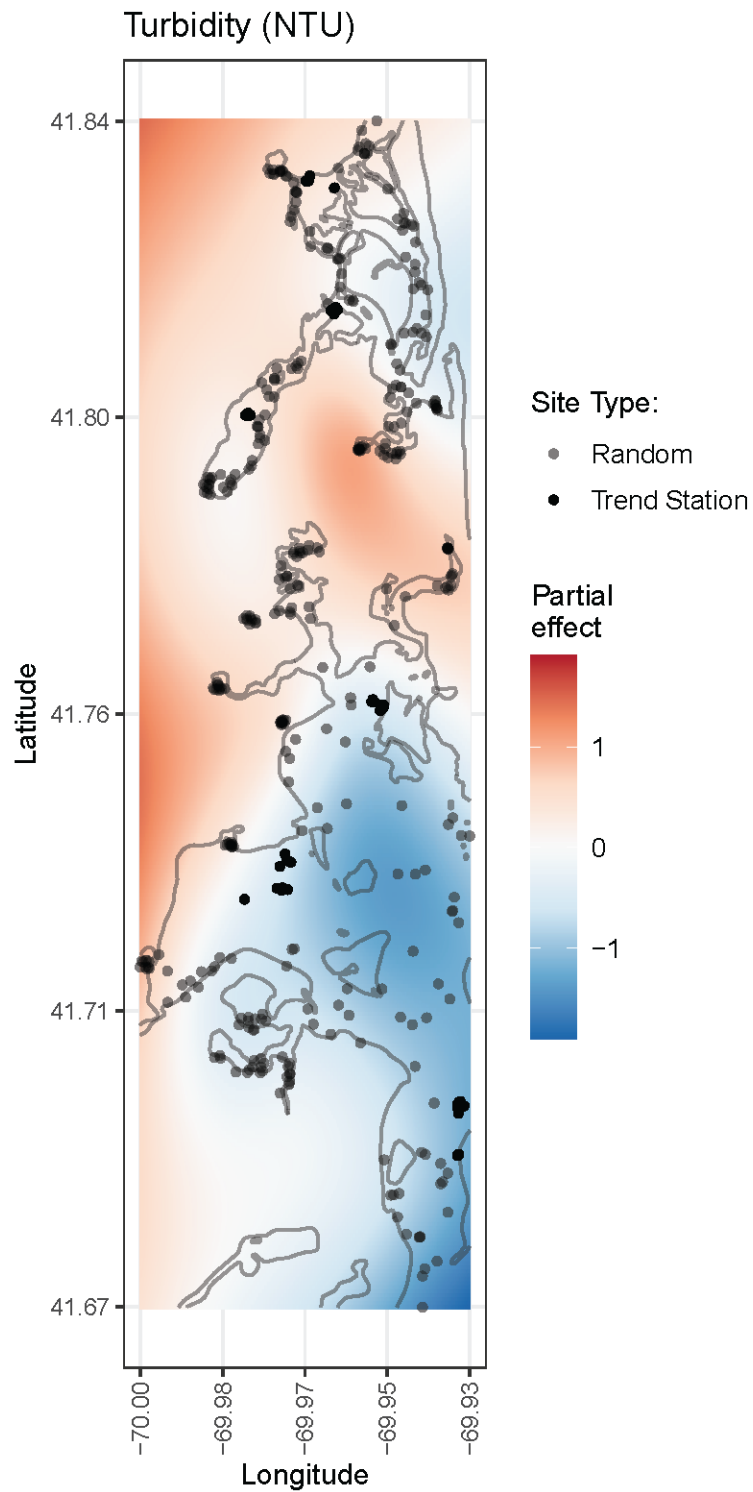


Figure 2-16. Mean surface for the generalized additive model latitude/longitude smooth of surface turbidity within Cape Cod National Seashore (all strata) during 2007-2019.

2.5.4 Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate that there are statistically significant increasing monotonic trends in both bottom dissolved oxygen (p -value = 0.004) and surface temperature (p -value = 0.043) during the period of 2007 to 2019 (Table 2-29). Additionally, there is a statistically significant decreasing monotonic trend in surface chlorophyll- a concentrations (p -value = 0.015).

Table 2-29. Summary of multivariate Mann-Kendall test for monotonic trend for each Cape Cod National Seashore (all strata) measure: 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.

Measure	Depth	Z_{MK}	p -value
Chlorophyll a ($\mu\text{g/L}$)	Surface	-2.43	0.015
Dissolved oxygen (mg/L)	Bottom	2.88	0.004
PAR attenuation (K_d (m^{-1}))	Water Column	-0.55	0.583
Salinity (psu)	Surface	-0.68	0.499
Temperature ($^{\circ}\text{C}$)	Surface	2.02	0.043
Turbidity (NTU)	Surface	0.10	0.919

3. Trend-Station Water Quality Data

3.1 Methods

3.1.1 Generalized Additive Model (GAM)

Generalized additive models (GAMs) are used to estimate trends in water quality measures for each trend station within an estuary. For each measure, 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 $f_{\text{station}_i}(\text{year})$ 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 2020). Each model is fit using the *mgcv* package (Wood 2011) and results were summarized/visualized using the *gratia* package (Simpson 2020).

3.1.2 Multivariate Mann-Kendall Trend Analysis

The multivariate Mann-Kendall test (trend R package; (Pohlert 2020)) is 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 (negative) values of the test statistic Z_{MK} indicates that measurements tend to increase (decrease) with time.

3.2 Summary Statistics

Yearly summary statistics for each trend station were computed for surface chlorophyll-*a* concentration (Table 3-1), bottom dissolved oxygen (Table 3-2), PAR attenuation (Table 3-3), surface salinity (Table 3-4), surface temperature (Table 3-5), and surface turbidity (Table 3-6).

Table 3-1. Yearly summary statistics for surface chlorophyll-*a* concentration ($\mu\text{g/L}$) at Cape Cod National Seashore trend stations. [SD = standard deviation]

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

Table 3-2. Yearly summary statistics for bottom dissolved oxygen concentration (mg/L) at Cape Cod National Seashore trend stations. [SD = standard deviation]

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

Table 3-3. Yearly summary statistics for PAR attenuation (K_d (m^{-1})) at Cape Cod National Seashore trend stations. [SD = standard deviation]

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

Table 3-4. Yearly summary statistics for surface salinity (psu) at Cape Cod National Seashore trend stations. [SD = standard deviation]

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

Table 3-5. Yearly summary statistics for surface temperature (°C) at Cape Cod National Seashore trend stations. [SD = standard deviation]

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

Table 3-6. Yearly summary statistics for surface turbidity (NTU) at Cape Cod National Seashore trend stations. [SD = standard deviation]

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

3.3 GAM Results

The generalized additive model summaries indicate that there exists statistically significant temporal trends (assuming a significance level of 0.05) at the trend stations in all water quality measures except salinity (Table 3-7). Notable observations from the fitted smooths for each measure are as follows:

3.3.1 Chlorophyll-*a* (near surface)

Temporal trends in chlorophyll-*a* are non-linear and differ by station (Figure 3-1). The most notable trend is the cyclic trend in chlorophyll-*a* concentration at hexagon 18 which also experiences the highest concentrations. No periods of statistically significant change were observed.

3.3.2 Dissolved Oxygen (near bottom)

The temporal trend in the bottom dissolved oxygen concentrations is slightly non-linear and relatively constant for each trend station (Figure 3-2). The yearly average concentrations are all above the 5 mg/L threshold (i.e., good quality category).

3.3.3 PAR Attenuation K_d (SAV standard)

Temporal trends for PAR attenuation are slightly non-linear and similar across trend stations (Figure 3-3). Hexagon 11 had relatively higher measurements and more within-year variability in 2007 and 2008 compared to the other trend stations.

3.3.4 Salinity (near surface)

There is no temporal trend in surface salinity and measurements tend to be slightly cyclical (Figure 3-4). No periods of significant temporal change were identified.

3.3.5 Temperature (near surface)

Temporal trends for all stations indicate a slight increase in surface water temperature with statistically significant increases occurring at hexagons 18 and 23 (Figure 3-5).

3.3.6 Turbidity (near surface)

Temporal trends in surface turbidity were slightly non-linear at stations within hexagons 7 and 18 (Figure 3-6). No periods of statistically significant change were observed.

Table 3-7. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore trend station model. Each respective F-statistic and p-value corresponds to the test of the hypotheses: $H_0: f(x) = 0$ versus $H_1: f(x) \neq 0$. Note: p-values are computed without considering uncertainty in the smoothing parameter estimates and may need to be interpreted with caution when near the α level. [edf = effective degrees of freedom, df_{ref} = reference degrees of freedom]

Measure	Depth	Model Term	edf(df_{ref})	F-value	p-value
Chlorophyll a ($\mu\text{g/L}$)	Surface	s(year,hex)	26.27 (65)	4.31	< 0.001
Dissolved oxygen (mg/L)	Bottom	s(year,hex)	13.68 (65)	0.85	< 0.001
PAR attenuation (K_d (m^{-1}))	Water Column	s(year,hex)	16.67 (65)	0.94	< 0.001
Salinity (psu)	Surface	s(year,hex)	2.59 (65)	0.07	0.102
Temperature ($^{\circ}\text{C}$)	Surface	s(year,hex)	9.90 (65)	3.60	< 0.001
Turbidity (NTU)	Surface	s(year,hex)	20.65 (65)	2.53	< 0.001

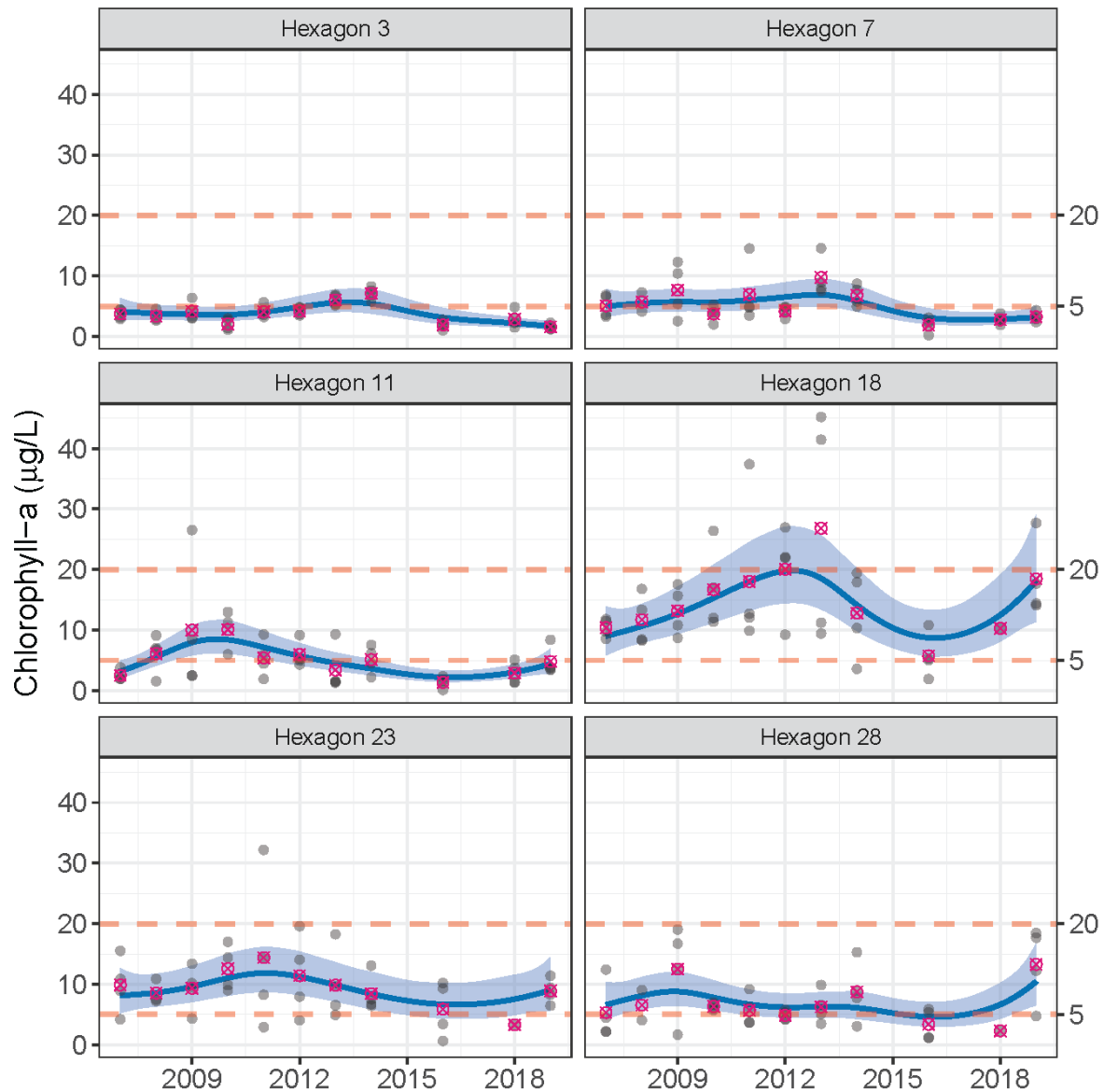


Figure 3-1. Mean surface chlorophyll-a concentration ($\mu\text{g/L}$) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines.

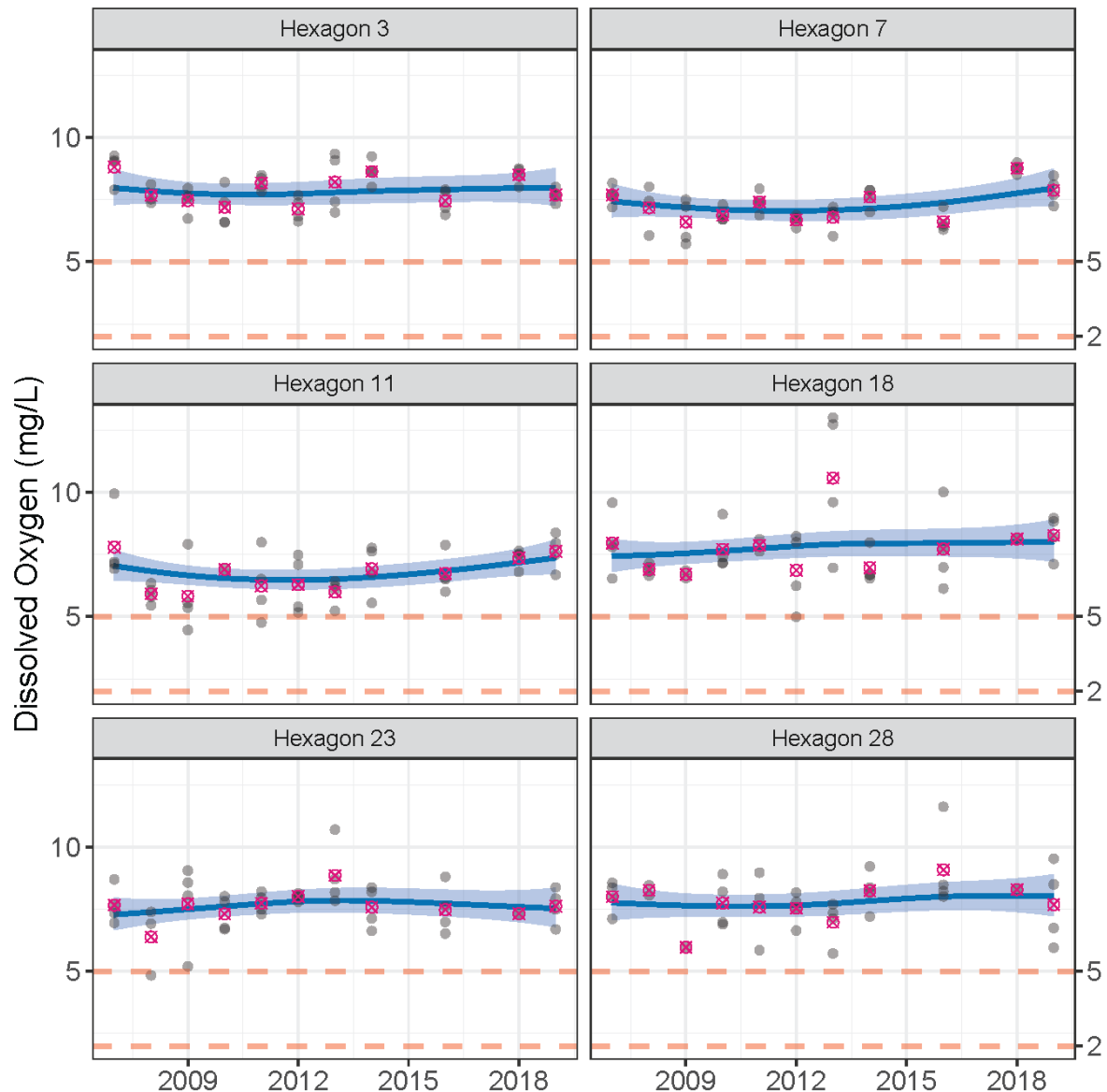


Figure 3-2. Mean bottom dissolved oxygen concentration (mg/L) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines.

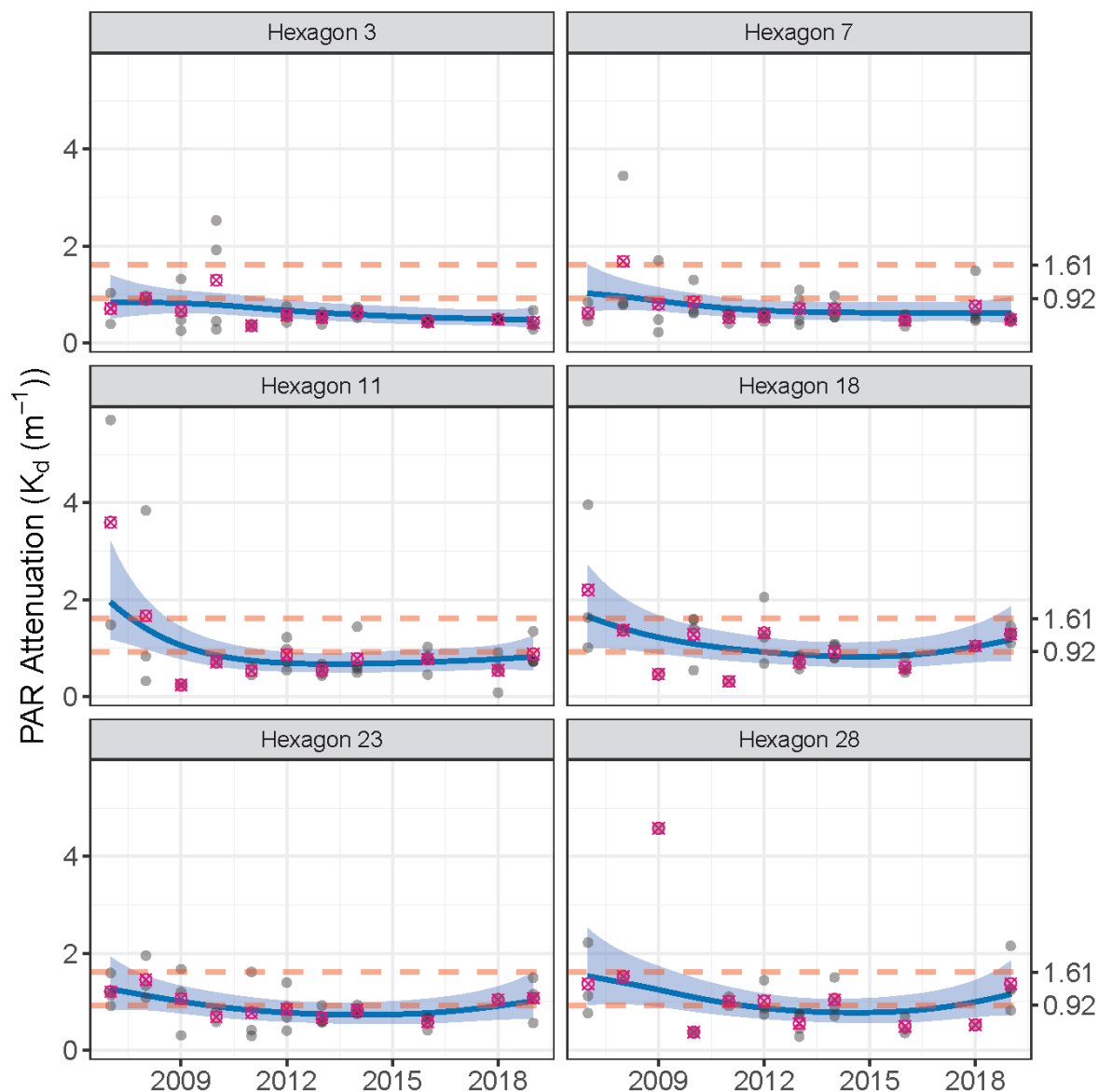


Figure 3-3. Mean PAR attenuation (K_d (m^{-1})) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines.

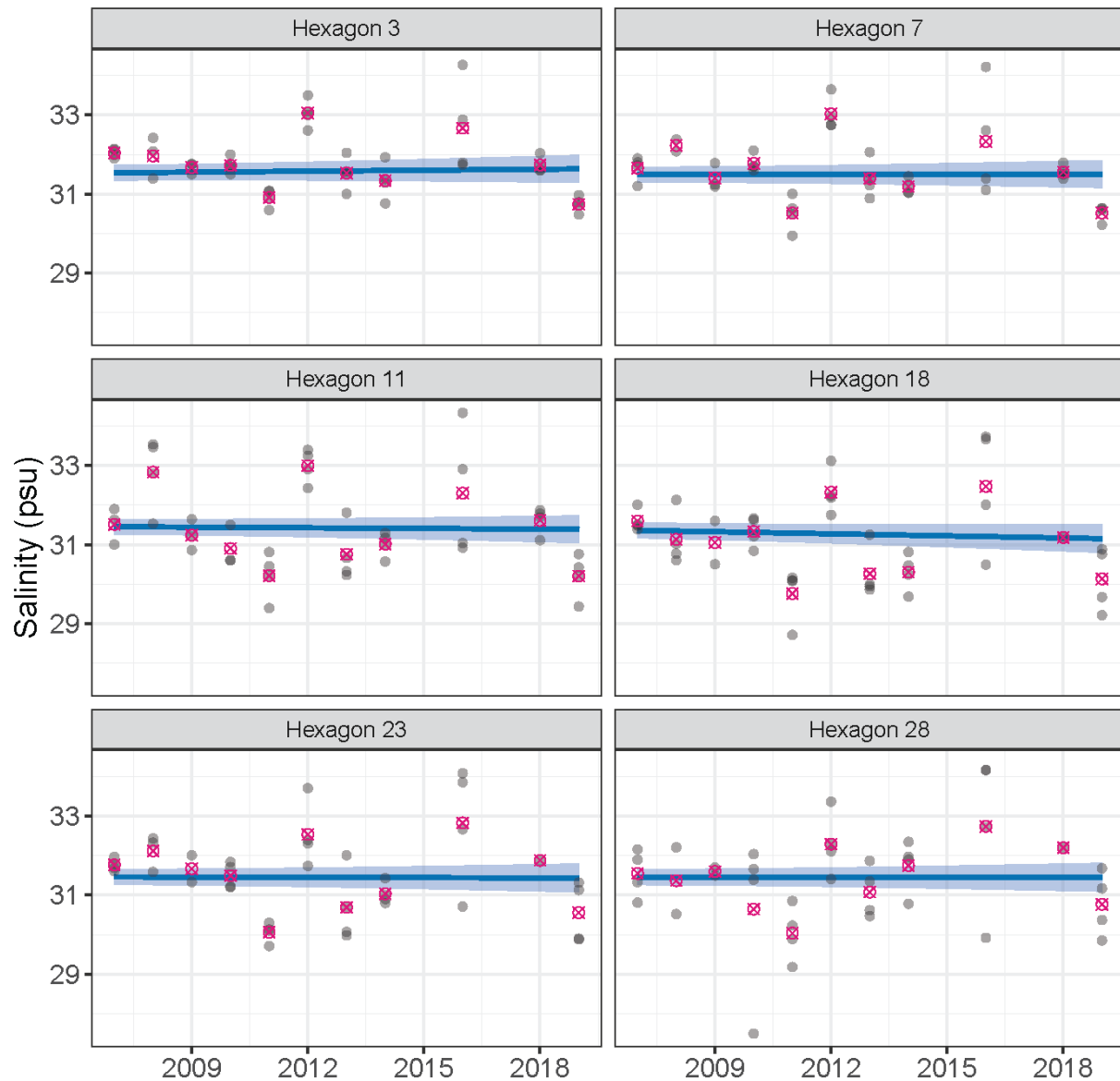


Figure 3-4. Mean surface salinity (psu) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively.

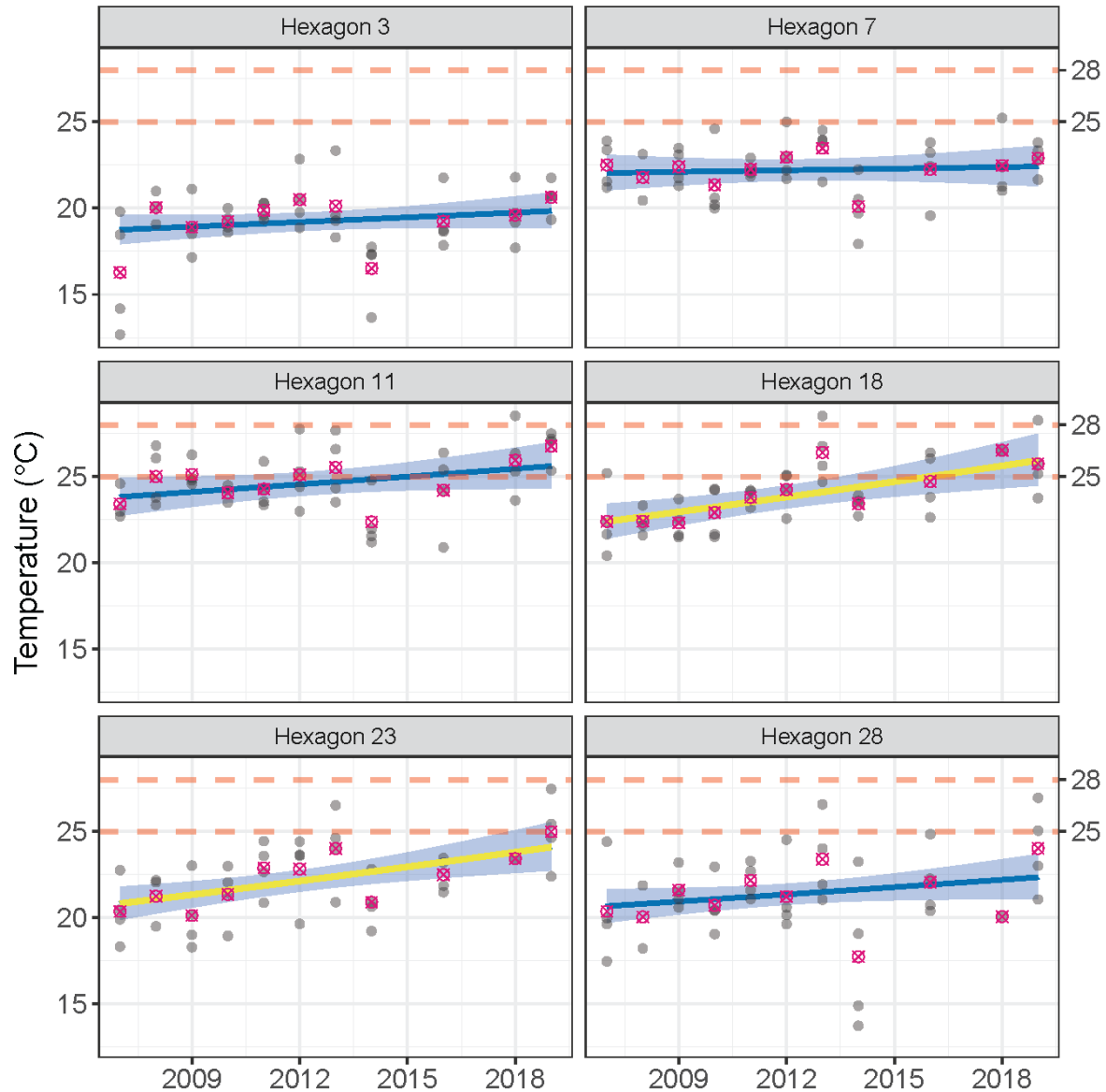


Figure 3-5. Mean surface temperature (°C) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines.

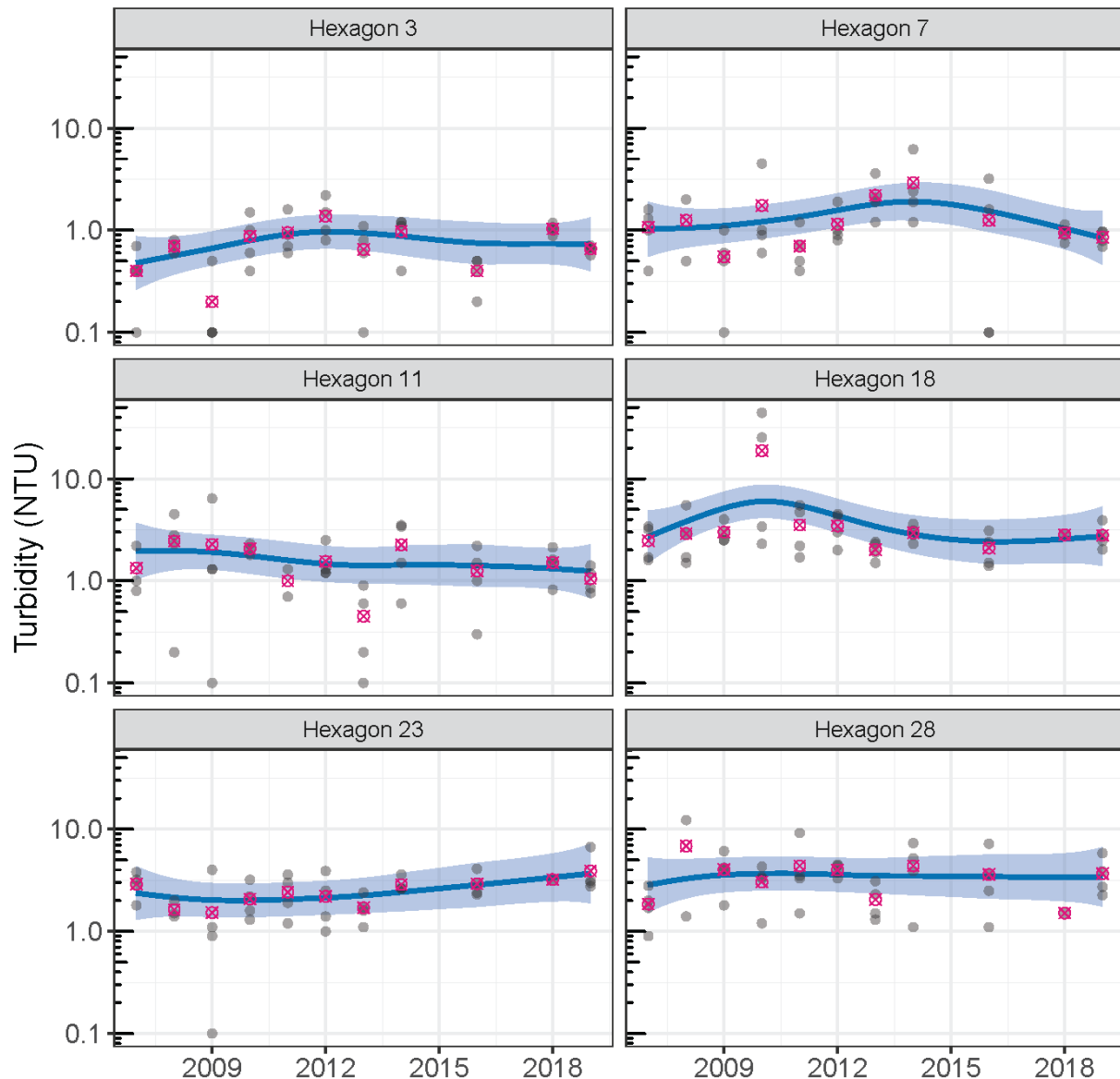


Figure 3-6. Mean surface turbidity (NTU) trend at each Cape Cod National Seashore trend station based on estimated generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Note: the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated trend.

3.4 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 monotonically increasing trend in both bottom dissolved oxygen and surface temperature at the trend stations during 2007 to 2019 (Table 3-8).

Table 3-8 Summary of multivariate Mann-Kendall test for monotonic trend in each measure for Cape Cod National Seashore trend stations: H_0 : no monotonic trend versus H_1 : monotonic trend is present. A positive (negative) value of the Mann-Kendall test statistic (Z_{MK}) indicates that measurements tend to increase (decrease) with time.

Measure	Depth	Z_{MK}	p -value
Chlorophyll a ($\mu\text{g/L}$)	Surface	-0.06	0.952
Dissolved oxygen (mg/L)	Bottom	2.16	0.031
PAR attenuation (K_d (m^{-1}))	Water Column	-0.65	0.518
Salinity (psu)	Surface	0.19	0.853
Temperature ($^{\circ}\text{C}$)	Surface	2.67	0.008
Turbidity (NTU)	Surface	1.66	0.097

4. Logging-Station Continuous Water Quality Data

4.1 Continuous Record Plots

Plots of the entire record of continuous data collected at each logging-station are not included in this report due to the large volume of figures produced. We refer the reader to the folder `/report/figures/` if inspection of the plots is desired. All plots follow the following filename format:

`ls_[park]_s[stratum]_[measure]_[year].pdf`

An example plot is provided in Figure 4-1.

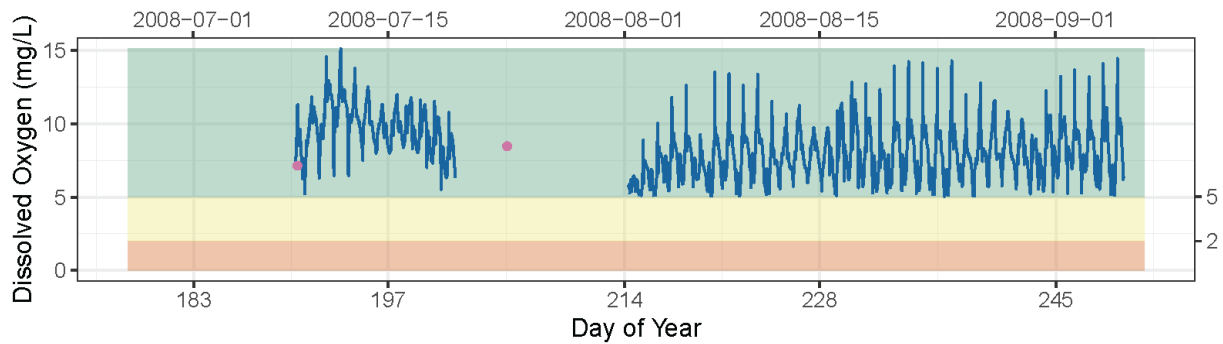


Figure 4-1. Continuous dissolved oxygen readings from sonde deployed at the Cape Cod National Seashore Pleasant Bay logging station in 2008. Magenta points represent discrete grab samples collected every week for quality assurance. Estuarine quality category thresholds (Table 2-1) are delineated by the background color.

4.2 Methods

4.2.1 Generalized Additive Model (GAM)

Generalized additive models (GAMs) are used to characterize intra-annual trends in continuous logging station data. For each water quality measure, we model 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 $f_{\text{year}_i}(\text{year})$ is a rank 20 TRPS smooth of doy for the i th year, $f(\text{hour})$ is a rank 24 cyclic cubic spline. The doy 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 measures exhibit diel patterns (e.g., dissolved oxygen). Temporal autocorrelation was not modeled due to the high computational cost of doing so with 15k-45k observations 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 included in the model.

Each model is fit using the *mgcv* package (Wood 2011) and results were summarized/visualized using the *gratia* package (Simpson 2020).

4.2.2 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 (Table 2-1).

4.3 Pleasant Bay Stratum Results

Notable observations from the fitted smooths and data summaries for each measure are as follows:

4.3.1 Chlorophyll-*a*

Intra-annual mean trends in chlorophyll-*a* concentration are relatively smooth for most years except 2010 (Figure 4-2). Chlorophyll-*a* condition within the Pleasant Bay stratum is variable and typically spans two condition categories per day (Figure 4-8).

4.3.2 Dissolved Oxygen

Intra-annual mean trends in dissolved oxygen are non-linear at this temporal scale and the cyclic nature appears to be consistent across years (Figure 4-2). Dissolved oxygen condition within the Pleasant Bay stratum is generally good with some days experiencing fair conditions for part of the day (Figure 4-9).

4.3.3 PAR Attenuation K_d

The highest mean PAR attenuation (1.04 m^{-1}) was observed in 2007 (Table 4-1). Intra-annual mean trends are relatively smooth with some years exhibiting increasing trends (Figure 4-2). The distribution of measurements in 2014 and 2019 are more highly right skewed compared to other years (Figure 4-3). PAR attenuation condition within the Pleasant Bay stratum is generally good with a majority of days experiencing both fair and poor conditions for part of the day (Figure 4-10).

4.3.4 pH

Measurements of pH obtained in 2018 and 2019 were much more periodic and stationary compared to 2014 (Figure 4-6). The distribution of measurements typically spans about 0.5 units (Figure 4-7).

4.3.5 Salinity

Intra-annual mean trends in salinity are non-linear with 2014 experiencing a large decreasing trend that appears somewhat anomalous (Figure 4-4). Salinity measurements in 2014 were more left skewed than normal and 2019 experienced skew in both tails (Figure 4-5).

4.3.6 Temperature

Intra-annual mean trends in water temperature are highly non-linear with a cyclic nature that appears to be consistent year over year (Figure 4-4). Water temperature measurements within each year typically span approximately 10 °C and are left skewed (Figure 4-5).

4.3.7 Turbidity

Intra-annual mean trends in turbidity are non-linear and differ year-to-year (Figure 4-4). Some years (e.g., 2018) have increasing trends for the period of measurement.

Table 4-1. Yearly summary statistics for measures collected at the Cape Cod National Seashore Pleasant Bay station. [SD = standard deviation]

Measure	Statistic	Sampling Year										
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019
Chlorophyll <i>a</i> (µg/L)	Mean	2.51	3.15	3.64	13.63	4.30	6.55	4.71	2.60	4.96	1.20	4.24
Chlorophyll <i>a</i> (µg/L)	SD	1.51	1.09	2.83	9.98	1.13	2.83	2.78	1.68	7.28	0.92	2.42
Chlorophyll <i>a</i> (µg/L)	n	2840.00	1837.00	2719.00	4510.00	2502.00	3163.00	3692.00	2995.00	3399.00	3529.00	3812.00
Depth (m)	Mean	0.89	1.02	1.04	1.12	1.29	1.12	1.26	1.09	1.13	1.09	1.23
Depth (m)	SD	0.46	0.48	0.47	0.48	0.47	0.43	0.45	0.43	0.39	0.40	0.37
Depth (m)	n	2878.00	5722.00	4611.00	5429.00	2506.00	3163.00	3738.00	3068.00	3651.00	3564.00	3935.00
dissolved oxygen (mg/L)	Mean	9.28	8.38	8.19	8.08	7.27	6.18	6.97	7.21	7.35	6.95	6.62
dissolved oxygen (mg/L)	SD	1.59	1.77	1.13	1.40	1.27	1.18	1.42	1.40	1.95	1.42	1.32
dissolved oxygen (mg/L)	n	2852.00	4411.00	2771.00	727.00	2506.00	3163.00	3737.00	3068.00	3651.00	3564.00	3935.00
PAR attenuation (K_d (m ⁻¹))	Mean	0.75	1.04	0.83	0.68	0.49	0.52	0.53	0.64	0.56	0.76	0.81
PAR attenuation (K_d (m ⁻¹))	SD	0.48	0.72	0.75	0.66	0.43	0.33	0.44	0.71	0.42	0.43	0.65
PAR attenuation (K_d (m ⁻¹))	n	392.00	921.00	730.00	673.00	469.00	578.00	774.00	551.00	342.00	740.00	989.00
pH	Mean	NA	NA	NA	NA	NA	NA	NA	7.94	NA	7.99	7.94
pH	SD	NA	NA	NA	NA	NA	NA	NA	0.16	NA	0.12	0.13
pH	n	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3068.00	0.00	3564.00	3935.00
Salinity (psu)	Mean	31.58	30.59	32.13	31.64	31.40	33.20	30.27	29.44	33.37	30.76	30.52
Salinity (psu)	SD	0.23	0.68	0.71	0.59	0.43	0.47	0.53	1.95	0.27	0.62	0.54
Salinity (psu)	n	2876.00	5722.00	2772.00	2386.00	2506.00	3163.00	3736.00	3068.00	3651.00	3564.00	3933.00
Temperature (°C)	Mean	21.85	22.00	21.55	22.70	23.03	24.13	24.35	22.33	24.43	23.99	24.51
Temperature (°C)	SD	2.13	2.11	2.48	2.57	2.11	1.85	2.13	1.64	2.04	2.04	1.73
Temperature (°C)	n	2878.00	5722.00	4611.00	5429.00	2506.00	3163.00	3738.00	3068.00	3651.00	3564.00	3935.00
Turbidity (NTU)	Mean	0.89	1.66	NA	NA	1.41	2.25	2.78	1.65	1.95	1.57	3.51
Turbidity (NTU)	SD	0.76	3.30	NA	NA	1.01	4.18	3.86	4.80	0.87	0.72	1.89
Turbidity (NTU)	n	1745.00	2038.00	0.00	0.00	2504.00	3102.00	3527.00	3048.00	3631.00	3526.00	3902.00

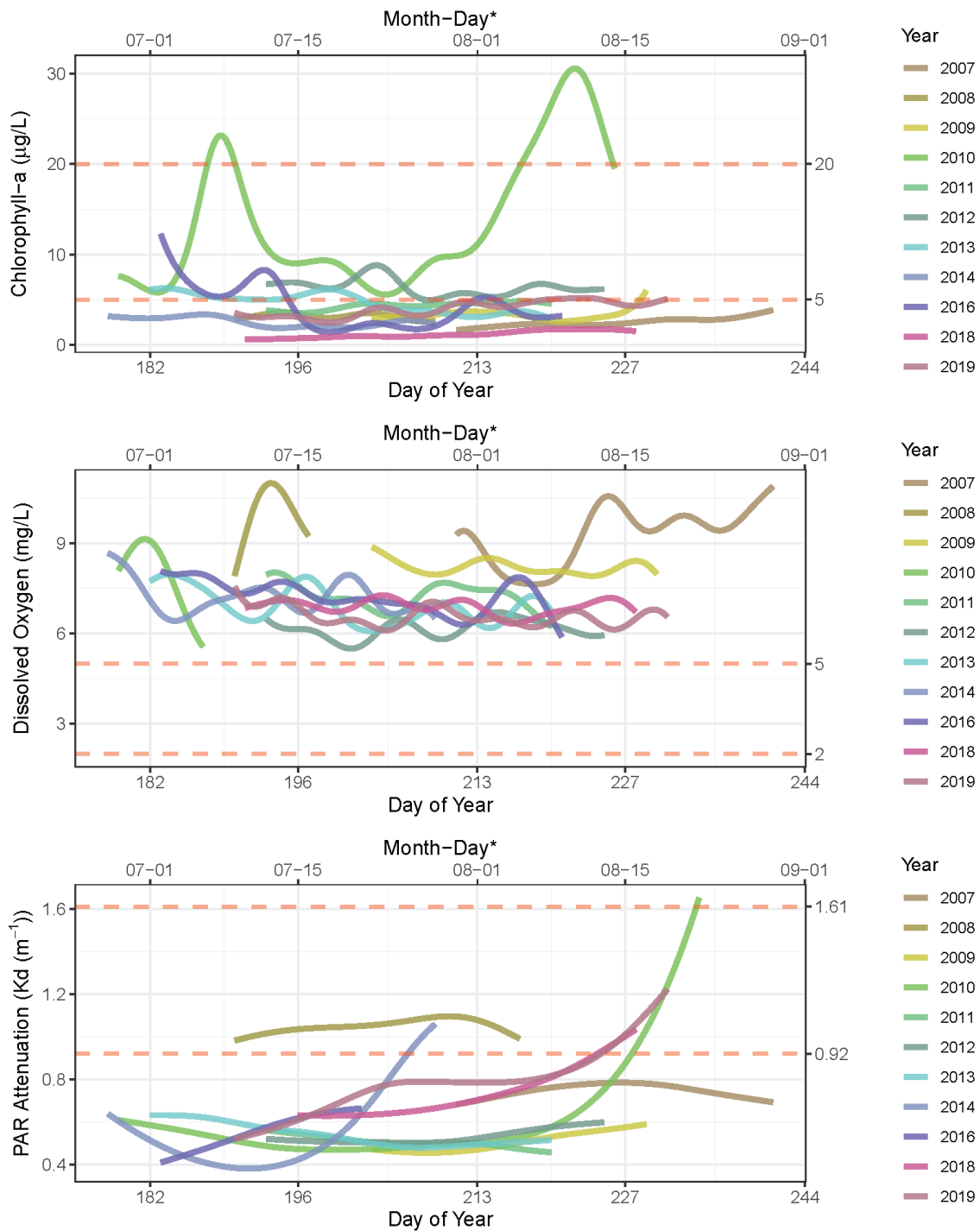


Figure 4-2. Distribution of index period time series values for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Pleasant Bay logging station. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: the y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated distributions for surface chlorophyll-a concentration.

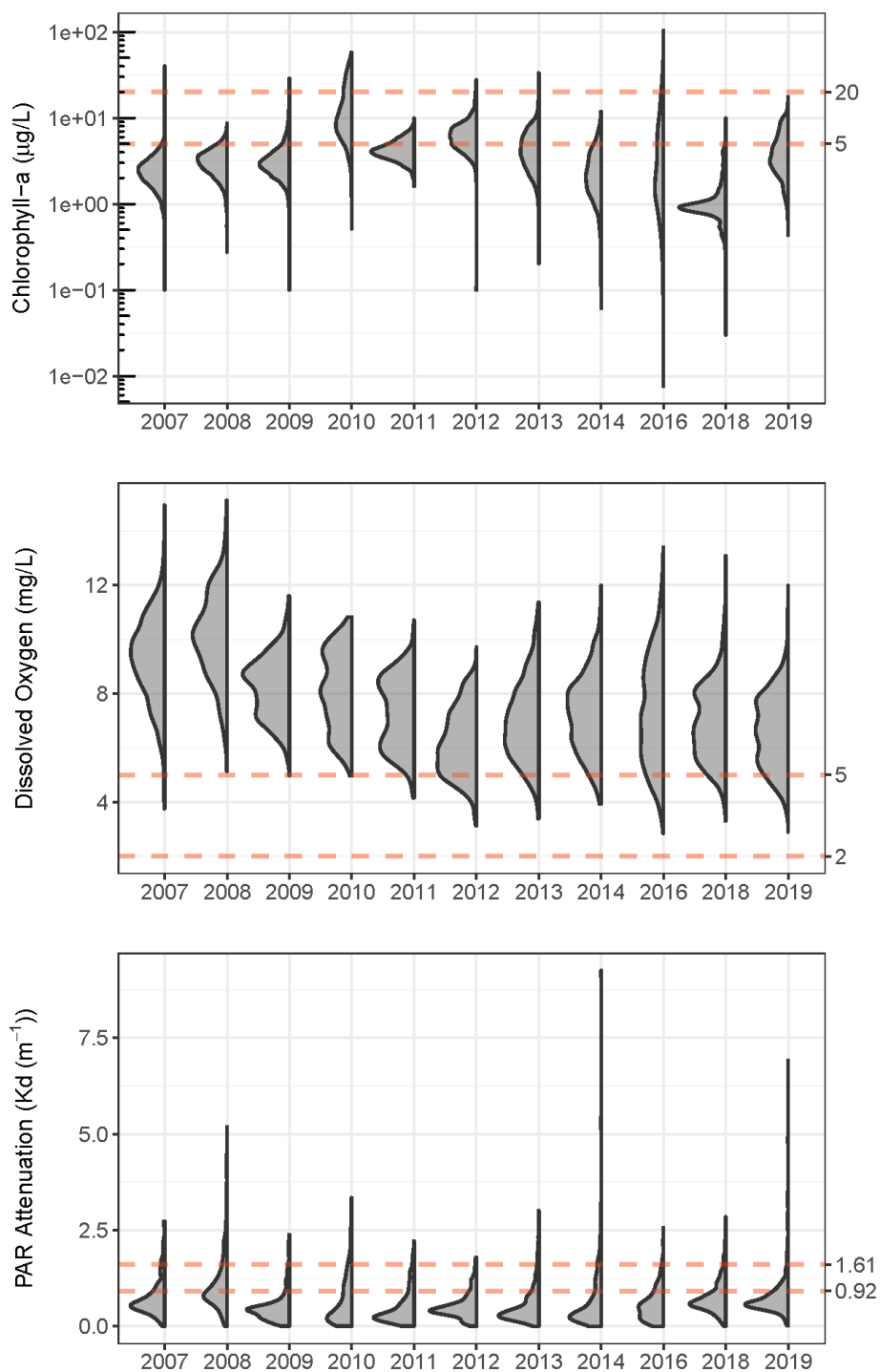


Figure 4-3. Distribution of index period time series values for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Fire Island National Seashore logging station. Estuarine quality category thresholds (Table 2-1) are plotted as red dashed lines. Note: the surface chlorophyll-a concentration y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated distributions.

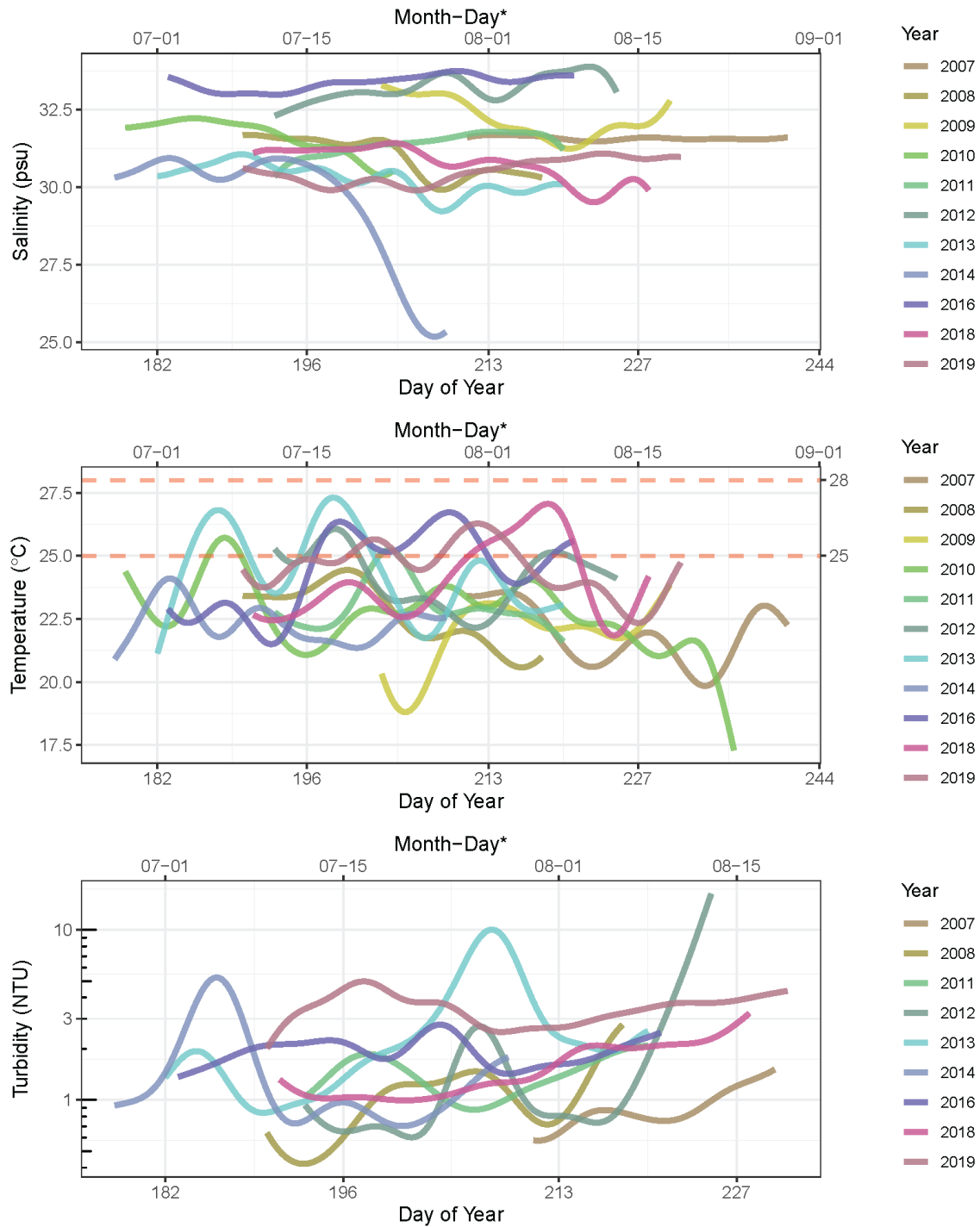


Figure 4-4. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Pleasant Bay logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: the y-axis is transformed to the log₁₀ scale to better visualize the estimated trends for surface turbidity.

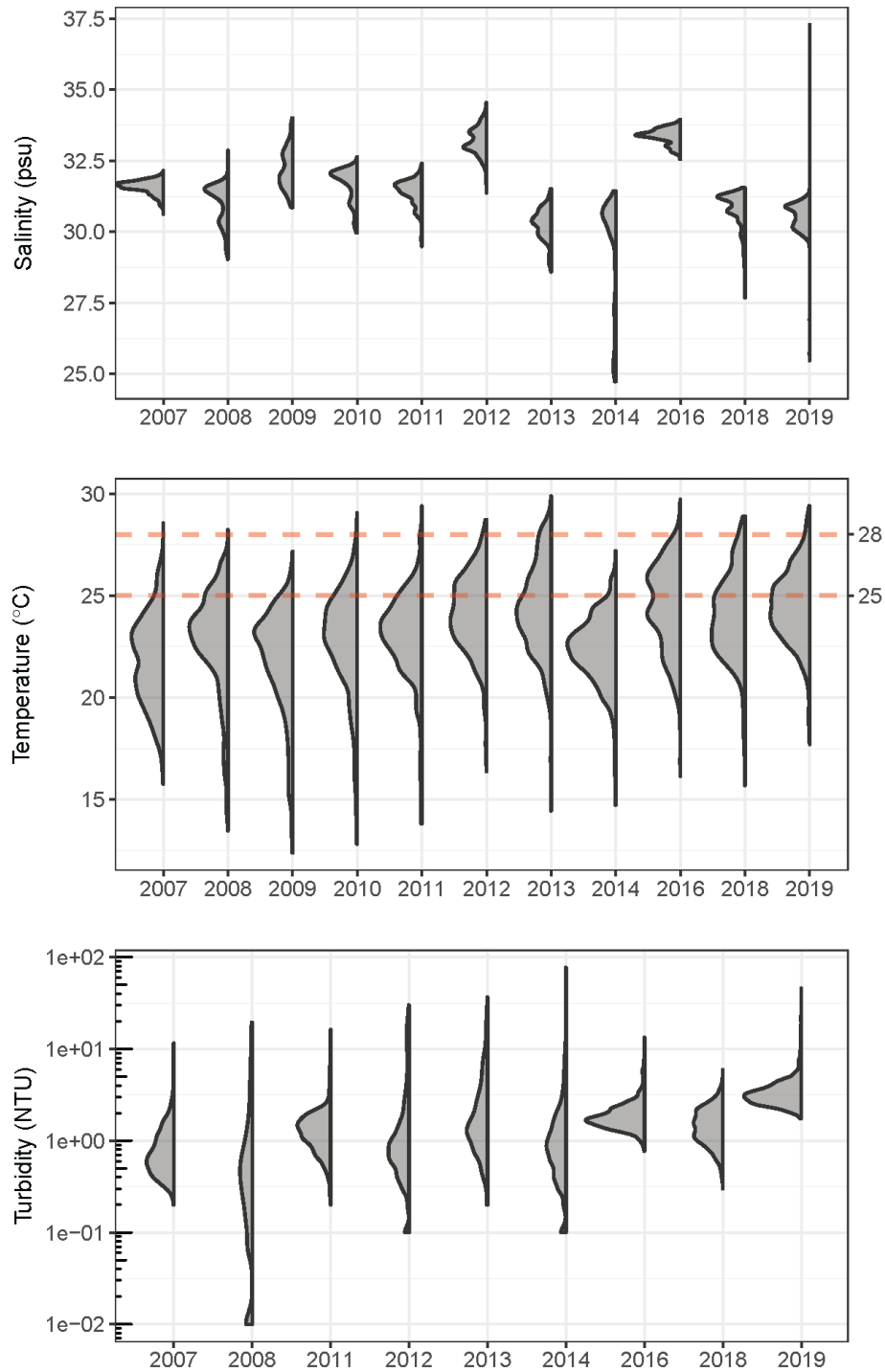


Figure 4-5. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Pleasant Bay logging station. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: the y-axis is transformed to the log₁₀ scale to better visualize the estimated distributions for surface turbidity.

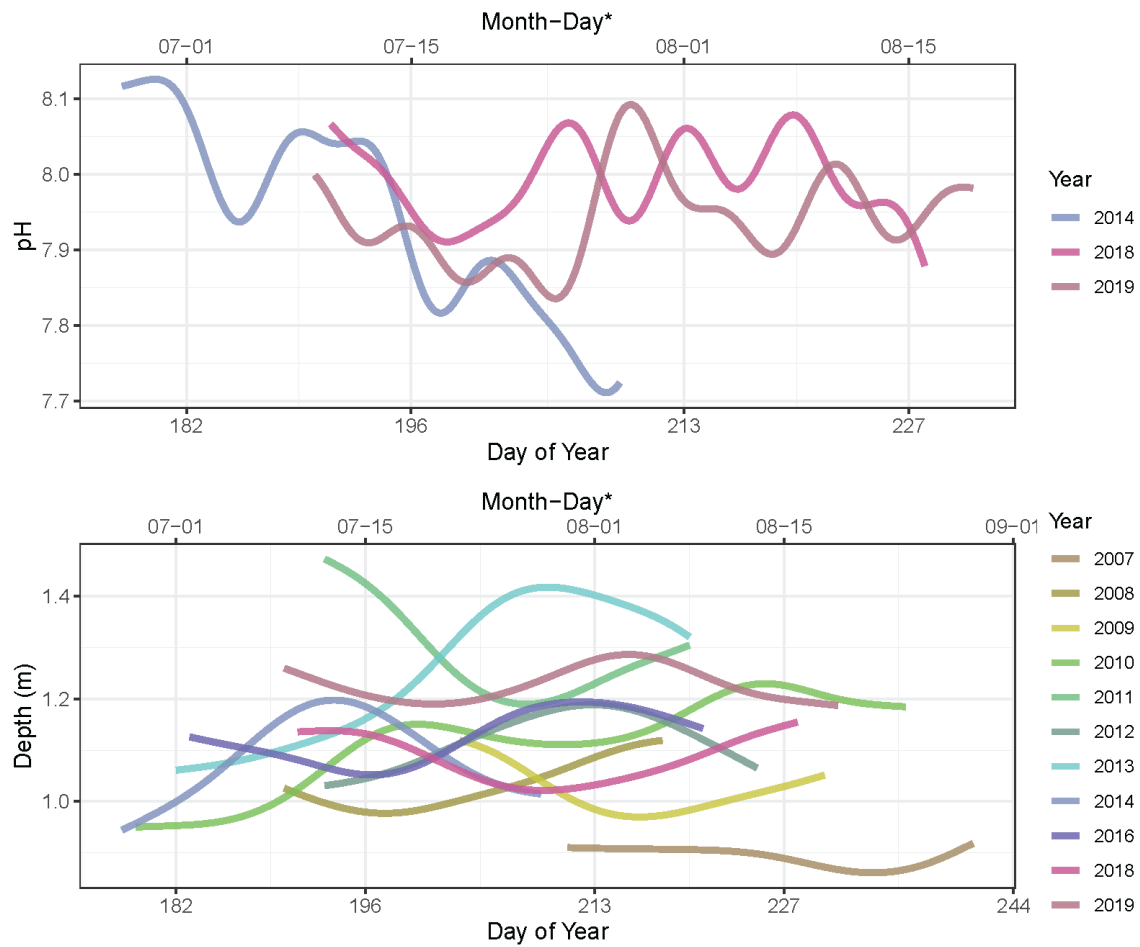


Figure 4-6. Intra-annual trends in pH (top) and depth (bottom) at the Cape Cod National Seashore Pleasant Bay logging station based on estimated generalized additive model smooths.

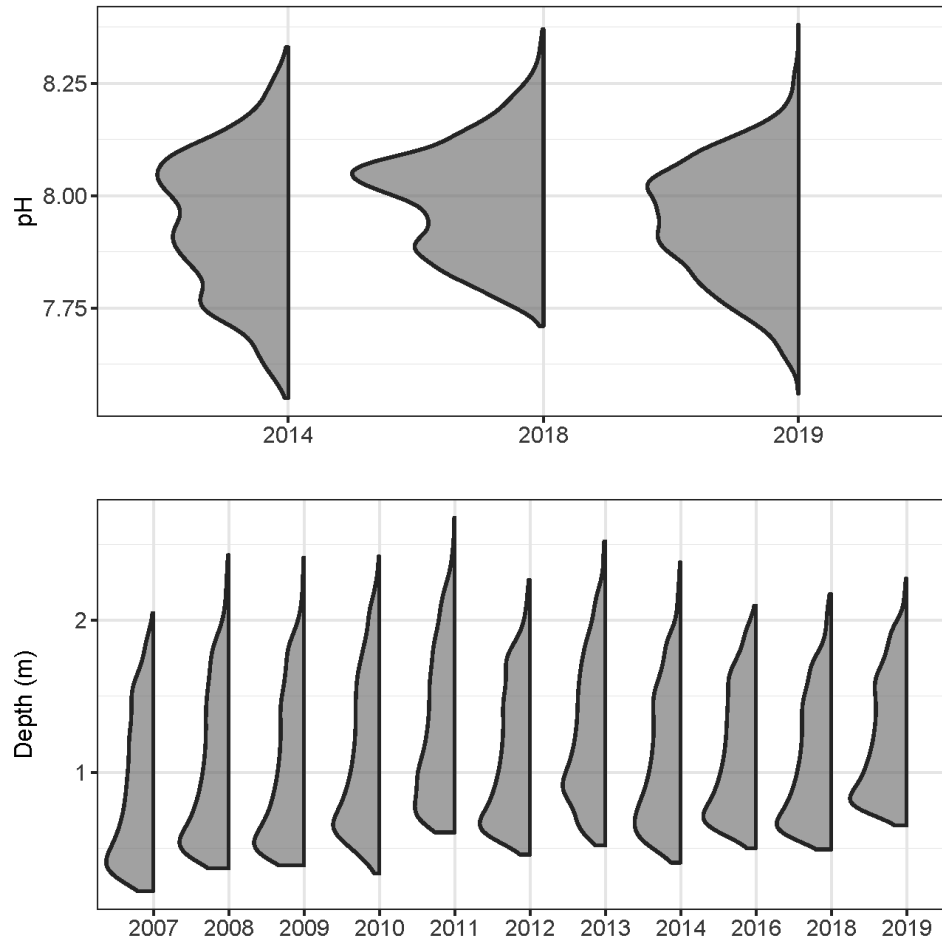


Figure 4-7. Distribution of index period time series values for pH (top) and depth (bottom) at the Cape Cod National Seashore Pleasant Bay logging station.

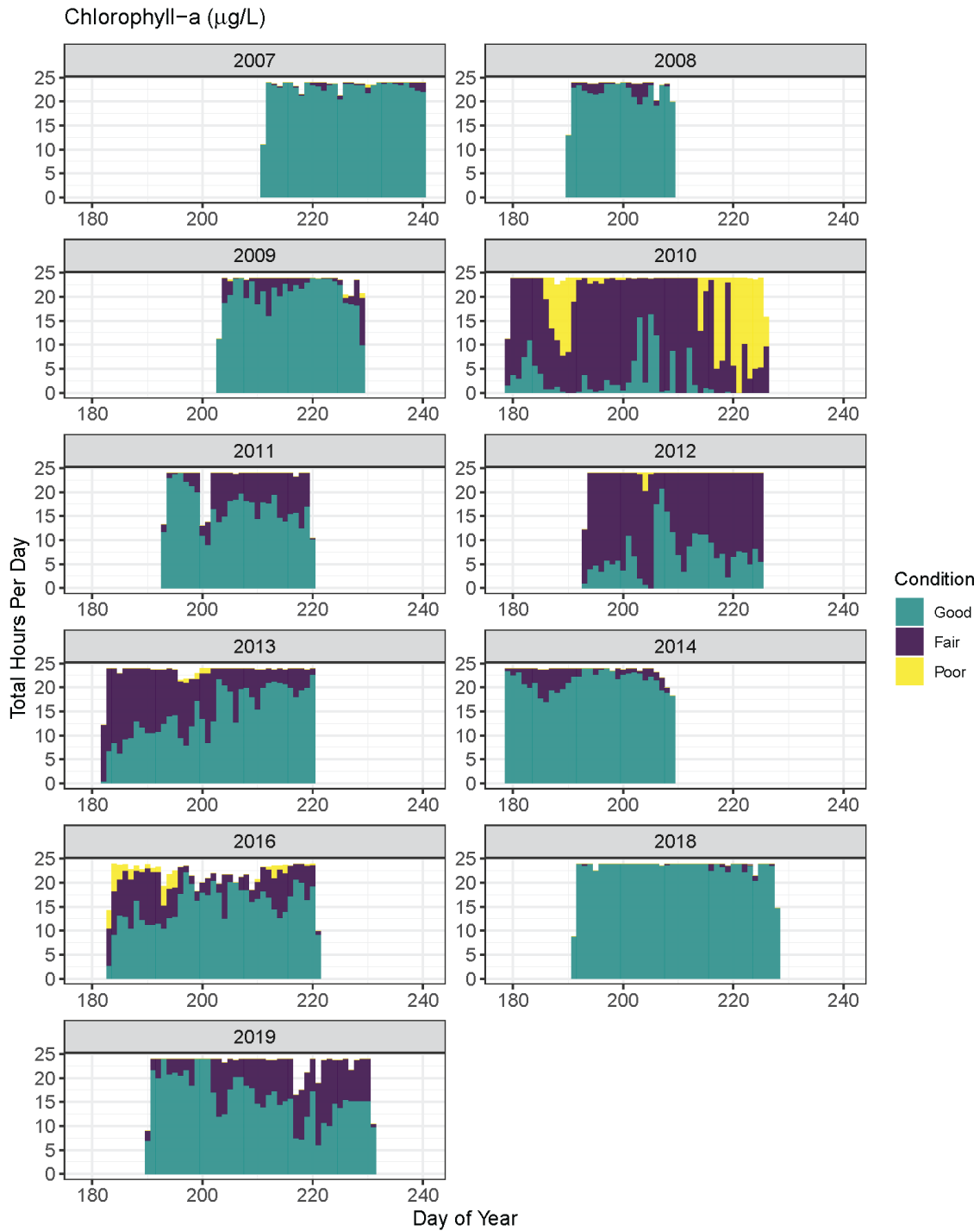


Figure 4-8. Total hours per day that surface chlorophyll-a concentration was observed within each condition category at the Cape Cod National Seashore Pleasant Bay logging station.

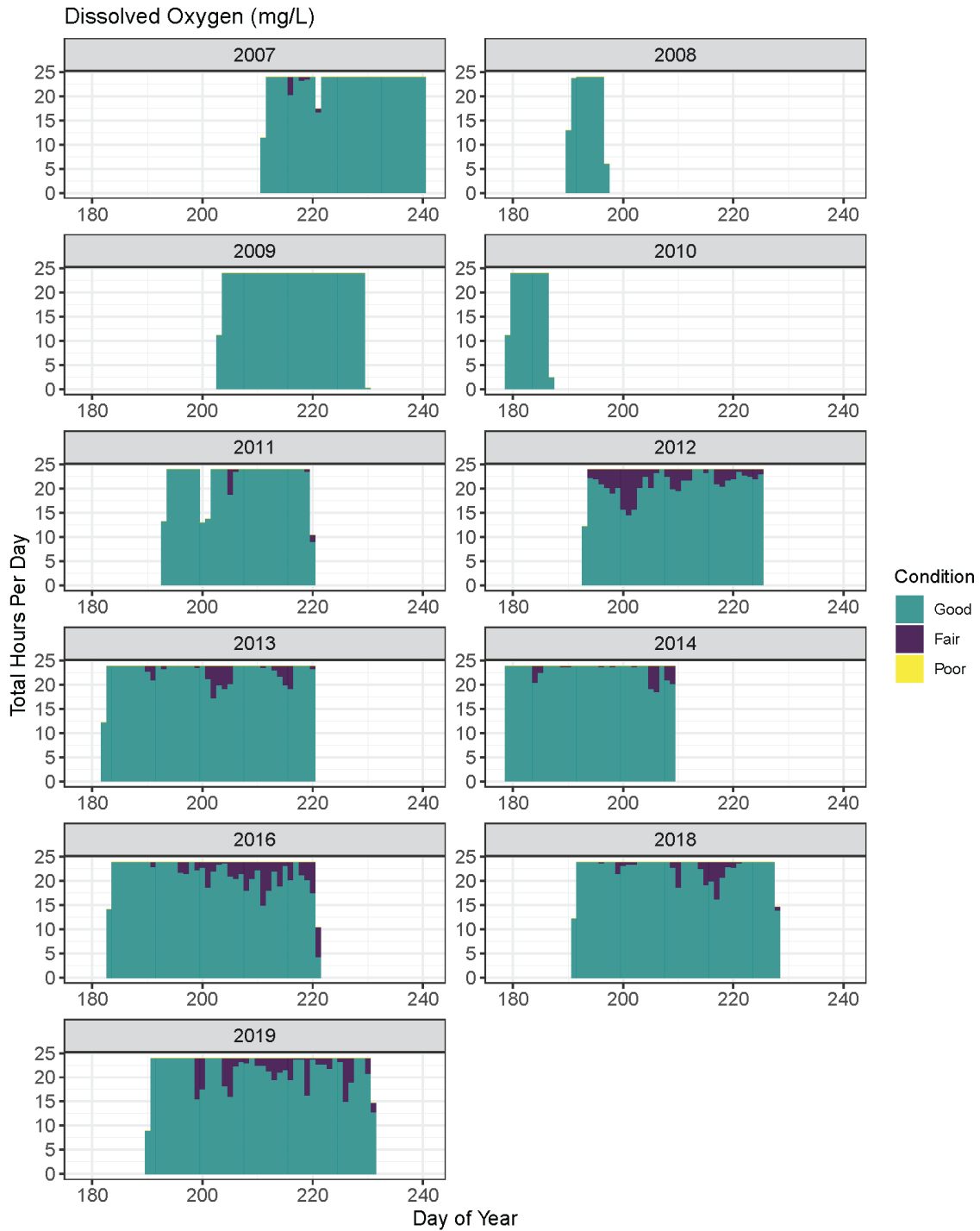


Figure 4-9. Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the Cape Cod National Seashore Pleasant Bay logging station.

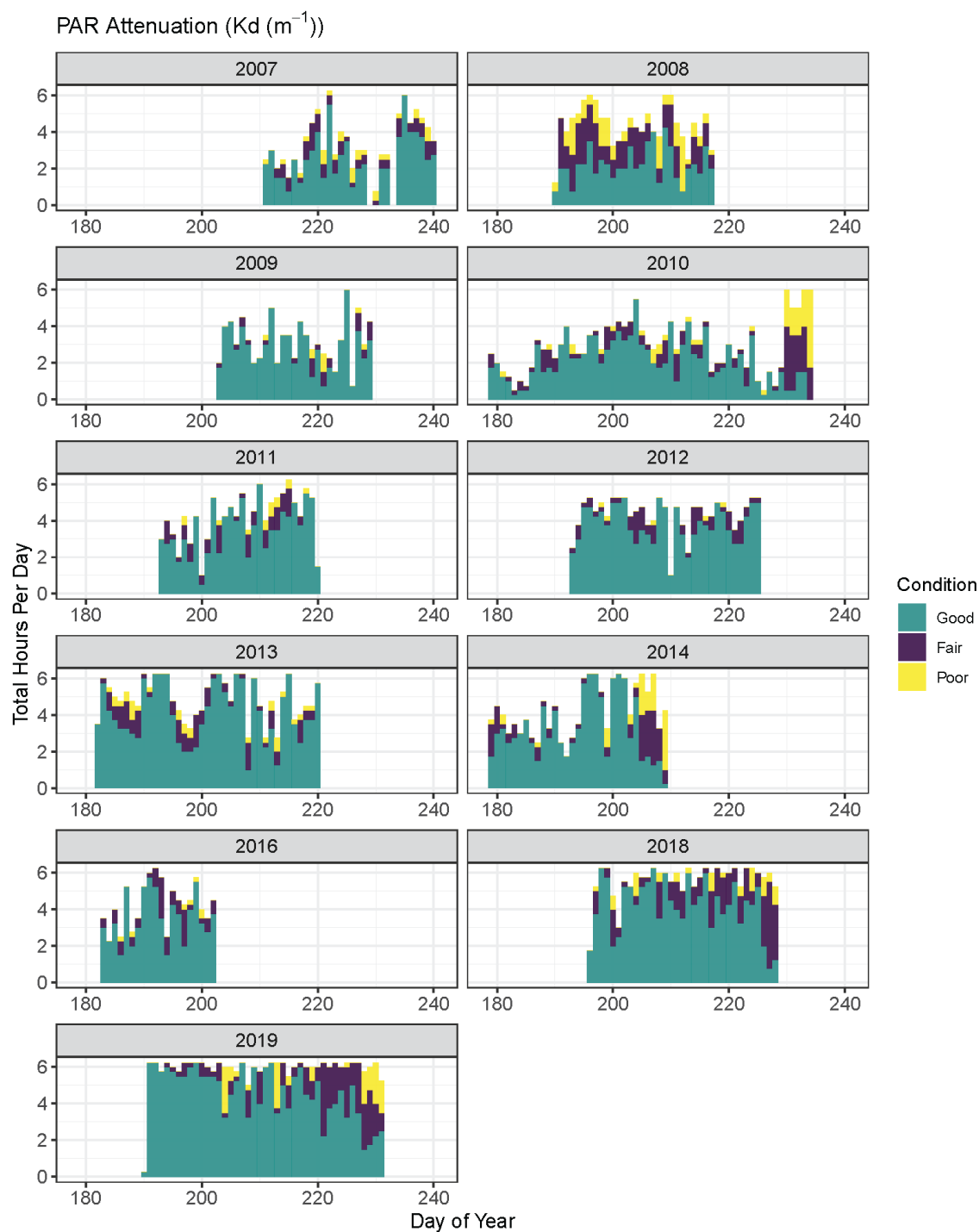


Figure 4-10. Total hours per day that PAR attenuation was observed within each condition category at the Cape Cod National Seashore Pleasant Bay logging station.

4.4 Nauset Harbor Stratum Results

Notable observations from the fitted smooths and data summaries for each measure are as follows:

4.3.1 Chlorophyll-*a*

Intra-annual mean trends in chlorophyll-*a* concentration is highly non-linear for most years (Figure 4-11) and the associated distribution of measurements tends to also be highly right skewed most years (Figure 4-12). Chlorophyll-*a* condition within Nauset Harbor stratum is generally variable and typically spans two condition categories per day (Figure 4-17).

4.3.2 Dissolved Oxygen

Intra-annual mean trends in dissolved oxygen are non-linear at this temporal scale and the cyclic nature appears to be consistent across years (Figure 4-11). Measurements in 2010 are noticeably different from most other years. Dissolved oxygen conditions are generally good with a few days experiencing fair conditions for part of the day (Figure 4-18).

4.3.3 PAR Attenuation K_d

The highest mean PAR attenuation observed in the Nauset Harbor stratum was 1.92 m^{-1} in 2010 (Table 4-2). Intra-annual trends are non-linear and appear to be increasing for most years (Figure 4-11). The distribution of measurements in 2007 and 2016 are more highly right skewed compared to other years (Figure 4-12). PAR attenuation condition within the Nauset Harbor stratum is generally good with a majority of days experiencing both fair and poor conditions for part of the day (Figure 4-19).

4.3.4 pH

Intra-annual trends in pH within the Nauset Harbor stratum are non-linear and appear to be non-stationary for some years (Figure 4-15). The distribution of measurements typically spans approximately 0.2 units (Figure 4-16).

4.3.5 Salinity

Intra-annual mean trends in salinity are non-linear and highly variable year-to-year (Figure 4-13). Salinity measurements prior to 2012 tended to be more variable and left-skewed (Figure 4-14).

4.3.6 Temperature

Intra-annual mean trends in water temperature are non-linear and appear to be relatively constant for the period of measurement each year (Figure 4-13). Water temperature measurements within each year typically span approximately 10°C (Figure 4-14).

4.3.7 Turbidity

Intra-annual mean trends in turbidity are relatively stationary with 2007 and 2008 having somewhat anomalous trends (Figure 4-13). Turbidity measurements over time have become less variable (Figure 4-14).

Table 4-2. Yearly summary statistics for measures collected at the Cape Cod National Seashore Nauset Harbor logging station. [SD = standard deviation]

Measure	Statistic	Sampling Year										
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019
Chlorophyll <i>a</i> (µg/L)	Mean	7.69	6.89	5.10	4.22	7.12	11.95	7.26	7.74	9.06	10.92	4.80
Chlorophyll <i>a</i> (µg/L)	SD	10.83	3.89	3.02	3.72	4.19	7.05	4.62	4.19	5.34	7.53	3.50
Chlorophyll <i>a</i> (µg/L)	n	2391.00	4115.00	4749.00	4492.00	3741.00	3261.00	3341.00	3241.00	3820.00	2599.00	2313.00
Depth (m)	Mean	0.95	1.09	1.15	0.83	0.93	1.42	0.93	1.29	1.26	0.87	1.43
Depth (m)	SD	0.45	0.47	0.43	0.42	0.44	0.41	0.36	0.39	0.31	0.30	0.30
Depth (m)	n	2919.00	6734.00	5467.00	6234.00	3750.00	3260.00	3356.00	3265.00	3820.00	2606.00	2319.00
dissolved oxygen (mg/L)	Mean	8.37	6.70	6.84	9.31	7.95	7.87	7.68	8.01	8.04	7.72	7.89
dissolved oxygen (mg/L)	SD	1.55	1.73	0.97	2.13	0.96	1.04	1.23	0.82	0.88	0.90	0.87
dissolved oxygen (mg/L)	n	2000.00	4308.00	5463.00	6231.00	3751.00	3247.00	3011.00	3268.00	3820.00	2606.00	2319.00
PAR attenuation (K_d (m ⁻¹))	Mean	1.13	0.74	0.66	1.92	0.84	0.66	0.58	0.84	0.98	0.67	0.85
PAR attenuation (K_d (m ⁻¹))	SD	0.73	0.73	0.63	1.02	0.66	0.48	0.38	0.42	1.16	0.39	0.23
PAR attenuation (K_d (m ⁻¹))	n	356.00	268.00	147.00	742.00	413.00	522.00	515.00	839.00	781.00	585.00	613.00
pH	Mean	NA	NA	NA	NA	NA	NA	NA	7.88	7.96	7.96	8.06
pH	SD	NA	NA	NA	NA	NA	NA	NA	0.07	0.07	0.08	0.07
pH	n	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3268.00	3818.00	2606.00	2319.00
Salinity (psu)	Mean	31.58	32.65	33.59	31.81	30.07	32.00	30.95	30.41	31.50	31.65	30.94
Salinity (psu)	SD	0.29	0.60	0.45	0.65	0.53	0.39	0.52	0.45	0.28	0.28	0.32
Salinity (psu)	n	2891.00	4346.00	4506.00	6219.00	3751.00	3259.00	3355.00	3240.00	3820.00	2605.00	2319.00
Temperature (°C)	Mean	18.29	18.65	19.03	18.92	19.53	18.90	21.16	17.76	19.44	20.51	20.13
Temperature (°C)	SD	2.43	2.55	2.42	3.21	2.75	2.76	2.80	2.92	2.50	2.04	2.50
Temperature (°C)	n	2919.00	6734.00	5467.00	6234.00	3751.00	3261.00	3356.00	3268.00	3820.00	2606.00	2319.00
Turbidity (NTU)	Mean	5.07	3.43	2.07	2.73	2.40	1.94	2.33	3.00	2.39	1.73	3.20
Turbidity (NTU)	SD	6.02	4.28	2.34	2.54	1.48	1.04	2.92	1.78	4.11	0.70	1.14
Turbidity (NTU)	n	2427.00	3718.00	1580.00	3193.00	3741.00	2990.00	2692.00	3233.00	3815.00	2601.00	2299.00

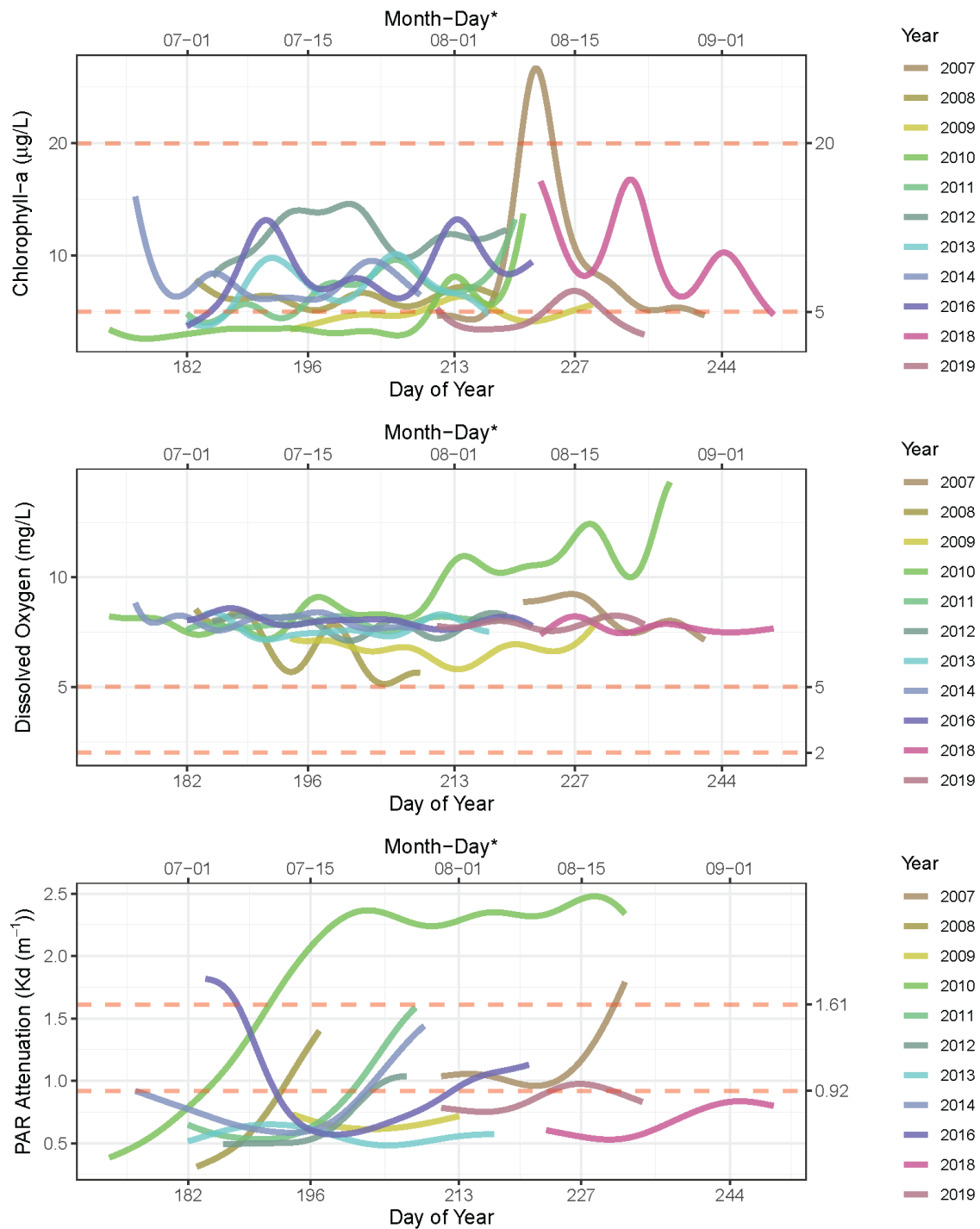


Figure 4-11. Intra-annual trends in for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Nauset Harbor logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines.

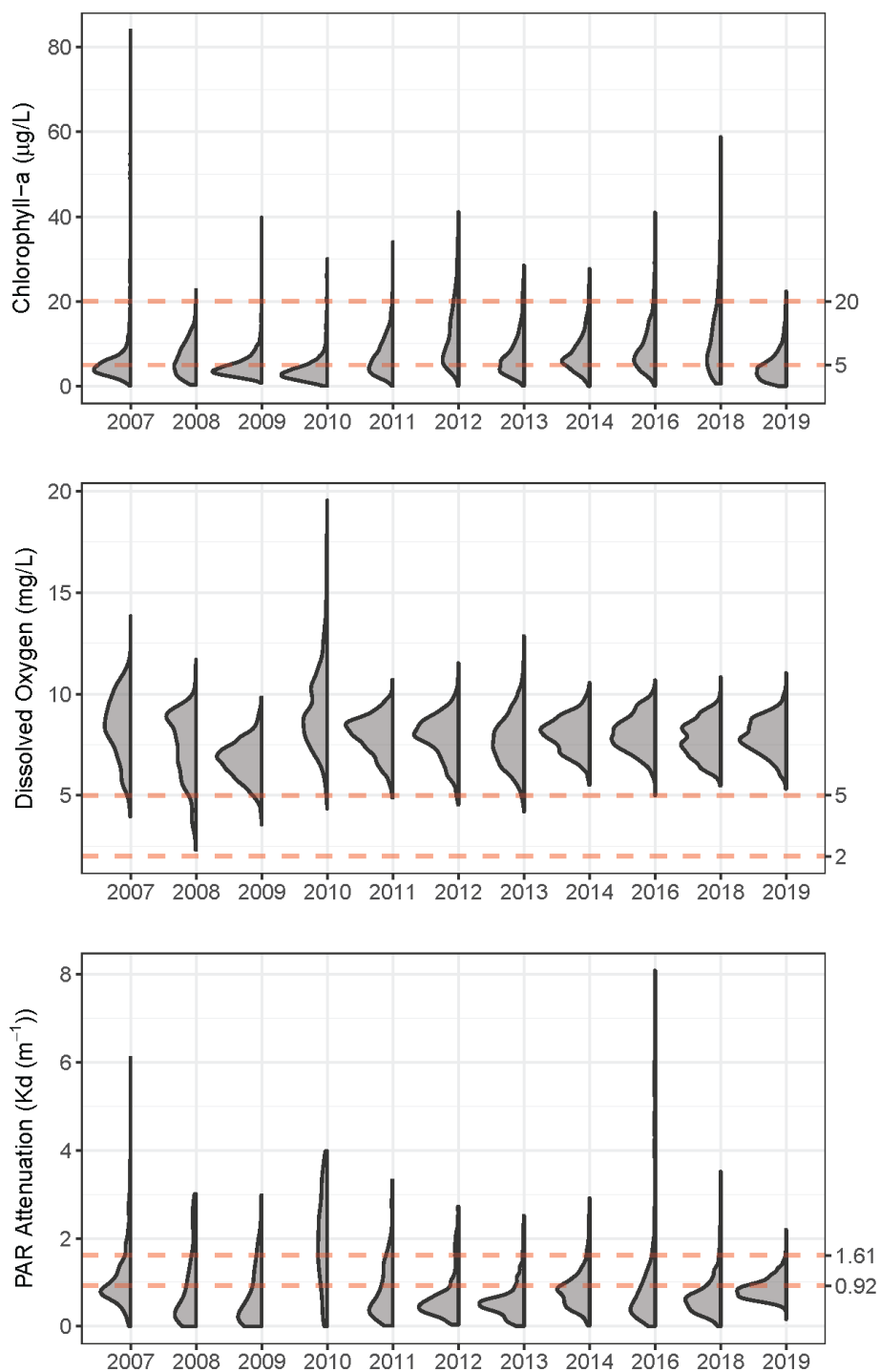


Figure 4-12. Distribution of index period time series values for surface chlorophyll-*a* concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Nauset Harbor logging station. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines.

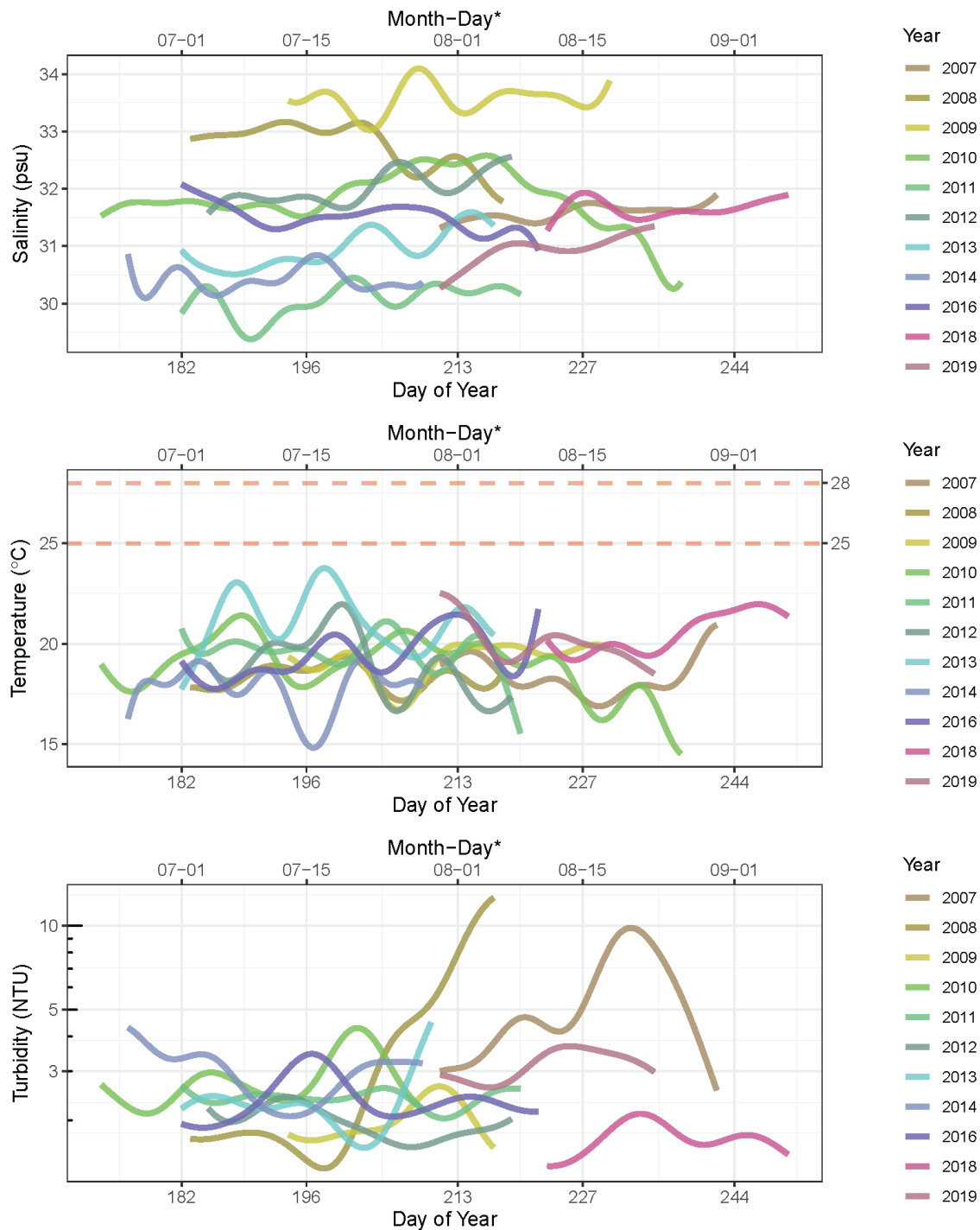


Figure 4-13. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Nauset Harbor logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: the y-axis is transformed to the log₁₀ scale to better visualize the estimated trends for surface turbidity.

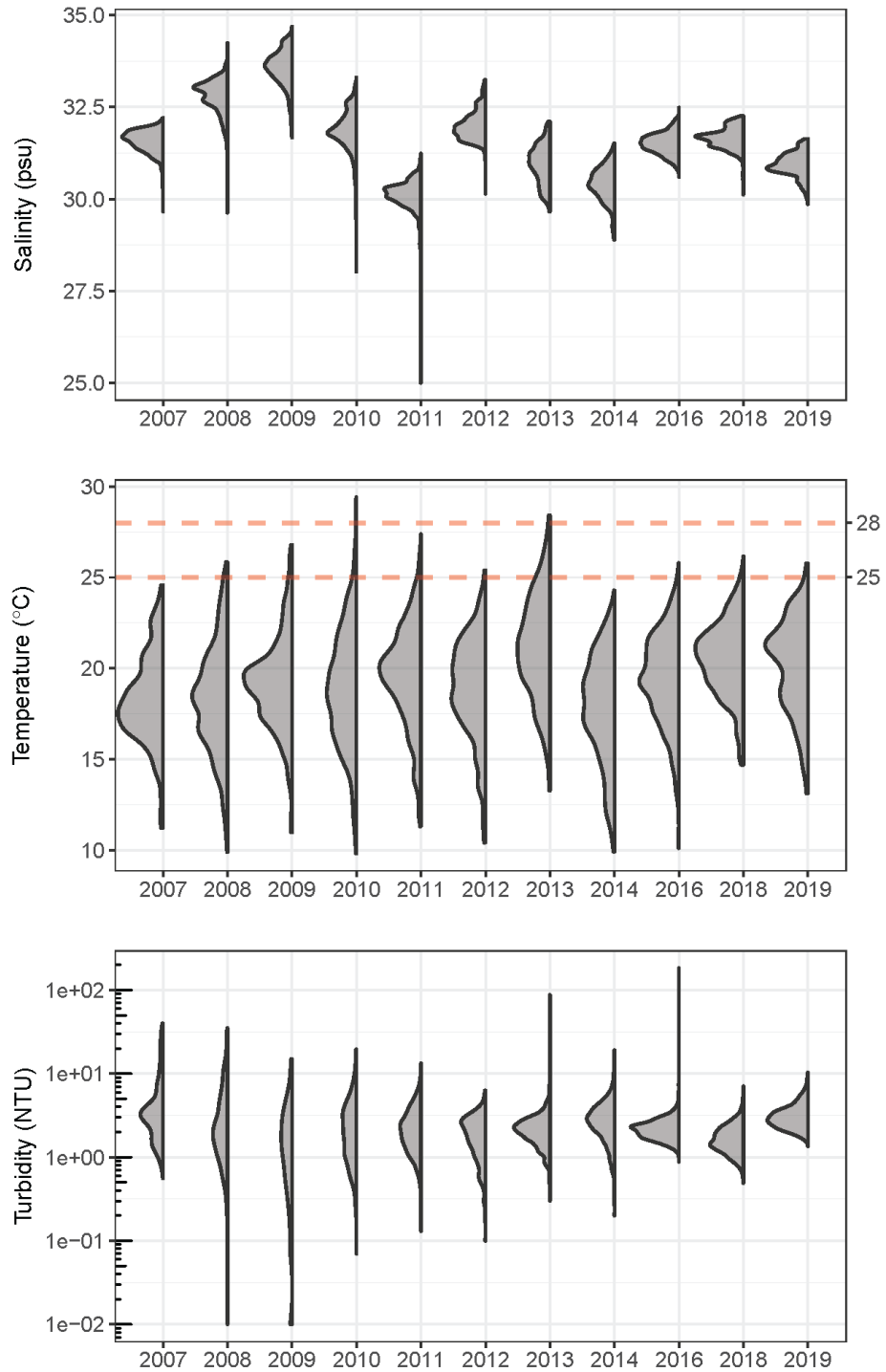


Figure 4-14. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Nauset Harbor logging station. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: the y-axis is transformed to the log₁₀ scale to better visualize the estimated distributions for surface turbidity.

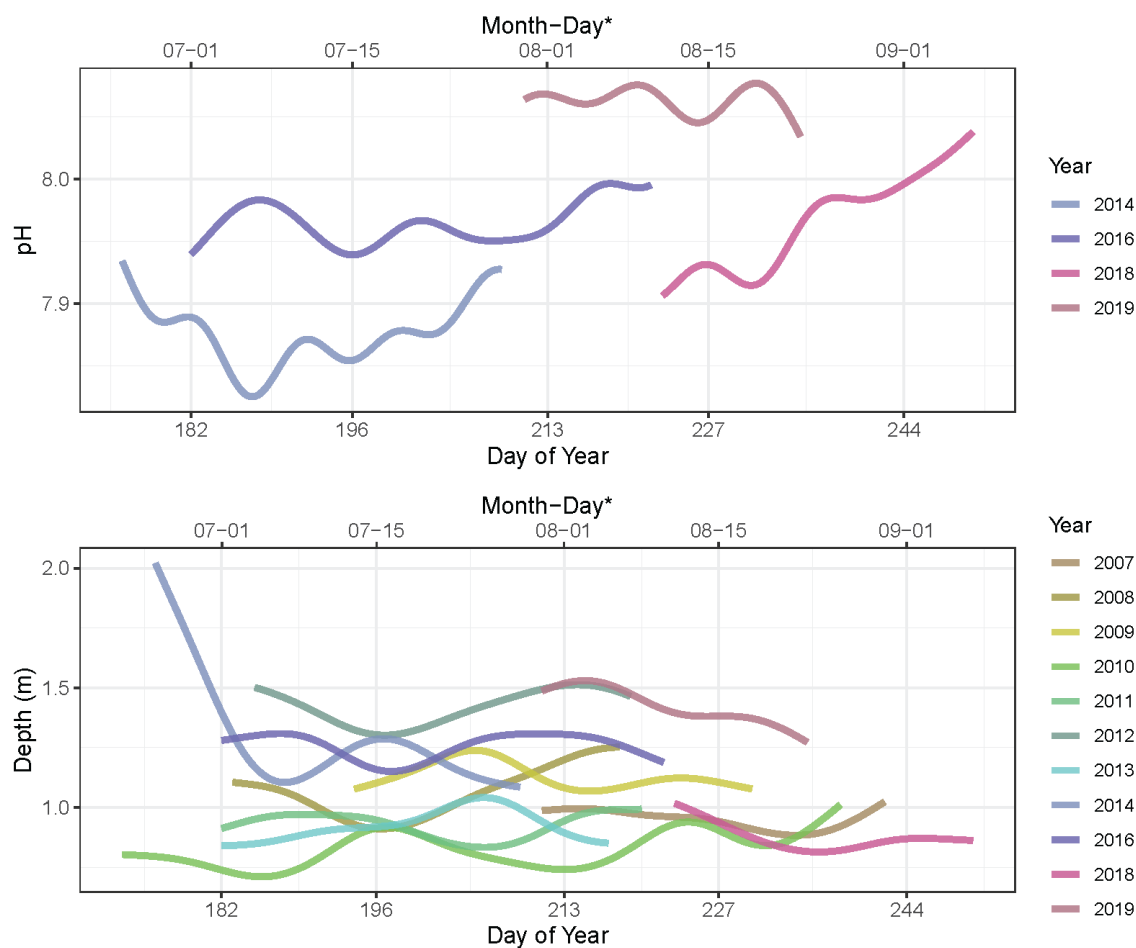


Figure 4-15. Intra-annual trends in pH (top) and depth (bottom) at the Cape Cod National Seashore Nauset Harbor logging station based on estimated generalized additive model smooths.

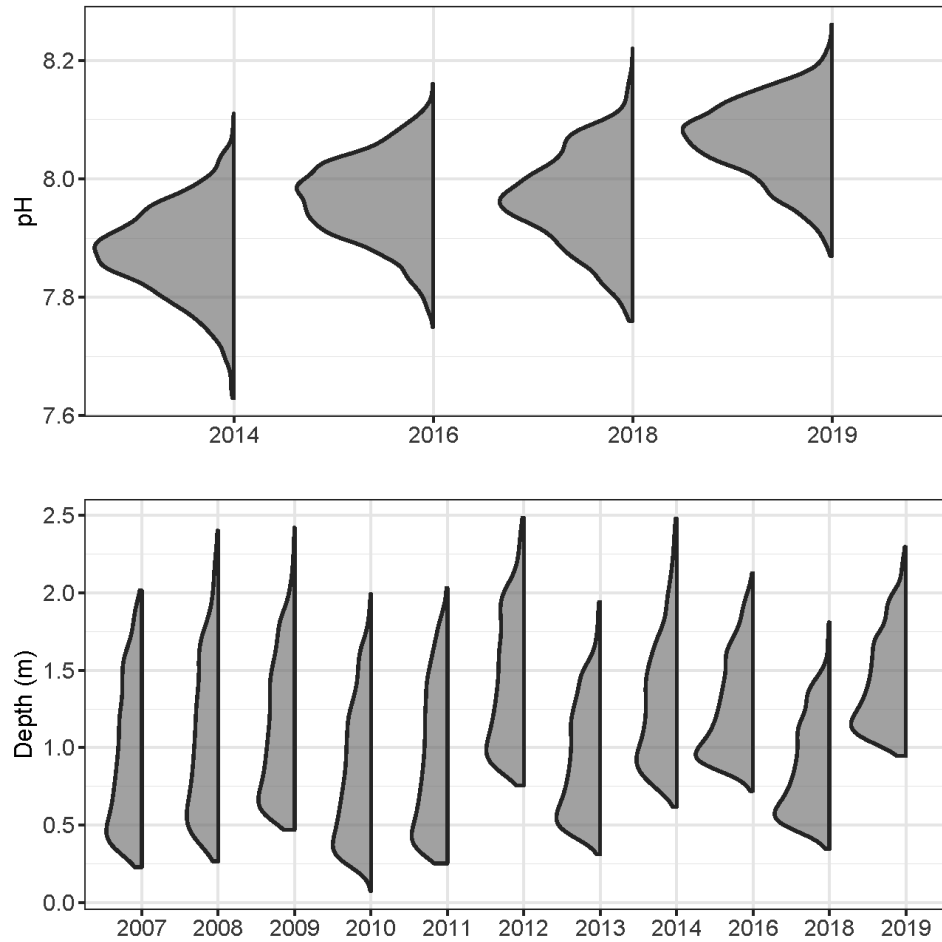


Figure 4-16. Distribution of index period time series values for pH (top) and depth (bottom) at the Cape Cod National Seashore Nauset Harbor logging station.

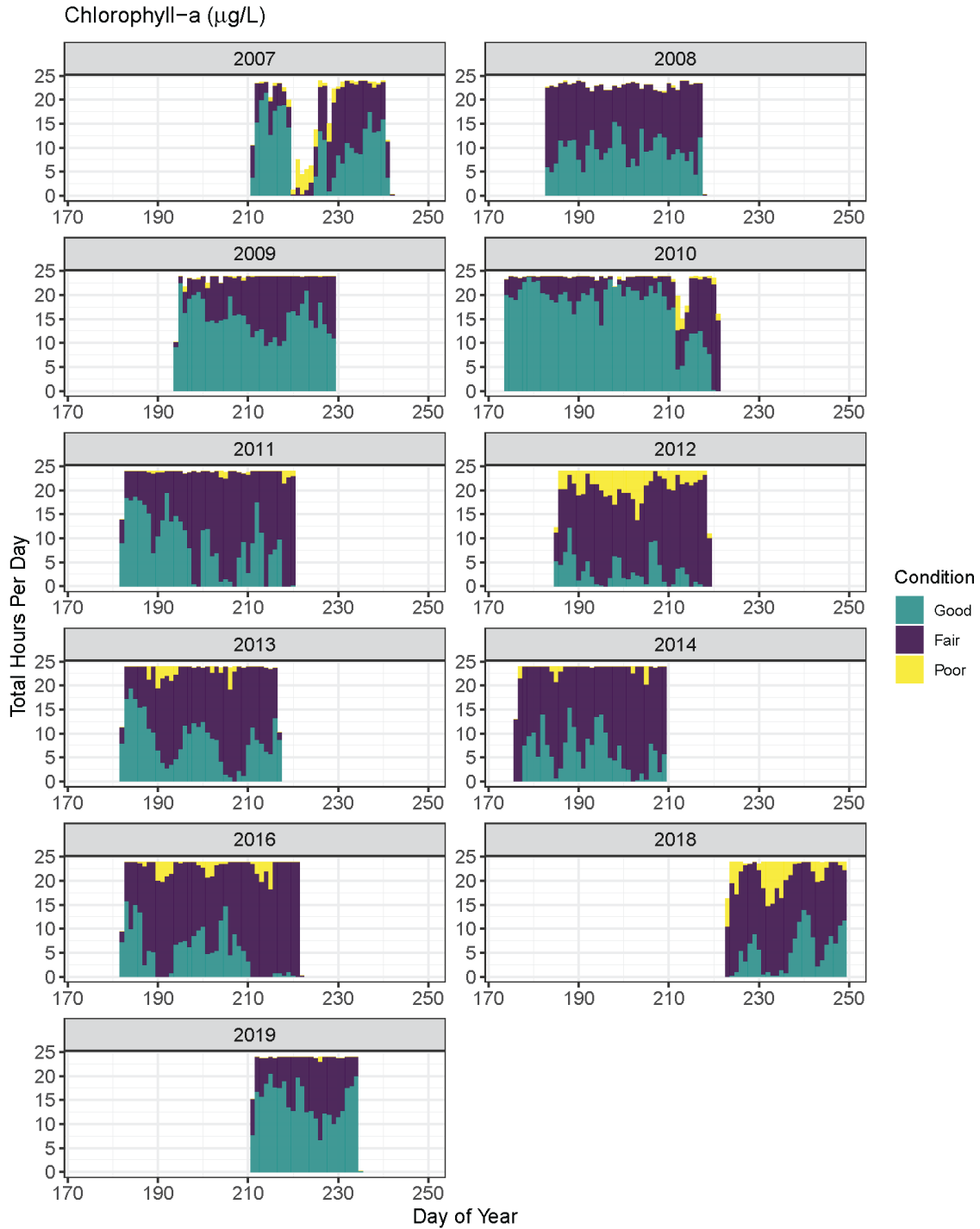


Figure 4-17. Total hours per day that surface chlorophyll-a concentration was observed within each condition category at the Cape Cod National Seashore Nauset Harbor logging station.

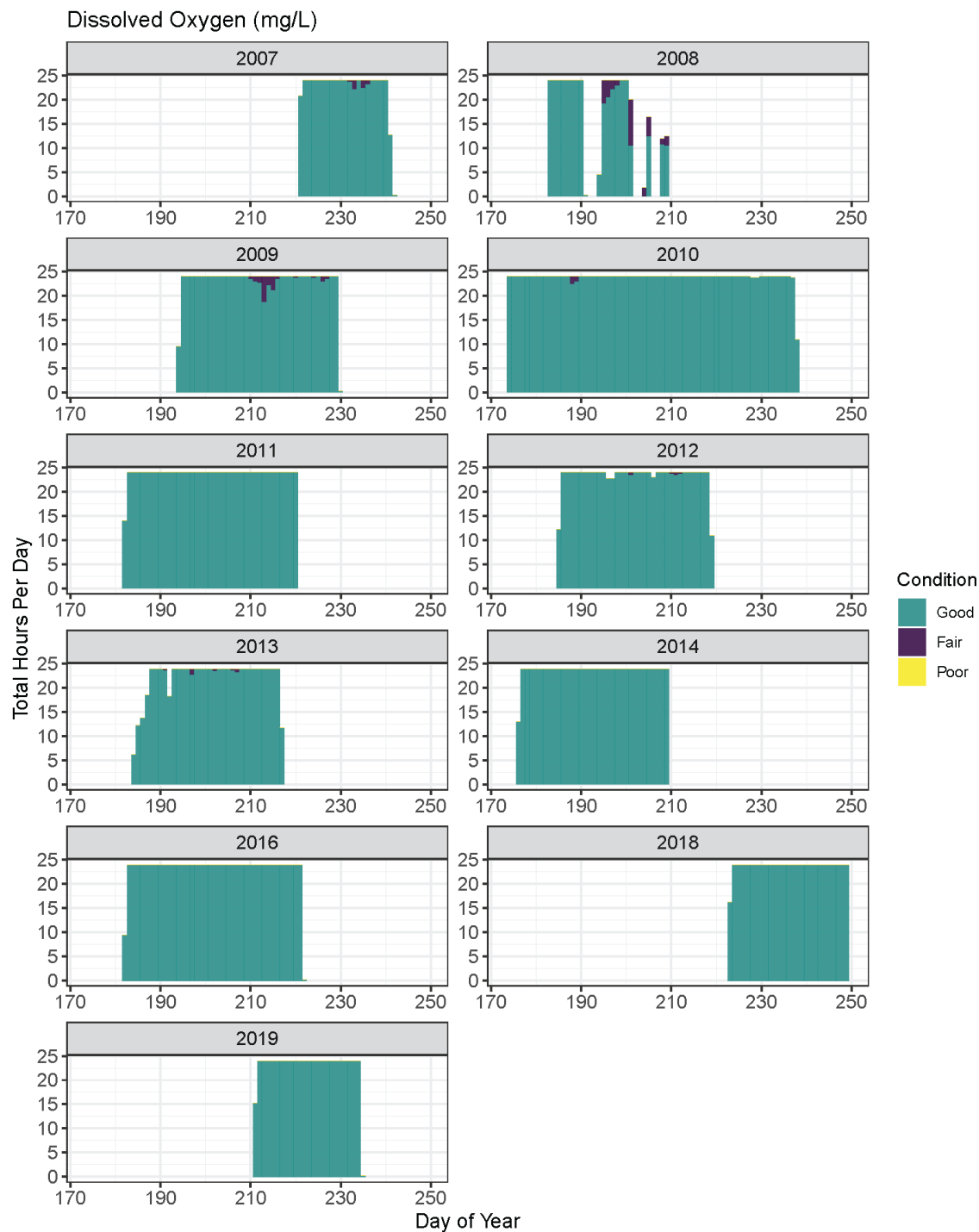


Figure 4-18. Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the Cape Cod National Seashore Nauset Harbor logging station.

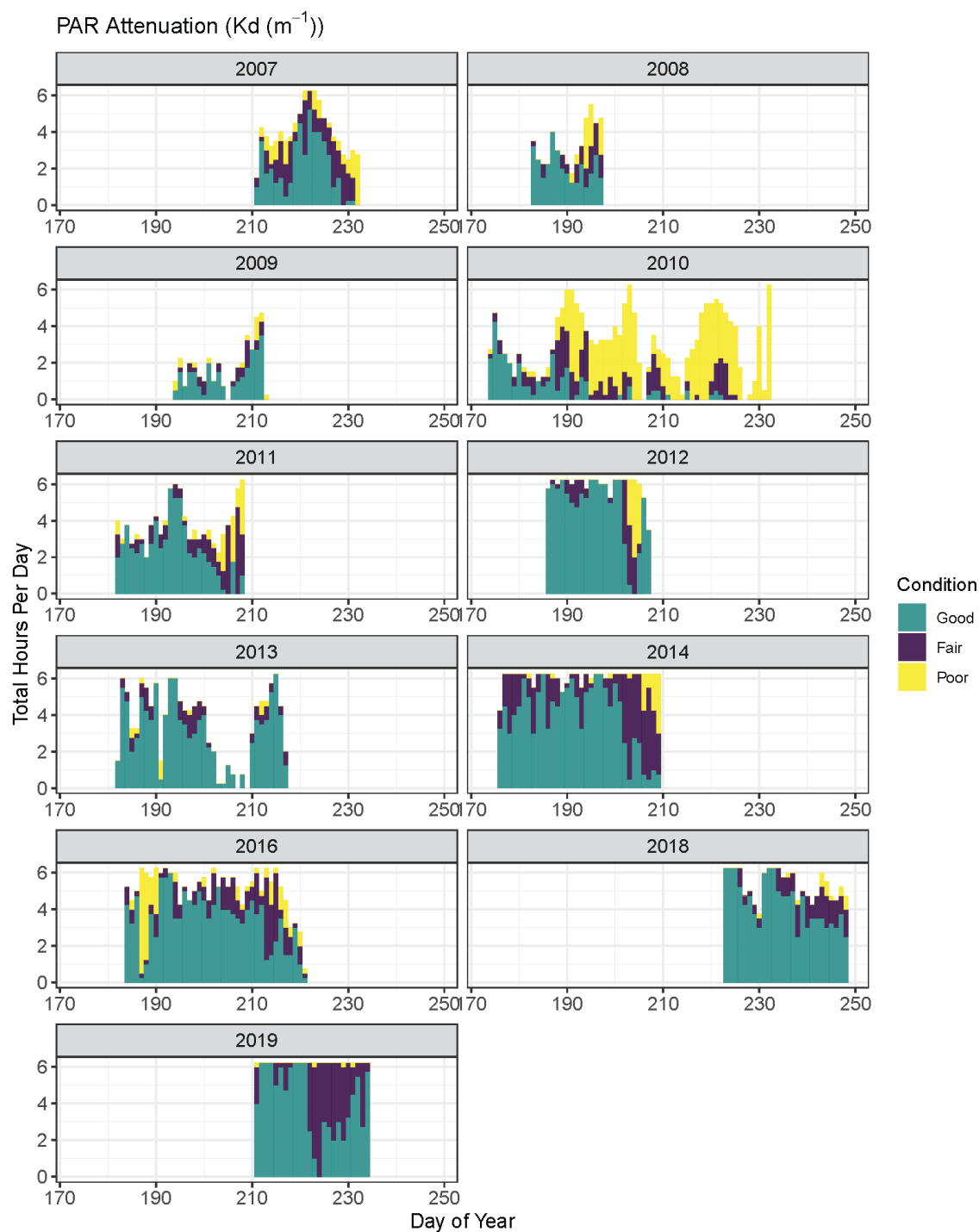


Figure 4-19. Total hours per day that PAR attenuation was observed within each condition category at the Cape Cod National Seashore Nauset Harbor logging station.

4.4 Salt Pond Stratum Results

Notable observations from the fitted smooths and data summaries for each measure are as follows:

4.3.1 Chlorophyll-*a*

Intra-annual mean trends in chlorophyll-*a* concentration within the Salt Pond stratum is non-linear with a similar trend across years except for 2011 and 2018 (Figure 4-20). The distribution of measurements in 2011 and 2016 tend to be more highly skewed than other years (Figure 4-21). Chlorophyll-*a* condition is generally variable and typically spans at least two condition categories per day (Figure 4-26).

4.3.2 Dissolved Oxygen

Intra-annual mean trends in dissolved oxygen are non-linear and cyclic at this temporal scale and the mean is variable across years (Figure 4-20). Except for 2010 and 2011 (where most days were poor), dissolved oxygen conditions are generally good with some days experiencing fair conditions for part of the day (Figure 4-26). Mean dissolved oxygen concentrations were at or below 1 mg/L during 2010 and 2011 (Table 4-3).

4.3.3 PAR Attenuation K_d

The PAR attenuation mean trend during 2019 was non-linear and was in good quality condition for a majority of the period of measurement (Figure 4-20). A majority of each day was observed in good condition (Figure 4-28).

4.3.4 pH

Intra-annual trends in pH were non-linear and most were non-stationary (Figure 4-24). The distribution of measurements tended to span approximately 0.5 units each year (Figure 4-25).

4.3.5 Salinity

Intra-annual mean trends in salinity were non-linear and ranged from being relatively smooth to very wiggly (Figure 4-22). Salinity measurements within each year typically span approximately 1 psu but there was more skew during the years from 2010 to 2016 (Figure 4-23).

4.3.6 Temperature

Intra-annual mean trends in water temperature are non-linear and for most years are relatively constant from July to August (Figure 4-22). Water temperature measurements have become more variable within each year over time and there is a clear increasing trend over time (Figure 4-23).

4.3.7 Turbidity

Intra-annual mean trends in turbidity were generally fairly smooth except for the 2009, 2010, and 2011 (Figure 4-22). Turbidity measurements in 2009, 2010, and 2011 were also more left-skewed than other years (Figure 4-23).

Table 4-3. Yearly summary statistics for measures collected at the Cape Cod National Seashore Salt Pond logging station. [SD = standard deviation]

Measure	Statistic	Sampling Year										
		2007	2008	2009	2010	2011	2012	2013	2014	2016	2018	2019
Chlorophyll <i>a</i> (µg/L)	Mean	11.65	20.90	22.97	15.17	18.50	21.74	16.41	9.11	99.07	16.50	11.65
Chlorophyll <i>a</i> (µg/L)	SD	10.28	11.25	10.87	19.02	30.94	16.13	9.16	8.08	46.91	5.68	10.28
Chlorophyll <i>a</i> (µg/L)	n	3277.00	3073.00	2100.00	6159.00	2335.00	3261.00	3217.00	3478.00	2604.00	1667.00	3277.00
Depth (m)	Mean	5.41	2.78	3.20	5.30	5.03	2.86	1.00	1.19	0.98	0.83	5.41
Depth (m)	SD	0.06	0.05	0.05	0.34	0.05	0.09	0.30	0.35	0.34	0.31	0.06
Depth (m)	n	3276.00	3078.00	3341.00	5115.00	4003.00	3256.00	3266.00	3733.00	2609.00	2008.00	3276.00
dissolved oxygen (mg/L)	Mean	4.88	6.63	5.75	1.01	0.90	4.39	7.97	7.16	6.41	6.76	4.88
dissolved oxygen (mg/L)	SD	1.66	1.51	1.20	1.68	1.29	1.85	2.18	2.08	1.92	2.06	1.66
dissolved oxygen (mg/L)	n	3277.00	3079.00	3349.00	2381.00	2350.00	3272.00	3266.00	3733.00	2609.00	2008.00	3277.00
PAR attenuation (K_d (m ⁻¹))	Mean	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.64	NA
PAR attenuation (K_d (m ⁻¹))	SD	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.22	NA
PAR attenuation (K_d (m ⁻¹))	n	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	409.00	0.00
pH	Mean	NA	NA	NA	NA	NA	NA	7.88	NA	7.78	7.94	NA
pH	SD	NA	NA	NA	NA	NA	NA	0.18	NA	0.17	0.17	NA
pH	n	0.00	0.00	0.00	0.00	0.00	0.00	3266.00	0.00	2609.00	2008.00	0.00
Salinity (psu)	Mean	31.18	29.84	31.34	32.13	31.89	30.22	30.37	32.13	30.52	29.86	31.18
Salinity (psu)	SD	0.13	0.25	0.25	0.71	1.33	0.45	0.56	0.55	0.26	0.22	0.13
Salinity (psu)	n	3277.00	3079.00	3160.00	6065.00	3014.00	1569.00	3265.00	3733.00	2609.00	2008.00	3277.00
Temperature (°C)	Mean	19.12	20.29	20.25	19.20	19.96	21.52	20.83	22.94	24.07	24.47	19.12
Temperature (°C)	SD	0.93	1.04	1.04	1.46	1.22	1.10	1.85	1.60	1.87	1.49	0.93
Temperature (°C)	n	3277.00	3079.00	3349.00	6235.00	4021.00	3272.00	3266.00	3733.00	2609.00	2008.00	3277.00
Turbidity (NTU)	Mean	4.01	3.42	2.11	22.25	8.14	3.07	2.34	3.88	3.86	4.49	4.01
Turbidity (NTU)	SD	2.50	2.46	1.65	25.06	7.29	1.57	1.33	0.88	0.91	1.04	2.50
Turbidity (NTU)	n	3275.00	3068.00	3314.00	6126.00	3960.00	3251.00	3260.00	3688.00	2600.00	2002.00	3275.00

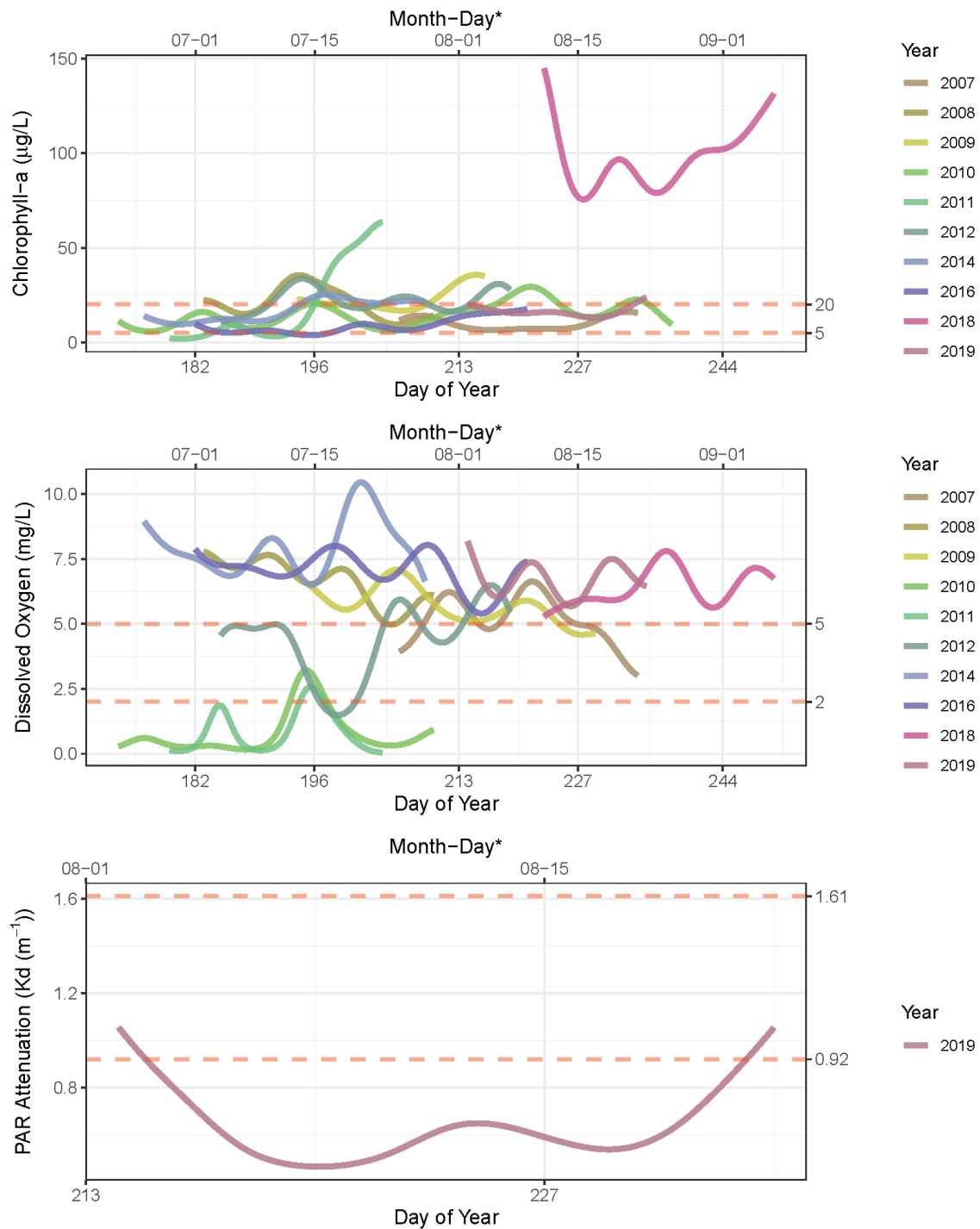


Figure 4-20. Intra-annual trends in for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Salt Pond logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines.

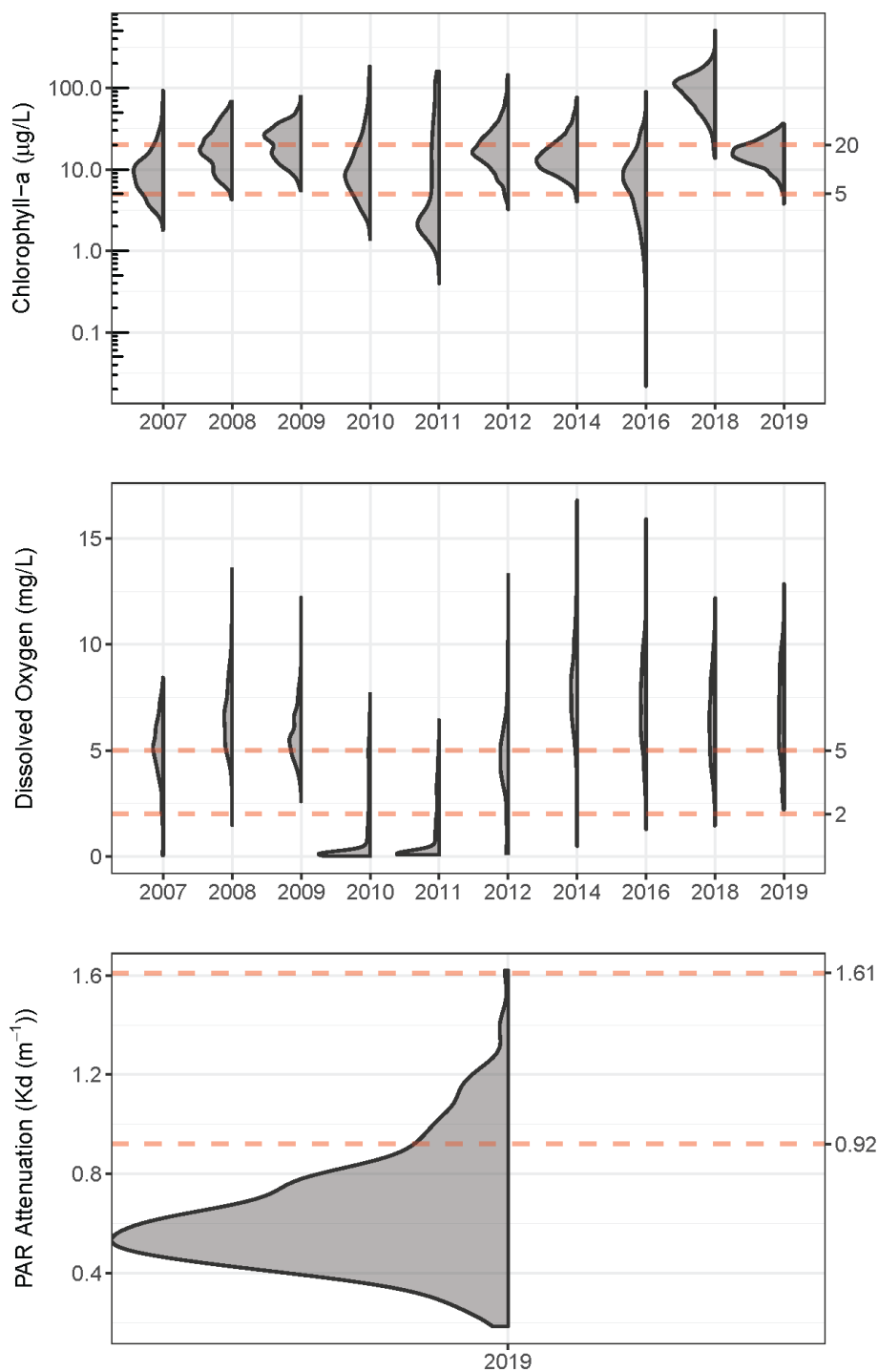


Figure 4-21. Distribution of index period time series values for surface chlorophyll-*a* concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Cape Cod National Seashore Salt Pond logging station. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: the surface chlorophyll-*a* concentration y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated distributions.

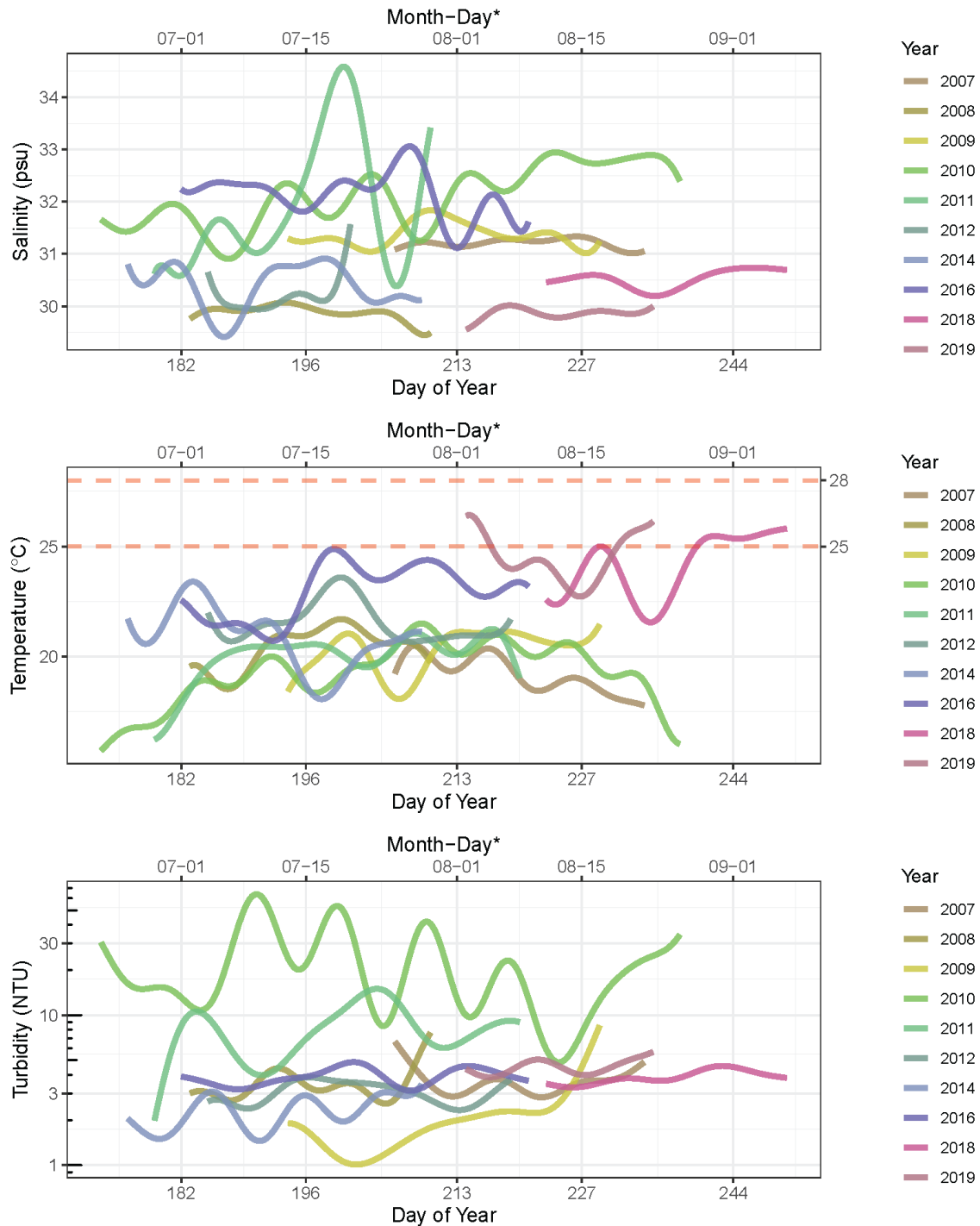


Figure 4-22. Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Salt Pond logging station based on estimated generalized additive model smooths. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: the surface turbidity y-axis is transformed to the log₁₀ scale to better visualize the estimated trends.

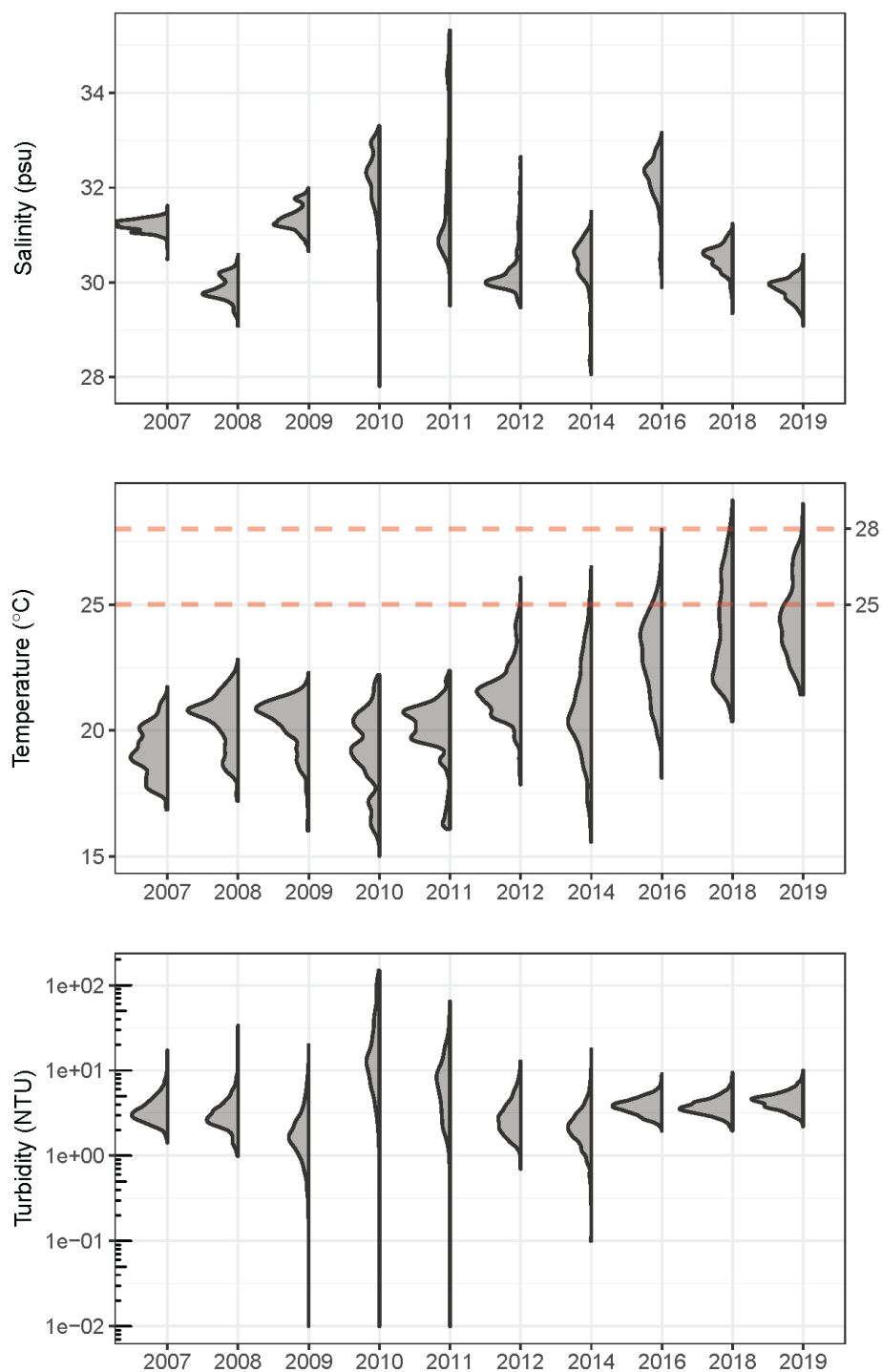


Figure 4-23. Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Cape Cod National Seashore Salt Pond logging station. Estuarine quality category thresholds (Table 2-1) plotted as red dashed lines. Note: the surface turbidity y-axis is transformed to the $\log_{10}$ scale to better visualize the estimated distributions.

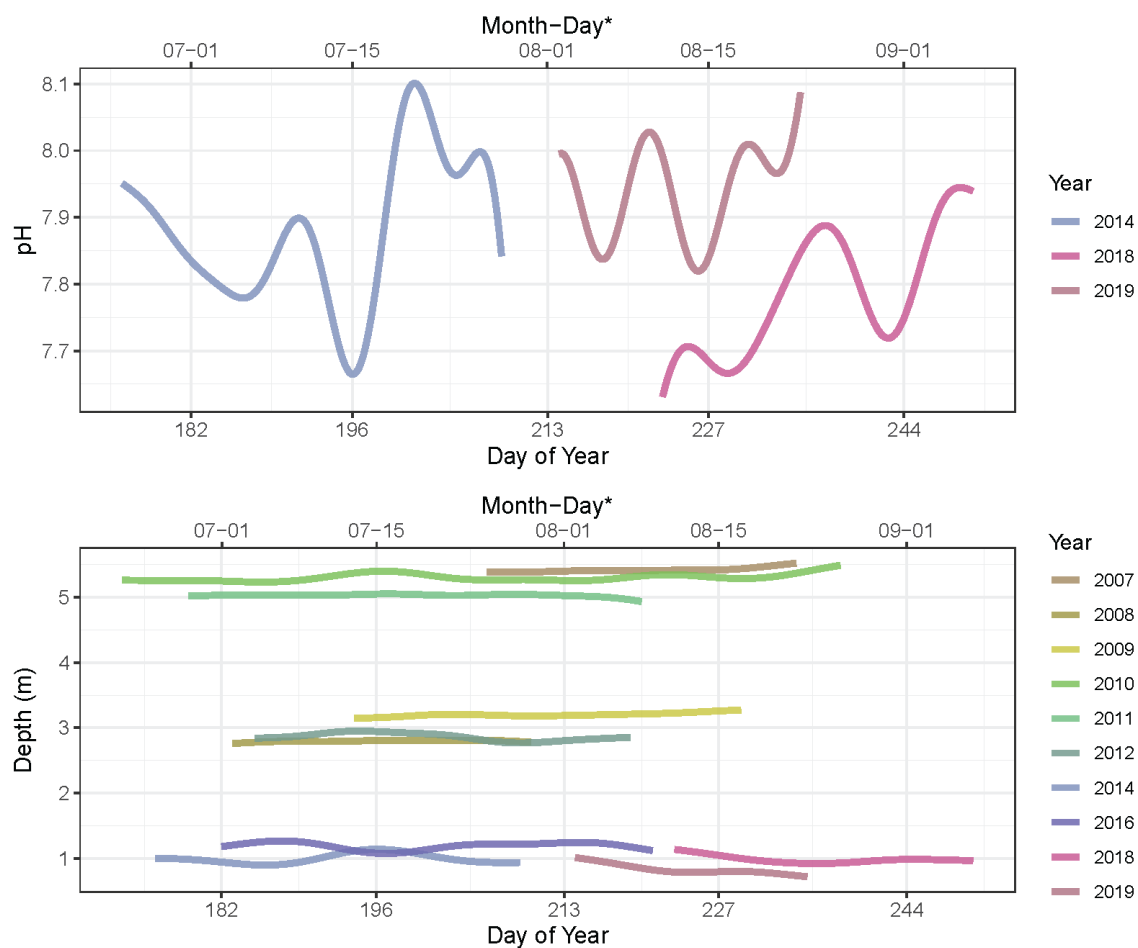


Figure 4-24 Intra-annual trends in pH (top) and depth (bottom) at the Cape Cod National Seashore Salt Pond logging station based on estimated generalized additive model smooths.

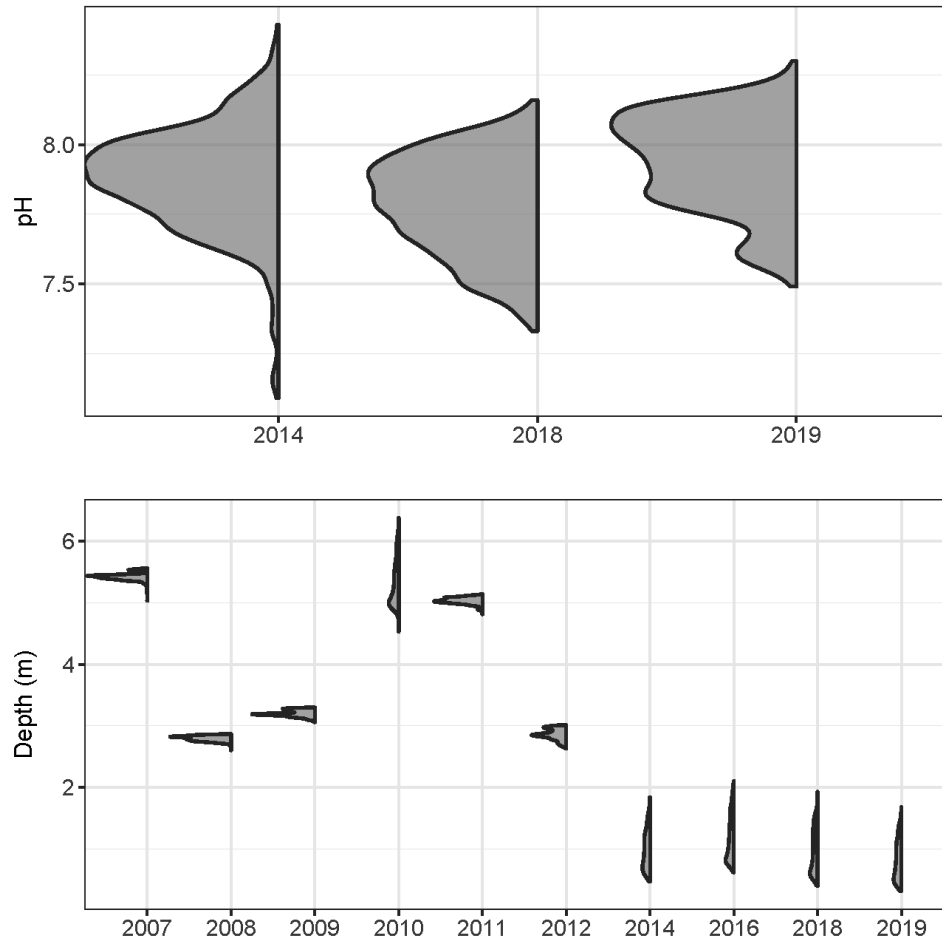


Figure 4-25. Distribution of index period time series values for pH (top) and depth (bottom) at the Cape Cod National Seashore Salt Pond logging station.

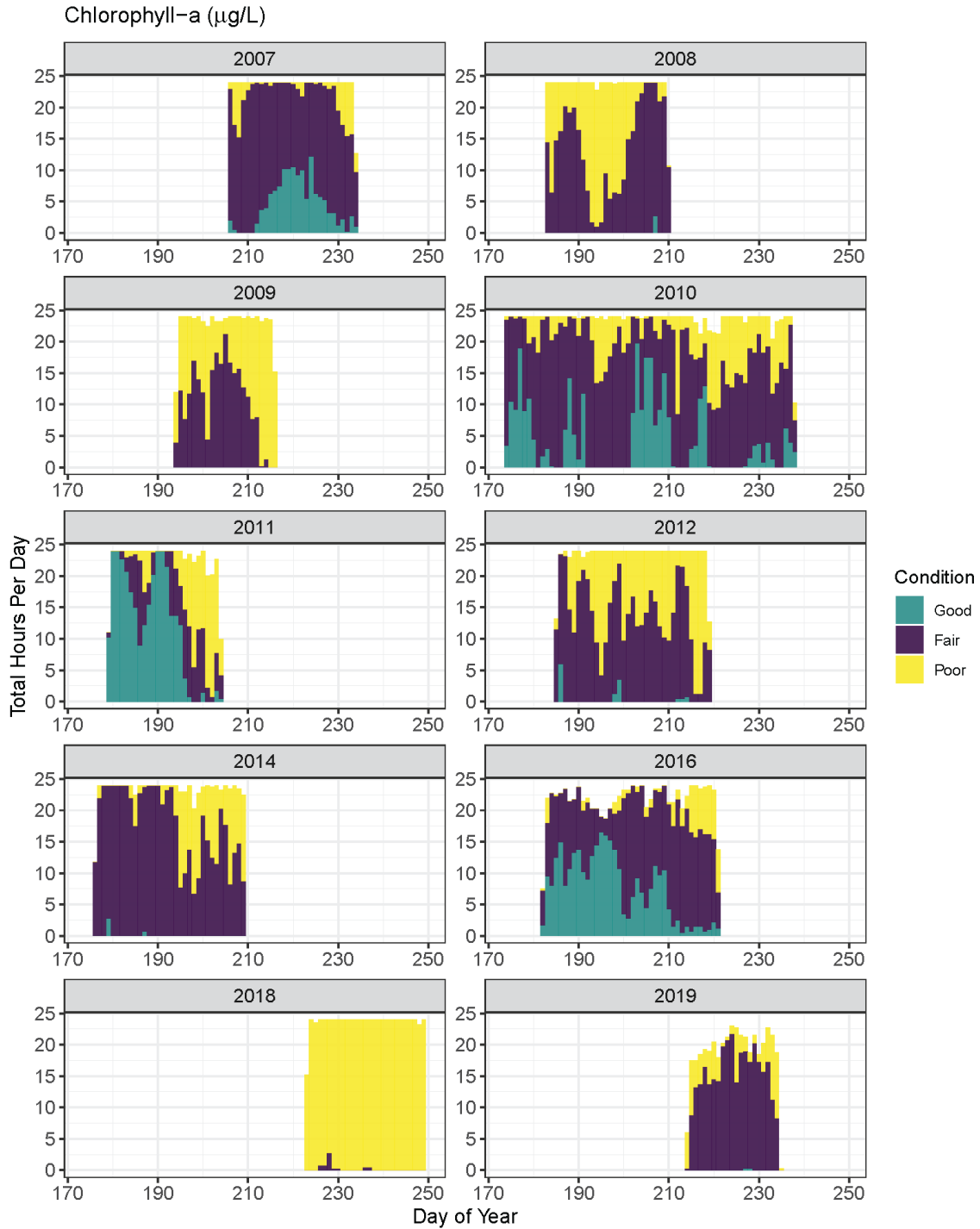


Figure 4-26. Total hours per day that surface chlorophyll-a concentration was observed within each condition category at the Cape Cod National Seashore Salt Pond logging station.

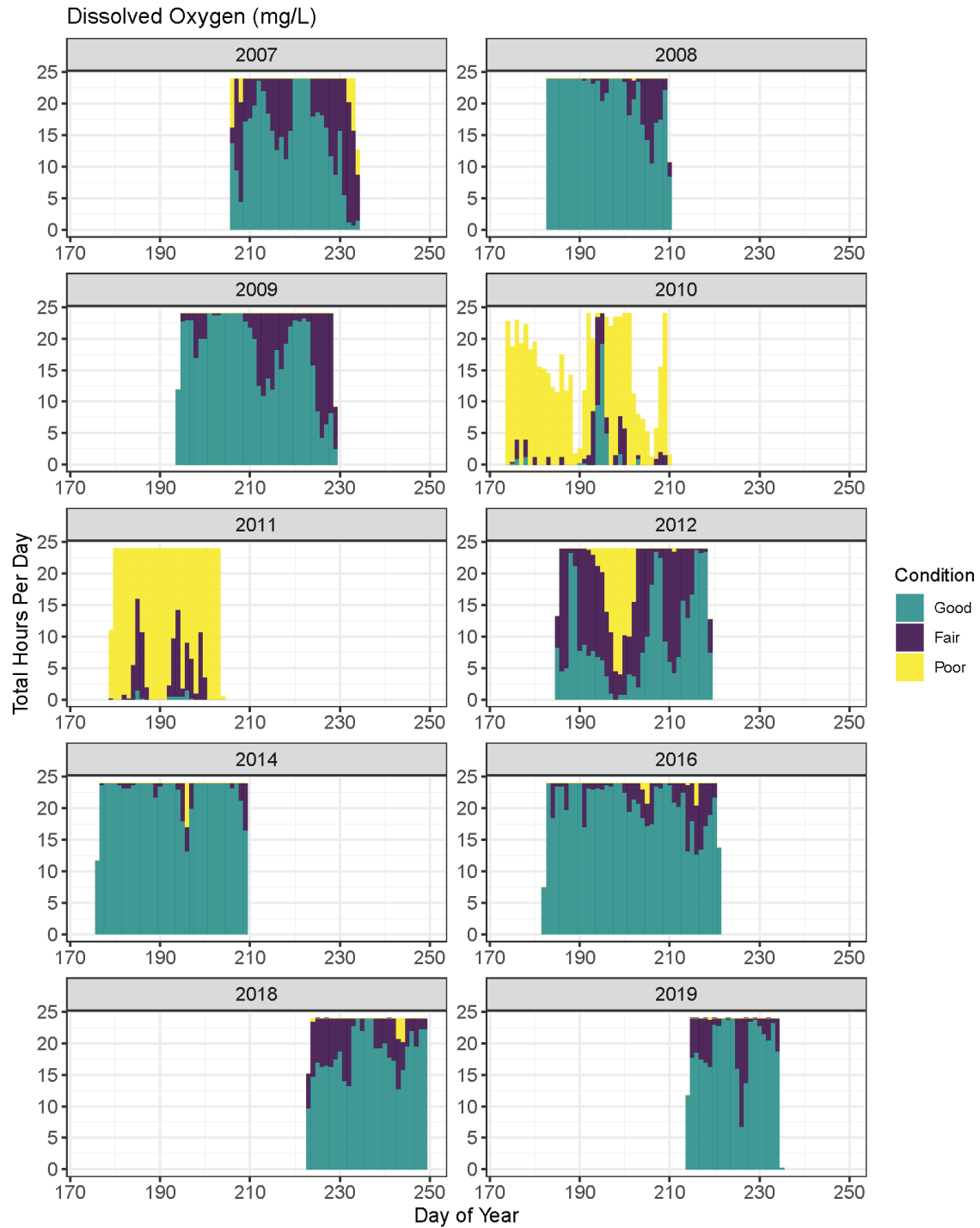


Figure 4-27. Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the Cape Cod National Seashore Salt Pond logging station.

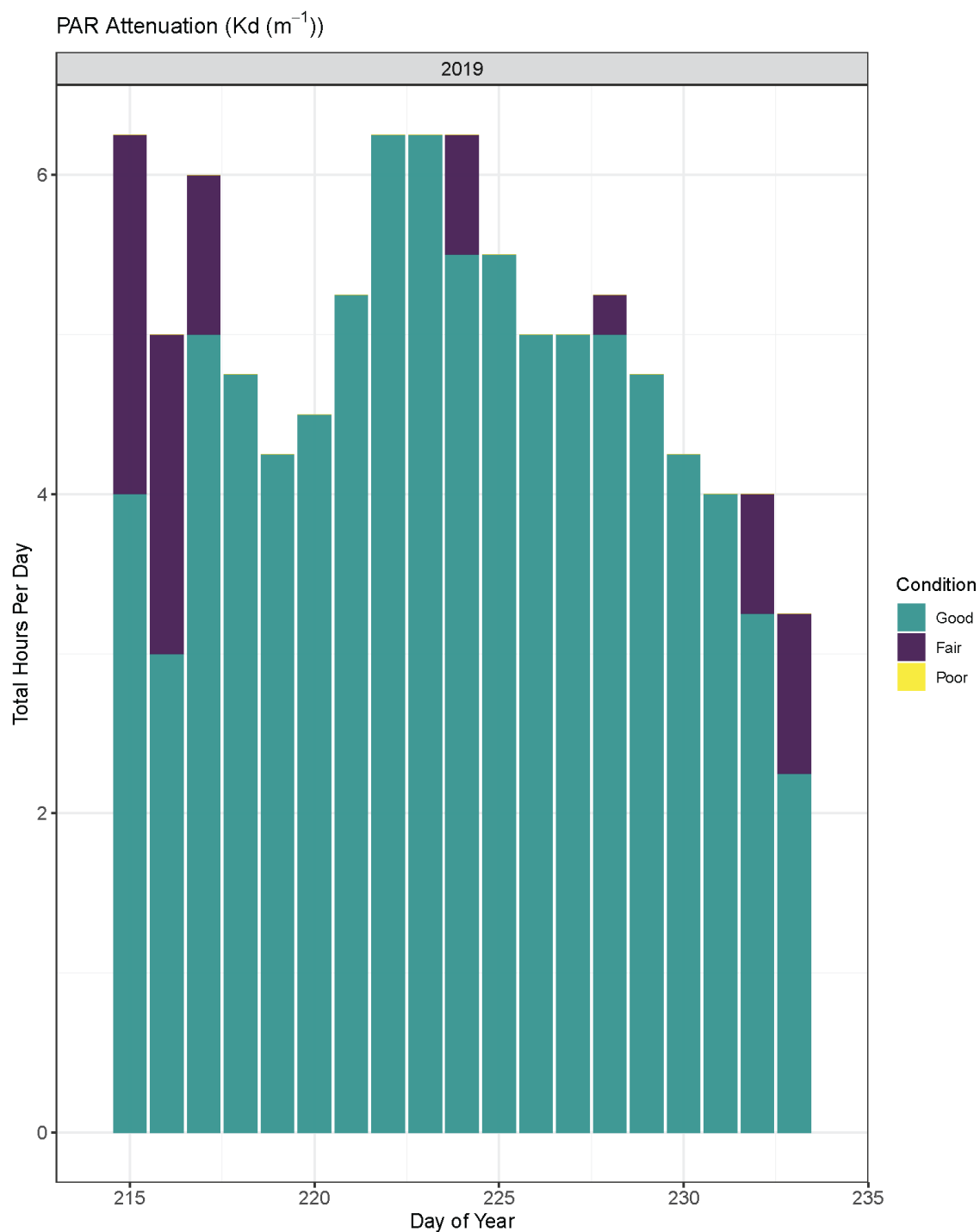


Figure 4-28. Total hours per day that PAR attenuation was observed within each condition category at the Cape Cod National Seashore Salt Pond logging station.

5. Seagrass Condition

5.1 Background

Seagrass monitoring data has been collected at the Duck Harbor Beach and Pleasant Bay SeagrassNet monitoring sites since 2003 following the standardized monitoring protocol outlined in Short et al. (2004). Each site consists of three permanent 50 m transects that run parallel to shore across an increasing depth gradient. Data are collected at twelve 0.25 m² quadrats located at fixed random locations along each transect. The two species being monitored are eelgrass (*Zostera marina*) and widgeon grass (*Ruppia maritima*).

5.2 Variable Derivations

While most seagrass measures are direct measurements, total biomass and the ratio of above to below ground biomass are measures that are derived from direct measurements. For eelgrass, total biomass is derived using the formula given in Table 23 from SOP 12 of the monitoring protocol (B. S. Kopp and Neckles 2009). For widgeon grass, shoots are too small to be reliably counted underwater in the field. Therefore, total biomass is instead estimated based on the formula:

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

where 0.0035 m² is the area of a 6.7 cm diameter corer. The ratio of above to below ground biomass for both species is computed using the formula:

$$\text{ratio} = \frac{\text{leaf} + \text{sheath (g)}}{\text{roots} + \text{rhizome (g)}}$$

5.3 Methods

5.3.1 Generalized Additive Model (GAM)

Generalized additive models (GAMs) are used to estimate trends in seagrass measures at different water depths at each monitoring site. For each species' response measure, 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 measure, several different distributions were utilized (Table 5-1). A summary of the model fit to each measure 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

overdispersion⁶. 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 Tweedie distribution⁷.
- Above:below ground 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.

Each model is fit using the `mgcv` package (Wood 2011) and results were summarized/visualized using the `gratia` package (Simpson 2020).

⁶ For the Poisson distribution, it is assumed that the mean is equal to the variance. However, sometimes counts can exhibit extra variation that is greater than the mean (i.e., overdispersion). 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.

⁷ The Tweedie distribution is a flexible probability distribution capable of handling continuous data with probability mass at zero. An alternative modeling approach for data such as these would be a hurdle model. However, inference from a model would concern probability of presence and mean total biomass conditional on presence. The Tweedie distribution was utilized in this analysis since we desire inference on total biomass. See Bonat and Kokonendji (2017) and Dunstan et al. (2013) for some illustrative examples of Tweedie regression models.

Table 5-1. Summary of the distribution, link function, and offset used to model each seagrass measure.

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

5.4 Duck Harbor Beach Results

5.4.1 Summary Statistics

Yearly and monthly (if applicable) summary statistics are provided for *Zostera marina* for the following: shoot density (Table 5-2), percent cover (Table 5-3), canopy height (Table 5-4), total biomass (Table 5-5), and ratio of above to below ground biomass (Table 5-6).

Table 5-2. Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* shoot density (per 1m²) at Cape Cod National Seashore Duck Harbor Beach. [SD = standard deviation]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2003-07	–	–	0	830.5	363.9	11	–	–	0
2003-10	758.7	296.1	12	610.7	363.6	12	NA	NA	NA
2004-01	932.4	285.6	11	NA	NA	NA	NA	NA	NA
2004-05	989.1	284.5	11	936.0	594.9	12	457.6	336.9	10
2004-08	919.3	328.9	11	725.3	447.9	12	376.7	343.6	11
2005-04	354.7	172.4	12	NA	NA	NA	168.0	145.5	6
2005-08	609.3	351.9	12	857.3	523.3	12	509.3	443.1	12
2006-07	836.0	376.5	12	686.7	554.6	12	0.0	0.0	12
2007-08	925.3	556.8	12	333.3	545.7	12	0.0	0.0	12
2008-08	452.3	474.3	12	275.3	494.5	12	1.0	3.5	12
2009-07	610.0	635.3	12	0.0	0.0	12	0.0	0.0	12
2010-07	261.7	412.1	12	66.0	152.3	12	2.7	3.6	12
2011-08	338.0	385.8	12	144.7	176.4	12	0.0	0.0	12
2012-07	636.0	450.0	12	133.7	162.8	12	0.0	0.0	12
2013-07	70.0	154.4	12	274.7	407.5	12	0.0	0.0	12
2014-07	0.3	1.2	12	279.0	352.3	12	0.0	0.0	12
2015-08	0.7	1.6	12	310.3	408.1	12	1.3	4.6	12
2016-07	1.7	3.2	12	362.7	358.6	12	NA	NA	NA
2017-06	0.0	0.0	12	165.3	215.3	12	0.0	0.0	12
2018-07	4.7	12.5	12	562.0	571.2	12	1.0	3.5	12
2019-08	0.0	0.0	12	545.0	579.0	12	NA	NA	NA
2019-10	NA	NA	NA	NA	NA	NA	0.0	0.0	12

Table 5-3. Yearly (monthly within year, if applicable) summary statistics for percent cover of *Zostera marina* at Cape Cod National Seashore Duck Harbor Beach. [SD = standard deviation]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2003-07	85.4	31.1	12	74.8	35.8	12	81.7	26.8	12
2003-10	89.2	28.7	12	73.3	40.3	12	NA	NA	NA
2004-01	79.2	26.5	12	NA	NA	NA	NA	NA	NA
2004-05	82.2	28.8	12	61.7	36.1	12	33.3	28.3	12
2004-08	88.3	27.2	12	70.8	38.9	12	53.3	37.4	12
2005-04	51.2	24.9	12	NA	NA	NA	19.2	19.6	6
2005-08	83.8	27.5	12	72.9	38.7	12	45.1	43.0	12
2006-07	76.7	29.8	12	57.5	41.6	12	0.0	0.0	12
2007-08	64.6	40.0	12	25.8	42.9	12	0.0	0.0	12
2008-08	45.9	48.3	12	17.9	30.6	12	0.1	0.3	12
2009-07	43.4	44.9	12	0.0	0.0	12	0.0	0.0	12
2010-07	22.1	30.8	12	5.6	14.1	12	0.4	0.5	12
2011-08	32.9	39.9	12	11.8	13.4	12	0.0	0.0	12
2012-07	40.4	23.4	12	19.5	27.3	12	0.0	0.0	12
2013-07	13.3	30.0	12	21.8	26.3	12	0.0	0.0	12
2014-07	0.1	0.3	12	30.8	37.9	12	0.0	0.0	12
2015-08	0.2	0.4	12	32.0	40.5	12	0.1	0.3	12
2016-07	0.2	0.5	12	39.2	37.0	12	NA	NA	NA
2017-06	0.0	0.0	12	26.8	35.3	12	0.0	0.0	12
2018-07	1.1	2.8	12	42.0	42.9	12	0.1	0.3	12
2019-08	0.0	0.0	12	44.5	43.3	12	NA	NA	NA
2019-10	NA	NA	NA	NA	NA	NA	0.0	0.0	12

Table 5-4. Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* canopy height at Cape Cod National Seashore Duck Harbor Beach. [SD = standard deviation]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2003-07	25.3	6.5	11	21.8	6.3	11	30.8	6.8	12
2003-10	46.8	12.5	11	37.5	10.7	10	NA	NA	NA
2004-01	19.4	10.3	12	NA	NA	NA	NA	NA	NA
2004-05	16.6	2.4	12	14.6	2.0	10	14.3	4.1	11
2004-08	43.4	13.7	12	25.1	4.4	10	35.6	5.3	9
2005-04	13.9	4.6	12	NA	NA	NA	12.0	3.5	4
2005-08	41.9	9.0	12	37.0	6.3	10	39.2	9.5	10
2006-07	30.2	10.0	12	27.0	5.8	9	–	–	0
2007-08	29.0	12.3	10	14.4	3.4	5	–	–	0
2008-08	24.7	9.7	9	19.8	4.6	4	7.0	–	1
2009-07	22.4	7.2	8	–	–	0	–	–	0
2010-07	22.9	2.0	7	7.8	3.2	10	10.4	4.3	5
2011-08	20.7	6.7	10	19.8	6.8	9	–	–	0
2012-07	16.2	2.1	10	11.8	4.0	8	–	–	0
2013-07	11.0	3.7	5	17.7	2.5	7	–	–	0
2014-07	9.0	–	1	14.3	4.0	6	–	–	0
2015-08	6.0	1.4	2	16.9	7.8	10	17.0	–	1
2016-07	10.0	1.7	3	18.5	5.5	11	NA	NA	NA
2017-06	–	–	0	20.4	2.5	8	–	–	0
2018-07	12.0	4.7	4	17.4	6.1	11	–	–	0
2019-08	–	–	0	24.0	7.2	9	NA	NA	NA
2019-10	NA	NA	NA	NA	NA	NA	–	–	0

Table 5-5. Yearly (monthly within year, if applicable) summary statistics for total biomass of *Zostera marina* at Cape Cod National Seashore Duck Harbor Beach. [SD = standard deviation]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2003-07	–	–	0	141.8	82.4	10	–	–	0
2003-10	118.0	67.0	12	112.3	66.4	12	NA	NA	NA
2004-01	87.8	52.8	5	NA	NA	NA	NA	NA	NA
2004-05	150.9	61.0	11	133.1	119.7	12	59.5	44.7	10
2004-08	233.2	71.6	11	104.2	80.8	12	119.5	113.1	11
2005-04	74.9	62.1	6	NA	NA	NA	26.7	27.9	6
2005-08	162.0	114.4	12	282.5	207.4	12	160.5	155.4	12
2006-07	202.1	102.8	12	184.4	198.5	12	0.0	0.0	12
2007-08	140.7	111.6	12	48.4	78.1	12	0.0	0.0	12
2008-08	88.6	97.6	12	42.5	78.2	12	0.0	0.0	11
2009-07	108.8	132.2	12	0.0	0.0	12	0.0	0.0	12
2010-07	35.6	60.6	12	15.5	42.9	10	0.1	0.2	12
2011-08	49.4	66.8	12	33.2	39.9	12	0.0	0.0	12
2012-07	77.8	74.2	12	21.3	30.9	12	0.0	0.0	12
2013-07	9.5	21.9	12	49.4	77.8	12	0.0	0.0	12
2014-07	0.0	0.0	11	66.1	96.4	12	0.0	0.0	12
2015-08	0.0	0.0	11	82.9	142.9	12	0.0	0.0	11
2016-07	0.2	0.4	12	84.1	92.3	12	NA	NA	NA
2017-06	0.0	0.0	12	44.7	70.2	12	0.0	0.0	12
2018-07	0.6	1.9	9	159.3	206.1	12	0.0	0.0	11
2019-08	0.0	0.0	12	126.0	127.0	12	NA	NA	NA
2019-10	NA	NA	NA	NA	NA	NA	0.0	0.0	12

Table 5-6. Yearly (monthly within year, if applicable) summary statistics for ratio of above to below ground biomass of *Zostera marina* at Cape Cod National Seashore Duck Harbor Beach. [SD = standard deviation]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2003-07	1.0	0.7	11	1.3	0.8	9	2.1	1.5	12
2003-10	1.6	0.5	11	2.4	2.1	10	NA	NA	NA
2004-01	2.0	0.9	5	NA	NA	NA	NA	NA	NA
2004-05	1.5	0.8	12	0.6	0.3	10	1.4	0.9	11
2004-08	1.9	1.6	12	1.1	0.8	10	3.0	2.0	9
2005-04	1.0	0.5	6	NA	NA	NA	1.1	0.7	4
2005-08	2.4	1.7	12	2.4	1.1	10	3.4	2.2	10
2006-07	3.1	1.8	12	2.0	1.0	10	–	–	0
2007-08	1.8	0.9	10	1.3	0.2	5	–	–	0
2008-08	1.8	1.3	9	2.7	0.7	5	–	–	0
2009-07	1.7	0.8	8	–	–	0	–	–	0
2010-07	2.4	1.9	7	2.2	0.2	8	4.0	2.8	5
2011-08	1.9	0.7	10	1.5	0.9	9	–	–	0
2012-07	2.3	1.7	10	1.3	1.1	8	–	–	0
2013-07	1.8	2.1	5	0.8	0.4	7	–	–	0
2014-07	–	–	0	0.7	0.6	6	–	–	0
2015-08	0.3	–	1	1.2	1.3	10	–	–	0
2016-07	1.0	0.3	3	2.1	3.6	11	NA	NA	NA
2017-06	–	–	0	1.0	0.5	8	–	–	0
2018-07	0.8	–	1	1.4	0.8	11	–	–	0
2019-08	–	–	0	1.5	0.8	9	NA	NA	NA
2019-10	NA	NA	NA	NA	NA	NA	–	–	0

5.4.2 GAM Results

The generalized additive model summaries indicate that there exists statistically significant temporal trends within transects for all *Zostera marina* measures (Table 5-7) and ancillary sediment measures (Table 5-8). Notable observations from the fitted smooths for each measure are as follows:

Shoot Density

Zostera marina shoot density is generally highest within the mid-depth transect and temporal trends differ between transects (Figure 5-1). Shoot density declined after 2005 in the deep transect and after 2012 in the shallow transect. Shoot density within the mid-depth transect has remained relatively constant but experienced a slight decline in 2010.

Percent Cover

Zostera marina experienced a decline in percent cover within the mid-depth transect around 2006 but has since been on the increase (Figure 5-2). There was a statistically significant decrease in percent cover within the deep transect of Duck Harbor from 2003 to 2006 that led to complete die off. The

shallow transect had decreasing percent cover from 2003 to 2013 and starting in 2014 there has been a non-recoverable die off.

Canopy Height

There has been an overall decreasing trend in *Zostera marina* canopy height within the shallow transect (Figure 5-3). The mid-depth transect experience a decline during 2005 to 2010 but has since been slightly increasing.

Total Biomass

Zostera marina experienced a decline in total biomass within the shallow transect around 2012 (Figure 5-4). Total biomass within the mid-depth transect has remained relatively constant over time with no periods of statistically significant change.

Above to Below Ground Biomass Ratio

Zostera marina above to below ground biomass ratio has remained relatively constant with no periods of statistically significant change (Figure 5-5).

Percent Fine Sediment

Percent fine sediment within the transects is low and temporal trends differ by transect (Figure 5-6). Since 2014, the percent fine sediment within the mid-depth and shallow transects has become more variable.

Percent Organic Material

Percent organic material within the transects is very low. Temporal trends differ by transect (Figure 5-7) and no periods of statistically significant change were identified.

Table 5-7. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Duck Harbor Beach *Zostera marina* models. 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]

Measure	Model Term	edf	p-value
Shoot density	–	29.84	< 0.001
Percent cover	s(year, transect)	14.29	< 0.001
Canopy height	s(year, transect)	24.52	< 0.001
Total biomass	s(year, transect)	21.96	< 0.001
Above:below ground biomass	s(year, transect)	9.54	< 0.001

Table 5-8. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Duck Harbor Beach ancillary sediment models. 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]

Measure	Model Term	edf	p-value
Percent fine sediment	s(year, transect)	30.34	< 0.001
Percent organic material	s(year, transect)	9.87	< 0.001

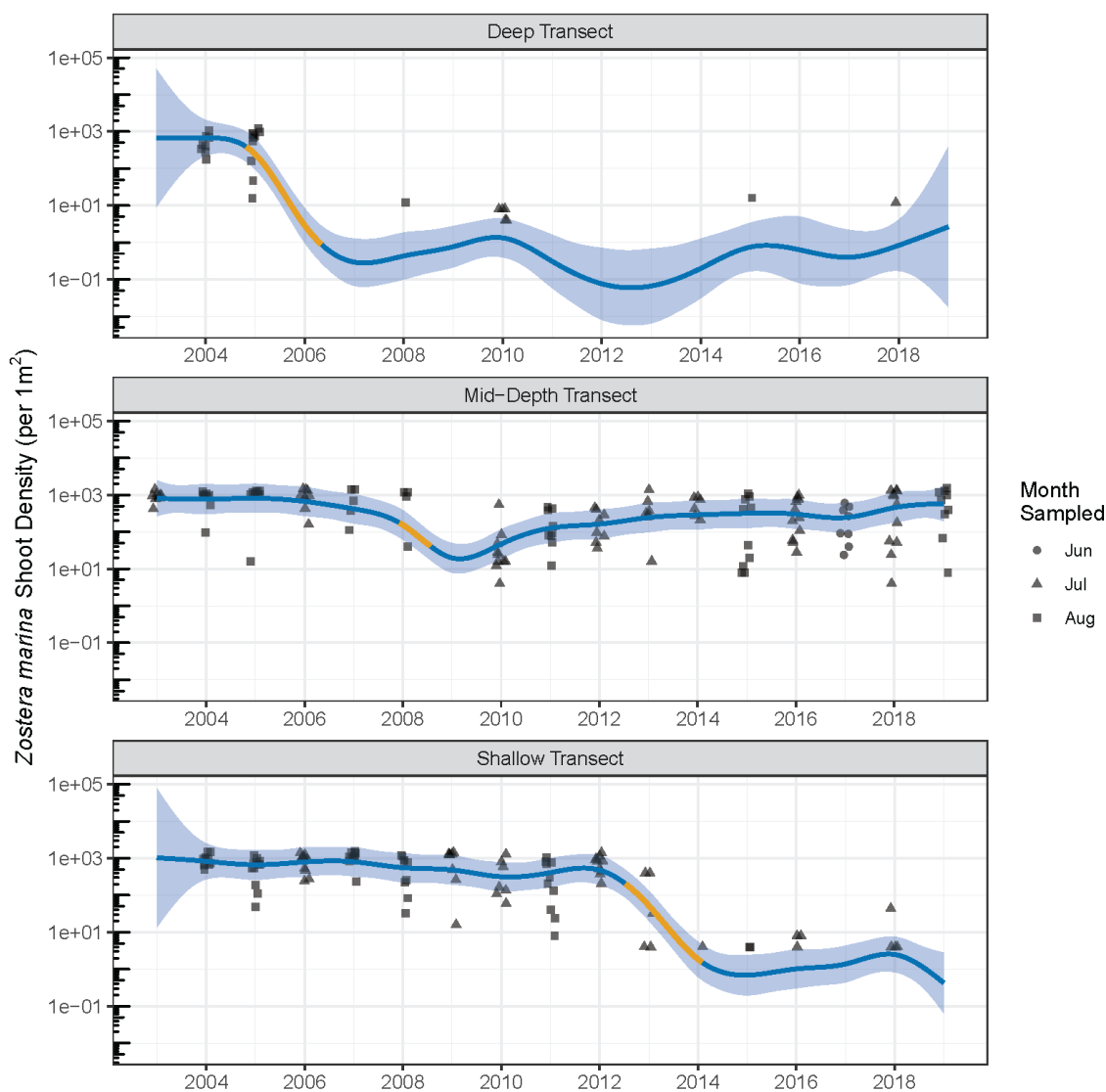


Figure 5-1. Trend in *Zostera marina* shoot density (per 1 m²) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

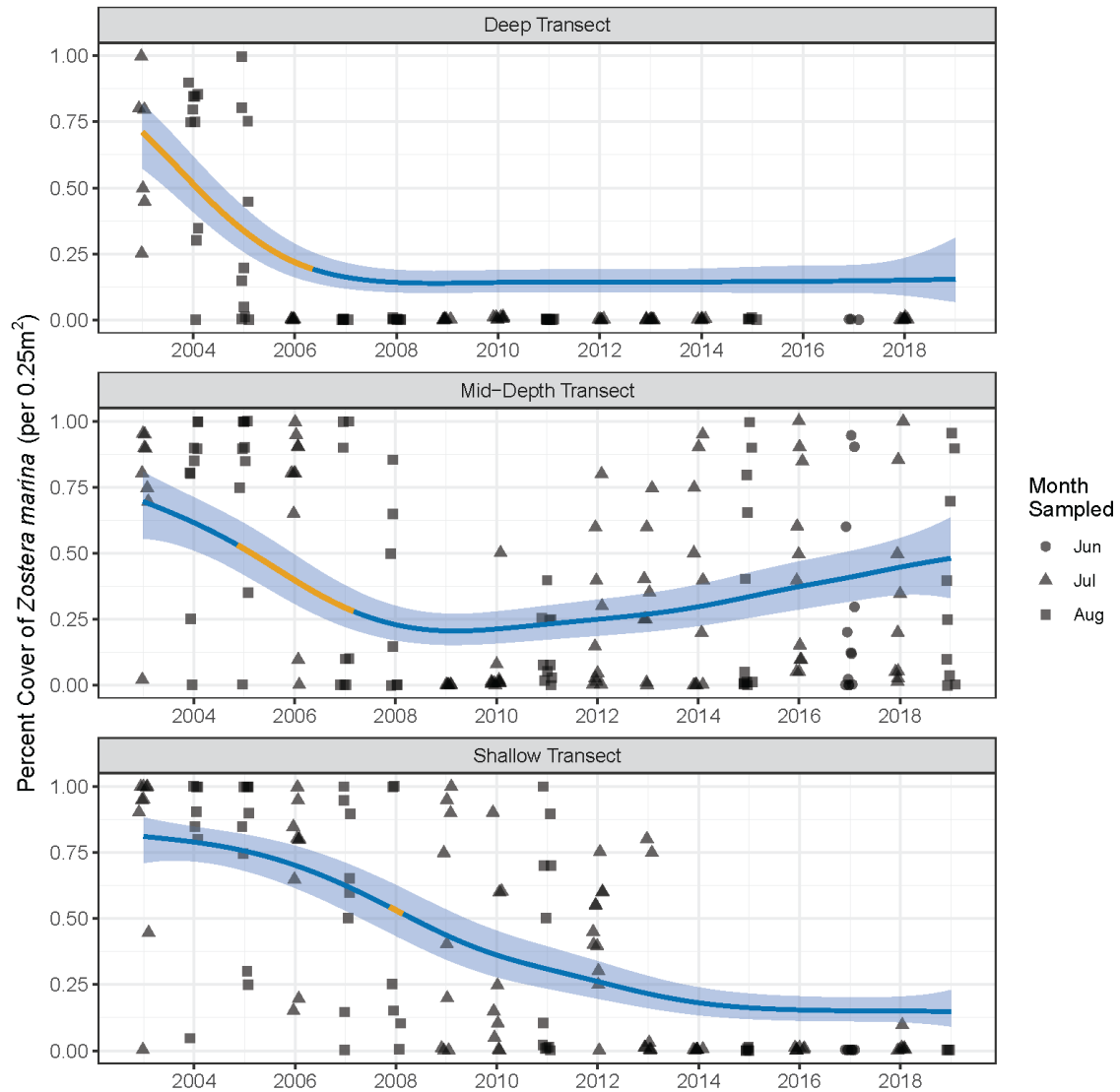


Figure 5-2. Trend in percent cover of *Zostera marina* (per 0.25 m²) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

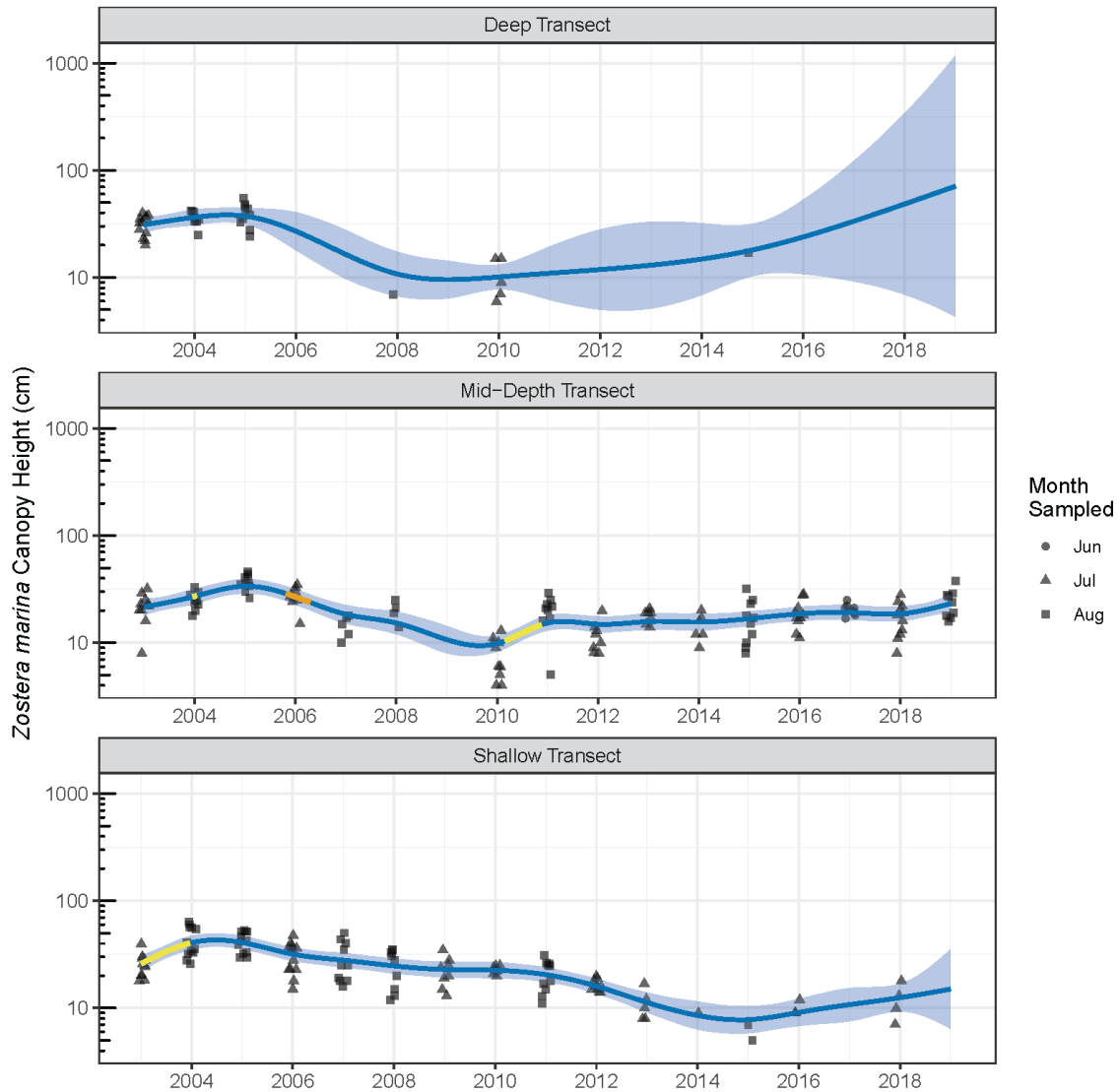


Figure 5-3. Trend in *Zostera marina* canopy height by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

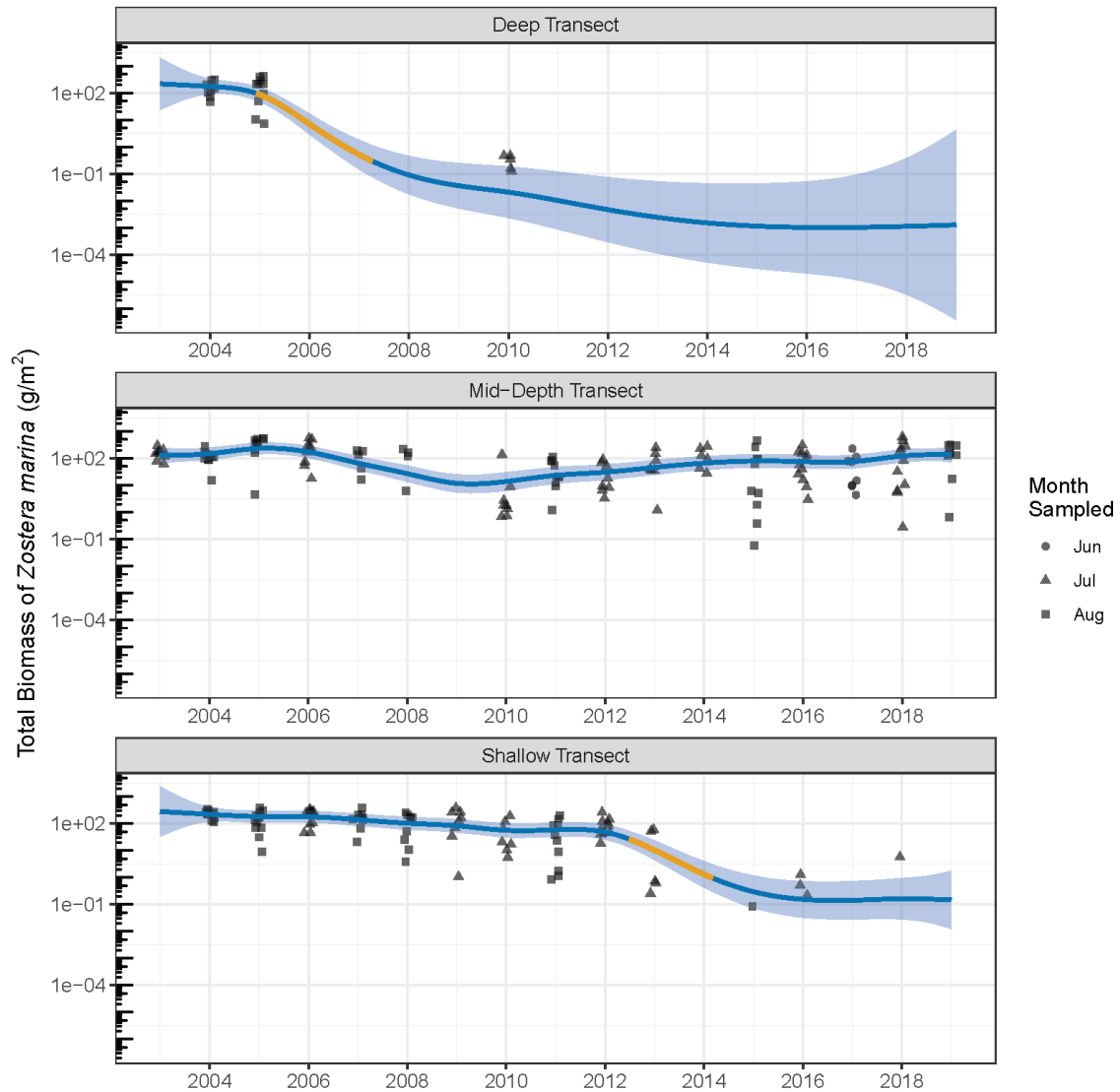


Figure 5-4. Trend in *Zostera marina* total biomass (g/m²) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange

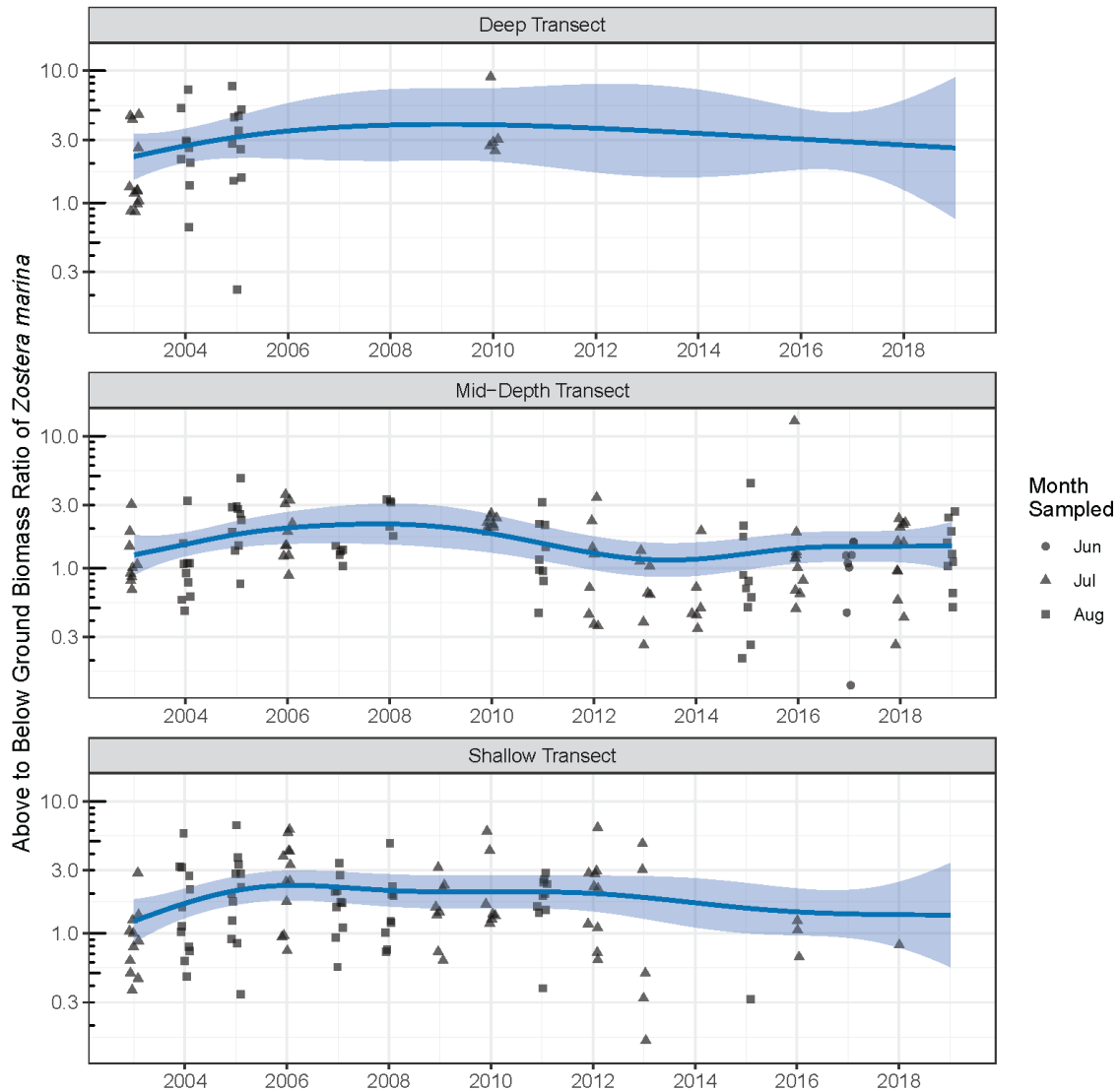


Figure 5-5. Trend in above to below ground biomass ratio of *Zostera marina* by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: y-axes are transformed to the $\log_{10}$ scale to better visualize the estimated trends

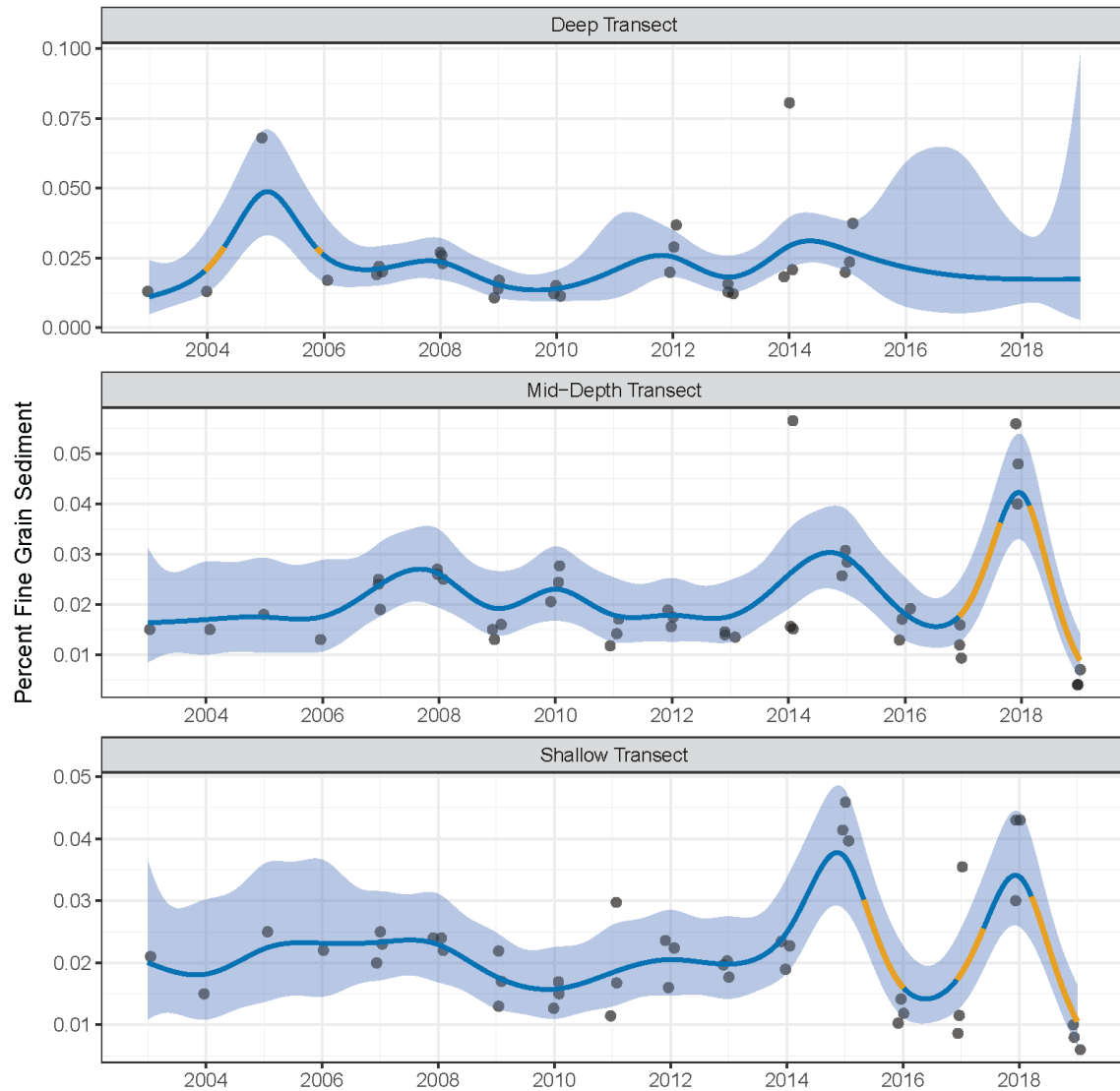


Figure 5-6. Trend in percent fine sediment (i.e., clay and silt) by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

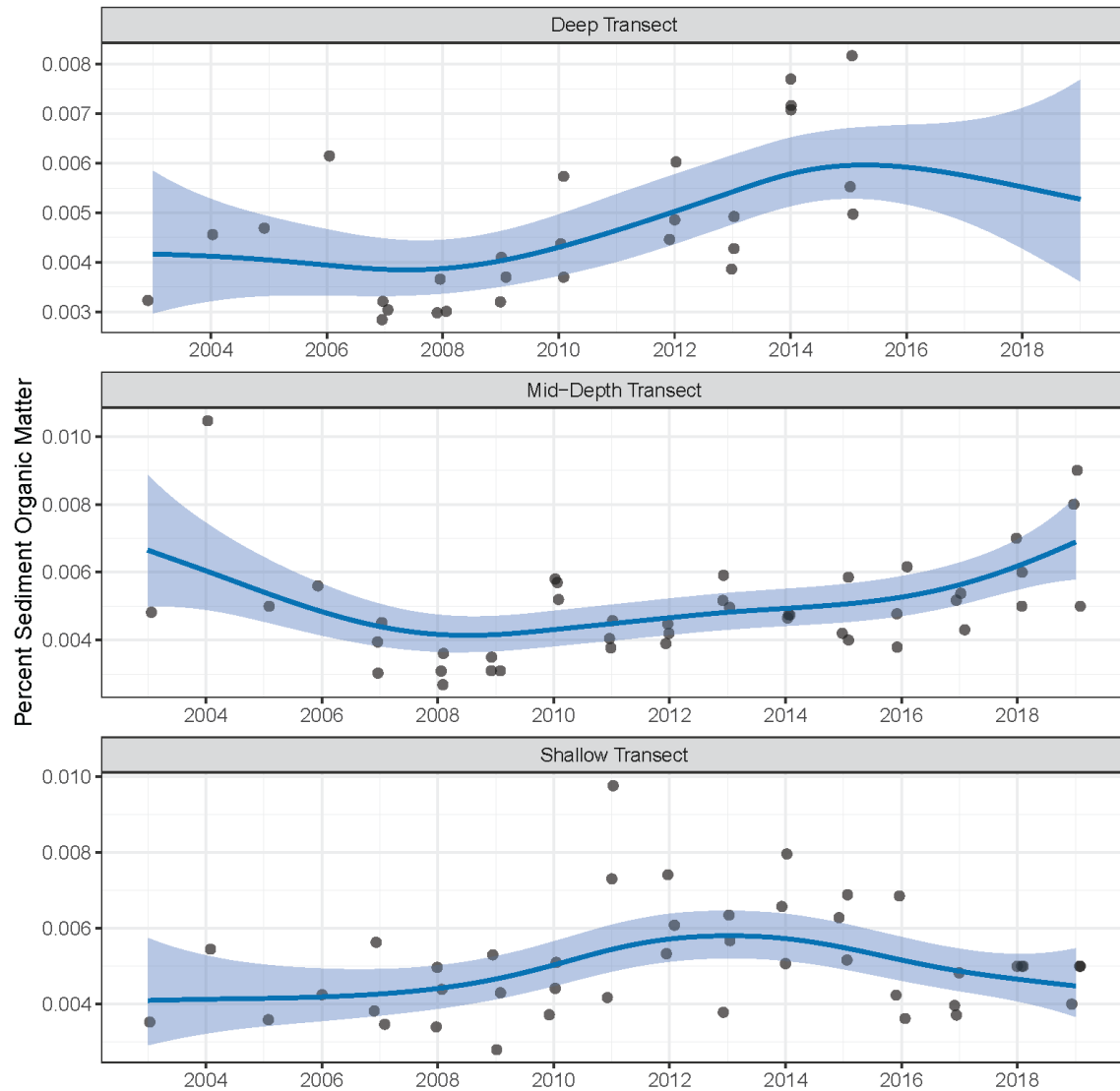


Figure 5-7. Trend in percent sediment organic material by transect at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

5.4.3 Water Temperature Summaries

Days wherein the daily average water temperature exceeds 25 °C generally occurs during the months of July and August for both the shallow and deep transects (Figure 5-8). The number of days exceeding 25 °C has been increasing over time.

(a) Daily Average Temperature > 25°C (Days/Month)

Shallow Transect (A)

2020	0	0	0	0	0	8	8	0	0	0	0
2019	0	0	0	0	0	2	3	0	0	0	0
2018	0	0	0	0	0	0	4	0	0	0	0
2017	0	0	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	4	6	0	0	0	0
2015	0	0	0	0	0	3	8	0	0	0	0
2014	0	0	0	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	10	0	0	0	0	0
2012	0	0	0	0	0	7	6	0	0	0	0
2011	0	0	0	0	0	1	0	0	0	0	0
2010	0	0	0	0	0	2	0	0	0	0	0
2009	0	0	0	0	0	0	2	0	0	0	0
2008	0	0	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	2	0	0	0	0
2005				0	0	0	1	0	0	0	0
2004	0	0	0	0	0	0	0				
2003							0	0	0	0	0
	1	3	4	5	6	7	8	9	10	11	12

Month

(b) Daily Average Temperature > 25°C (Days/Month)

Deep Transect (C)

2020	0	0	0	0	0	8	4	0			
2019	0	0	0	0	0	2	1	0	0	0	0
2018	0	0	0	0	0	0	0	0	0	0	0
2017	0	0	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	2	4	0	0	0	0
2015	0	0	0	0	0	2	5	0	0	0	0
2014	0	0	0	0	0	0	0	0	0	0	0
2013						3	0	0	0	0	0
2012	0	0	0	0							
2011	0	0	0	0	0	0	0	0	0	0	0
2010	0	0	0	0	0	2	0	0	0	0	0
2009	0	0	0	0	0	0	2	0	0	0	0
2008	0	0	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	0	0	0	0	0
2005				0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0				
2003							0	0	0	0	0
	1	3	4	5	6	7	8	9	10	11	12

Month

Figure 5-8. Number of days per month wherein average daily water temperature exceeded 25 °C for the (a) shallow and (b) deep transects at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed.

5.5 Pleasant Bay Results

5.5.1 Summary Statistics

Yearly and monthly (if applicable) summary statistics are provided for *Zostera marina* for the following: shoot density (Table 5-9), percent cover (Table 5-10), canopy height (Table 5-11), total biomass (Table 5-12), and ratio of above to below ground biomass (Table 5-13).

Table 5-9. Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* shoot density (per 1m²) at Cape Cod National Seashore Pleasant Bay. [SD = standard deviation]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2003-07	–	–	0	830.5	363.9	11	–	–	0
2003-10	758.7	296.1	12	610.7	363.6	12	NA	NA	NA
2004-01	932.4	285.6	11	NA	NA	NA	NA	NA	NA
2004-05	989.1	284.5	11	936.0	594.9	12	457.6	336.9	10
2004-08	919.3	328.9	11	725.3	447.9	12	376.7	343.6	11
2005-04	354.7	172.4	12	NA	NA	NA	168.0	145.5	6
2005-08	609.3	351.9	12	857.3	523.3	12	509.3	443.1	12
2006-07	836.0	376.5	12	686.7	554.6	12	0.0	0.0	12
2007-08	925.3	556.8	12	333.3	545.7	12	0.0	0.0	12
2008-08	452.3	474.3	12	275.3	494.5	12	1.0	3.5	12
2009-07	610.0	635.3	12	0.0	0.0	12	0.0	0.0	12
2010-07	261.7	412.1	12	66.0	152.3	12	2.7	3.6	12
2011-08	338.0	385.8	12	144.7	176.4	12	0.0	0.0	12
2012-07	636.0	450.0	12	133.7	162.8	12	0.0	0.0	12
2013-07	70.0	154.4	12	274.7	407.5	12	0.0	0.0	12
2014-07	0.3	1.2	12	279.0	352.3	12	0.0	0.0	12
2015-08	0.7	1.6	12	310.3	408.1	12	1.3	4.6	12
2016-07	1.7	3.2	12	362.7	358.6	12	NA	NA	NA
2017-06	0.0	0.0	12	165.3	215.3	12	0.0	0.0	12
2018-07	4.7	12.5	12	562.0	571.2	12	1.0	3.5	12
2019-08	0.0	0.0	12	545.0	579.0	12	NA	NA	NA
2019-10	NA	NA	NA	NA	NA	NA	0.0	0.0	12

Table 5-10. Yearly (monthly within year, if applicable) summary statistics for percent cover of *Zostera marina* at Cape Cod National Seashore Pleasant Bay. [SD = standard deviation]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2003-07	50.4	31.4	12	77.9	16.8	12	68.9	35.8	12
2003-10	82.5	26.7	12	96.7	8.9	12	NA	NA	NA
2004-05	71.7	23.0	12	77.5	12.7	12	68.8	21.8	12
2004-07	84.6	23.7	12	97.9	5.0	12	98.3	3.9	12
2005-04	75.0	16.2	12	NA	NA	NA	30.3	35.2	12
2005-08	100.0	0.0	12	95.8	14.4	12	59.3	43.5	12
2006-07	1.2	2.3	12	26.7	26.1	12	62.9	17.4	12
2007-08	7.3	11.0	12	85.4	21.6	12	41.2	40.1	12
2008-08	17.6	21.1	12	97.9	7.2	12	78.3	32.8	12
2009-07	45.1	31.8	12	99.2	2.9	12	28.4	28.1	12
2010-07	11.4	15.5	12	84.6	16.3	12	66.7	27.0	12
2011-08	27.2	29.9	12	96.7	7.2	12	98.3	3.3	12
2012-07	45.4	37.4	12	96.2	7.7	12	25.0	27.2	12
2013-07	21.3	26.4	12	88.3	16.4	12	38.7	31.8	12
2014-07	38.8	33.7	12	80.0	38.1	12	60.4	26.8	12
2015-08	43.1	30.8	12	44.2	32.6	12	18.8	18.3	12
2016-07	59.2	28.5	12	80.4	34.5	12	67.1	29.3	12
2017-06	65.4	20.5	12	60.4	19.5	12	3.0	4.9	12
2018-07	45.8	33.6	12	78.8	34.5	12	13.8	19.6	12
2019-08	31.2	17.1	12	30.0	21.1	12	6.7	10.7	12

Table 5-11. Yearly (monthly within year, if applicable) summary statistics for *Zostera marina* canopy height at Cape Cod National Seashore Pleasant Bay. [SD = standard deviation]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2003-07	20.6	4.0	12	42.5	5.5	12	77.4	23.3	12
2003-10	32.9	7.0	12	48.2	5.5	12	NA	NA	NA
2004-05	10.9	2.2	12	16.4	2.6	12	39.9	7.0	12
2004-07	38.9	9.7	12	64.2	3.3	12	95.3	7.8	12
2005-04	11.3	1.7	12	NA	NA	NA	32.6	12.9	11
2005-08	45.9	5.2	12	74.9	7.9	12	65.7	27.1	12
2006-07	14.3	0.6	3	31.0	7.9	10	55.8	7.6	12
2007-08	12.5	4.6	8	49.4	12.5	12	53.8	21.3	11
2008-08	16.7	4.7	12	58.3	4.6	12	76.1	16.3	12
2009-07	25.6	6.9	12	65.2	6.4	12	65.7	8.7	9
2010-07	16.7	6.7	10	37.8	2.6	12	68.8	15.6	12
2011-08	20.9	5.3	10	54.0	9.2	12	89.6	10.5	12
2012-07	32.3	3.1	10	64.3	10.8	12	71.5	18.7	10
2013-07	22.8	5.9	9	51.9	5.4	12	50.0	18.8	12
2014-07	26.5	5.9	11	58.5	3.7	10	85.4	12.4	12
2015-08	30.3	5.0	12	30.1	6.9	10	31.7	9.5	11
2016-07	37.2	7.9	12	72.6	16.0	11	90.3	5.6	12
2017-06	40.4	6.0	12	39.8	9.5	12	30.0	18.1	5
2018-07	28.3	7.9	12	63.8	18.5	12	78.2	15.3	8
2019-08	18.5	3.1	12	30.1	7.5	12	68.0	14.6	4

Table 5-12. Yearly (monthly within year, if applicable) summary statistics for total biomass of *Zostera marina* at Cape Cod National Seashore Pleasant Bay. [SD = standard deviation]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2003-07	—	—	0	193.6	76.9	10	—	—	0
2003-10	63.2	57.0	12	67.1	23.5	12	NA	NA	NA
2004-05	59.4	37.0	12	107.5	41.0	12	103.1	65.9	12
2004-07	138.2	60.2	12	232.2	66.3	12	185.0	100.9	12
2005-04	48.2	12.4	6	NA	NA	NA	19.5	19.1	6
2005-08	125.5	47.4	12	123.4	79.4	12	97.9	102.3	10
2006-07	0.3	0.6	12	53.7	79.0	12	92.9	60.5	12
2007-08	10.5	20.6	9	119.7	118.3	12	45.3	68.1	11
2008-08	32.0	39.1	12	202.2	104.2	12	204.4	102.2	12
2009-07	79.8	74.9	12	243.7	60.2	12	71.3	76.6	12
2010-07	17.1	23.7	11	207.2	125.1	12	137.4	71.0	12
2011-08	70.0	78.4	11	314.8	133.6	12	276.1	148.1	12
2012-07	176.0	196.6	12	189.4	86.0	12	88.4	128.0	12
2013-07	36.6	66.6	12	181.5	98.4	12	51.9	68.9	12
2014-07	83.4	92.3	12	150.7	93.9	12	238.4	242.5	12
2015-08	126.0	83.6	11	60.3	51.8	11	45.4	49.7	9
2016-07	295.9	194.1	11	230.5	152.0	11	279.8	147.5	12
2017-06	184.3	119.4	12	72.3	30.3	12	7.6	14.9	10
2018-07	94.0	90.8	12	122.7	109.2	12	29.2	43.3	10
2019-08	33.6	23.8	11	40.8	44.8	11	12.2	22.5	12

Table 5-13. Yearly (monthly within year, if applicable) summary statistics for ratio of above to below ground biomass of *Zostera marina* at Cape Cod National Seashore Pleasant Bay. [SD = standard deviation]

Date	Shallow Transect			Mid-Depth Transect			Deep Transect		
	Mean	SD	n	Mean	SD	n	Mean	SD	n
2003-07	3.0	1.8	12	3.3	3.6	10	7.0	4.1	12
2003-10	2.0	0.8	12	2.0	0.5	12	NA	NA	NA
2004-05	0.9	0.4	12	1.3	0.3	12	5.0	2.1	12
2004-07	2.2	0.7	12	3.9	1.8	12	9.6	11.0	12
2005-04	0.6	0.1	6	NA	NA	NA	2.7	1.2	5
2005-08	2.5	1.8	12	5.7	8.0	12	6.4	4.0	11
2006-07	2.4	1.2	3	16.2	29.1	12	4.7	5.3	12
2007-08	2.0	0.9	5	3.0	1.9	12	3.9	3.3	10
2008-08	2.2	1.7	12	3.1	2.4	12	15.3	13.4	12
2009-07	2.5	1.8	12	6.0	3.9	12	90.1	211.8	9
2010-07	1.6	0.9	9	2.5	1.0	12	3.6	1.7	12
2011-08	1.3	0.7	9	3.0	1.2	12	4.9	2.7	12
2012-07	1.5	0.8	10	2.7	1.5	12	7.6	8.2	10
2013-07	2.3	1.2	9	3.3	2.3	12	5.0	1.7	12
2014-07	1.8	0.8	11	1.4	0.5	10	6.1	4.1	12
2015-08	2.3	1.5	11	2.0	0.8	9	4.0	3.5	8
2016-07	2.2	1.7	11	4.1	2.2	10	4.7	3.4	12
2017-06	1.9	0.9	12	3.0	1.3	12	2.1	0.6	3
2018-07	3.1	2.8	12	2.2	1.3	12	3.9	3.3	6
2019-08	2.8	3.1	11	2.2	0.9	11	7.0	2.9	4

5.5.2 GAM Results

The generalized additive model summaries indicate that there exists statistically significant temporal trends within transects for all *Zostera marina* measures (Table 5-14) and ancillary sediment measures (Table 5-15). Notable observations from the fitted smooths for each measure are as follows:

Shoot Density

Zostera marina shoot density is generally highest within the mid-depth transect and temporal trends differ between transects (Figure 5-9). Shoot density decreased after 2005 within the shallow transect but has since recovered. Variability within a given year is lowest within the mid-depth transect.

Percent Cover

Zostera marina trends in percent cover have been highly non-linear and differ by transect (Figure 5-10). There was a statistically significant decrease in percent cover within the shallow transect around 2006 but it has since recovered. The deep transect has seen several periods of statistically significant change but has been decreasing in recent years. The mid-depth transect has historically had high percent cover but recently measurements have become more variable within the year.

Canopy Height

The trend in *Zostera marina* canopy height is cyclical in nature, particularly within the deep and mid-depth transects (Figure 5-11).

Total Biomass

Zostera marina total biomass has been relatively constant within the deep and mid-depth transects (Figure 5-12). The shallow transect has been experiencing generally increasing total biomass after a statistically significant decline from 2005 to 2006.

Above to Below Ground Biomass Ratio

Zostera marina above to below ground biomass ratio has remained relatively constant within each transect (Figure 5-13).

Percent Fine Sediment

Percent fine sediment within the deep and mid-depth transects increased from 2008 to 2014 and has remained relatively constant since (Figure 5-14). The increase around 2011 within the deep transect was statistically significant.

Percent Organic Material

Percent organic material within the transects is very low. Both the deep and mid-depth transects experienced an increase in percent organic material from 2010 to 2013 and have since remained relatively constant (Figure 5-15). The shallow transect had a period of statistically significant decline around 2006 and has remained near zero since.

Table 5-14. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Pleasant Bay *Zostera marina* models. 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]

Measure	Model Term	edf	p-value
Shoot density	s(year, transect)	41.16	< 0.001
Percent cover	s(year, transect)	45.38	< 0.001
Canopy height	s(year, transect)	47.80	< 0.001
Total biomass	s(year, transect)	42.63	< 0.001
Above:below ground biomass	s(year, transect)	32.05	< 0.001

Table 5-15. Approximate significance of the generalized additive model smooth terms for each Cape Cod National Seashore Pleasant Bay ancillary sediment models. 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]

Measure	Model Term	edf	p-value
Percent fine sediment	s(year, transect)	12.87	< 0.001
Percent organic material	s(year, transect)	13.82	< 0.001

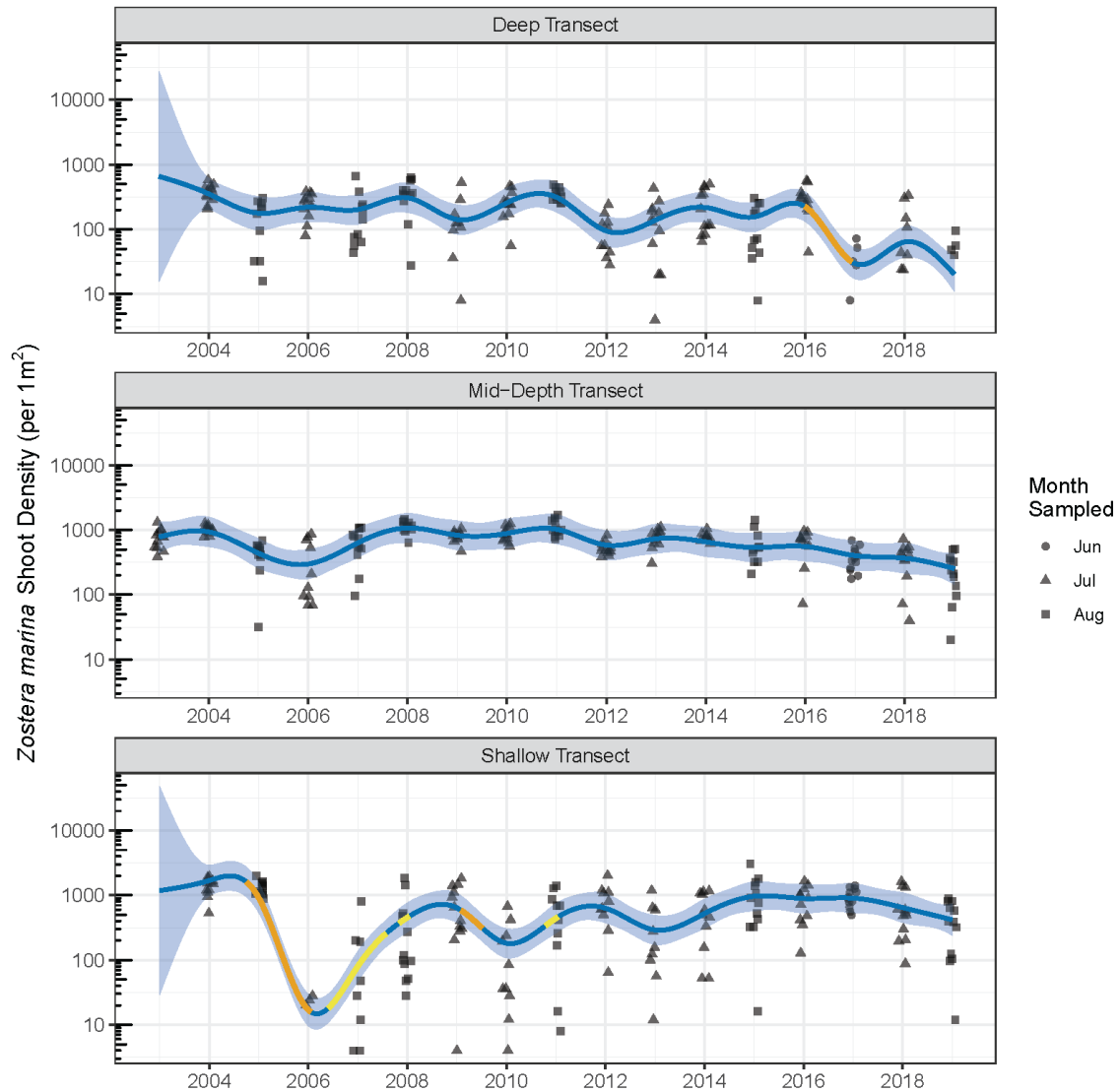


Figure 5-9. Trend in *Zostera marina* shoot density (per 1 m²) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

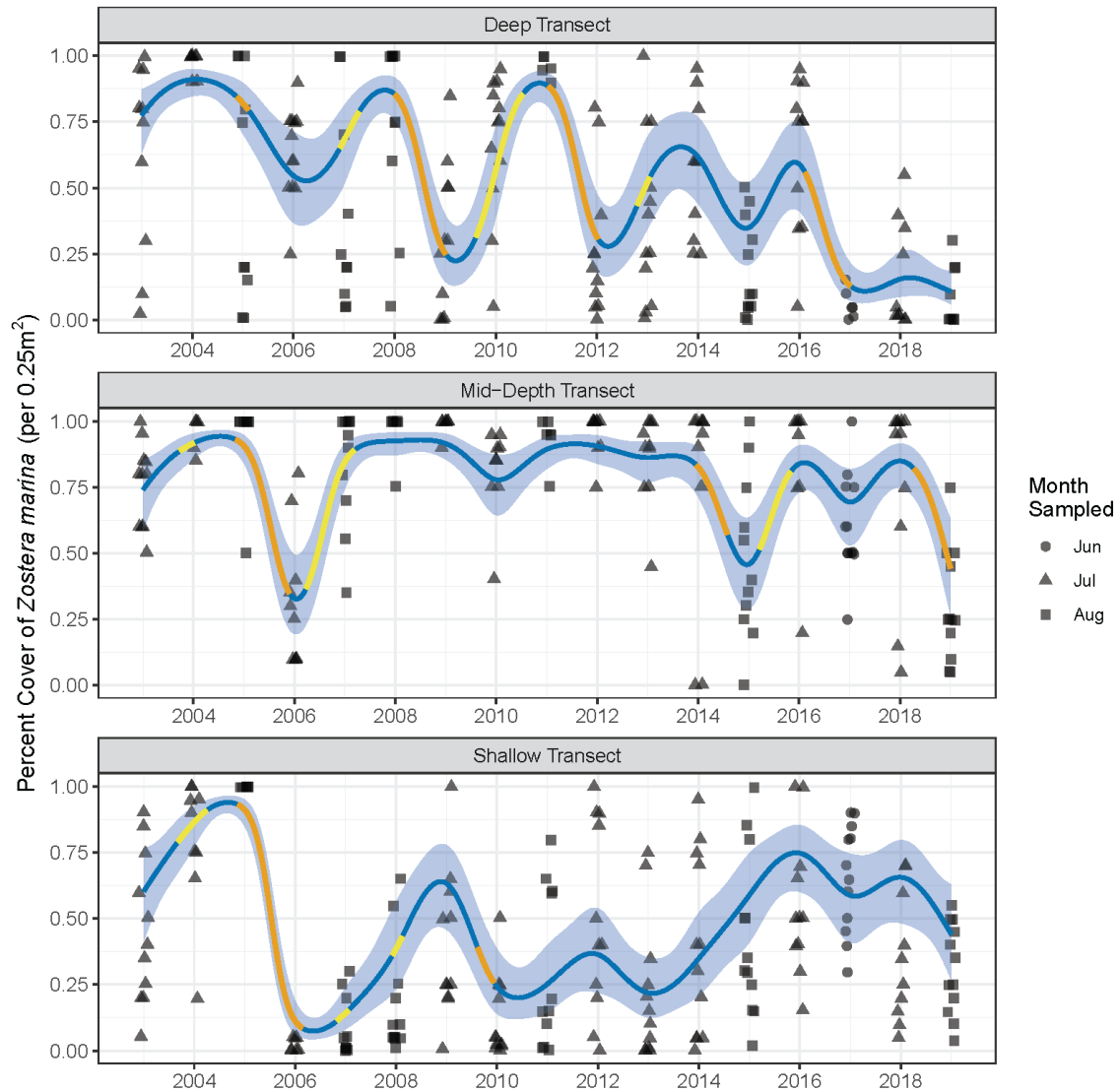


Figure 5-10. Trend in percent cover (per 0.25 m²) of *Zostera marina* by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

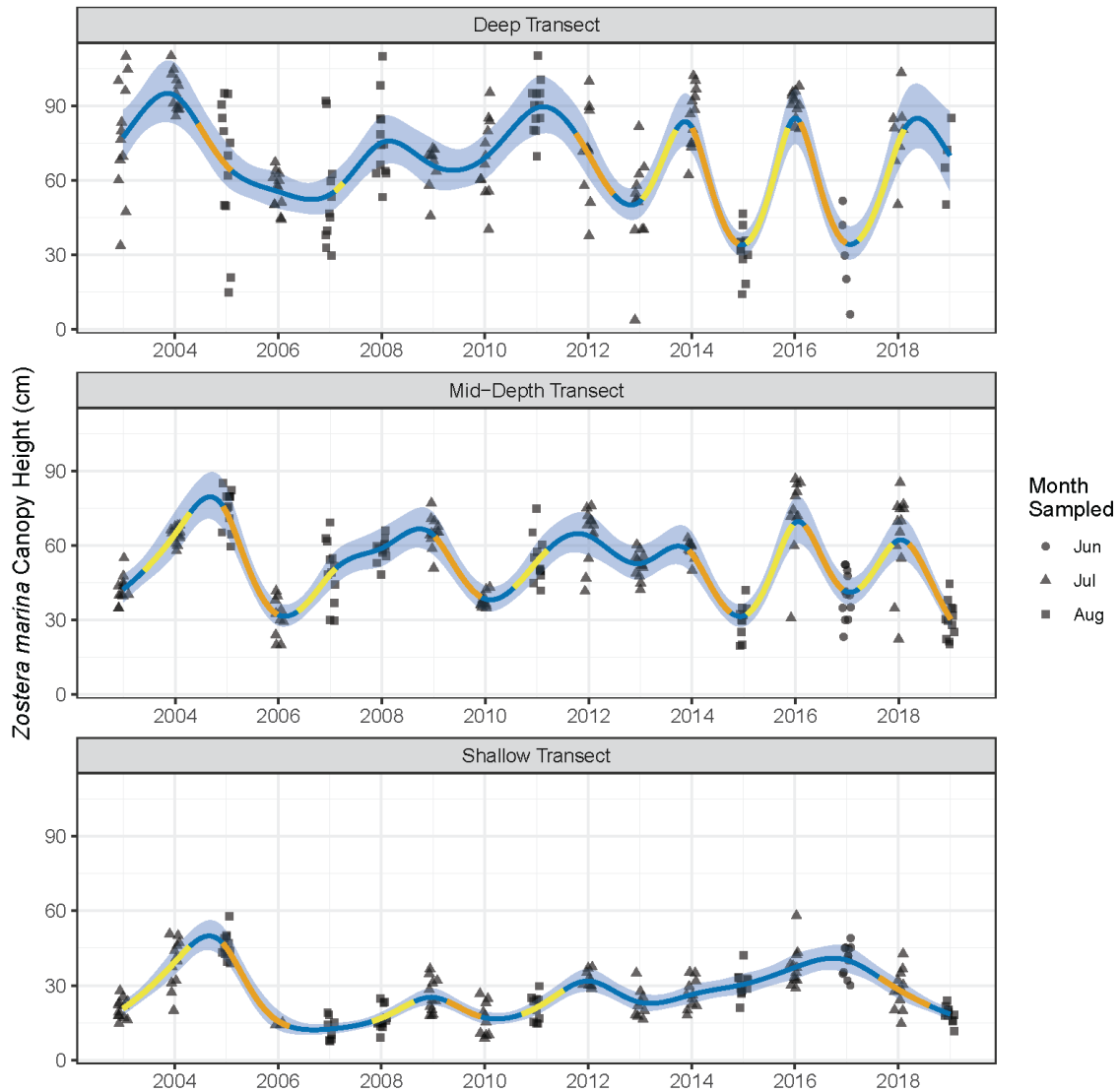


Figure 5-11. Trend in *Zostera marina* canopy height (cm) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

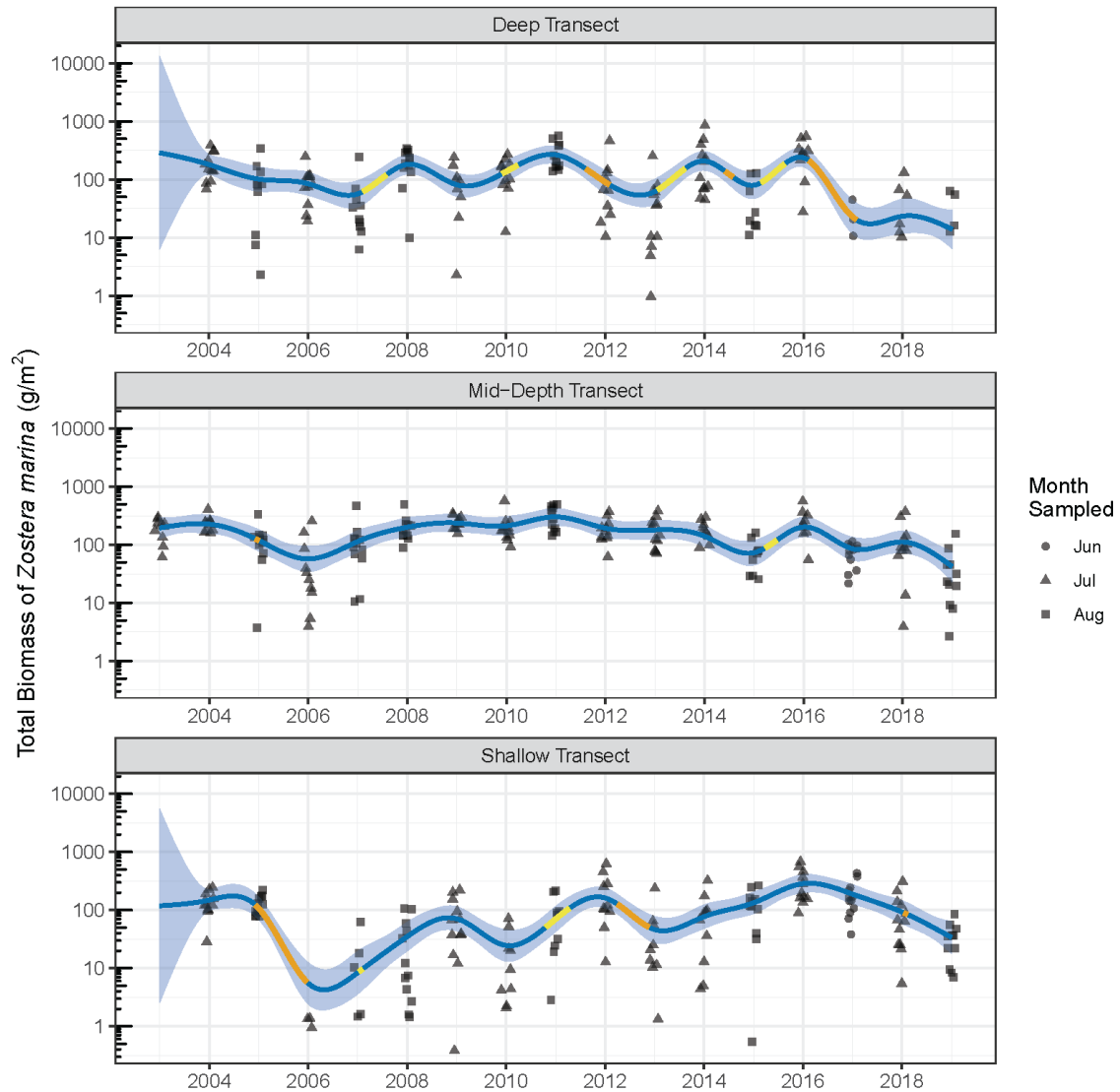


Figure 5-12. Trend in *Zostera marina* total biomass (g/m²) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

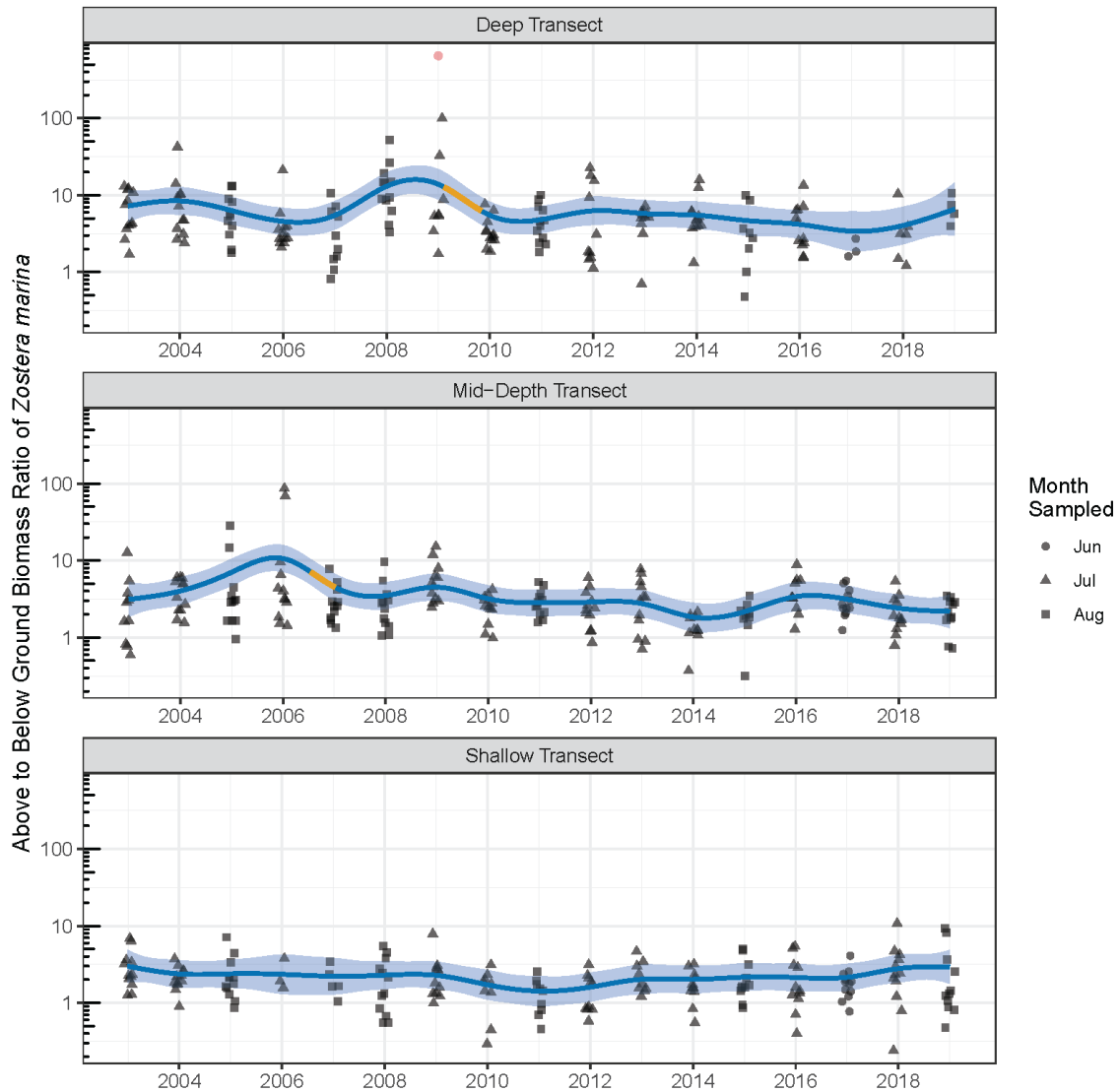


Figure 5-13. Trend in above to below ground biomass ratio of *Zostera marina* by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: y-axes are transformed to the log₁₀ scale to better visualize the estimated trends.

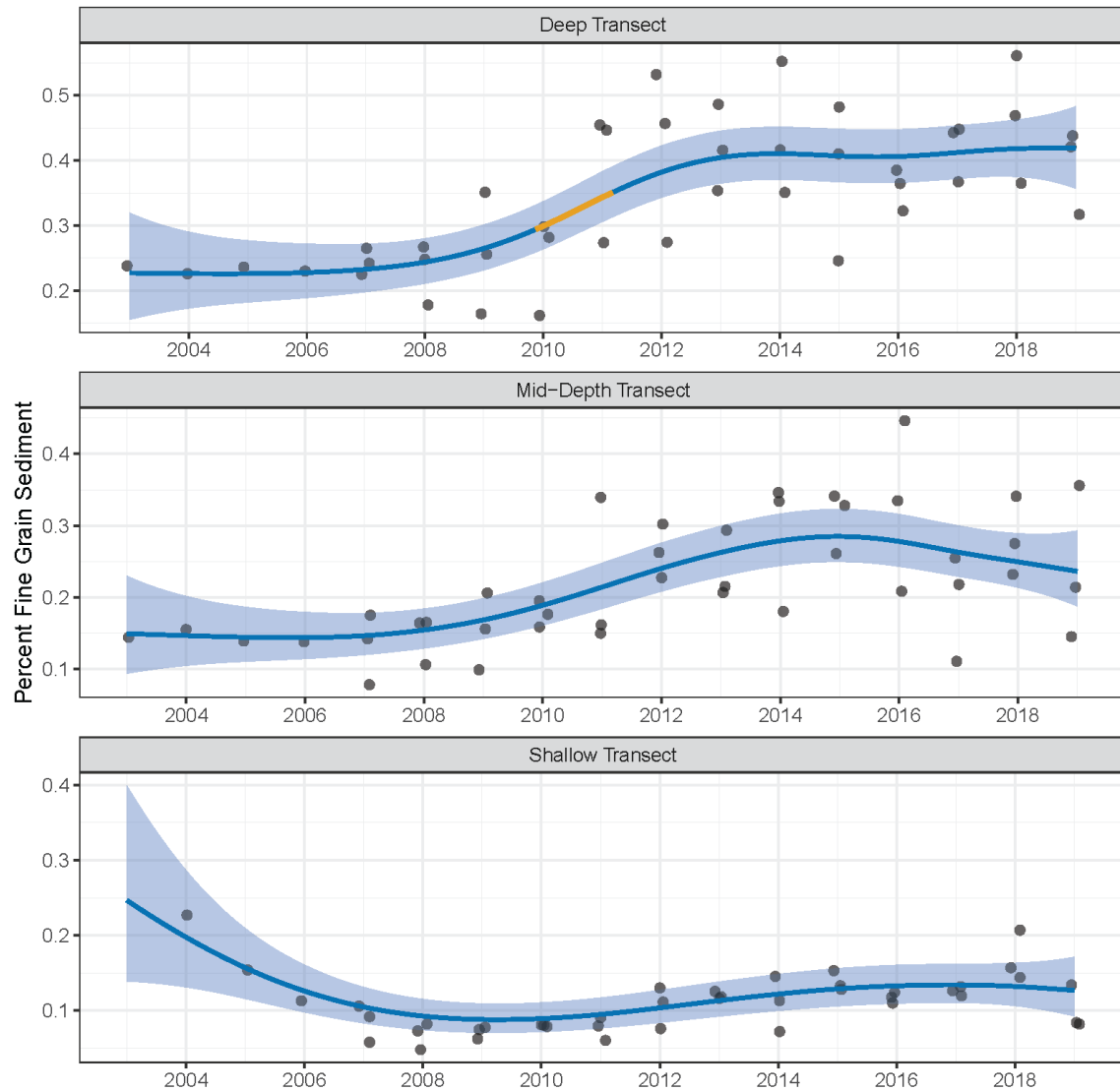


Figure 5-14. Trend in percent fine sediment (i.e., clay and silt) by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

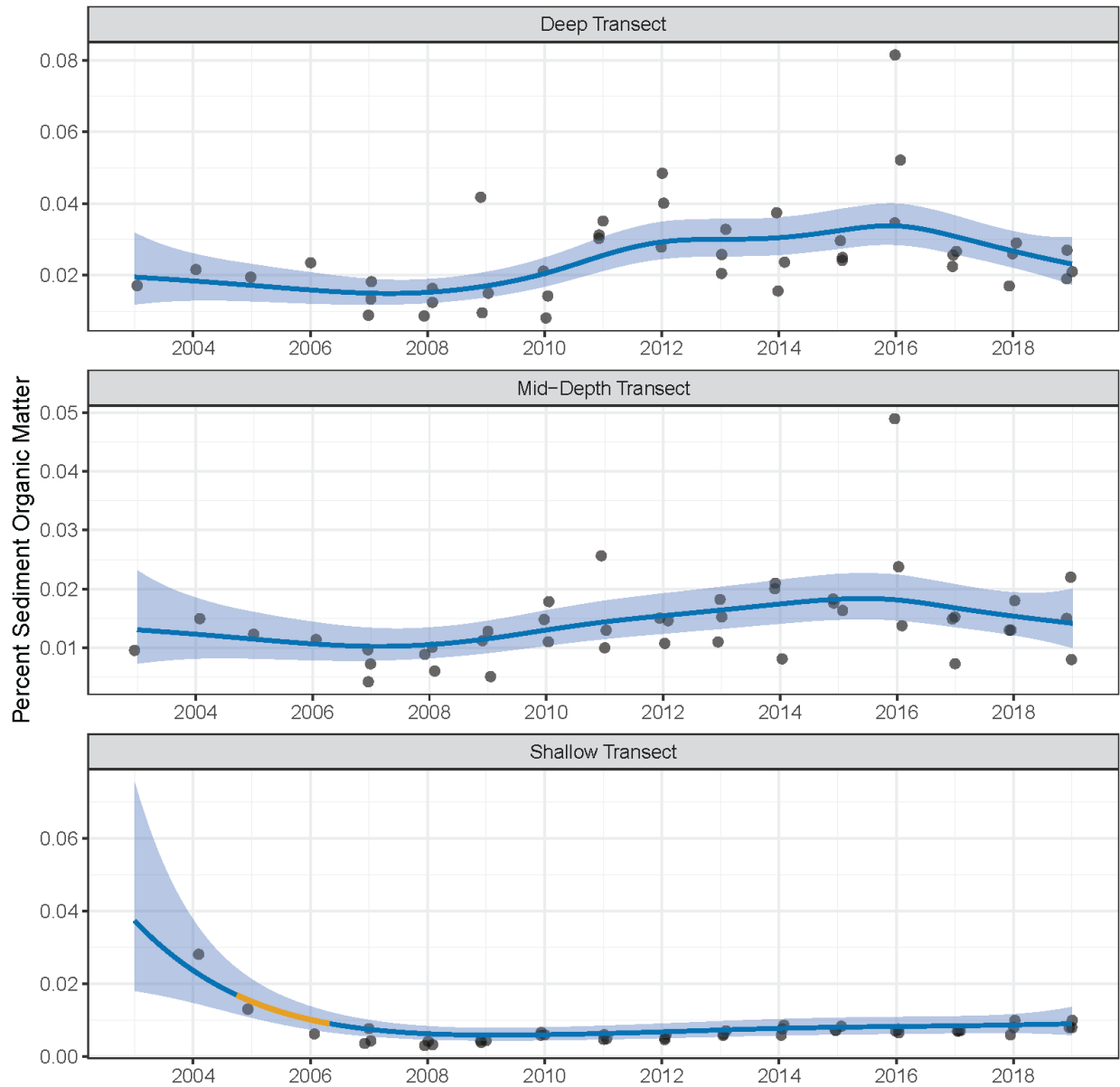


Figure 5-15. Trend in percent sediment organic material by transect at the Cape Cod National Seashore Pleasant Bay reference seagrass bed based on estimated generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

5.5.3 Water Temperature Summaries

Days wherein the daily average water temperature exceeds 25 °C generally occurs during the months of July and August for both the shallow and deep transects (Figure 5-16). The number of days exceeding 25 °C has generally been increasing over time, although 2003 to 2006 was also particularly warm within the Pleasant Bay stratum during July and August.

(a) Daily Average Temperature > 25°C (Days/Month)

Shallow Transect (A)

2020	0	0	0	0	0	15	13	0	0	0	0
2019	0	0	0	0	0	17	9	0	0	0	0
2018	0	0	0	0	0	8	15	3	0	0	0
2017	0	0	0	0	0	4	0	0	0	0	0
2016	0	0	0	0	0	15	11	0	0	0	0
2015	0	0	0	0	0	9	10	0	0	0	0
2014	0	0	0	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	15	0	0	0	0	0
2012	0	0	0	0	3	8	8	0	0	0	0
2011	0	0	0	0	0	2	0	0	0	0	0
2010	0	0	0	0	0	3	0	2	0	0	0
2009	0	0	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	10	8	0	0	0	0
2005				0	0	9	15	1	0	0	0
2004	0	0	0	0	0	5	5				
2003						12	13	0	0	0	0
	1	3	4	5	6	7	8	9	10	11	12

Month

(b) Daily Average Temperature > 25°C (Days/Month)

Deep Transect (C)

2020	0	0	0	0	0	9	10	0	0	0	0
2019	0	0	0	0	0	11	5	0	0	0	0
2018	0	0	0	0	0	7	13	3	0	0	0
2017	0	0	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	10	10	0	0	0	0
2015	0	0	0	0	0	9	8	0	0	0	0
2014	0	0	0	0	0	0	0	0	0	0	0
2013	0	0	0	0	0	12	0	0	0	0	0
2012	0	0	0	0	1	6	4	0	0	0	0
2011	0	0	0	0	0	0	0	0	0	0	0
2010	0	0	0	0	0	3	0	0	0	0	0
2009	0	0	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	5	8	0	0	0	0
2005				0	0	4	6	0	0	0	0
2004	0	0	0	0	0	2	1				
2003						6	8	0	0	0	0
	1	3	4	5	6	7	8	9	10	11	12

Month

Figure 5-16. Number of days per month wherein average daily water temperature exceeded 25 °C for the (a) shallow and (b) deep transects at the Cape Cod National Seashore Duck Harbor Beach reference seagrass bed.

6. Power Simulations

6.1 Methods

Power analyses are a function of the following five parameters: (1) power: the probability of rejecting the null hypothesis when it is false; (2) sample size; (3) type I error rate (alpha level): the probability of rejecting the null hypothesis given that it is true; (4) magnitude of the trend coefficient; and (5) variance of the measure. Increasing the value of the sample size, type I error rate, or trend coefficient, while holding the remaining parameters constant, will result in increased power. Decreasing the variance, while holding the remaining parameters constant, will also result in increased power. If given values for four of the parameters, it is possible to solve for the remaining parameter value.

The empirical power to detect a linear trend in the mean over time is estimated using Monte Carlo simulation following the method detailed in Gelman and Hill (2006). Power simulations are performed using the spatial-station monitoring data for the following measures: surface chlorophyll-*a* concentration, bottom dissolved oxygen concentration, and PAR attenuation.

The simulation framework⁸ consists of two steps: (1) use a process model to generate a time series with a true underlying trend with dispersion (variance) approximately equal to what has been observed in past monitoring data; (2) use estimation model to estimate the trend. The systematic component of the process model is defined mathematically as:

$$\log(\mu_i) = \beta_0 + \beta_1 \cdot \text{year}_i + f(\text{longitude}_i, \text{latitude}_i),$$

where β_1 is the linear trend and $f(\text{longitude}_i, \text{latitude}_i)$ is the predicted spatial effect estimated from the models fit in Section 2. Simulated locations ($i = 1, \dots, 30$) within each tessellated hexagon were randomly sampled with replacement from all previous locations within the hexagon. The random component of the simulated trend consists of response values being drawn from:

$$\text{response}_i \sim \text{Gamma}(\mu_i, \phi),$$

where the dispersion parameter ϕ equals to the estimated dispersion (i.e., residual variation) from the corresponding model fit in Section 2 (Table 6-1).

Trends were simulated for a period of both 10 and 20 years. The sampling interval was simulated to occur every 1-3 years for the 10-year simulation and every 1-5 years for the 20-year simulation. The magnitude of the linear trend (β_1) was varied so as to sufficiently characterize the estimated power curve. It is possible that past estimates of variability may be too conservative and not representative

⁸ An example of a similar framework applied to monitoring brown bear density in southwestern Alaska is detailed in Reynolds, Thompson, and Russell (2011).

of future variability due to changing climate. Therefore, additional scenarios wherein the dispersion was doubled were also included in the simulations.

To estimate the empirical power for a given simulation scenario, one thousand hypothetical time series were simulated according to the process model defined above. The estimation model consisted of a GAM with year as a parametric term and a Gaussian process smooth of spatial location within the estuary. Empirical power is equal to the proportion of the thousand regressions that rejected the null hypothesis $H_0: \beta_1 = 0$ in favor of $H_1: \beta_1 \neq 0$, assuming a type I error rate equal to 0.05.

Note that while the simulated mean trend is linear on the link function scale, back-transforming to the original scale results in a non-linear mean trend (Figure 6-1). Interpretation of the β_1 parameter is as follows: for every 1-year increase in time, the mean of the response values increases by a factor of $\exp(\beta_1)$. For example, $\beta_1 = 0.05$ in Figure 6-1 which corresponds to an approximate 5.1% increase in the mean each year ($\exp(0.05) \approx 1.051$).

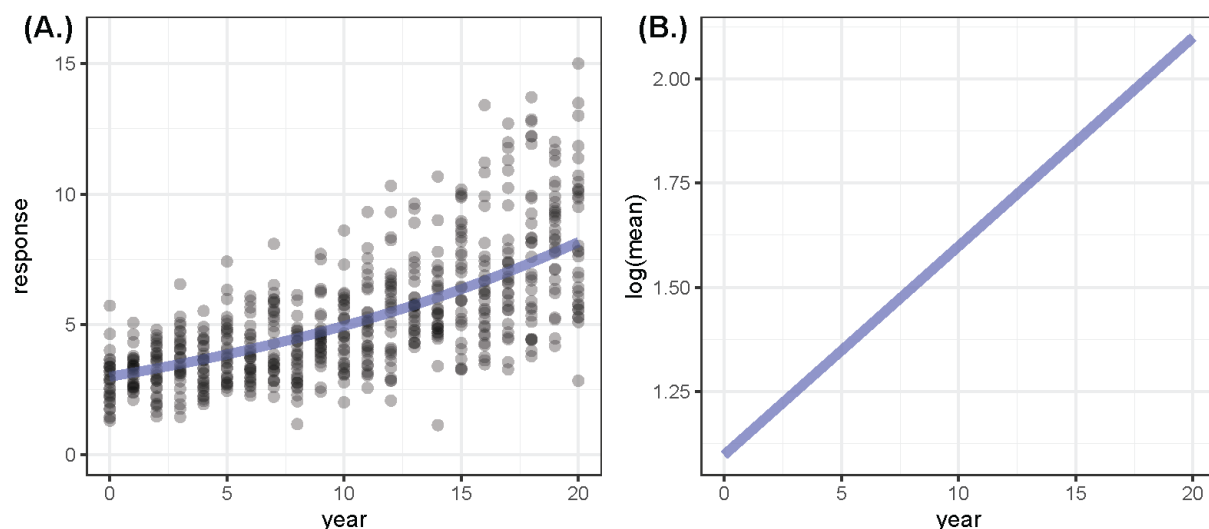


Figure 6-1. (A.) Process model realizations (black dots) representing samples from 30 sites within a hypothetical estuary. The i th hexagon's response value is simulated from $\text{Gamma}(\mu_i, 0.1)$, where $\ln(\mu_i) = 3 + 0.05 \cdot \text{year}_i$. The blue curve represents the true underlying mean trend. (B.) True underlying trend on the link function scale.

Table 6-1. Process model dispersion (ϕ) used to simulate trends in each water quality measure.

Measure	Pleasant Bay	Nauset Harbor	Salt Pond	All Strata
Chlorophyll <i>a</i> ($\mu\text{g/L}$)	0.386	0.261	0.524	0.404
Dissolved oxygen (mg/L)	0.035	0.059	0.162	0.081
PAR attenuation (K_d (m^{-1}))	0.283	0.423	0.514	0.437

6.2 Simulation Results

6.2.1 Pleasant Bay Stratum

Estimated power for detecting a linear trend within the Pleasant Bay Stratum is summarized in both graphical and tabular format for surface chlorophyll-*a* concentration (Figure 6-2; Table 6-2), bottom dissolved oxygen concentration (Figure 6-3; Table 6-3), and PAR attenuation (Figure 6-4; Table 6-4).

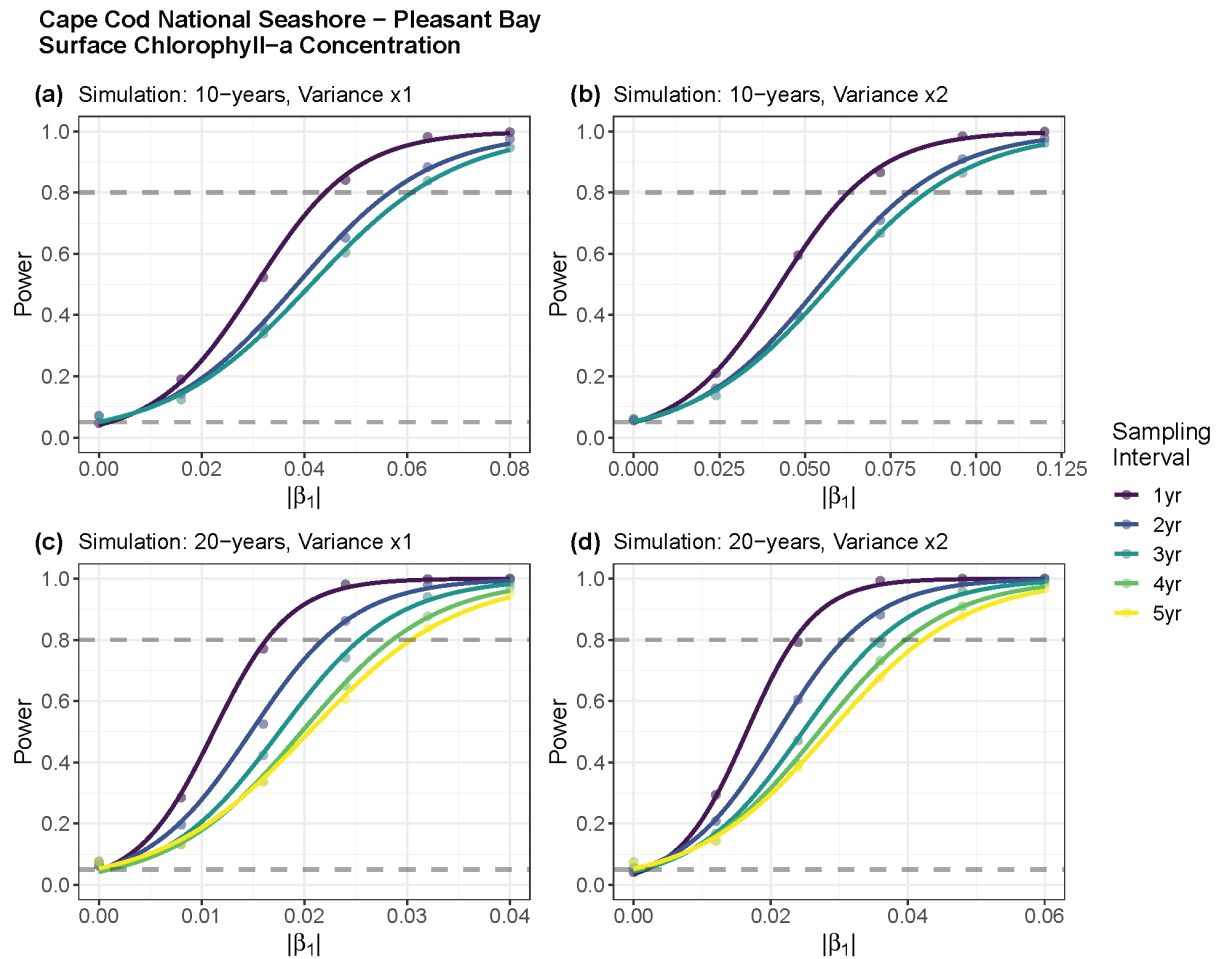


Figure 6-2. Estimated power to detect a linear trend in mean surface chlorophyll-*a* concentration within the Pleasant Bay stratum of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-2. Estimated power to detect a linear trend in mean surface chlorophyll-*a* concentration large enough to cross both quality thresholds within the Pleasant Bay stratum of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean surface chlorophyll-*a* concentration from the generalized additive model fit in Section 2.2.2 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	5	0.020	0.26	0.20	0.18	NA	NA
10 yrs	×1	20	0.159	1.00	1.00	1.00	NA	NA
10 yrs	×2	5	0.020	0.17	0.14	0.13	NA	NA
10 yrs	×2	20	0.159	1.00	1.00	0.99	NA	NA
20 yrs	×1	5	0.010	0.43	0.28	0.21	0.18	0.19
20 yrs	×1	20	0.079	1.00	1.00	1.00	1.00	1.00
20 yrs	×2	5	0.010	0.22	0.17	0.14	0.14	0.13
20 yrs	×2	20	0.079	1.00	1.00	1.00	1.00	0.99

2019 Estimate: 4.08 $\mu\text{g/L}$

**Cape Cod National Seashore – Pleasant Bay
Bottom Dissolved Oxygen Concentration**

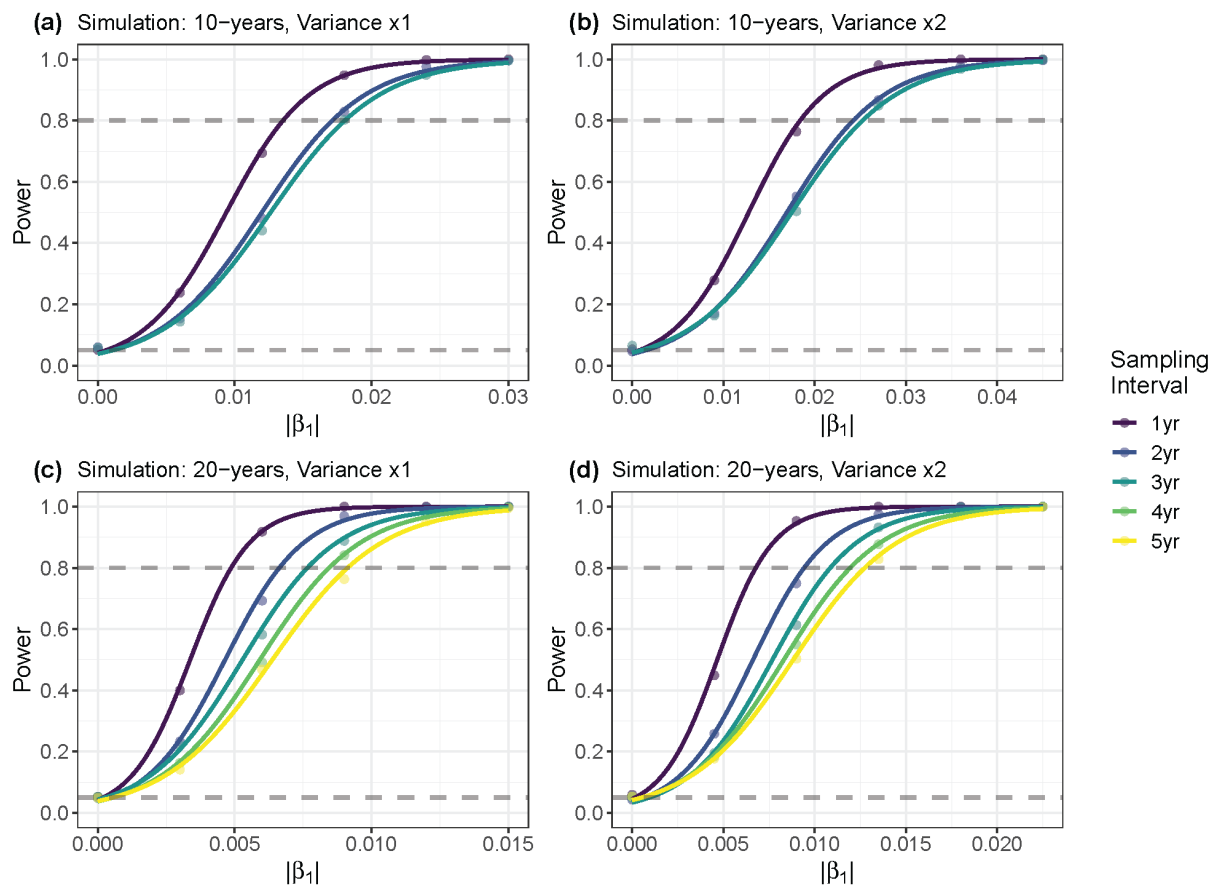


Figure 6-3. Estimated power to detect a linear trend in mean bottom dissolved oxygen concentration within the Pleasant Bay stratum of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-3. Estimated power to detect a linear trend in mean bottom dissolved oxygen concentration large enough to cross both quality thresholds within the Pleasant Bay stratum of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean bottom dissolved oxygen concentration from the generalized additive model fit in Section 2.2.2 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	2	−0.136	1.00	1.00	1.00	NA	NA
10 yrs	×1	5	−0.045	1.00	1.00	1.00	NA	NA
10 yrs	×2	2	−0.136	1.00	1.00	1.00	NA	NA
10 yrs	×2	5	−0.045	1.00	0.99	0.99	NA	NA
20 yrs	×1	2	−0.068	1.00	1.00	1.00	1.00	1.00
20 yrs	×1	5	−0.022	1.00	1.00	1.00	1.00	1.00
20 yrs	×2	2	−0.068	1.00	1.00	1.00	1.00	1.00
20 yrs	×2	5	−0.022	1.00	1.00	1.00	1.00	0.99

2019 Estimate: 7.81 mg/L

**Cape Cod National Seashore – Pleasant Bay
PAR Attenuation**

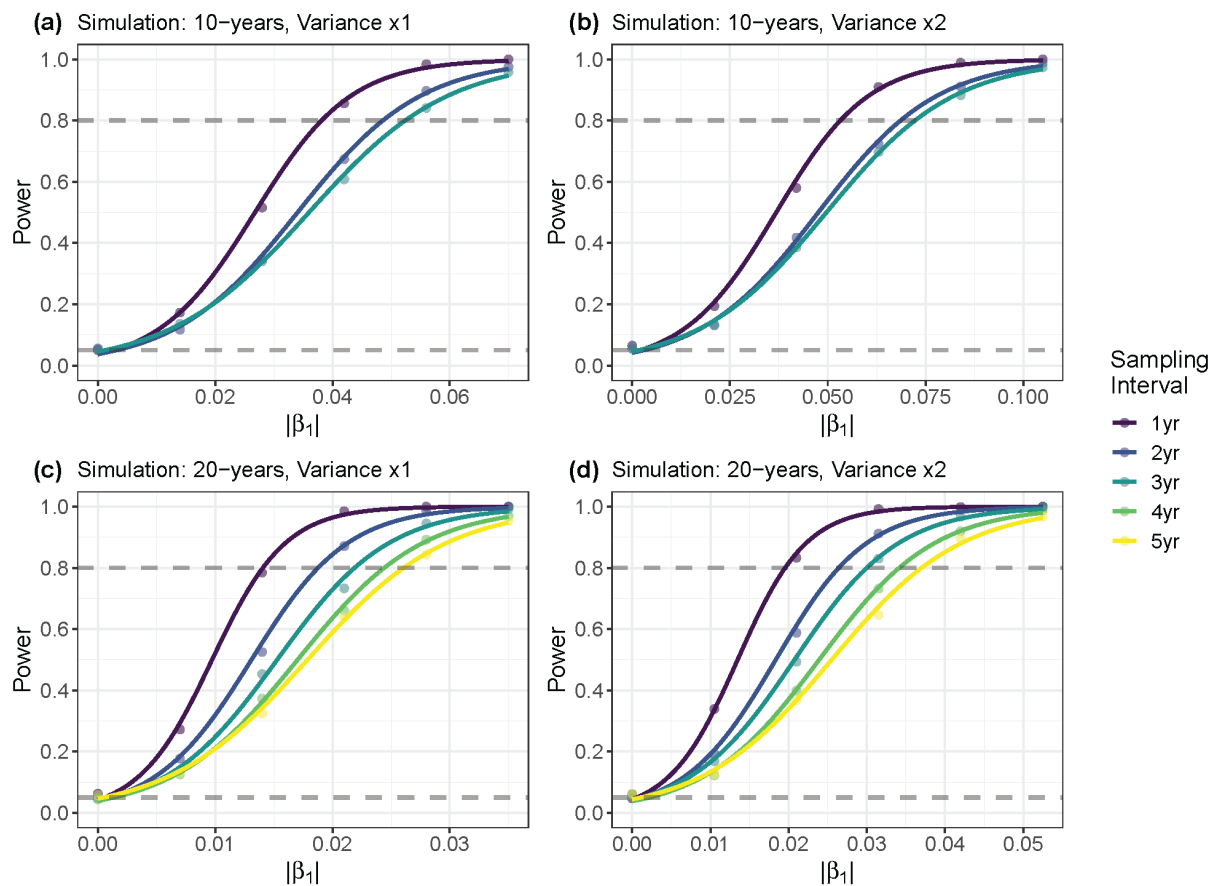


Figure 6-4. Estimated power to detect a linear trend in mean PAR attenuation within the Pleasant Bay stratum of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-4. Estimated power to detect a linear trend in mean PAR attenuation large enough to cross both quality thresholds within the Pleasant Bay stratum of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean PAR attenuation from the generalized additive model fit in Section 2.2.2 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	0.92	0.023	0.38	0.25	0.25	NA	NA
10 yrs	×1	1.61	0.079	1.00	0.99	0.97	NA	NA
10 yrs	×2	0.92	0.023	0.23	0.16	0.16	NA	NA
10 yrs	×2	1.61	0.079	0.97	0.89	0.86	NA	NA
20 yrs	×1	0.92	0.011	0.63	0.39	0.30	0.26	0.25
20 yrs	×1	1.61	0.039	1.00	1.00	0.99	0.99	0.97
20 yrs	×2	0.92	0.011	0.38	0.23	0.20	0.15	0.15
20 yrs	×2	1.61	0.039	1.00	0.97	0.94	0.89	0.84

2019 Estimate: 0.73 m⁻¹

6.2.2 Nauset Harbor Stratum

Estimated power for detecting a linear trend within the Nauset Harbor Stratum is summarized in both graphical and tabular format for surface chlorophyll-*a* concentration (Figure 6-5; Table 6-5), bottom dissolved oxygen concentration (Figure 6-6; Table 6-6), and PAR attenuation (Figure 6-7; Table 6-7).

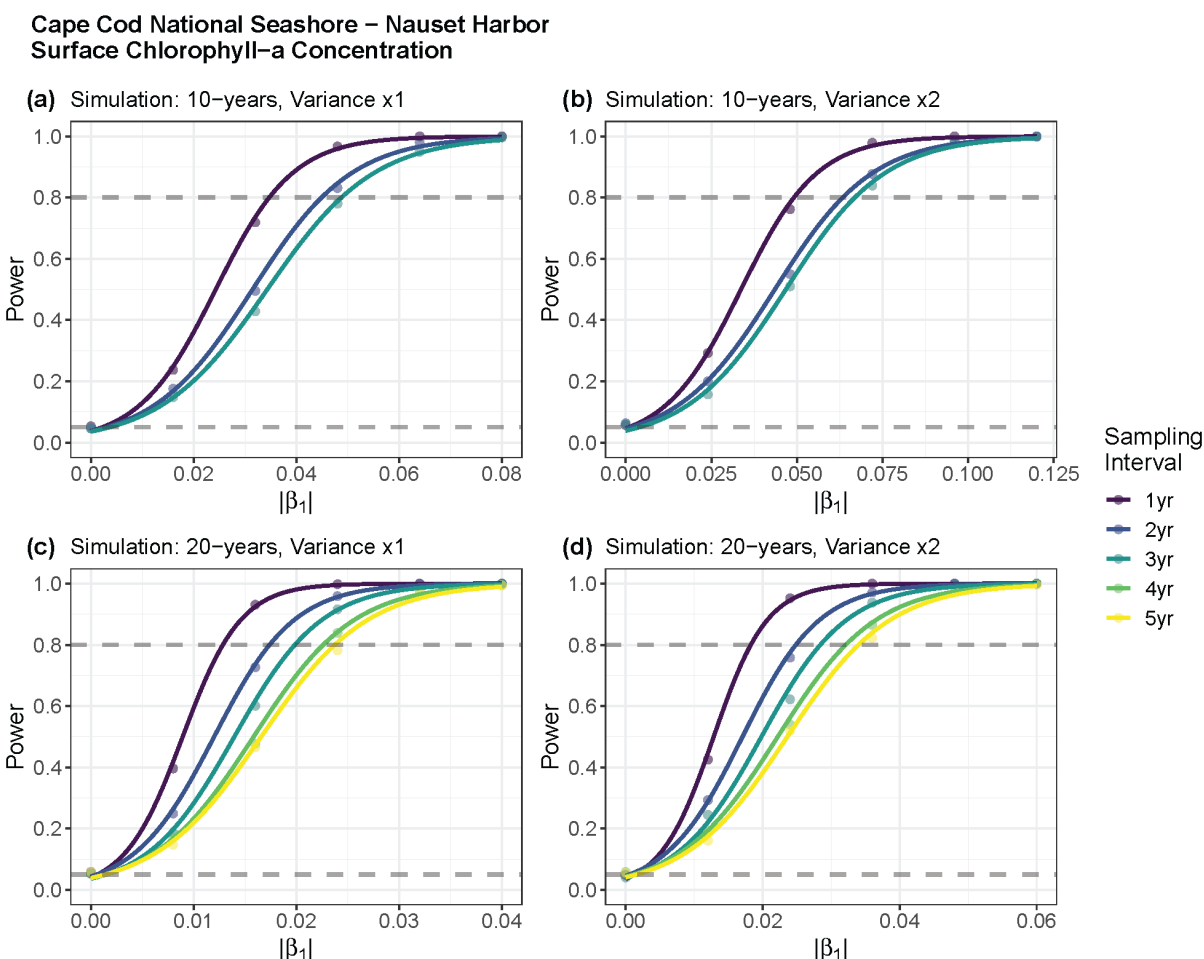


Figure 6-5. Estimated power to detect a linear trend in mean surface chlorophyll-*a* concentration within the Nauset Harbor stratum of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-5. Estimated power to detect a linear trend in mean surface chlorophyll-*a* concentration large enough to cross both quality thresholds within the Nauset Harbor stratum of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean surface chlorophyll-*a* concentration from the generalized additive model fit in Section 2.3.2 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	5	−0.040	0.89	0.70	0.63	NA	NA
10 yrs	×1	20	0.099	1.00	1.00	1.00	NA	NA
10 yrs	×2	5	−0.040	0.63	0.43	0.38	NA	NA
10 yrs	×2	20	0.099	1.00	0.98	0.97	NA	NA
20 yrs	×1	5	−0.020	0.98	0.88	0.80	0.70	0.65
20 yrs	×1	20	0.049	1.00	1.00	1.00	1.00	1.00
20 yrs	×2	5	−0.020	0.86	0.62	0.50	0.42	0.38
20 yrs	×2	20	0.049	1.00	1.00	0.99	0.98	0.97

2019 Estimate: 7.44 $\mu\text{g/L}$

**Cape Cod National Seashore – Nauset Harbor
Bottom Dissolved Oxygen Concentration**

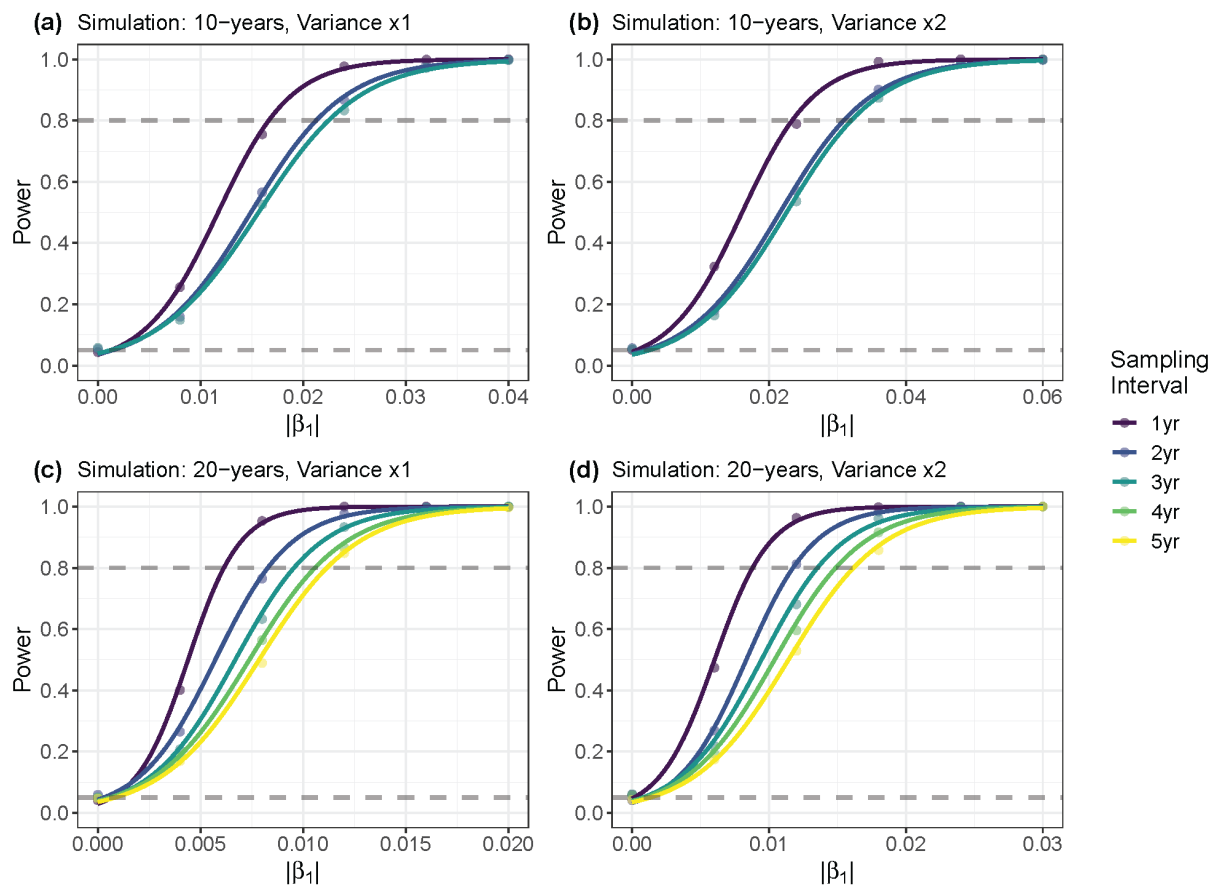


Figure 6-6. Estimated power to detect a linear trend in mean bottom dissolved oxygen concentration within the Nauset Harbor stratum of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-6. Estimated power to detect a linear trend in mean bottom dissolved oxygen concentration large enough to cross both quality thresholds within the Nauset Harbor stratum of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean bottom dissolved oxygen concentration from the generalized additive model fit in Section 2.3.2 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	2	−0.131	1.00	1.00	1.00	NA	NA
10 yrs	×1	5	−0.039	1.00	0.99	0.99	NA	NA
10 yrs	×2	2	−0.131	1.00	1.00	1.00	NA	NA
10 yrs	×2	5	−0.039	0.99	0.93	0.92	NA	NA
20 yrs	×1	2	−0.065	1.00	1.00	1.00	1.00	1.00
20 yrs	×1	5	−0.020	1.00	1.00	1.00	1.00	0.99
20 yrs	×2	2	−0.065	1.00	1.00	1.00	1.00	1.00
20 yrs	×2	5	−0.020	1.00	0.99	0.97	0.95	0.92

2019 Estimate: 7.39 mg/L

**Cape Cod National Seashore – Nauset Harbor
PAR Attenuation**

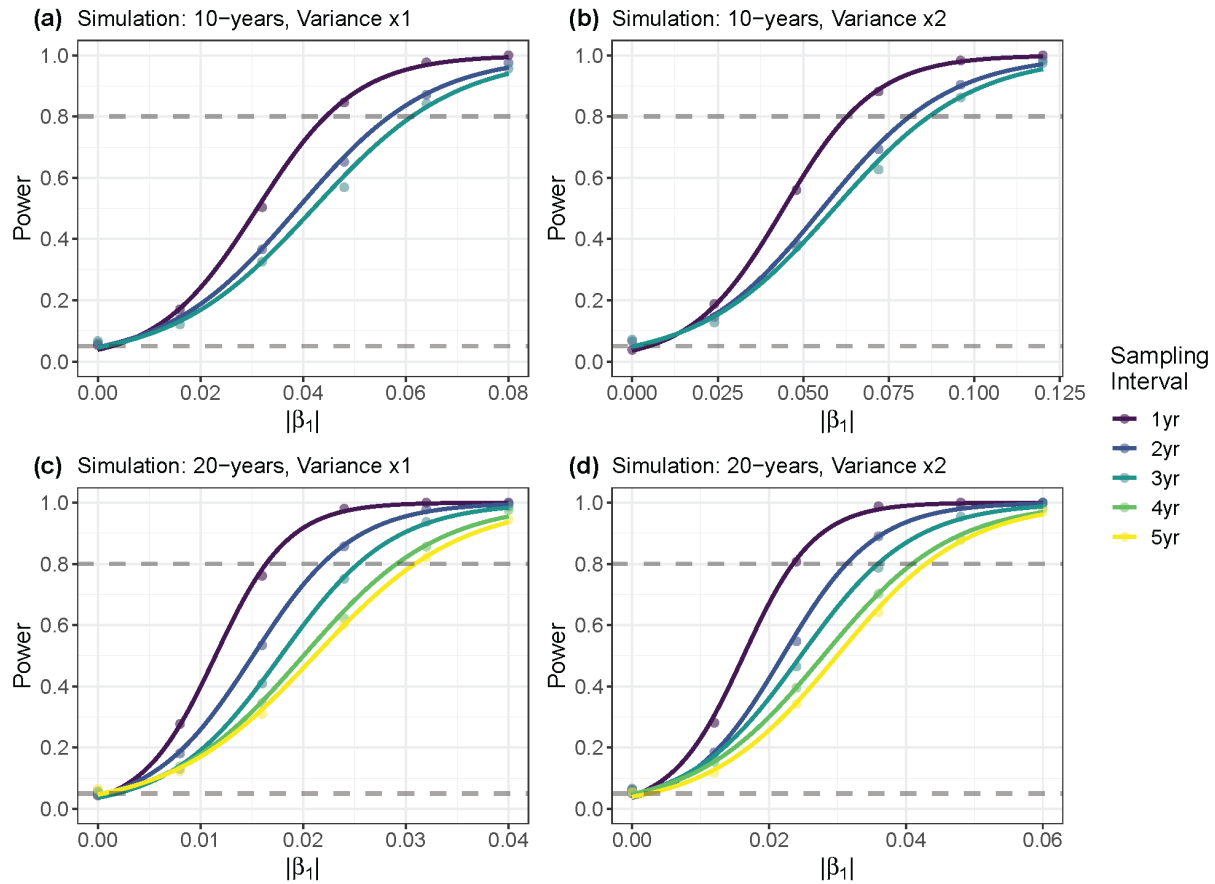


Figure 6-7. Estimated power to detect a linear trend in mean PAR attenuation within the Nauset Harbor stratum of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-7. Estimated power to detect a linear trend in mean PAR attenuation large enough to cross both quality thresholds within the Nauset Harbor stratum of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean PAR attenuation from the generalized additive model fit in Section 2.3.2 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	0.92	−0.004	0.06	0.06	0.06	NA	NA
10 yrs	×1	1.61	0.052	0.89	0.73	0.67	NA	NA
10 yrs	×2	0.92	−0.004	0.05	0.06	0.06	NA	NA
10 yrs	×2	1.61	0.052	0.63	0.45	0.41	NA	NA
20 yrs	×1	0.92	−0.002	0.07	0.07	0.05	0.06	0.06
20 yrs	×1	1.61	0.026	0.98	0.90	0.81	0.71	0.66
20 yrs	×2	0.92	−0.002	0.06	0.05	0.06	0.06	0.05
20 yrs	×2	1.61	0.026	0.86	0.64	0.53	0.44	0.39

2019 Estimate: 0.96 m^{−1}

6.2.3 Salt Pond Stratum

Estimated power for detecting a linear trend within the Salt Pond Stratum is summarized in both graphical and tabular format for surface chlorophyll-*a* concentration (Figure 6-8; Table 6-8), bottom dissolved oxygen concentration (Figure 6-9; Table 6-9), and PAR attenuation (Figure 6-10; Table 6-10).

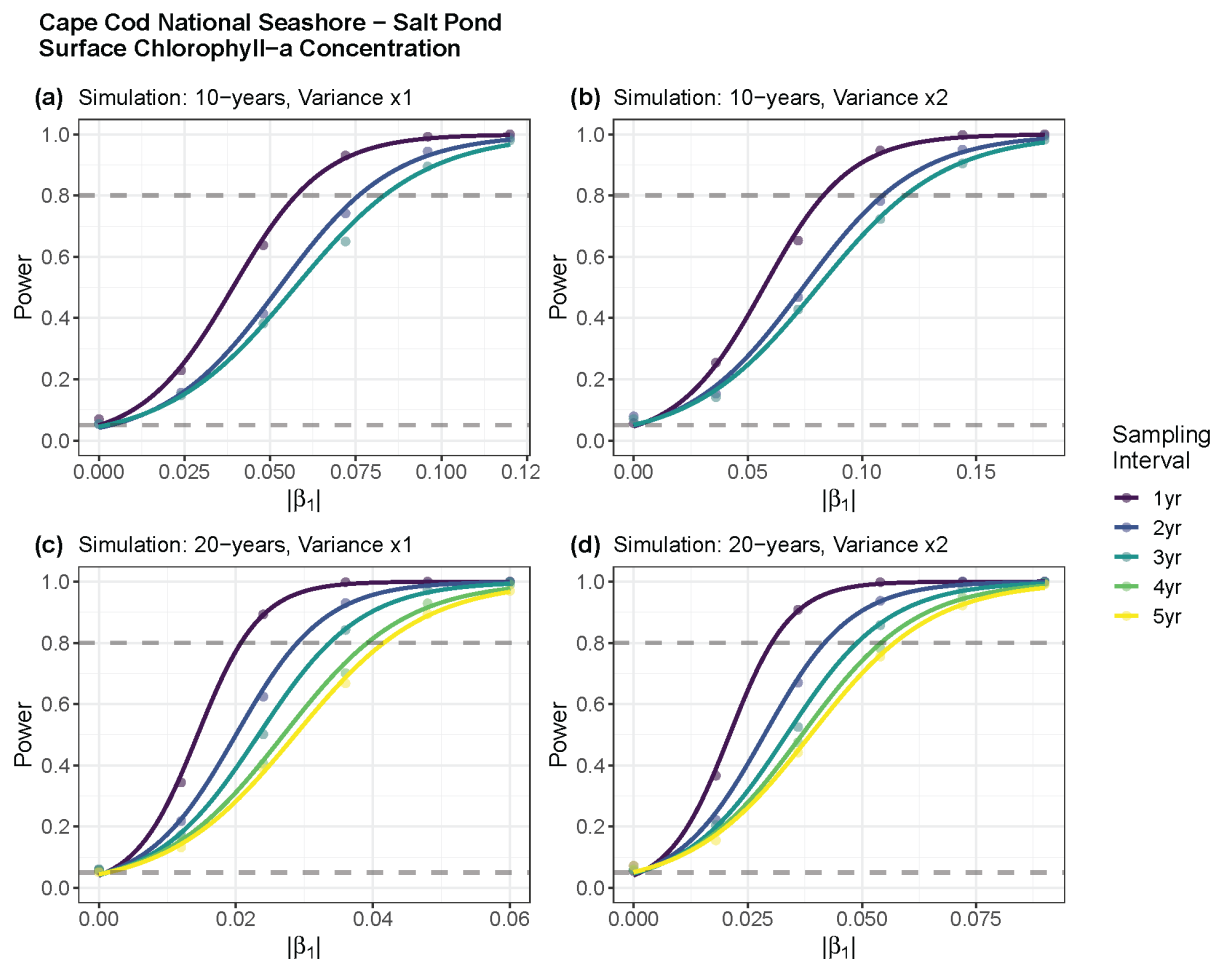


Figure 6-8. Estimated power to detect a linear trend in mean surface chlorophyll-*a* concentration within the Salt Pond stratum of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-8. Estimated power to detect a linear trend in mean surface chlorophyll-*a* concentration large enough to cross both quality thresholds within the Salt Pond stratum of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean surface chlorophyll-*a* concentration from the generalized additive model fit in Section 2.4.2 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	5	−0.084	0.97	0.87	0.81	NA	NA
10 yrs	×1	20	0.054	0.76	0.53	0.46	NA	NA
10 yrs	×2	5	−0.084	0.81	0.60	0.53	NA	NA
10 yrs	×2	20	0.054	0.46	0.31	0.28	NA	NA
20 yrs	×1	5	−0.042	1.00	0.97	0.93	0.85	0.81
20 yrs	×1	20	0.027	0.94	0.75	0.63	0.51	0.46
20 yrs	×2	5	−0.042	0.96	0.81	0.68	0.60	0.56
20 yrs	×2	20	0.027	0.72	0.46	0.36	0.32	0.29

2019 Estimate: 11.61 $\mu\text{g/L}$

**Cape Cod National Seashore – Salt Pond
Bottom Dissolved Oxygen Concentration**

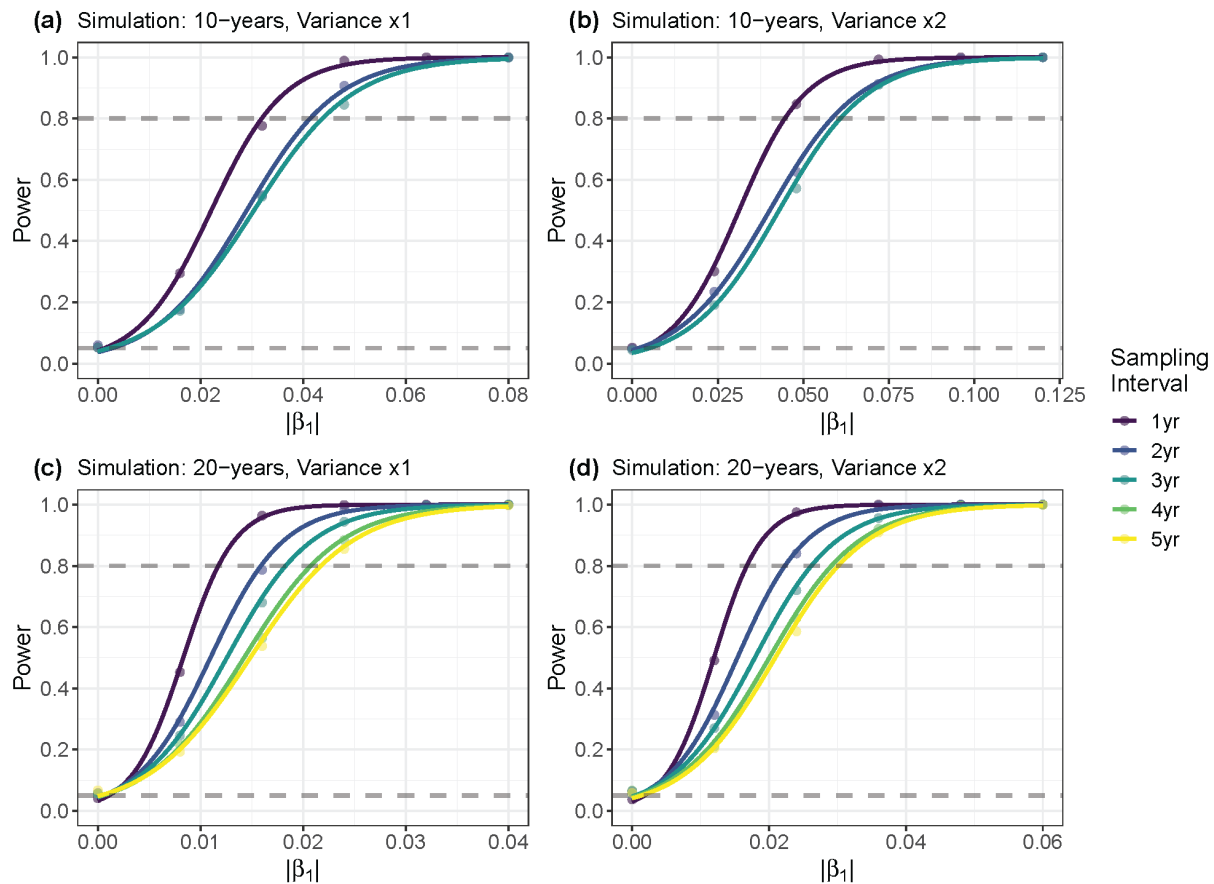


Figure 6-9. Estimated power to detect a linear trend in mean bottom dissolved oxygen concentration within the Salt Pond stratum of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-9. Estimated power to detect a linear trend in mean bottom dissolved oxygen concentration large enough to cross both quality thresholds within the Salt Pond stratum of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean bottom dissolved oxygen concentration from the generalized additive model fit in Section 2.4.2 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	2	−0.106	1.00	1.00	1.00	NA	NA
10 yrs	×1	5	−0.014	0.24	0.16	0.15	NA	NA
10 yrs	×2	2	−0.106	1.00	0.99	0.99	NA	NA
10 yrs	×2	5	−0.014	0.14	0.12	0.10	NA	NA
20 yrs	×1	2	−0.053	1.00	1.00	1.00	1.00	1.00
20 yrs	×1	5	−0.007	0.37	0.24	0.21	0.17	0.17
20 yrs	×2	2	−0.053	1.00	1.00	1.00	0.99	0.99
20 yrs	×2	5	−0.007	0.19	0.16	0.14	0.12	0.11

2019 Estimate: 5.75 mg/L

Cape Cod National Seashore – Salt Pond PAR Attenuation

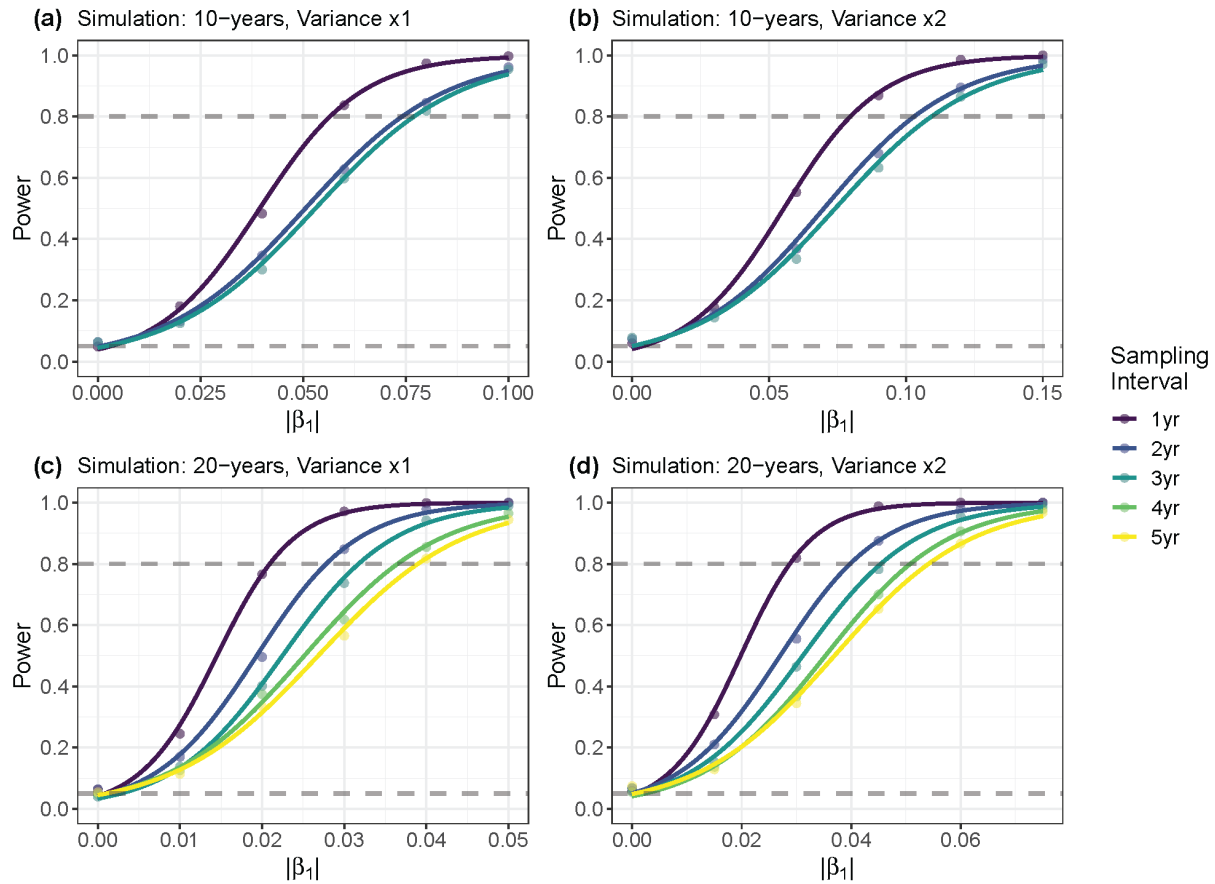


Figure 6-10. Estimated power to detect a linear trend in mean PAR attenuation within the Salt Pond stratum of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-10. Estimated power to detect a linear trend in mean PAR attenuation large enough to cross both quality thresholds within the Salt Pond stratum of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean PAR attenuation from the generalized additive model fit in Section 2.4.2 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	0.92	0.000	0.04	0.05	0.05	NA	NA
10 yrs	×1	1.61	0.056	0.79	0.58	0.55	NA	NA
10 yrs	×2	0.92	0.000	0.04	0.05	0.05	NA	NA
10 yrs	×2	1.61	0.056	0.51	0.36	0.33	NA	NA
20 yrs	×1	0.92	0.000	0.04	0.04	0.03	0.04	0.05
20 yrs	×1	1.61	0.028	0.95	0.81	0.70	0.59	0.54
20 yrs	×2	0.92	0.000	0.05	0.05	0.05	0.04	0.05
20 yrs	×2	1.61	0.028	0.78	0.53	0.43	0.34	0.33

2019 Estimate: 0.92 m⁻¹

6.2.4 All Strata

Estimated power for detecting a linear trend within all strata is summarized in both graphical and tabular format for surface chlorophyll-*a* concentration (Figure 6-11; Table 6-11), bottom dissolved oxygen concentration (Figure 6-12; Table 6-12), and PAR attenuation (Figure 6-13; Table 6-13).

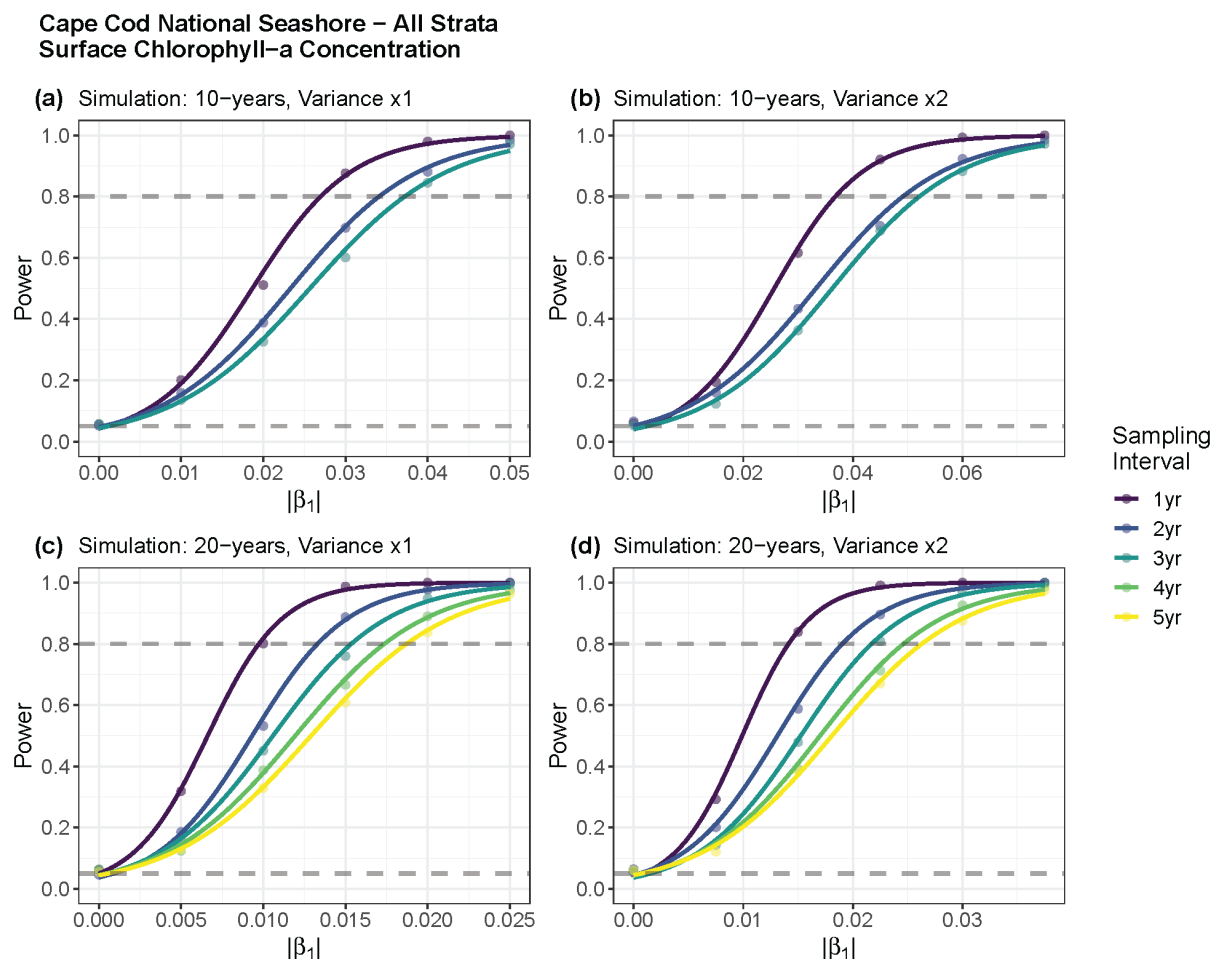


Figure 6-11. Estimated power to detect a linear trend in mean surface chlorophyll-*a* concentration within all strata of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-11. Estimated power to detect a linear trend in mean surface chlorophyll-*a* concentration large enough to cross both quality thresholds within all strata of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean surface chlorophyll-*a* concentration from the generalized additive model fit in Section 2.5.3 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	5	−0.032	0.90	0.74	0.67	NA	NA
10 yrs	×1	20	0.107	1.00	1.00	1.00	NA	NA
10 yrs	×2	5	−0.032	0.68	0.46	0.40	NA	NA
10 yrs	×2	20	0.107	1.00	1.00	1.00	NA	NA
20 yrs	×1	5	−0.016	0.98	0.90	0.82	0.73	0.66
20 yrs	×1	20	0.054	1.00	1.00	1.00	1.00	1.00
20 yrs	×2	5	−0.016	0.87	0.65	0.53	0.44	0.40
20 yrs	×2	20	0.054	1.00	1.00	1.00	1.00	1.00

2019 Estimate: 6.85 $\mu\text{g/L}$

**Cape Cod National Seashore – All Strata
Bottom Dissolved Oxygen Concentration**

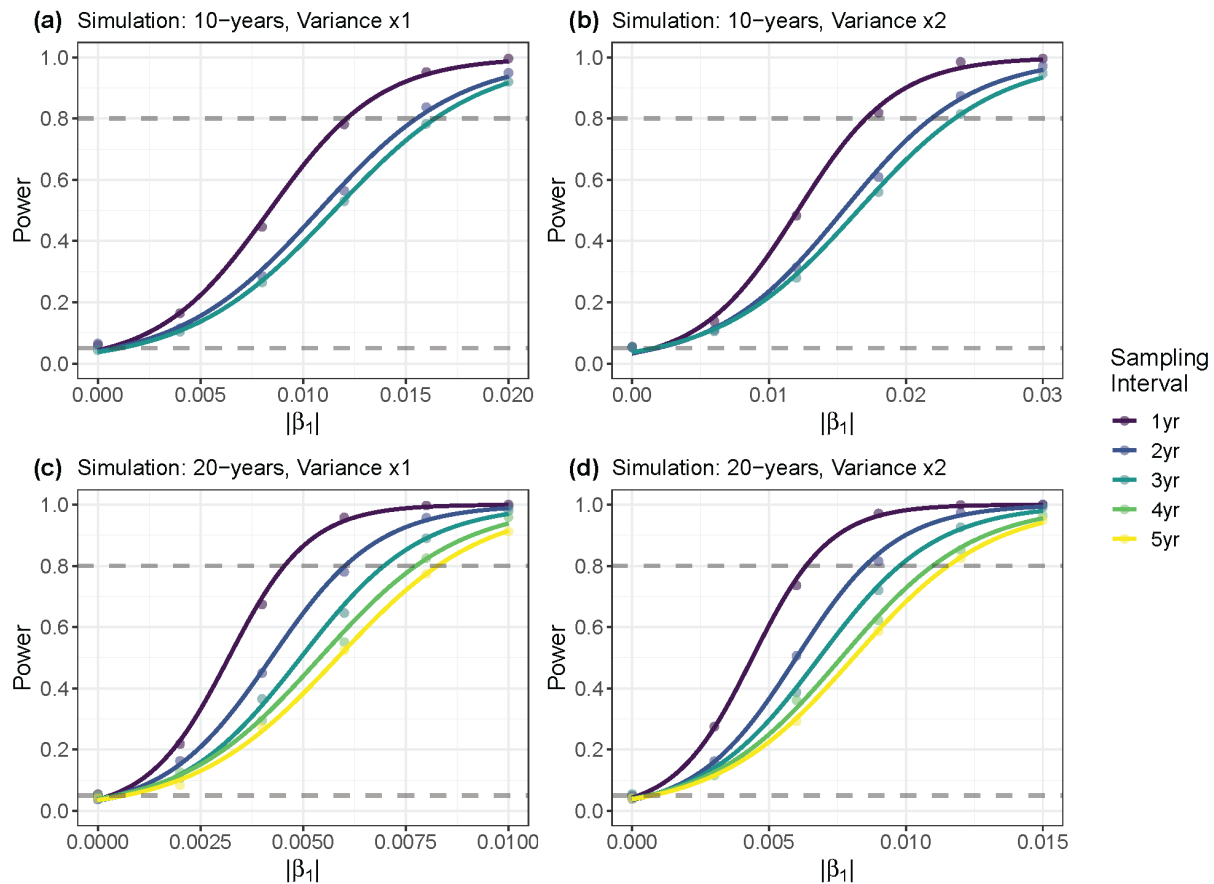


Figure 6-12. Estimated power to detect a linear trend in mean bottom dissolved oxygen concentration within all strata of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-12. Estimated power to detect a linear trend in mean bottom dissolved oxygen concentration large enough to cross both quality thresholds within all strata of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean bottom dissolved oxygen concentration from the generalized additive model fit in Section 2.5.3 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	2	−0.124	1.00	1.00	1.00	NA	NA
10 yrs	×1	5	−0.033	1.00	1.00	1.00	NA	NA
10 yrs	×2	2	−0.124	1.00	1.00	1.00	NA	NA
10 yrs	×2	5	−0.033	1.00	0.98	0.96	NA	NA
20 yrs	×1	2	−0.062	1.00	1.00	1.00	1.00	1.00
20 yrs	×1	5	−0.016	1.00	1.00	1.00	1.00	1.00
20 yrs	×2	2	−0.062	1.00	1.00	1.00	1.00	1.00
20 yrs	×2	5	−0.016	1.00	1.00	0.99	0.97	0.96

2019 Estimate: 6.94 mg/L

**Cape Cod National Seashore – All Strata
PAR Attenuation**

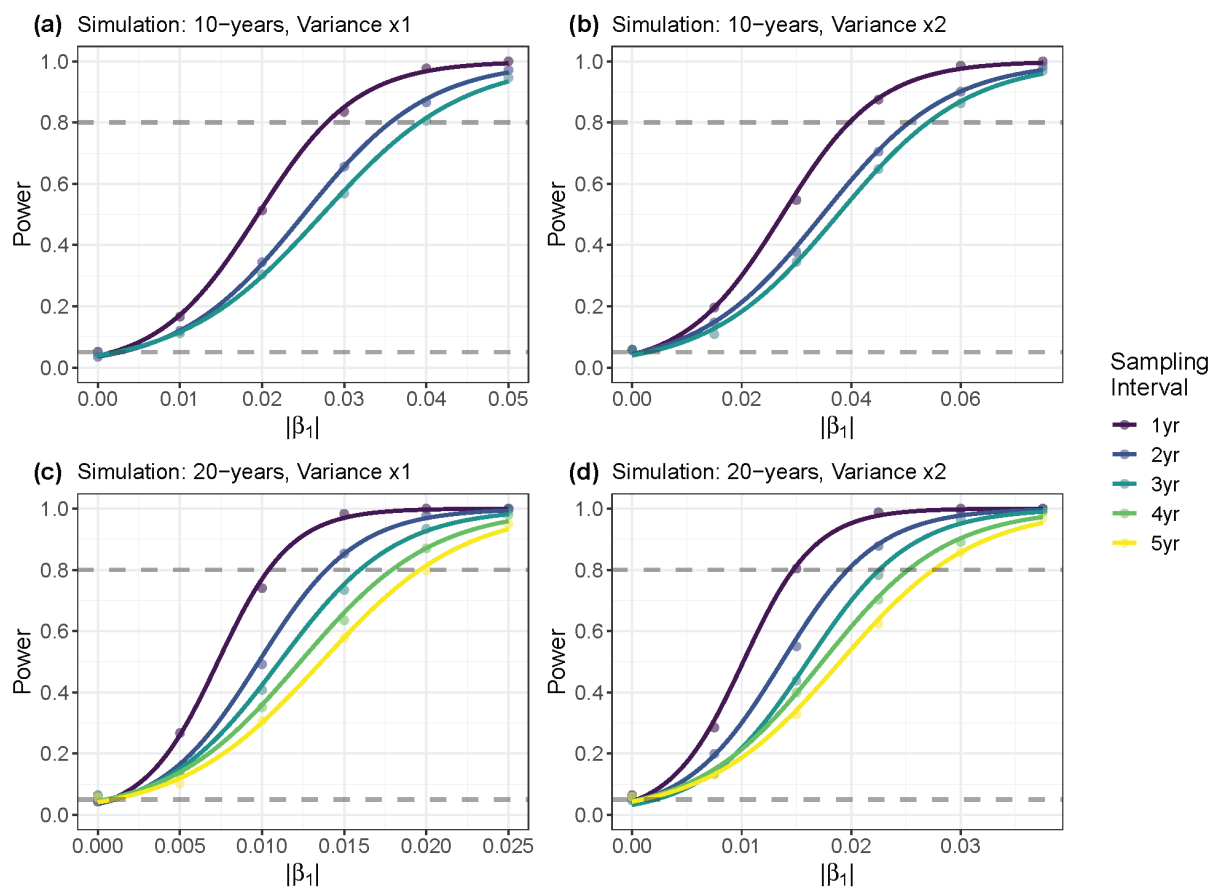


Figure 6-13. Estimated power to detect a linear trend in mean PAR attenuation within all strata of Cape Cod National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (d) correspond to simulations wherein the process model variance has been doubled. Note: the x-axis may not be consistent across simulations because the linear trend (β_1) within each simulation was varied so as to sufficiently characterize the estimated power curve.

Table 6-13. Estimated power to detect a linear trend in mean PAR attenuation large enough to cross both quality thresholds within all strata of Cape Cod National Seashore. The β_1 column value corresponds to the magnitude of trend that would result in the mean equaling the stated threshold value, assuming the stated duration and process variance multiplier. For reference, the most current estimate of mean PAR attenuation from the generalized additive model fit in Section 2.5.3 is provided in the table footnotes.

Period	Variance	Threshold	β_1	Power by Sampling Interval				
				1yr	2yr	3yr	4yr	5yr
10 yrs	×1	0.92	0.006	0.09	0.07	0.07	NA	NA
10 yrs	×1	1.61	0.062	1.00	0.99	0.98	NA	NA
10 yrs	×2	0.92	0.006	0.08	0.07	0.06	NA	NA
10 yrs	×2	1.61	0.062	0.98	0.91	0.88	NA	NA
20 yrs	×1	0.92	0.003	0.11	0.09	0.09	0.09	0.07
20 yrs	×1	1.61	0.031	1.00	1.00	1.00	0.99	0.98
20 yrs	×2	0.92	0.003	0.10	0.08	0.06	0.07	0.07
20 yrs	×2	1.61	0.031	1.00	0.98	0.96	0.91	0.87

2019 Estimate: 0.87 m⁻¹

6.3 Discussion

6.3.1 Key Question #1

Is the frequency of sampling appropriate or are we over or under sampling?

Power analyses were performed to assess the adequacy of the sampling interval for detecting estuary-wide trends in surface chlorophyll-*a* concentration, bottom dissolved oxygen concentration, and PAR attenuation.

Prior to determining whether decreasing the sampling frequency has merit, we must first consider the following: (1) what magnitude of change over a period of 10 or 20 years is ecologically meaningful and/or large enough to warrant corrective action by managers? and (2) how important are shorter-term fluctuations/trends in the decision-making by managers and/or for understanding the current state of the system? Regarding item (1), it is important to remember that although the β_1 values are relatively small when interpreting change on a yearly basis, these changes are compounded over time. For example, β_1 value of 0.02 corresponds to a yearly multiplicative increase of approximately 2% (i.e., $\exp(0.02) \approx 1.02$) in the mean of the measure. However, over a period of 10 and 20 years, this corresponds to an increase of approximately 22.1% and 49.2%, respectively. Regarding item (2), it is important to remember that the power to detect trend is estimated assuming a true mean trend that is both constant and linear through time for a period of 10 or 20 years (see Figure 6-1).

Accordingly, all power estimates provided in this report do not reflect the ability to detect shorter-term trends or fluctuations.

Based on discussions with NCBN scientists, a measure's change from one condition category to another is ecologically meaningful and could potentially warrant corrective action by park managers. Accordingly, the magnitude of trend (β_1) that would result in a measure changing to another condition category after a period of 10 or 20 years was computed using the established condition thresholds and the most recent year's estimate of the measure's mean. Power for each of these

scenarios was then estimated by identifying where the β_1 values intersect the power curve. Estimated power to detect changes from one threshold to another have been summarized in tabular format following each power curve figure.

In general, power to detect a change to the condition category will be impacted by:

1. How close the current estimate is to the next threshold - the closer it is, the lower the power to detect the change will be (all else equal).
2. The residual (i.e., process) variance - the larger it is, the lower the power to detect the change will be (all else equal).
3. The time frame over which changes need to be detected - the larger it is, the higher the power to detect the change will be (all else equal).

For example, consider the power summary for PAR attenuation (Table 6-13). From the table's footnotes, the estimated mean PAR attenuation in 2019 was 0.87m^{-1} . Looking across all simulation scenarios, we see that there is low power to detect changes from the good to fair category (i.e., 0.92m^{-1} threshold) and high power to detect changes from good to poor category (i.e., 1.62m^{-1} threshold), regardless of sampling interval. The recommended sampling interval in these simulation scenarios is dependent on which change is more relevant from a management perspective. If changes to the next condition category are of interest (i.e., good to fair), then the recommendation for each scenario would be to sample every year. Since power to detect such a change is estimated to be below 80%, from a practical standpoint we'd likely instead conclude that the sampling interval should not be decreased rather than recommend increasing the interval from every 2-years to every year.

Because measures are sampled concurrently, power to detect changes in all three measures should be considered. Applying the process in the preceding paragraph to each measure, we'd arrive at the following table of results:

Measure (current condition)	Time Period + Process Variance Multiplier			
	10 yrs + x1	10 yrs + x2	20 yrs + x1	20 yrs + x2
Surface chlorophyll-a (fair)	1 yr	1 yr	1 yr	1 yr
Bottom dissolved oxygen (good)	3 yr	3 yr	5 yr	5 yr
PAR attenuation (poor)	1 yr	1 yr	1 yr	1 yr
Recommendation*	1 yr	1 yr	1 yr	1 yr

*Based on minimum sampling interval within given scenario with at least 80% power.

Assuming that each measure is equally important to detect changes in, the recommendation under each scenario (i.e., column) would be to sample every year, or as frequently as resources permit. Again, these results correspond to detecting changes from the 'good' to 'fair' category for PAR attenuation and bottom dissolved oxygen, and from 'fair' to 'poor' in surface chlorophyll-a.

The ENE protocol is applicable on a network-wide scale and it is logistically undesirable to vary the sampling interval for each individual park. Given that the recommendation for at least one

park/estuary is to maintain or increase the sampling interval, the network-wide recommendation would be to not decrease the current sampling interval and, if resources permit, increase the sampling interval.

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Appendix A

Short Primer on Generalized Additive Models

First, consider the following multiple linear regression model (Equation 1):

$$\mathbf{y} = \beta_0 + \beta_1 \mathbf{x}_1 + \beta_2 \mathbf{x}_2 + \boldsymbol{\epsilon},$$

where $\mathbf{y}$ is a vector of response values, $\mathbf{x}_1$ and $\mathbf{x}_2$ are covariate vectors, β_0 , β_1 and β_2 are the model parameters to be estimated, and $\boldsymbol{\epsilon}$ is the vector of error terms such that $\boldsymbol{\epsilon} \sim N(0, \sigma^2)$. Generalized additive models (GAMs) extend the standard linear model by allowing the model to fit non-linear functions (smooshs) in place of the linear components $\beta_j \mathbf{x}_j$. The GAM version of Equation 1 is written mathematically as:

$$\mathbf{y} = \beta_0 + f_1(\mathbf{x}_1) + f_2(\mathbf{x}_2) + \boldsymbol{\epsilon},$$

where f_1 and f_2 are non-linear functions. The model is an additive model because a separate smooth is computed for each covariate and contributions are then added together. This is advantageous from an inferential perspective because it means we are able to examine the effect of each covariate on the response, while holding all of the other covariates fixed.

Each f_j is represented parametrically within the model as a sum of K basis functions⁹:

$$f_j(\mathbf{x}_j) = \sum_{k=1}^K \beta_{j,k} b_{j,k}(\mathbf{x}_j),$$

where $b_{j,k}$ is the k th basis function and $\beta_{j,k}$ are estimated basis coefficients. Although there are a multitude of basis functions that can be used, smoothing splines are the most common. For reference, the default smoothing spline in the `mgcv` package is the thin plate regression spline (TPRS; (Wood 2003)). The value of K is referred to as the rank of the basis expansion and represents an upper limit on the expected complexity of the true underlying trend in the data. Furthermore, the upper limit is constrained to be less than or equal to the number of data points. In practice, the actual value of K specified is not critical; instead it must simply be large enough to provide the smooth enough flexibility to approximate the true underlying function f . The `mgcv::gam.check()` function provides a test that can be used to determine whether the rank should be increased (at the expense of additional computation time).

In order to prevent overfitting to the data, the degree of wiggleness of a smooth is controlled through the use of a wiggleness penalty and smoothing parameter. The smoothness parameter (denoted by λ) controls the extent to which the penalty contributes to the likelihood function. Simpson (2018) recommends that λ be estimated via restricted maximum likelihood (REML) for best results. Since

⁹ See Hefley et al. (2017) for an introduction to basis functions with applications to ecology.

each smooth is being penalized/constrained, the complexity of the smooth is measured using effective degrees of freedom (edf). The edf can be a non-integer value and higher values indicate a more wiggly smooth.

To provide a more tangible example of a GAM and its associated basis expansion, we will simulate some data and fit a GAM to it. Simulated data are generated using the nonlinear model (Equation 2):

$$y_i = \exp(x_i \cdot \cos(4\pi \cdot x_i)) + \epsilon_i,$$

where $x_i \sim \text{Uniform}(0, 0.8)$, $\epsilon_i \sim \text{Normal}(0, 0.2)$, and $i = 1, \dots, 400$ (see Figure A-1)

Using the `mgcv` package, we can fit a GAM with a rank 6 TPRS basis and REML smoothness selection with the following code:

```
> gam(y ~ s(x, k = 6, bs = "tp"), family = "gaussian", method = "REML")
```

The fitted smooth $\hat{f}(x)$ is plotted in black in panel (b) of Figure A-1. We can see that it does a pretty good job of approximating the true underlying function $f(x)$ (red curve). Additionally, Figure A-1 (c) depicts the six basis functions that are added together to form $\hat{f}(x)$.

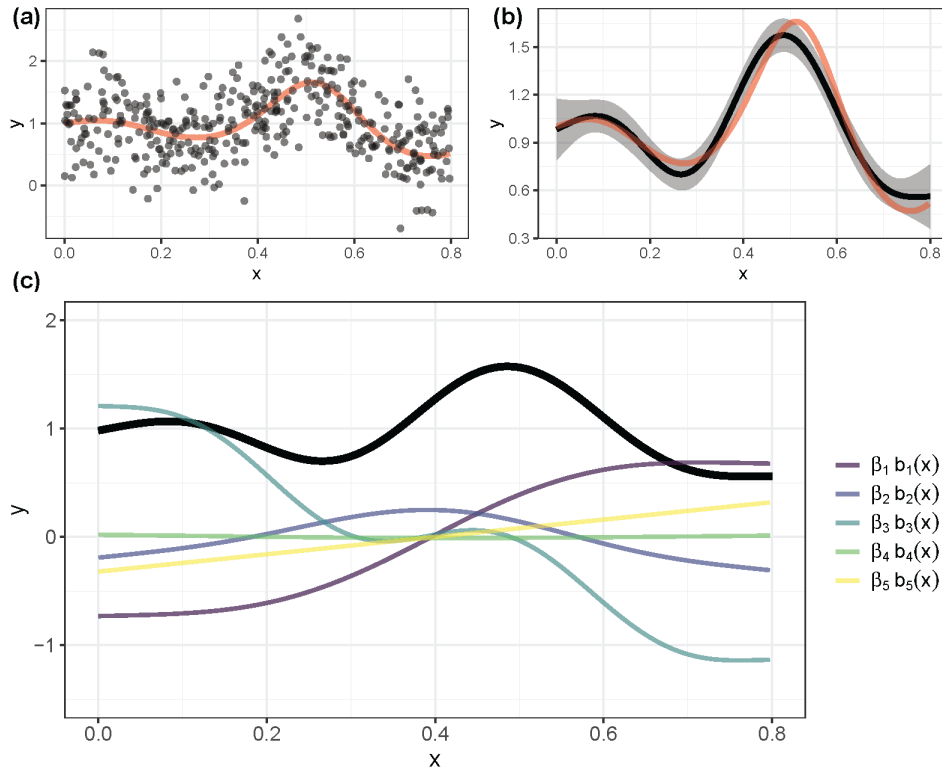


Figure A-1. (a) Data simulated from the nonlinear model given by Equation 2 and depicted in red. (b) Fitted generalized additive model smooth in black with corresponding 95% pointwise confidence interval in gray. True underlying curve provided in red for reference. (c) The six thin plate regression splines basis functions that make up the rank 6 basis expansion of $\hat{f}(x)$ (black curve).

MCT Family-Wise Error Rate

The type I error rate (alpha level; α) is the probability of rejecting the null hypothesis, given that it is true. For a single test, this is sometimes referred to as the experiment-wise or nominal error rate. In the case of a multiple comparison test, we are performing many tests simultaneously and collectively refer to them as a family of tests. Performing many tests, however, increases our chances of making a type I error. Specifically, the probability of making a type I error when performing m independent tests equals:

$$1 - (1 - \alpha)^m,$$

which we denote as the family-wise error rate. Based on this result, it is clear that as the family-wise error rate is much larger (inflated) compared to the nominal error rate. For example, consider CACO which has 11 years of monitoring data and therefore has 55 potential pairwise comparisons.

Assuming a nominal error rate of 0.05, we would expect at least one type I error to be committed for the set of 55 tests approximately 94% of the time. To assure that the family-wise error rate is at most the prescribed alpha level, several methods have been developed to adjust (inflate) the p-values from each individual test.