



## **Estuarine Nutrient Enrichment Monitoring: Data Summary and Trend Analysis for Assateague Island National Seashore**

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## **Acronyms and Abbreviations**

|      |                                       |
|------|---------------------------------------|
| ASIS | Assateague Island 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 Assateague Island National Seashore to date (Table 1-1).

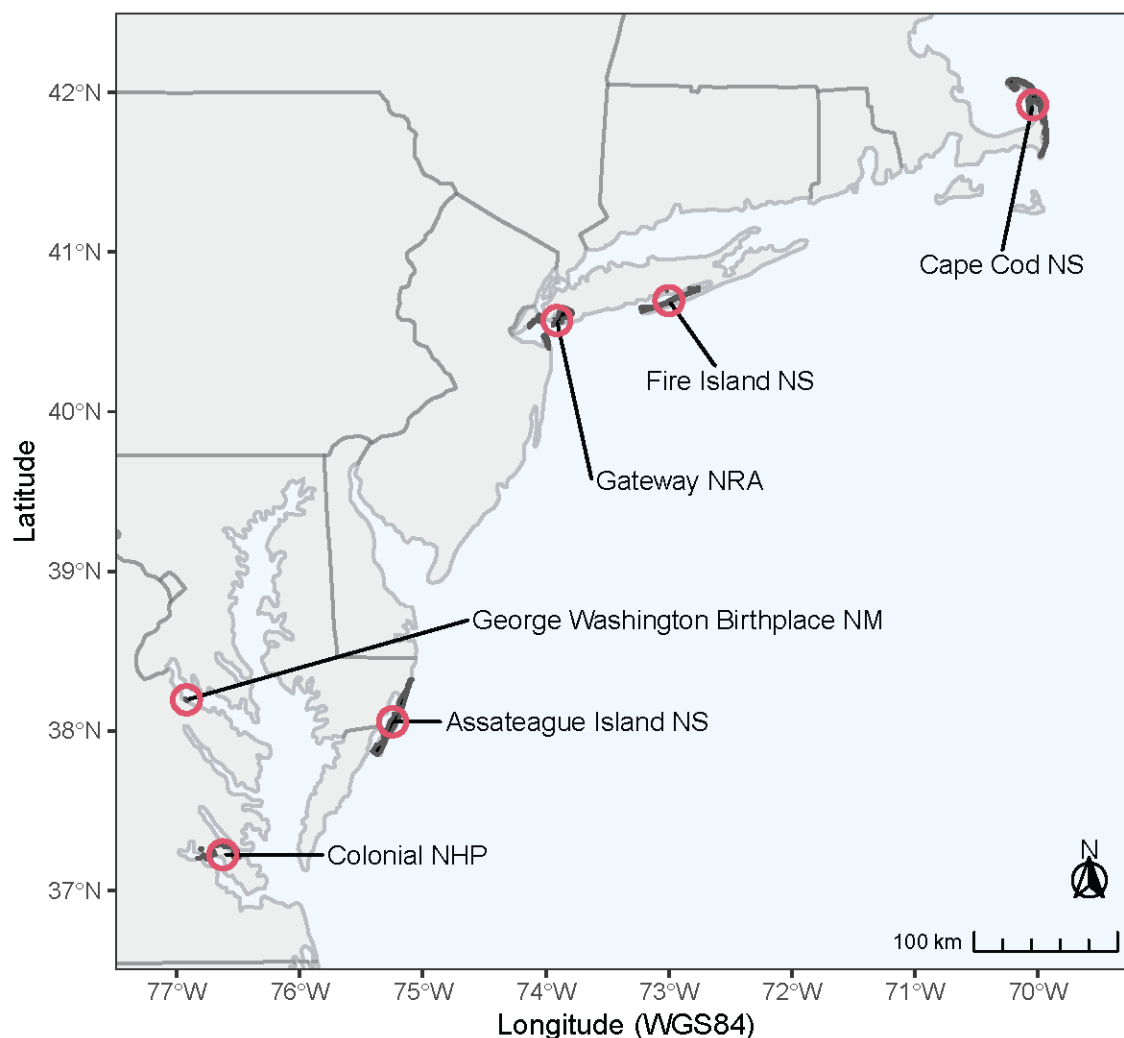


**Figure 1-1.** Locations of Northeast Coastal and Barrier Inventory & Monitoring (I&M) Network parks monitored for estuarine nutrient enrichment.

**Table 1-1.** Sampling years for water quality and seagrass monitoring within Assateague Island National Seashore.

| <b>Year</b> | <b>Water Quality</b> | <b>Seagrass</b> |
|-------------|----------------------|-----------------|
| 2003        | not sampled          | not sampled     |
| 2004        | not sampled          | not sampled     |
| 2005        | sampled              | not sampled     |
| 2006        | sampled              | not sampled     |
| 2007        | not sampled          | not sampled     |
| 2008        | sampled              | not sampled     |
| 2009        | not sampled          | sampled         |
| 2010        | sampled              | sampled         |
| 2011        | not sampled          | sampled         |
| 2012        | sampled              | sampled         |
| 2013        | not sampled          | sampled         |
| 2014        | sampled              | sampled         |
| 2015        | not sampled          | sampled         |
| 2016        | sampled              | sampled         |
| 2017        | not sampled          | sampled         |
| 2018        | sampled              | sampled         |
| 2019        | not sampled          | sampled         |
| 2020        | sampled              | not 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  $i^{\text{th}}$  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 (Shields, Parrish, and Moore 2019) and blue crab (Bauer and Miller 2010a, 2010b) 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  $i^{\text{th}}$  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 $\mu\text{g/L}$     | 5-20 $\mu\text{g/L}$        | > 20 $\mu\text{g/L}$    |
| Dissolved oxygen (near bottom)       | > 5 mg/L                | 2-5 mg/L                    | < 2 mg/L                |
| PAR attenuation $K_d$ (SAV standard) | < 0.92 $\text{m}^{-1}$  | < 0.92-1.61 $\text{m}^{-1}$ | > 1.61 $\text{m}^{-1}$  |
| Water temperature (near surface)     | < 28 $^{\circ}\text{C}$ | 28-33 $^{\circ}\text{C}$    | > 33 $^{\circ}\text{C}$ |

\*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  $p$ -values<sup>1</sup>.

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 of PAR attenuation between years 2006 and 2014 (Figure 2-3). 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 2-3 is provided in Table 2-8. For this comparison we would state: it is estimated that the median PAR attenuation in ASIS during 2006 is  $\exp(0.473) \approx 1.60$  times the median during 2014 (95% CI equal to  $(1.15, 2.24)^2$ ). Stated another way: with 95% confidence, it is estimated that the median PAR attenuation in ASIS during 2006 is between 1.15 and 2.24 times the median in 2014.

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

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<sup>1</sup> See Appendix A for additional discussion of MCT family-wise error rate and  $p$ -value adjustments.

<sup>2</sup> The confidence intervals given in Table 2-8 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 mean<sup>3</sup>). 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 specification<sup>4</sup>) 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).

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<sup>3</sup> 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  $(2 \cdot 5 \cdot 7)^{1/3} = 70^{1/3} \approx 4.12$ .

<sup>4</sup> 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 monotonically<sup>5</sup> 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 both PAR attenuation ( $Z_{MK} = -1.72$ ;  $p$ -value = 0.086) and surface turbidity ( $Z_{MK} = -2.03$ ;  $p$ -value = 0.042).

## **2.2 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:

### **2.2.1 Chlorophyll-*a* (near surface)**

Area-weighted average near surface chlorophyll-*a* ranged from 9.48 to 25.43  $\mu\text{g/L}$  and was fair (i.e., 5-20  $\mu\text{g/L}$ ) for a majority of the index periods. Poor area-weighted average condition ( $> 20 \mu\text{g/L}$ ) was observed in both 2010 and 2012. The proportion of the estuary categorized as fair condition ranged from 33 to 89%. Approximately 50% of the estuary was in poor condition during 2010 and 2016. The maximum observed proportion of area in good condition (i.e.,  $< 5 \mu\text{g/L}$ ) during the index periods was 15.3%.

### **2.2.2 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 6.01 to 6.96  $\text{mg/L}$ . The majority of area ( $> 70\%$ ) within the estuary was characterized as in good condition. For each index period, no area was characterized as having poor dissolved oxygen condition (i.e.,  $< 2 \text{ mg/L}$ ).

### **2.2.3 PAR Attenuation $K_d$ (SAV standard)**

Area-weighted average PAR attenuation was poor for every index period (i.e.,  $K_d > 1.61 \text{ m}^{-1}$ ) and ranged from 1.77 to 2.85  $\text{m}^{-1}$  (Table 2-2). The majority of the estuary was characterized as being poor, with the exception of 2014 when only 47% was poor and 29% was good (Table 2-3).

### **2.2.4 pH**

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

### **2.2.5 Salinity**

Area-weighted average salinity ranged from 27.45 (surface depth in 2005) to 32.27 psu (bottom depth in 2012).

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<sup>5</sup> 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.

### **2.2.6 Temperature (near surface)**

Area-weighted average near surface water temperature ranged from 25.66 to 30.08 °C, and exceeded 28 °C during five index periods. Excluding 2012 and 2014 (which were the coolest), temperatures in the 28-33 °C range were observed in at least 40% of the estuary (highest years were 2010 and 2020 with 78% and 88%, respectively).

### **2.2.7 Turbidity**

Area-weighted average turbidity ranged from 9.24 (surface in 2020) to 31.89 NTU (bottom depth in 2010).

**Table 2-2.** Area-weighted average water quality condition at Assateague Island National Seashore during the index periods of 2005-2020.

| Measure                                     | Depth        | Sampling year |        |       |        |        |        |       |       |        |
|---------------------------------------------|--------------|---------------|--------|-------|--------|--------|--------|-------|-------|--------|
|                                             |              | 2005          | 2006   | 2008  | 2010   | 2012   | 2014   | 2016  | 2018  | 2020   |
| Chlorophyll <i>a</i> (µg/L)                 | Surface      | 16.11         | 17.16  | 13.91 | 21.40  | 25.43  | 9.48   | 19.64 | 13.04 | 12.65  |
| Dissolved oxygen (% saturation)             | Surface      | 102.57        | 106.42 | 96.43 | 104.02 | 100.21 | 101.05 | 99.70 | 93.60 | 102.48 |
| Dissolved oxygen (% saturation)             | Mid-Depth    | 100.06        | 100.08 | 93.43 | 93.47  | 96.34  | 98.27  | 95.4  | 90.43 | 98.84  |
| Dissolved oxygen (% saturation)             | Bottom       | 95.45         | 91.47  | 90.79 | 100.44 | 94.65  | 101.40 | 96.00 | 89.5  | 97.08  |
| Dissolved oxygen (mg/L)                     | Surface      | 6.91          | 6.94   | 6.43  | 6.78   | 6.70   | 6.93   | 6.57  | 6.26  | 6.50   |
| Dissolved oxygen (mg/L)                     | Mid-Depth    | 6.76          | 6.61   | 6.23  | 6.16   | 6.44   | 6.76   | 6.28  | 6.06  | 6.30   |
| Dissolved oxygen (mg/L)                     | Bottom       | 6.45          | 6.08   | 6.07  | 6.54   | 6.35   | 6.96   | 6.34  | 6.01  | 6.18   |
| PAR attenuation ( $K_d$ (m <sup>-1</sup> )) | Water Column | 2.73          | 2.85   | 2.21  | 2.84   | 2.34   | 1.77   | 2.35  | 2.54  | 1.90   |
| pH                                          | Surface      | NA            | NA     | NA    | NA     | NA     | NA     | NA    | 7.88  | 7.88   |
| pH                                          | Mid-Depth    | NA            | NA     | NA    | NA     | NA     | NA     | NA    | 7.87  | 7.88   |
| pH                                          | Bottom       | NA            | NA     | NA    | NA     | NA     | NA     | NA    | 7.86  | 7.86   |
| Salinity (psu)                              | Surface      | 27.45         | 29.93  | 31.50 | 30.33  | 32.19  | 30.78  | 28.99 | 28.33 | 31.56  |
| Salinity (psu)                              | Mid-Depth    | 27.5          | 29.90  | 31.67 | 29.51  | 32.11  | 30.77  | 29.15 | 27.94 | 31.53  |
| Salinity (psu)                              | Bottom       | 27.61         | 29.95  | 31.79 | 30.53  | 32.27  | 30.84  | 29.02 | 28.43 | 31.61  |
| Temperature (°C)                            | Surface      | 27.89         | 28.96  | 26.99 | 28.76  | 26.70  | 25.66  | 28.69 | 28.04 | 30.08  |
| Temperature (°C)                            | Mid-Depth    | 27.76         | 28.32  | 26.92 | 28.41  | 26.76  | 25.50  | 28.71 | 28.05 | 29.81  |
| Temperature (°C)                            | Bottom       | 27.63         | 28.05  | 26.69 | 28.49  | 26.56  | 25.53  | 28.56 | 27.82 | 29.8   |
| Turbidity (NTU)                             | Surface      | 19.99         | 15.80  | 13.38 | 18.38  | 12.89  | 9.79   | 10.47 | 11.68 | 9.24   |
| Turbidity (NTU)                             | Mid-Depth    | 18.62         | 17.04  | 17.09 | 25.14  | 11.32  | 9.59   | 10.64 | 12.05 | 9.30   |
| Turbidity (NTU)                             | Bottom       | 21.53         | 20.94  | 18.26 | 31.89  | 17.03  | 12.79  | 14.78 | 15.91 | 12.16  |

**Table 2-3.** Proportion of monitored estuarine resources falling into each quality category at Assateague Island National Seashore during the index periods of 2005-2020.

| Measure                                      | Condition | Sampling Year |      |      |      |      |      |      |      |      |
|----------------------------------------------|-----------|---------------|------|------|------|------|------|------|------|------|
|                                              |           | 2005          | 2006 | 2008 | 2010 | 2012 | 2014 | 2016 | 2018 | 2020 |
| Bottom dissolved oxygen (mg/L)               | Good      | 89.3          | 70.4 | 89.3 | 82.0 | 93.6 | 98.7 | 98.5 | 92.3 | 89.4 |
| Bottom dissolved oxygen (mg/L)               | Fair      | 10.7          | 29.6 | 10.7 | 18.0 | 6.4  | 1.3  | 1.5  | 7.7  | 10.6 |
| Bottom dissolved oxygen (mg/L)               | Poor      | 0.0           | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| Bottom dissolved oxygen (mg/L)               | Missing   | 0.0           | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| Chlorophyll a ( $\mu\text{g/L}$ )            | Good      | 0.8           | 8.2  | 7.9  | 15.3 | 0.0  | 8.7  | 0.0  | 8.9  | 15.2 |
| Chlorophyll a ( $\mu\text{g/L}$ )            | Fair      | 64.8          | 59.6 | 74.6 | 33.6 | 59.3 | 89.6 | 50.8 | 74.1 | 65.5 |
| Chlorophyll a ( $\mu\text{g/L}$ )            | Poor      | 34.4          | 32.2 | 17.5 | 51.0 | 40.7 | 1.7  | 49.2 | 16.9 | 19.3 |
| 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  |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | Good      | 0.0           | 0.0  | 1.9  | 15.3 | 0.0  | 29.2 | 0.0  | 0.0  | 12.1 |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | Fair      | 4.7           | 10.0 | 32.0 | 13.5 | 12.5 | 23.8 | 20.8 | 13.9 | 16.7 |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | Poor      | 95.3          | 80.1 | 63.2 | 71.2 | 87.5 | 47.0 | 79.2 | 86.1 | 71.1 |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | Missing   | 0.0           | 10.0 | 2.9  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| Surface Temperature ( $^{\circ}\text{C}$ )   | < 28      | 61.4          | 37.4 | 63.0 | 22.1 | 84.0 | 98.8 | 30.3 | 49.1 | 12.5 |
| Surface Temperature ( $^{\circ}\text{C}$ )   | 28-33     | 38.6          | 62.6 | 37.0 | 77.9 | 16.0 | 1.2  | 69.7 | 50.9 | 87.5 |
| Surface Temperature ( $^{\circ}\text{C}$ )   | > 33      | 0.0           | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  | 0.0  |
| Surface Temperature ( $^{\circ}\text{C}$ )   | Missing   | 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 Assateague Island National Seashore.

| <b>Year</b> | <b>Start</b> | <b>End</b> |
|-------------|--------------|------------|
| 2005        | 2005-08-01   | 2005-08-03 |
| 2006        | 2006-07-25   | 2006-08-09 |
| 2008        | 2008-07-23   | 2008-08-14 |
| 2010        | 2010-07-07   | 2010-07-30 |
| 2012        | 2012-08-08   | 2012-08-30 |
| 2014        | 2014-08-04   | 2014-08-28 |
| 2016        | 2016-07-12   | 2016-08-03 |
| 2018        | 2018-08-07   | 2018-08-27 |
| 2020        | 2020-07-07   | 2020-07-28 |

## **2.3 GLMM Results**

For each measure, 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 2-5). Notable observations from the multiple comparison tests (MCT) for each measure are as follows:

### **2.3.1 Chlorophyll-*a* (near surface)**

The MCT results indicate that mean log near surface chlorophyll-*a* concentrations in 2010 and 2012 were statistically different from most other index periods (Figure 2-1; Table 2-6).

### **2.3.2 Dissolved Oxygen (near bottom)**

The MCT results indicate that mean log bottom dissolved oxygen in 2014 is statistically different compared to 2010 and 2018 (Figure 2-2; Table 2-7). There is no strong evidence of statistical differences between the other index period pairs.

### **2.3.4 PAR Attenuation $K_d$ (SAV standard)**

The MCT results indicate that mean log PAR attenuation in 2014 is statistically different compared to most other years (Figure 2-3; Table 2-8). There is no strong evidence of statistical differences between the other index period pairs.

### **2.3.5 Salinity (near surface)**

The MCT results indicate that mean log surface salinity in 2012 is statistically different compared to 2005, 2010, 2016 and 2018 (Figure 2-4; Table 2-9). Additionally, 2020 is statistically different compared to 2005, 2016, and 2018.

### **2.3.6 Temperature (near surface)**

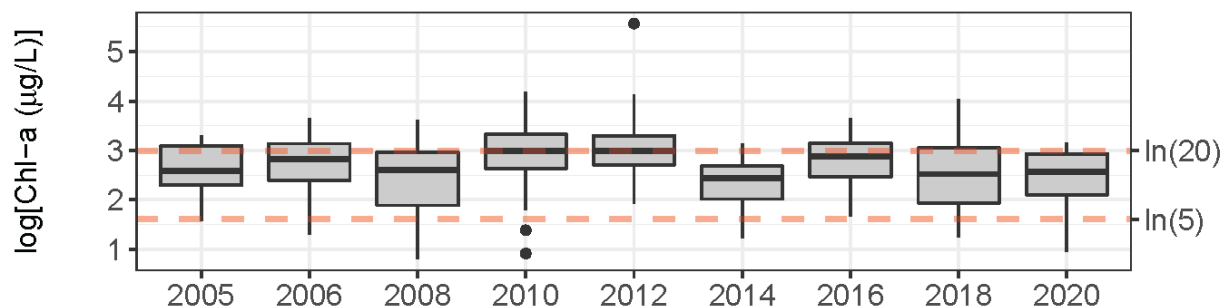
The MCT results indicate that mean log surface water temperature in 2008 - 2014 are statistically different from most other index periods (Figure 2-5; Table 2-10). The box plots indicate that there is more year-to-year variability than within-year variability compared to the other measures.

### 2.3.7 Turbidity (near surface)

The MCT results indicate that mean log surface turbidity in 2014 is statistically different compared to 2005, 2006, 2010, and 2012 (Figure 2-6; Table 2-11), and is estimated to be lower in each instance. There is no strong evidence of statistical differences between the other index period pairs.

**Table 2-5.** Analysis of variance for the general linear mixed model fit to log-transformed water quality measurements collected within Assateague Island National Seashore. Each respective *F*-statistic and *p*-value corresponds to the test of the hypotheses:  $H_0$ : the mean of the log-transformed 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(s)     | D.F.     | F-value | p-value | MCT Results |
|---------------------------------------------|--------------|----------|---------|---------|-------------|
| Chlorophyll <i>a</i> (µg/L)                 | Surface      | (8, 214) | 6.29    | < 0.005 | Figure 2-1  |
| Dissolved oxygen (mg/L)                     | Bottom       | (8, 214) | 2.18    | 0.03    | Figure 2-2  |
| PAR attenuation ( $K_d$ (m <sup>-1</sup> )) | Water Column | (8, 209) | 3.41    | < 0.005 | Figure 2-3  |
| Salinity (psu)                              | Surface      | (8, 214) | 5.14    | < 0.005 | Figure 2-4  |
| Temperature (°C)                            | Surface      | (8, 214) | 13.64   | < 0.005 | Figure 2-5  |
| Turbidity (NTU)                             | Surface      | (8, 214) | 4.01    | < 0.005 | Figure 2-6  |



|      |        |        |        |        |       |        |       |       |       |
|------|--------|--------|--------|--------|-------|--------|-------|-------|-------|
| 2020 | 0.103  | 0.227  | 0.036  | 0.456  | 0.642 | -0.105 | 0.349 | 0.091 | 2.450 |
| 2018 | 0.012  | 0.136  | -0.055 | 0.365  | 0.551 | -0.196 | 0.258 | 2.540 | 0.999 |
| 2016 | -0.246 | -0.122 | -0.313 | 0.107  | 0.294 | -0.454 | 2.800 | 0.605 | 0.198 |
| 2014 | 0.208  | 0.332  | 0.141  | 0.561  | 0.747 | 2.350  | 0.024 | 0.874 | 0.997 |
| 2012 | -0.539 | -0.415 | -0.606 | -0.186 | 3.100 | 0.000  | 0.423 | 0.002 | 0.000 |
| 2010 | -0.353 | -0.229 | -0.420 | 2.910  | 0.902 | 0.002  | 0.997 | 0.151 | 0.024 |
| 2008 | 0.067  | 0.191  | 2.490  | 0.052  | 0.000 | 0.981  | 0.332 | 1.000 | 1.000 |
| 2006 | -0.124 | 2.680  | 0.888  | 0.747  | 0.058 | 0.254  | 0.993 | 0.984 | 0.753 |
| 2005 | 2.560  | 0.999  | 1.000  | 0.586  | 0.079 | 0.966  | 0.914 | 1.000 | 1.000 |
|      | 2005   | 2006   | 2008   | 2010   | 2012  | 2014   | 2016  | 2018  | 2020  |



**Figure 2-1.** (Top): Boxplot of log surface chlorophyll-*a* concentration by year within Assateague Island National Seashore. Estuarine quality category thresholds (Table 2-1) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface chlorophyll-*a* concentration within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus 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 2-6.

**Table 2-6.** Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface chlorophyll-*a* concentration within Assateague Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

| Contrast    | Estimate | SE    | $t_{214}$ | <i>p</i> -value | 95% CI           |
|-------------|----------|-------|-----------|-----------------|------------------|
| 2005 - 2006 | -0.124   | 0.182 | -0.681    | 0.999           | (-0.694, 0.445)  |
| 2005 - 2008 | 0.067    | 0.182 | 0.369     | 1.000           | (-0.502, 0.637)  |
| 2005 - 2010 | -0.353   | 0.182 | -1.935    | 0.586           | (-0.922, 0.217)  |
| 2005 - 2012 | -0.539   | 0.182 | -2.957    | 0.080           | (-1.109, 0.030)  |
| 2005 - 2014 | 0.208    | 0.182 | 1.141     | 0.966           | (-0.361, 0.778)  |
| 2005 - 2016 | -0.246   | 0.182 | -1.347    | 0.914           | (-0.815, 0.324)  |
| 2005 - 2018 | 0.012    | 0.182 | 0.066     | 1.000           | (-0.557, 0.582)  |
| 2005 - 2020 | 0.103    | 0.182 | 0.566     | 1.000           | (-0.466, 0.673)  |
| 2006 - 2008 | 0.191    | 0.135 | 1.417     | 0.888           | (-0.231, 0.613)  |
| 2006 - 2010 | -0.229   | 0.135 | -1.692    | 0.747           | (-0.651, 0.193)  |
| 2006 - 2012 | -0.415   | 0.135 | -3.072    | 0.058           | (-0.837, 0.007)  |
| 2006 - 2014 | 0.332    | 0.135 | 2.459     | 0.254           | (-0.090, 0.754)  |
| 2006 - 2016 | -0.121   | 0.135 | -0.899    | 0.993           | (-0.543, 0.301)  |
| 2006 - 2018 | 0.136    | 0.135 | 1.008     | 0.984           | (-0.286, 0.558)  |
| 2006 - 2020 | 0.227    | 0.135 | 1.683     | 0.753           | (-0.195, 0.649)  |
| 2008 - 2010 | -0.420   | 0.135 | -3.109    | 0.053           | (-0.842, 0.002)  |
| 2008 - 2012 | -0.606   | 0.135 | -4.489    | 0.000           | (-1.028, -0.184) |
| 2008 - 2014 | 0.141    | 0.135 | 1.043     | 0.981           | (-0.281, 0.563)  |
| 2008 - 2016 | -0.313   | 0.135 | -2.316    | 0.333           | (-0.735, 0.109)  |
| 2008 - 2018 | -0.055   | 0.135 | -0.408    | 1.000           | (-0.477, 0.367)  |
| 2008 - 2020 | 0.036    | 0.135 | 0.266     | 1.000           | (-0.386, 0.458)  |
| 2010 - 2012 | -0.186   | 0.135 | -1.380    | 0.902           | (-0.608, 0.236)  |
| 2010 - 2014 | 0.561    | 0.135 | 4.151     | 0.002           | (0.139, 0.983)   |
| 2010 - 2016 | 0.107    | 0.135 | 0.793     | 0.997           | (-0.315, 0.529)  |
| 2010 - 2018 | 0.365    | 0.135 | 2.700     | 0.151           | (-0.057, 0.787)  |
| 2010 - 2020 | 0.456    | 0.135 | 3.375     | 0.024           | (0.034, 0.878)   |
| 2012 - 2014 | 0.747    | 0.135 | 5.531     | 0.000           | (0.325, 1.169)   |
| 2012 - 2016 | 0.293    | 0.135 | 2.173     | 0.422           | (-0.128, 0.715)  |
| 2012 - 2018 | 0.551    | 0.135 | 4.080     | 0.002           | (0.129, 0.973)   |
| 2012 - 2020 | 0.642    | 0.135 | 4.755     | 0.000           | (0.220, 1.064)   |
| 2014 - 2016 | -0.454   | 0.135 | -3.358    | 0.025           | (-0.876, -0.032) |
| 2014 - 2018 | -0.196   | 0.135 | -1.451    | 0.874           | (-0.618, 0.226)  |
| 2014 - 2020 | -0.105   | 0.135 | -0.776    | 0.997           | (-0.527, 0.317)  |
| 2016 - 2018 | 0.258    | 0.135 | 1.907     | 0.605           | (-0.164, 0.680)  |
| 2016 - 2020 | 0.349    | 0.135 | 2.582     | 0.197           | (-0.073, 0.771)  |
| 2018 - 2020 | 0.091    | 0.135 | 0.675     | 0.999           | (-0.331, 0.513)  |

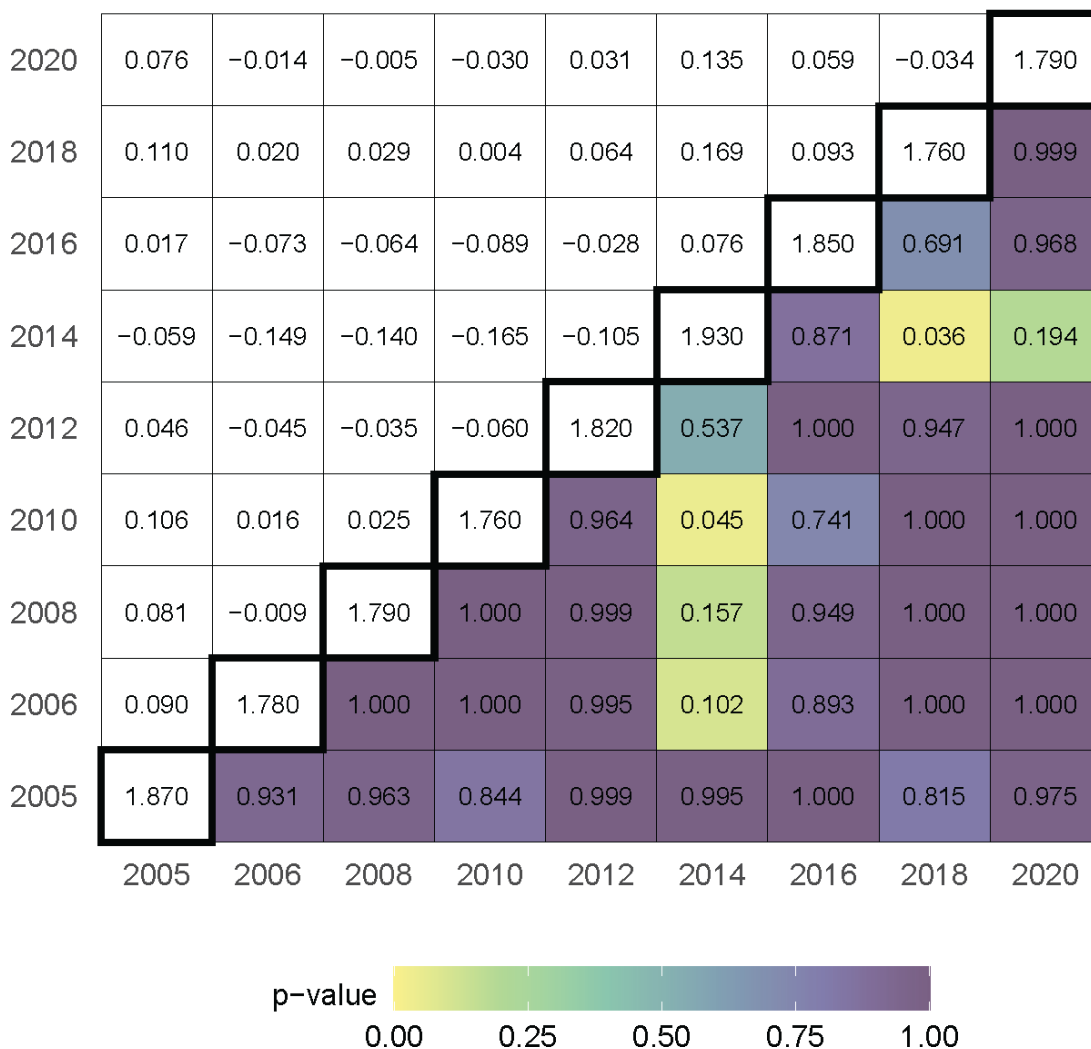
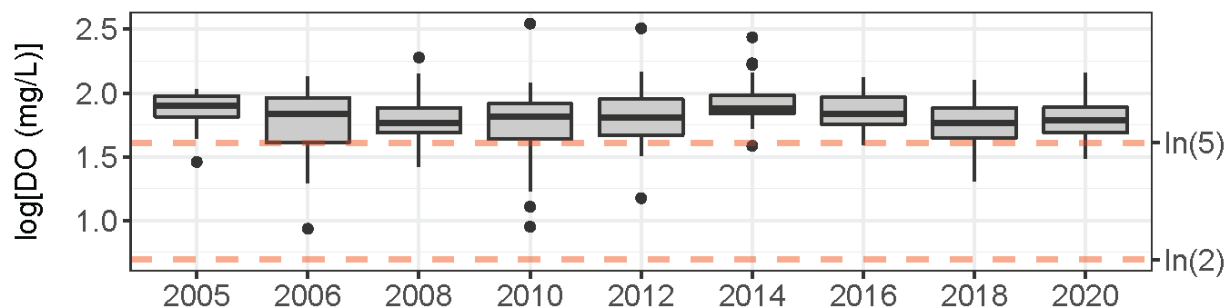


**Figure 2-2.** (Top): Boxplot of log bottom dissolved oxygen concentration by year within Assateague Island National Seashore. Estuarine quality category thresholds (Table 2-1) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log bottom dissolved oxygen concentration within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus 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 2-7.

**Table 2-7.** Summary of the multiple comparison test results for all possible yearly contrasts of mean log bottom dissolved oxygen concentration within Assateague Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

| Contrast    | Estimate | SE    | $t_{214}$ | p-value | 95% CI           |
|-------------|----------|-------|-----------|---------|------------------|
| 2005 - 2006 | 0.090    | 0.070 | 1.294     | 0.931   | (-0.128, 0.309)  |
| 2005 - 2008 | 0.081    | 0.070 | 1.160     | 0.963   | (-0.137, 0.300)  |
| 2005 - 2010 | 0.106    | 0.070 | 1.516     | 0.844   | (-0.113, 0.324)  |
| 2005 - 2012 | 0.046    | 0.070 | 0.652     | 0.999   | (-0.173, 0.264)  |
| 2005 - 2014 | -0.059   | 0.070 | -0.843    | 0.995   | (-0.277, 0.160)  |
| 2005 - 2016 | 0.017    | 0.070 | 0.245     | 1.000   | (-0.201, 0.236)  |
| 2005 - 2018 | 0.110    | 0.070 | 1.574     | 0.815   | (-0.108, 0.329)  |
| 2005 - 2020 | 0.076    | 0.070 | 1.090     | 0.975   | (-0.142, 0.295)  |
| 2006 - 2008 | -0.009   | 0.052 | -0.180    | 1.000   | (-0.172, 0.154)  |
| 2006 - 2010 | 0.016    | 0.052 | 0.297     | 1.000   | (-0.148, 0.179)  |
| 2006 - 2012 | -0.045   | 0.052 | -0.860    | 0.995   | (-0.208, 0.118)  |
| 2006 - 2014 | -0.149   | 0.052 | -2.864    | 0.102   | (-0.312, 0.014)  |
| 2006 - 2016 | -0.073   | 0.052 | -1.405    | 0.893   | (-0.236, 0.090)  |
| 2006 - 2018 | 0.020    | 0.052 | 0.376     | 1.000   | (-0.143, 0.183)  |
| 2006 - 2020 | -0.014   | 0.052 | -0.274    | 1.000   | (-0.177, 0.149)  |
| 2008 - 2010 | 0.025    | 0.052 | 0.477     | 1.000   | (-0.138, 0.188)  |
| 2008 - 2012 | -0.035   | 0.052 | -0.680    | 0.999   | (-0.199, 0.128)  |
| 2008 - 2014 | -0.140   | 0.052 | -2.684    | 0.157   | (-0.303, 0.023)  |
| 2008 - 2016 | -0.064   | 0.052 | -1.226    | 0.949   | (-0.227, 0.099)  |
| 2008 - 2018 | 0.029    | 0.052 | 0.555     | 1.000   | (-0.134, 0.192)  |
| 2008 - 2020 | -0.005   | 0.052 | -0.094    | 1.000   | (-0.168, 0.158)  |
| 2010 - 2012 | -0.060   | 0.052 | -1.157    | 0.964   | (-0.223, 0.103)  |
| 2010 - 2014 | -0.165   | 0.052 | -3.161    | 0.045   | (-0.328, -0.002) |
| 2010 - 2016 | -0.089   | 0.052 | -1.703    | 0.740   | (-0.252, 0.074)  |
| 2010 - 2018 | 0.004    | 0.052 | 0.078     | 1.000   | (-0.159, 0.167)  |
| 2010 - 2020 | -0.030   | 0.052 | -0.571    | 1.000   | (-0.193, 0.133)  |
| 2012 - 2014 | -0.105   | 0.052 | -2.004    | 0.537   | (-0.268, 0.059)  |
| 2012 - 2016 | -0.028   | 0.052 | -0.546    | 1.000   | (-0.192, 0.135)  |
| 2012 - 2018 | 0.064    | 0.052 | 1.235     | 0.947   | (-0.099, 0.228)  |
| 2012 - 2020 | 0.031    | 0.052 | 0.586     | 1.000   | (-0.132, 0.194)  |
| 2014 - 2016 | 0.076    | 0.052 | 1.458     | 0.871   | (-0.087, 0.239)  |
| 2014 - 2018 | 0.169    | 0.052 | 3.239     | 0.036   | (0.006, 0.332)   |
| 2014 - 2020 | 0.135    | 0.052 | 2.590     | 0.194   | (-0.028, 0.298)  |
| 2016 - 2018 | 0.093    | 0.052 | 1.781     | 0.691   | (-0.070, 0.256)  |
| 2016 - 2020 | 0.059    | 0.052 | 1.132     | 0.968   | (-0.104, 0.222)  |
| 2018 - 2020 | -0.034   | 0.052 | -0.649    | 0.999   | (-0.197, 0.129)  |

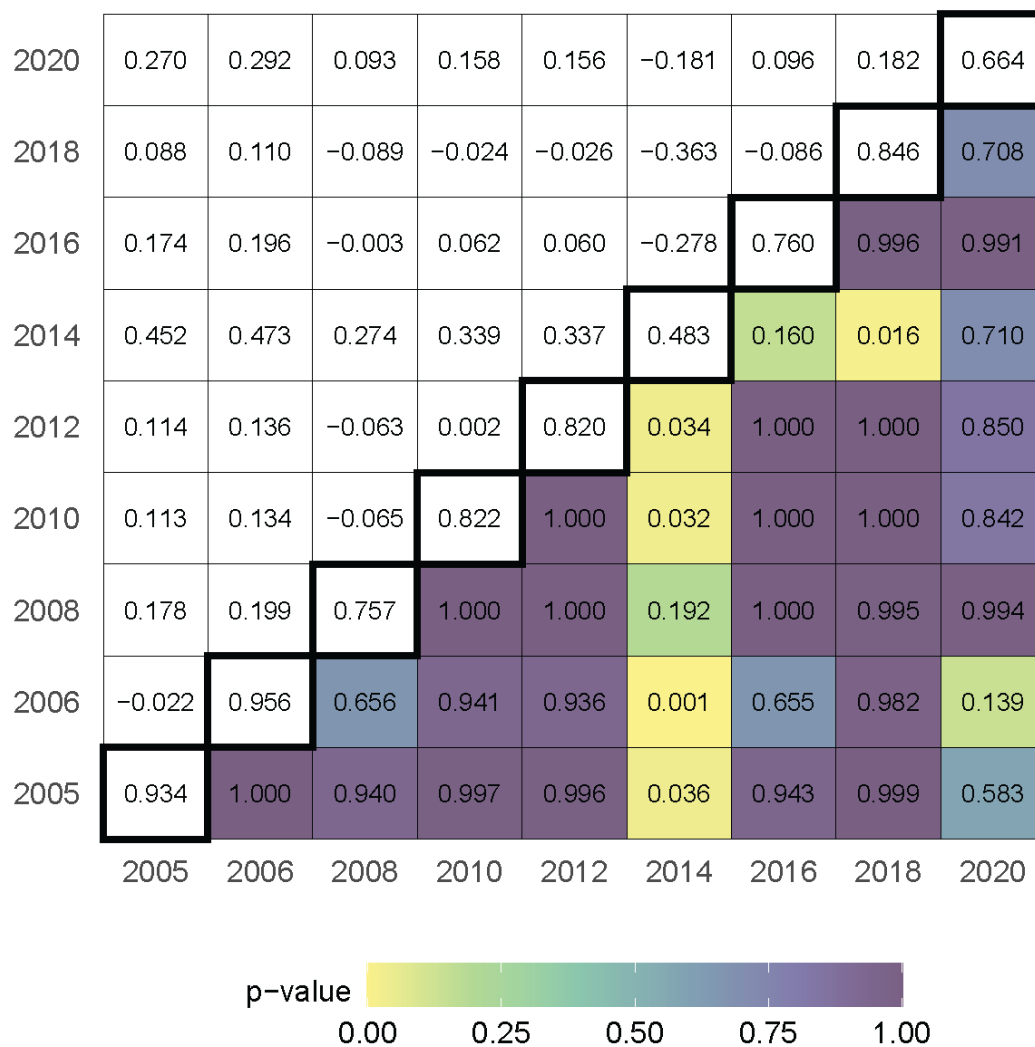
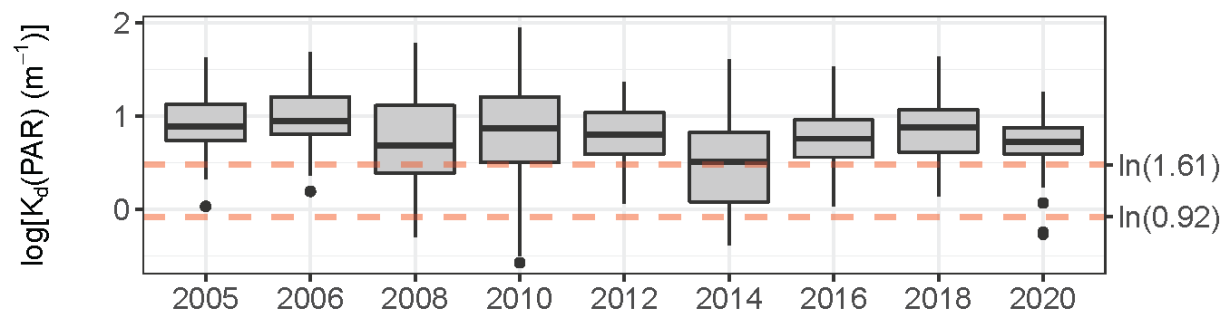


**Figure 2-3.** (Top): Boxplot of log PAR attenuation by year within Assateague Island National Seashore. Estuarine quality category thresholds (Table 2-1) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log PAR attenuation within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus 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 2-8.

**Table 2-8.** Summary of the multiple comparison test results for all possible yearly contrasts of mean log PAR attenuation within Assateague Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

| Contrast    | Estimate | SE    | $t_{209}$ | $p$ -value | 95% CI           |
|-------------|----------|-------|-----------|------------|------------------|
| 2005 - 2006 | -0.022   | 0.142 | -0.153    | 1.000      | (-0.465, 0.422)  |
| 2005 - 2008 | 0.178    | 0.141 | 1.263     | 0.940      | (-0.262, 0.617)  |
| 2005 - 2010 | 0.113    | 0.139 | 0.808     | 0.996      | (-0.323, 0.548)  |
| 2005 - 2012 | 0.114    | 0.139 | 0.820     | 0.996      | (-0.321, 0.550)  |
| 2005 - 2014 | 0.452    | 0.139 | 3.241     | 0.036      | (0.016, 0.887)   |
| 2005 - 2016 | 0.174    | 0.139 | 1.249     | 0.943      | (-0.262, 0.610)  |
| 2005 - 2018 | 0.088    | 0.139 | 0.634     | 0.999      | (-0.347, 0.524)  |
| 2005 - 2020 | 0.270    | 0.139 | 1.939     | 0.583      | (-0.166, 0.706)  |
| 2006 - 2008 | 0.199    | 0.109 | 1.833     | 0.655      | (-0.141, 0.539)  |
| 2006 - 2010 | 0.134    | 0.107 | 1.258     | 0.941      | (-0.199, 0.468)  |
| 2006 - 2012 | 0.136    | 0.107 | 1.274     | 0.937      | (-0.198, 0.470)  |
| 2006 - 2014 | 0.473    | 0.107 | 4.436     | 0.000      | (0.140, 0.807)   |
| 2006 - 2016 | 0.196    | 0.107 | 1.834     | 0.655      | (-0.138, 0.529)  |
| 2006 - 2018 | 0.110    | 0.107 | 1.031     | 0.982      | (-0.224, 0.444)  |
| 2006 - 2020 | 0.292    | 0.107 | 2.735     | 0.140      | (-0.042, 0.625)  |
| 2008 - 2010 | -0.065   | 0.106 | -0.615    | 0.999      | (-0.395, 0.265)  |
| 2008 - 2012 | -0.063   | 0.106 | -0.599    | 1.000      | (-0.393, 0.267)  |
| 2008 - 2014 | 0.274    | 0.106 | 2.595     | 0.192      | (-0.056, 0.604)  |
| 2008 - 2016 | -0.003   | 0.106 | -0.033    | 1.000      | (-0.334, 0.327)  |
| 2008 - 2018 | -0.089   | 0.106 | -0.845    | 0.995      | (-0.419, 0.241)  |
| 2008 - 2020 | 0.093    | 0.106 | 0.877     | 0.994      | (-0.238, 0.423)  |
| 2010 - 2012 | 0.002    | 0.104 | 0.017     | 1.000      | (-0.322, 0.326)  |
| 2010 - 2014 | 0.339    | 0.104 | 3.272     | 0.033      | (0.015, 0.663)   |
| 2010 - 2016 | 0.062    | 0.104 | 0.594     | 1.000      | (-0.263, 0.386)  |
| 2010 - 2018 | -0.024   | 0.104 | -0.234    | 1.000      | (-0.348, 0.300)  |
| 2010 - 2020 | 0.158    | 0.104 | 1.521     | 0.842      | (-0.166, 0.482)  |
| 2012 - 2014 | 0.337    | 0.104 | 3.255     | 0.034      | (0.013, 0.661)   |
| 2012 - 2016 | 0.060    | 0.104 | 0.577     | 1.000      | (-0.264, 0.384)  |
| 2012 - 2018 | -0.026   | 0.104 | -0.251    | 1.000      | (-0.350, 0.298)  |
| 2012 - 2020 | 0.156    | 0.104 | 1.504     | 0.850      | (-0.168, 0.480)  |
| 2014 - 2016 | -0.278   | 0.104 | -2.678    | 0.159      | (-0.602, 0.047)  |
| 2014 - 2018 | -0.363   | 0.104 | -3.505    | 0.016      | (-0.687, -0.039) |
| 2014 - 2020 | -0.181   | 0.104 | -1.751    | 0.710      | (-0.505, 0.143)  |
| 2016 - 2018 | -0.086   | 0.104 | -0.827    | 0.996      | (-0.410, 0.238)  |
| 2016 - 2020 | 0.096    | 0.104 | 0.927     | 0.991      | (-0.228, 0.420)  |
| 2018 - 2020 | 0.182    | 0.104 | 1.755     | 0.708      | (-0.142, 0.506)  |

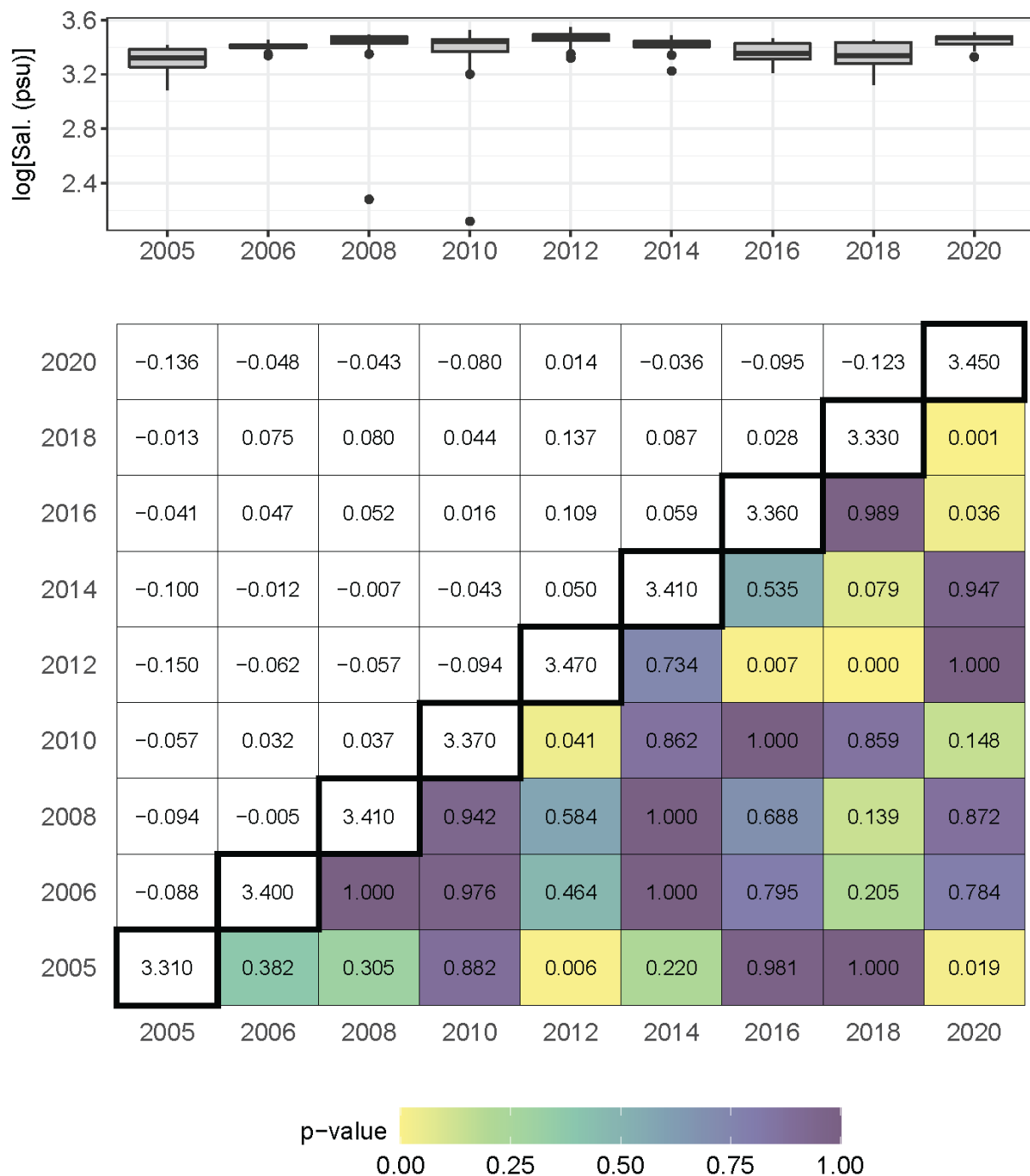


**Figure 2-4.** (Top): Boxplot of log surface salinity by year within Assateague Island National Seashore. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface salinity within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus 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 2-9.

**Table 2-9.** Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface salinity within Assateague Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

| Contrast    | Estimate | SE    | $t_{214}$ | p-value | 95% CI           |
|-------------|----------|-------|-----------|---------|------------------|
| 2005 - 2006 | -0.088   | 0.040 | -2.235    | 0.383   | (-0.212, 0.035)  |
| 2005 - 2008 | -0.094   | 0.040 | -2.364    | 0.305   | (-0.217, 0.030)  |
| 2005 - 2010 | -0.057   | 0.040 | -1.432    | 0.882   | (-0.180, 0.067)  |
| 2005 - 2012 | -0.150   | 0.040 | -3.802    | 0.005   | (-0.274, -0.027) |
| 2005 - 2014 | -0.100   | 0.040 | -2.530    | 0.221   | (-0.224, 0.024)  |
| 2005 - 2016 | -0.041   | 0.040 | -1.039    | 0.981   | (-0.165, 0.083)  |
| 2005 - 2018 | -0.013   | 0.040 | -0.331    | 1.000   | (-0.137, 0.111)  |
| 2005 - 2020 | -0.136   | 0.040 | -3.445    | 0.019   | (-0.260, -0.013) |
| 2006 - 2008 | -0.005   | 0.029 | -0.175    | 1.000   | (-0.097, 0.087)  |
| 2006 - 2010 | 0.032    | 0.029 | 1.080     | 0.976   | (-0.060, 0.124)  |
| 2006 - 2012 | -0.062   | 0.029 | -2.111    | 0.464   | (-0.154, 0.030)  |
| 2006 - 2014 | -0.012   | 0.029 | -0.397    | 1.000   | (-0.104, 0.080)  |
| 2006 - 2016 | 0.047    | 0.029 | 1.610     | 0.795   | (-0.045, 0.139)  |
| 2006 - 2018 | 0.075    | 0.029 | 2.564     | 0.205   | (-0.017, 0.167)  |
| 2006 - 2020 | -0.048   | 0.029 | -1.630    | 0.784   | (-0.140, 0.044)  |
| 2008 - 2010 | 0.037    | 0.029 | 1.255     | 0.942   | (-0.055, 0.129)  |
| 2008 - 2012 | -0.057   | 0.029 | -1.936    | 0.585   | (-0.149, 0.035)  |
| 2008 - 2014 | -0.007   | 0.029 | -0.222    | 1.000   | (-0.098, 0.085)  |
| 2008 - 2016 | 0.052    | 0.029 | 1.785     | 0.688   | (-0.039, 0.144)  |
| 2008 - 2018 | 0.080    | 0.029 | 2.739     | 0.138   | (-0.011, 0.172)  |
| 2008 - 2020 | -0.043   | 0.029 | -1.455    | 0.872   | (-0.135, 0.049)  |
| 2010 - 2012 | -0.094   | 0.029 | -3.191    | 0.042   | (-0.186, -0.002) |
| 2010 - 2014 | -0.043   | 0.029 | -1.478    | 0.862   | (-0.135, 0.048)  |
| 2010 - 2016 | 0.016    | 0.029 | 0.530     | 1.000   | (-0.076, 0.107)  |
| 2010 - 2018 | 0.044    | 0.029 | 1.484     | 0.860   | (-0.048, 0.135)  |
| 2010 - 2020 | -0.080   | 0.029 | -2.711    | 0.148   | (-0.172, 0.012)  |
| 2012 - 2014 | 0.050    | 0.029 | 1.714     | 0.734   | (-0.042, 0.142)  |
| 2012 - 2016 | 0.109    | 0.029 | 3.721     | 0.008   | (0.017, 0.201)   |
| 2012 - 2018 | 0.137    | 0.029 | 4.675     | 0.000   | (0.045, 0.229)   |
| 2012 - 2020 | 0.014    | 0.029 | 0.481     | 1.000   | (-0.078, 0.106)  |
| 2014 - 2016 | 0.059    | 0.029 | 2.007     | 0.535   | (-0.033, 0.151)  |
| 2014 - 2018 | 0.087    | 0.029 | 2.961     | 0.079   | (-0.005, 0.179)  |
| 2014 - 2020 | -0.036   | 0.029 | -1.233    | 0.947   | (-0.128, 0.056)  |
| 2016 - 2018 | 0.028    | 0.029 | 0.954     | 0.989   | (-0.064, 0.120)  |
| 2016 - 2020 | -0.095   | 0.029 | -3.240    | 0.036   | (-0.187, -0.003) |
| 2018 - 2020 | -0.123   | 0.029 | -4.194    | 0.001   | (-0.215, -0.031) |

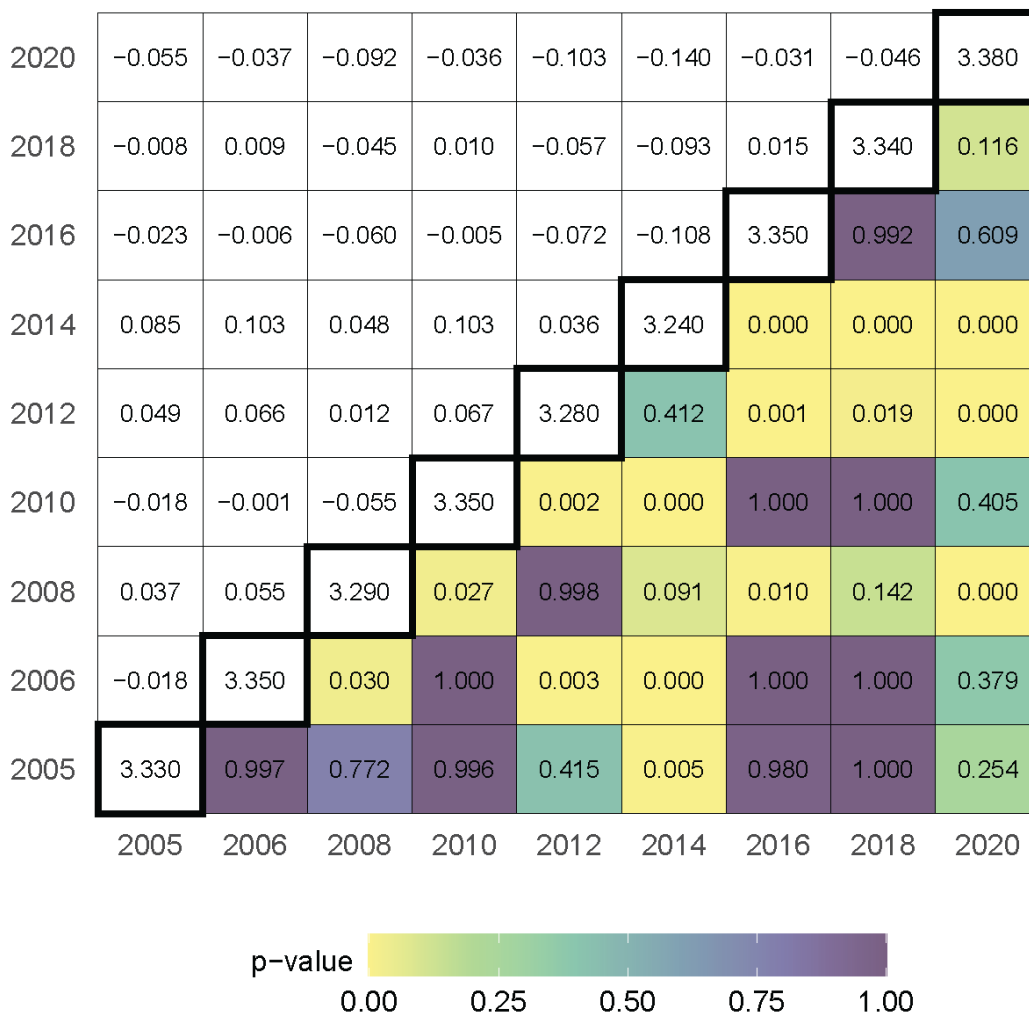
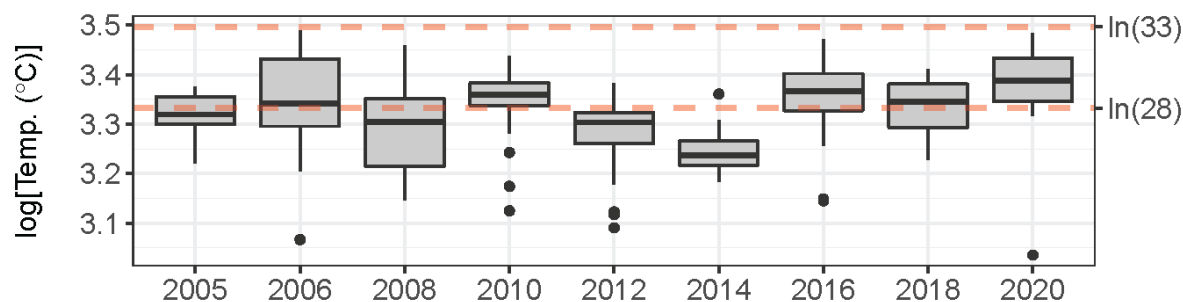
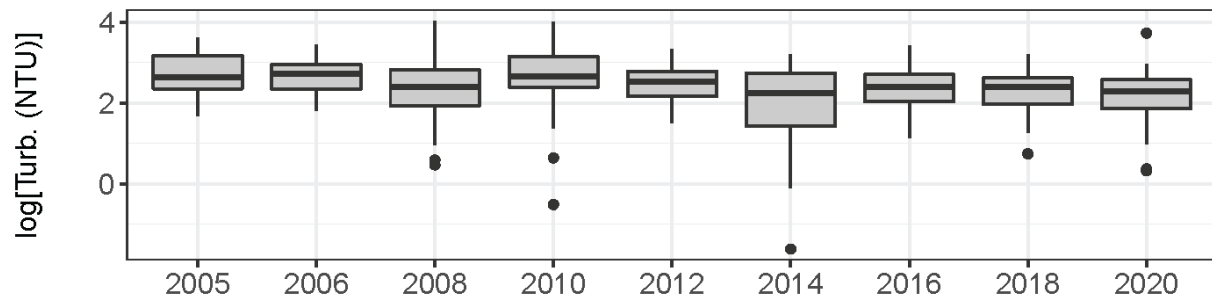


**Figure 2-5.** (Top): Boxplot of log surface temperature by year within Assateague Island National Seashore. Estuarine quality category thresholds (Table 2-1) are plotted as red dashed lines. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface temperature within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus 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 2-10.

**Table 2-10.** Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface temperature within Assateague Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

| Contrast    | Estimate | SE    | $t_{214}$ | p-value | 95% CI           |
|-------------|----------|-------|-----------|---------|------------------|
| 2005 - 2006 | -0.018   | 0.022 | -0.797    | 0.997   | (-0.087, 0.052)  |
| 2005 - 2008 | 0.037    | 0.022 | 1.651     | 0.772   | (-0.033, 0.106)  |
| 2005 - 2010 | -0.018   | 0.022 | -0.826    | 0.996   | (-0.088, 0.051)  |
| 2005 - 2012 | 0.049    | 0.022 | 2.184     | 0.414   | (-0.021, 0.118)  |
| 2005 - 2014 | 0.085    | 0.022 | 3.810     | 0.005   | (0.015, 0.154)   |
| 2005 - 2016 | -0.023   | 0.022 | -1.048    | 0.980   | (-0.093, 0.046)  |
| 2005 - 2018 | -0.008   | 0.022 | -0.373    | 1.000   | (-0.078, 0.061)  |
| 2005 - 2020 | -0.055   | 0.022 | -2.459    | 0.254   | (-0.124, 0.015)  |
| 2006 - 2008 | 0.055    | 0.017 | 3.298     | 0.030   | (0.003, 0.106)   |
| 2006 - 2010 | -0.001   | 0.017 | -0.039    | 1.000   | (-0.052, 0.051)  |
| 2006 - 2012 | 0.066    | 0.017 | 4.016     | 0.002   | (0.015, 0.118)   |
| 2006 - 2014 | 0.103    | 0.017 | 6.206     | 0.000   | (0.051, 0.154)   |
| 2006 - 2016 | -0.006   | 0.017 | -0.339    | 1.000   | (-0.057, 0.046)  |
| 2006 - 2018 | 0.009    | 0.017 | 0.571     | 1.000   | (-0.042, 0.061)  |
| 2006 - 2020 | -0.037   | 0.017 | -2.240    | 0.379   | (-0.089, 0.015)  |
| 2008 - 2010 | -0.055   | 0.017 | -3.337    | 0.027   | (-0.107, -0.004) |
| 2008 - 2012 | 0.012    | 0.017 | 0.719     | 0.998   | (-0.040, 0.064)  |
| 2008 - 2014 | 0.048    | 0.017 | 2.908     | 0.090   | (-0.004, 0.100)  |
| 2008 - 2016 | -0.060   | 0.017 | -3.637    | 0.010   | (-0.112, -0.008) |
| 2008 - 2018 | -0.045   | 0.017 | -2.727    | 0.143   | (-0.097, 0.007)  |
| 2008 - 2020 | -0.092   | 0.017 | -5.537    | 0.000   | (-0.143, -0.040) |
| 2010 - 2012 | 0.067    | 0.017 | 4.056     | 0.002   | (0.015, 0.119)   |
| 2010 - 2014 | 0.103    | 0.017 | 6.245     | 0.000   | (0.052, 0.155)   |
| 2010 - 2016 | -0.005   | 0.017 | -0.300    | 1.000   | (-0.057, 0.047)  |
| 2010 - 2018 | 0.010    | 0.017 | 0.610     | 1.000   | (-0.042, 0.062)  |
| 2010 - 2020 | -0.036   | 0.017 | -2.200    | 0.404   | (-0.088, 0.015)  |
| 2012 - 2014 | 0.036    | 0.017 | 2.189     | 0.412   | (-0.015, 0.088)  |
| 2012 - 2016 | -0.072   | 0.017 | -4.355    | 0.001   | (-0.124, -0.020) |
| 2012 - 2018 | -0.057   | 0.017 | -3.445    | 0.020   | (-0.109, -0.005) |
| 2012 - 2020 | -0.103   | 0.017 | -6.256    | 0.000   | (-0.155, -0.052) |
| 2014 - 2016 | -0.108   | 0.017 | -6.545    | 0.000   | (-0.160, -0.057) |
| 2014 - 2018 | -0.093   | 0.017 | -5.635    | 0.000   | (-0.145, -0.042) |
| 2014 - 2020 | -0.140   | 0.017 | -8.445    | 0.000   | (-0.191, -0.088) |
| 2016 - 2018 | 0.015    | 0.017 | 0.910     | 0.992   | (-0.037, 0.067)  |
| 2016 - 2020 | -0.031   | 0.017 | -1.901    | 0.610   | (-0.083, 0.020)  |
| 2018 - 2020 | -0.046   | 0.017 | -2.811    | 0.116   | (-0.098, 0.005)  |



|      |       |       |        |       |       |        |       |       |       |
|------|-------|-------|--------|-------|-------|--------|-------|-------|-------|
| 2020 | 0.549 | 0.528 | 0.193  | 0.440 | 0.348 | -0.224 | 0.199 | 0.166 | 2.140 |
| 2018 | 0.383 | 0.362 | 0.027  | 0.274 | 0.182 | -0.390 | 0.033 | 2.310 | 0.986 |
| 2016 | 0.350 | 0.329 | -0.006 | 0.241 | 0.150 | -0.423 | 2.340 | 1.000 | 0.957 |
| 2014 | 0.773 | 0.752 | 0.417  | 0.664 | 0.572 | 1.920  | 0.222 | 0.324 | 0.917 |
| 2012 | 0.200 | 0.180 | -0.155 | 0.092 | 2.490 | 0.021  | 0.993 | 0.975 | 0.485 |
| 2010 | 0.109 | 0.088 | -0.247 | 2.590 | 1.000 | 0.003  | 0.879 | 0.782 | 0.179 |
| 2008 | 0.356 | 0.335 | 2.340  | 0.864 | 0.991 | 0.240  | 1.000 | 1.000 | 0.964 |
| 2006 | 0.021 | 2.670 | 0.541  | 1.000 | 0.977 | 0.000  | 0.565 | 0.432 | 0.047 |
| 2005 | 2.690 | 1.000 | 0.812  | 1.000 | 0.993 | 0.020  | 0.826 | 0.744 | 0.266 |
|      | 2005  | 2006  | 2008   | 2010  | 2012  | 2014   | 2016  | 2018  | 2020  |



**Figure 2-6.** (Top): Boxplot of log surface turbidity by year within Assateague Island National Seashore. (Bottom): Compact display of the multiple comparison test results. The bolded diagonal elements contain the mean log surface turbidity within each year. Upper diagonal cells contain the difference between the means of the years indicated by the row and column names (earlier minus 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 2-11.

**Table 2-11.** Summary of the multiple comparison test results for all possible yearly contrasts of mean log surface turbidity within Assateague Island National Seashore. Note: all estimates and confidence interval bounds are reported on the log scale. [SE = standard error; CI = confidence interval]

| Contrast    | Estimate | SE    | $t_{214}$ | p-value | 95% CI          |
|-------------|----------|-------|-----------|---------|-----------------|
| 2005 - 2006 | 0.021    | 0.225 | 0.093     | 1.000   | (-0.684, 0.726) |
| 2005 - 2008 | 0.356    | 0.225 | 1.579     | 0.812   | (-0.349, 1.060) |
| 2005 - 2010 | 0.109    | 0.225 | 0.483     | 1.000   | (-0.596, 0.813) |
| 2005 - 2012 | 0.200    | 0.225 | 0.889     | 0.993   | (-0.504, 0.905) |
| 2005 - 2014 | 0.773    | 0.225 | 3.429     | 0.020   | (0.068, 1.478)  |
| 2005 - 2016 | 0.350    | 0.225 | 1.553     | 0.826   | (-0.355, 1.055) |
| 2005 - 2018 | 0.383    | 0.225 | 1.697     | 0.744   | (-0.322, 1.087) |
| 2005 - 2020 | 0.549    | 0.225 | 2.435     | 0.266   | (-0.156, 1.254) |
| 2006 - 2008 | 0.335    | 0.168 | 1.999     | 0.541   | (-0.189, 0.859) |
| 2006 - 2010 | 0.088    | 0.168 | 0.525     | 1.000   | (-0.436, 0.612) |
| 2006 - 2012 | 0.180    | 0.168 | 1.072     | 0.977   | (-0.344, 0.703) |
| 2006 - 2014 | 0.752    | 0.168 | 4.489     | 0.000   | (0.228, 1.276)  |
| 2006 - 2016 | 0.329    | 0.168 | 1.964     | 0.566   | (-0.195, 0.853) |
| 2006 - 2018 | 0.362    | 0.168 | 2.158     | 0.432   | (-0.162, 0.885) |
| 2006 - 2020 | 0.528    | 0.168 | 3.152     | 0.046   | (0.004, 1.052)  |
| 2008 - 2010 | -0.247   | 0.168 | -1.474    | 0.864   | (-0.771, 0.277) |
| 2008 - 2012 | -0.155   | 0.168 | -0.928    | 0.991   | (-0.679, 0.368) |
| 2008 - 2014 | 0.417    | 0.168 | 2.489     | 0.239   | (-0.107, 0.941) |
| 2008 - 2016 | -0.006   | 0.168 | -0.035    | 1.000   | (-0.530, 0.518) |
| 2008 - 2018 | 0.027    | 0.168 | 0.159     | 1.000   | (-0.497, 0.550) |
| 2008 - 2020 | 0.193    | 0.168 | 1.153     | 0.964   | (-0.331, 0.717) |
| 2010 - 2012 | 0.092    | 0.168 | 0.547     | 1.000   | (-0.432, 0.615) |
| 2010 - 2014 | 0.664    | 0.168 | 3.964     | 0.003   | (0.140, 1.188)  |
| 2010 - 2016 | 0.241    | 0.168 | 1.439     | 0.879   | (-0.283, 0.765) |
| 2010 - 2018 | 0.274    | 0.168 | 1.633     | 0.782   | (-0.250, 0.797) |
| 2010 - 2020 | 0.440    | 0.168 | 2.627     | 0.179   | (-0.084, 0.964) |
| 2012 - 2014 | 0.572    | 0.168 | 3.417     | 0.021   | (0.049, 1.096)  |
| 2012 - 2016 | 0.150    | 0.168 | 0.892     | 0.993   | (-0.374, 0.673) |
| 2012 - 2018 | 0.182    | 0.168 | 1.086     | 0.975   | (-0.342, 0.706) |
| 2012 - 2020 | 0.348    | 0.168 | 2.080     | 0.485   | (-0.175, 0.872) |
| 2014 - 2016 | -0.423   | 0.168 | -2.525    | 0.223   | (-0.947, 0.101) |
| 2014 - 2018 | -0.390   | 0.168 | -2.330    | 0.325   | (-0.914, 0.133) |
| 2014 - 2020 | -0.224   | 0.168 | -1.337    | 0.917   | (-0.748, 0.300) |
| 2016 - 2018 | 0.033    | 0.168 | 0.194     | 1.000   | (-0.491, 0.556) |
| 2016 - 2020 | 0.199    | 0.168 | 1.188     | 0.957   | (-0.325, 0.723) |
| 2018 - 2020 | 0.166    | 0.168 | 0.994     | 0.986   | (-0.357, 0.690) |

## **2.4 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 2-12). Notable observations from the fitted smooths for each measure are as follows:

### **2.4.1 Chlorophyll-*a* (near surface)**

Chlorophyll-*a* exhibited a highly non-linear temporal trend (edf = 6.30). There were two periods of statistically significant increases (between 2008-2012 and 2014-2016) and one decreasing period between 2012 and 2014 (Figure 2-7). High concentrations of chlorophyll-*a* are spatially concentrated along the northwestern shore of Chincoteague Bay and Newport Bay (Figure 2-8). Based on the fitted model, both time and location account for 44.2% of the variability in chlorophyll-*a* concentrations (Table 2-13).

### **2.4.2 Dissolved Oxygen (near bottom)**

Although there is no statistically significant temporal trend, there is a significant spatial trend in bottom dissolved oxygen, with higher concentrations occurring in the northern end of the estuary on the eastern shore (Figure 2-9). The fitted model does very poorly explaining variation in dissolved oxygen concentrations, with time and location accounting for only 7.6% of the variation (Table 2-13).

### **2.4.3 PAR Attenuation $K_d$ (SAV standard)**

The temporal trend in PAR attenuation is slightly concave upward (edf = 1.23) with the period prior to 2014 exhibiting a slight decreasing trend (Figure 2-7). Spatially, PAR attenuation tends to be higher on the western shore compared to the eastern shore, and more so in the northern end of Chincoteague Bay and Newport Bay (Figure 2-10). Based on the fitted model, both time and location account for only 20.4% of the variability in PAR attenuation (Table 2-13).

### **2.4.4 Salinity (near surface)**

Surface salinity exhibited a highly non-linear temporal trend (edf = 7.39) with an approximately linear decreasing trend during the period from 2012 to 2018 (Figure 2-7), with an increase in 2020. Spatially, salinity is lowest in Newport Bay and highest in the southern end of Chincoteague Bay (Figure 2-11). The fitted GAM had the best fit amongst the measures, with time and location accounting for 62.9% of the variation in salinity (Table 2-13).

### **2.4.5 Temperature (near surface)**

Surface water temperature exhibited a highly non-linear temporal trend (edf = 6.96) with cyclic periods of statistically significant increases and decreases (Figure 2-7 (continued)). Temperatures have seen two periods of significant increases since 2014. Spatially, surface temperatures are the highest in the west central region of the estuary (Figure 2-12), with cooler temperatures observed at the northern- and southern-most extents. Based on the fitted model, both time and location account for only 46.7% of the variability in water temperature (Table 2-13).

### **2.4.6 Turbidity (near surface)**

The temporal trend in surface turbidity suggests a potential step trend around 2012 (Figure 2-7 (continued)). Spatially, turbidity is higher on the west shore with the highest measurements occurring

on the southwestern end of the estuary (Figure 2-13). Time and location account for only 14.2% of the variation in turbidity (Table 2-13).

**Table 2-12.** Approximate significance of the generalized additive model smooth terms for each 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  $\alpha$  level. [edf = effective degrees of freedom]

| Measure                                      | Depth        | Model Term   | edf   | $F$ -value | $p$ -value |
|----------------------------------------------|--------------|--------------|-------|------------|------------|
| Chlorophyll $a$ ( $\mu\text{g/L}$ )          | Surface      | s(year)      | 6.30  | 4.98       | < 0.001    |
| Chlorophyll $a$ ( $\mu\text{g/L}$ )          | Surface      | s(long, lat) | 10.87 | 1.60       | < 0.001    |
| Dissolved oxygen (mg/L)                      | Bottom       | s(year)      | 1.37  | 0.30       | 0.166      |
| Dissolved oxygen (mg/L)                      | Bottom       | s(long, lat) | 4.57  | 0.24       | 0.016      |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | Water Column | s(year)      | 1.23  | 1.06       | 0.003      |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | Water Column | s(long, lat) | 5.74  | 0.95       | < 0.001    |
| Salinity (psu)                               | Surface      | s(year)      | 7.39  | 29.56      | < 0.001    |
| Salinity (psu)                               | Surface      | s(long, lat) | 7.87  | 3.52       | < 0.001    |
| Temperature ( $^{\circ}\text{C}$ )           | Surface      | s(year)      | 6.96  | 13.47      | < 0.001    |
| Temperature ( $^{\circ}\text{C}$ )           | Surface      | s(long, lat) | 7.32  | 1.81       | < 0.001    |
| Turbidity (NTU)                              | Surface      | s(year)      | 0.94  | 1.88       | < 0.001    |
| Turbidity (NTU)                              | Surface      | s(long, lat) | 1.88  | 0.50       | < 0.001    |

**Table 2-13.** Proportion of null deviance explained by the explanatory variables for each model.

| Measure                                      | Deviance Explained |
|----------------------------------------------|--------------------|
| Chlorophyll $a$ ( $\mu\text{g/L}$ )          | 44.2%              |
| Dissolved oxygen (mg/L)                      | 7.6%               |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | 20.4%              |
| Salinity (psu)                               | 62.9%              |
| Temperature ( $^{\circ}\text{C}$ )           | 46.7%              |
| Turbidity (NTU)                              | 14.2%              |

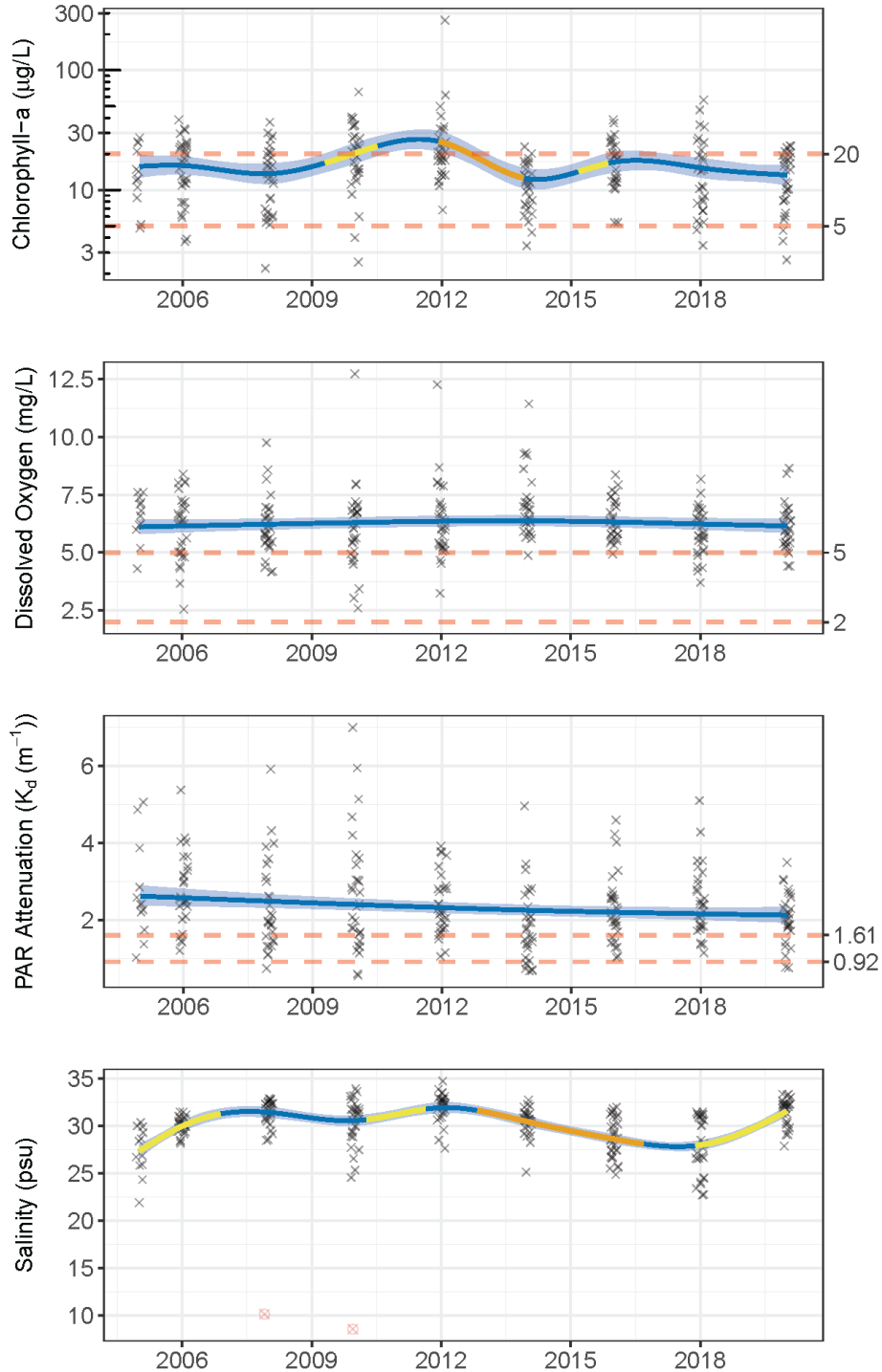


**Figure 2-7.** Trends in Assateague Island National Seashore water quality measures based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Estuarine quality category thresholds (Table 2-1) 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; (2) observations that were excluded from model fitting are plotted in red.

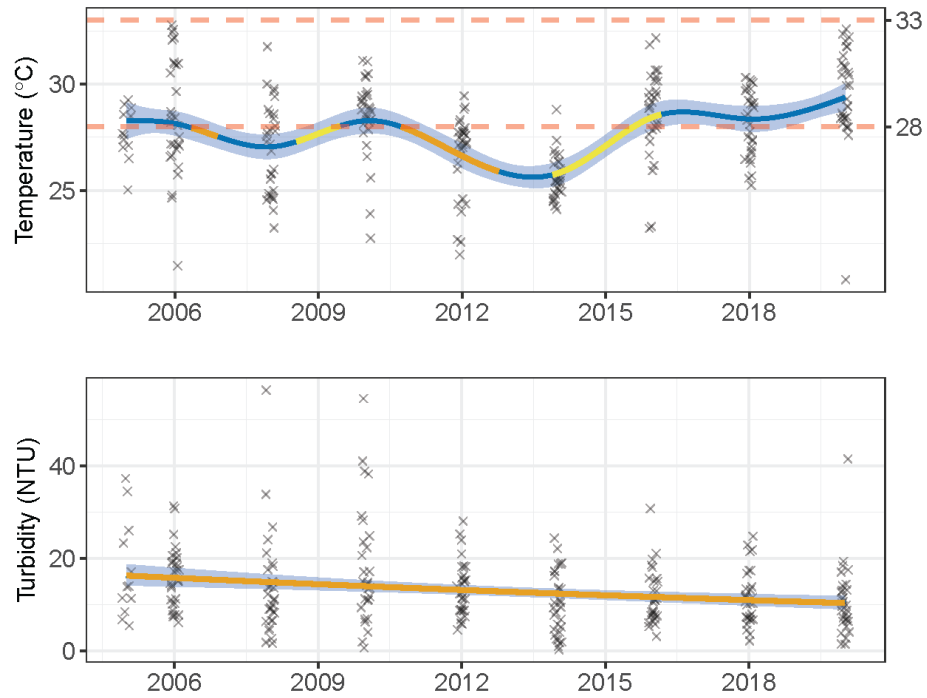


**Figure 2-7 (continued).** Trends in Assateague Island National Seashore water quality measures based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: (1) in some instances, the y-axis is transformed to the  $\log_{10}$  scale to better visualize the estimated trend; (2) observations that were excluded from model fitting are plotted in red.

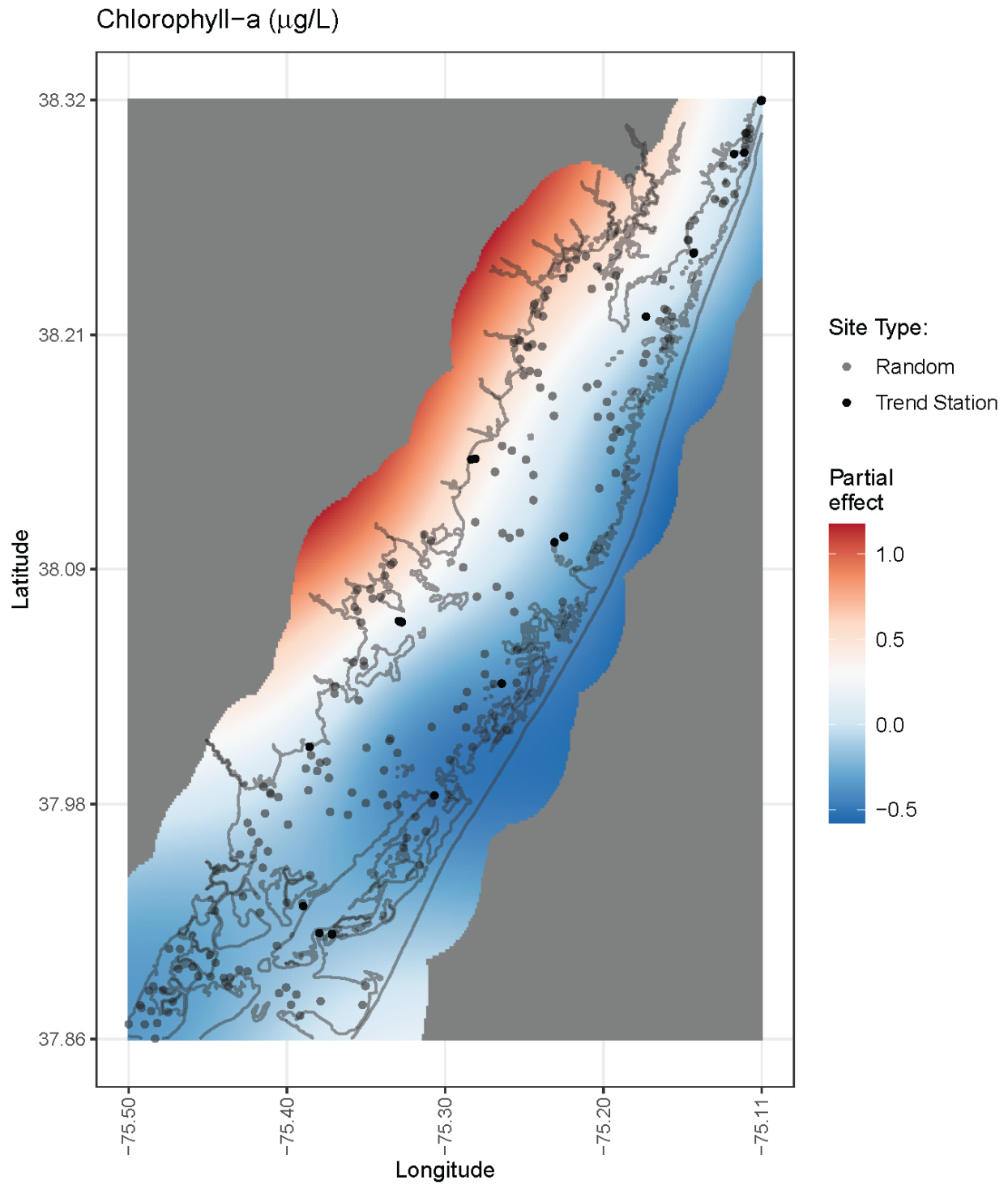


**Figure 2-8.** Mean surface for the generalized additive model latitude/longitude smooth of surface chlorophyll-a concentration ( $\mu\text{g/L}$ ) within Assateague Island National Seashore during 2005-2020.

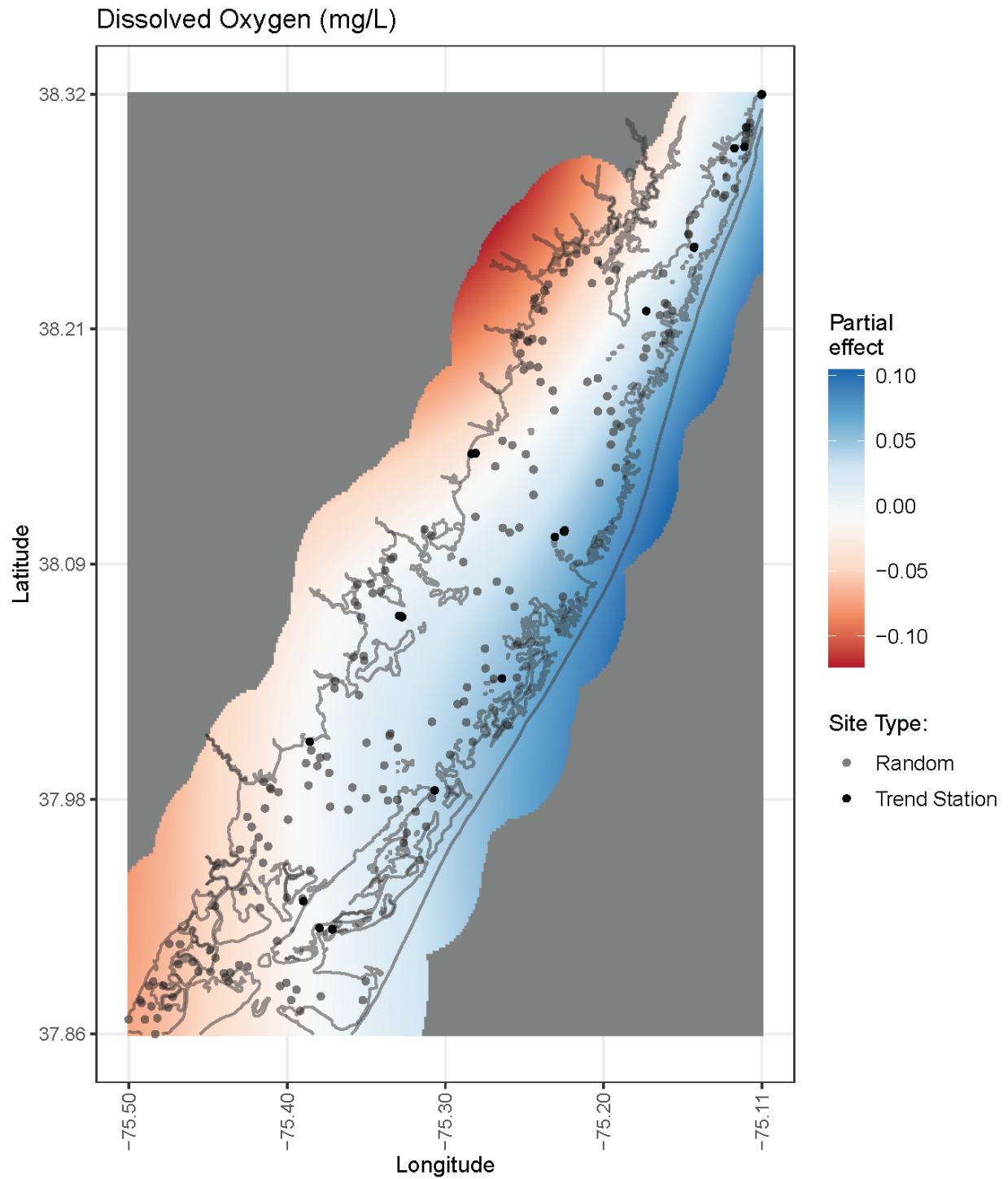


**Figure 2-9.** Mean surface for the generalized additive model latitude/longitude smooth of bottom dissolved oxygen concentration (mg/L) within Assateague Island National Seashore during 2005-2020.

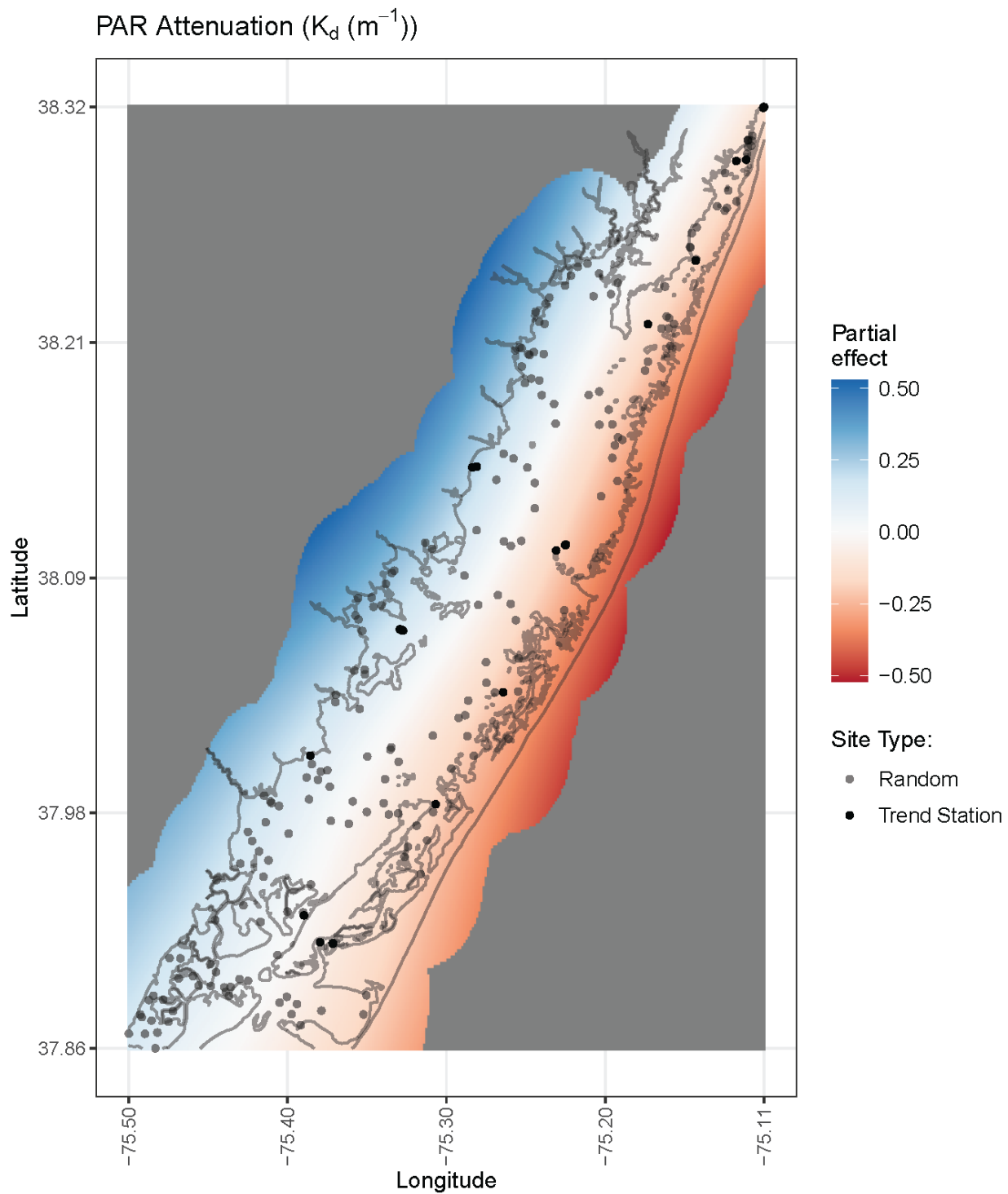


**Figure 2-10.** Mean surface for the generalized additive model latitude/longitude smooth of PAR attenuation ( $K_d$  ( $m^{-1}$ )) within Assateague Island National Seashore during 2005-2020.

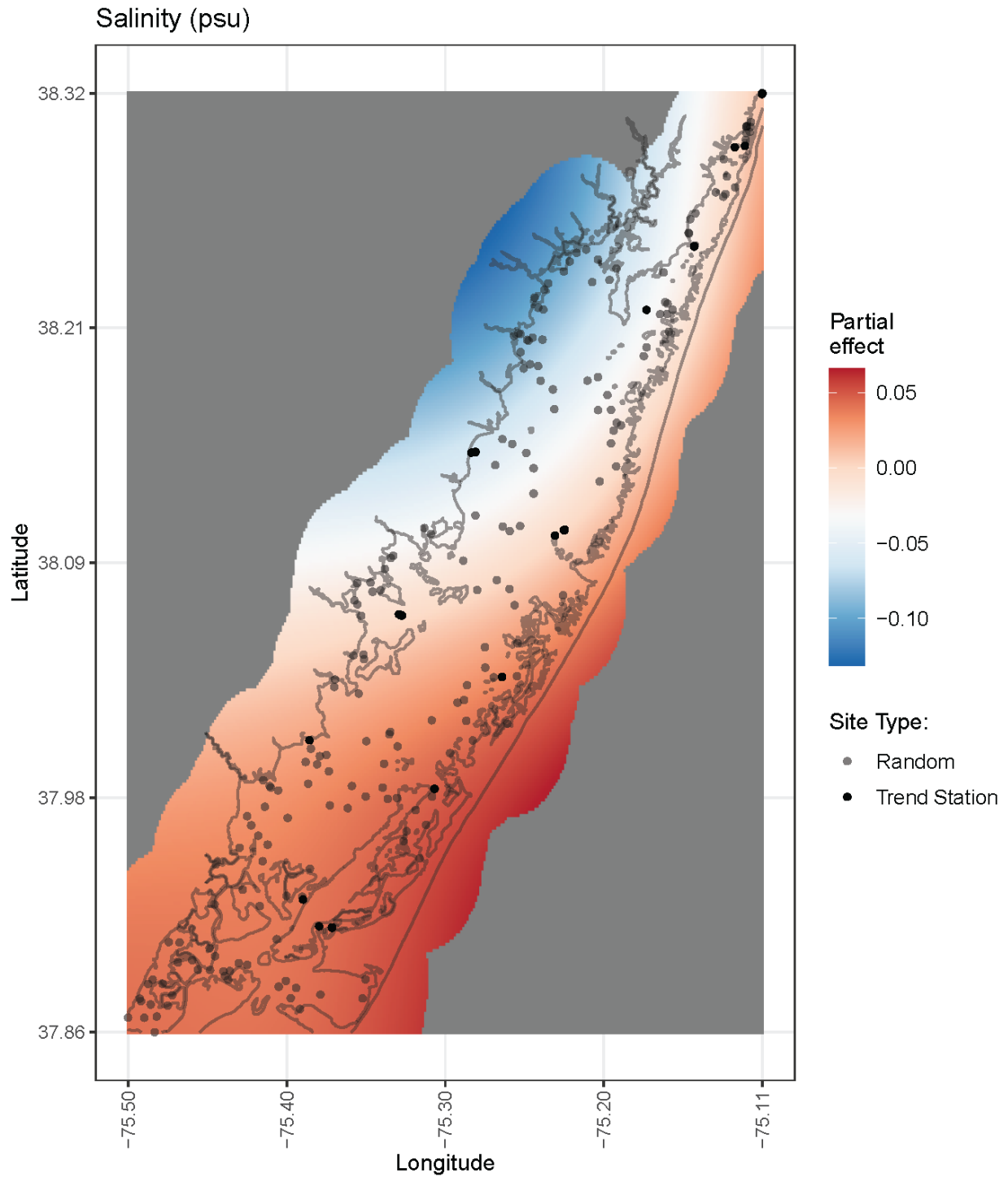


**Figure 2-11.** Mean surface for the generalized additive model latitude/longitude smooth of surface salinity (psu) within Assateague Island National Seashore during 2005-2020.

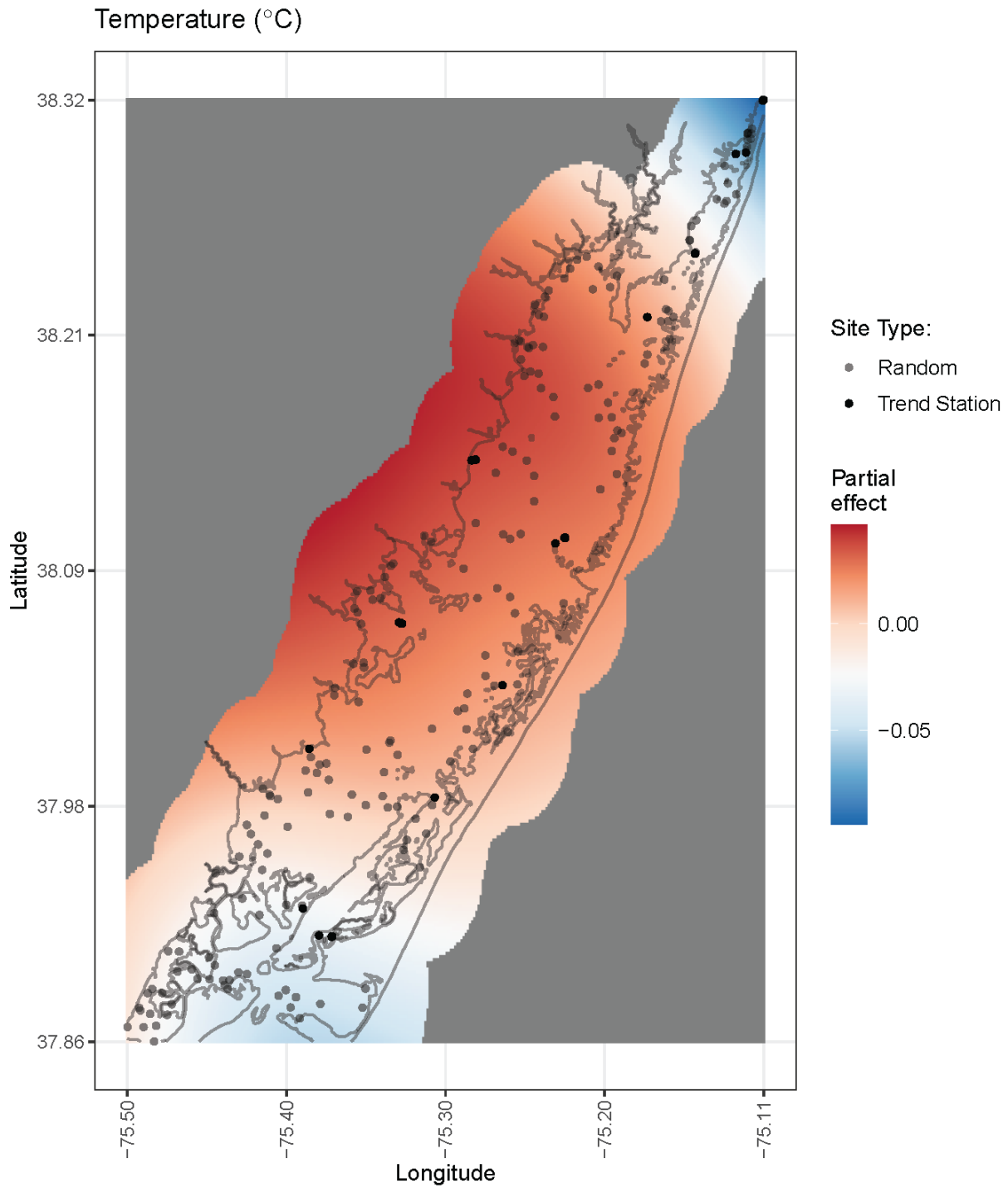


**Figure 2-12.** Mean surface for the generalized additive model latitude/longitude smooth of surface temperature (°C) within Assateague Island National Seashore during 2005-2020.

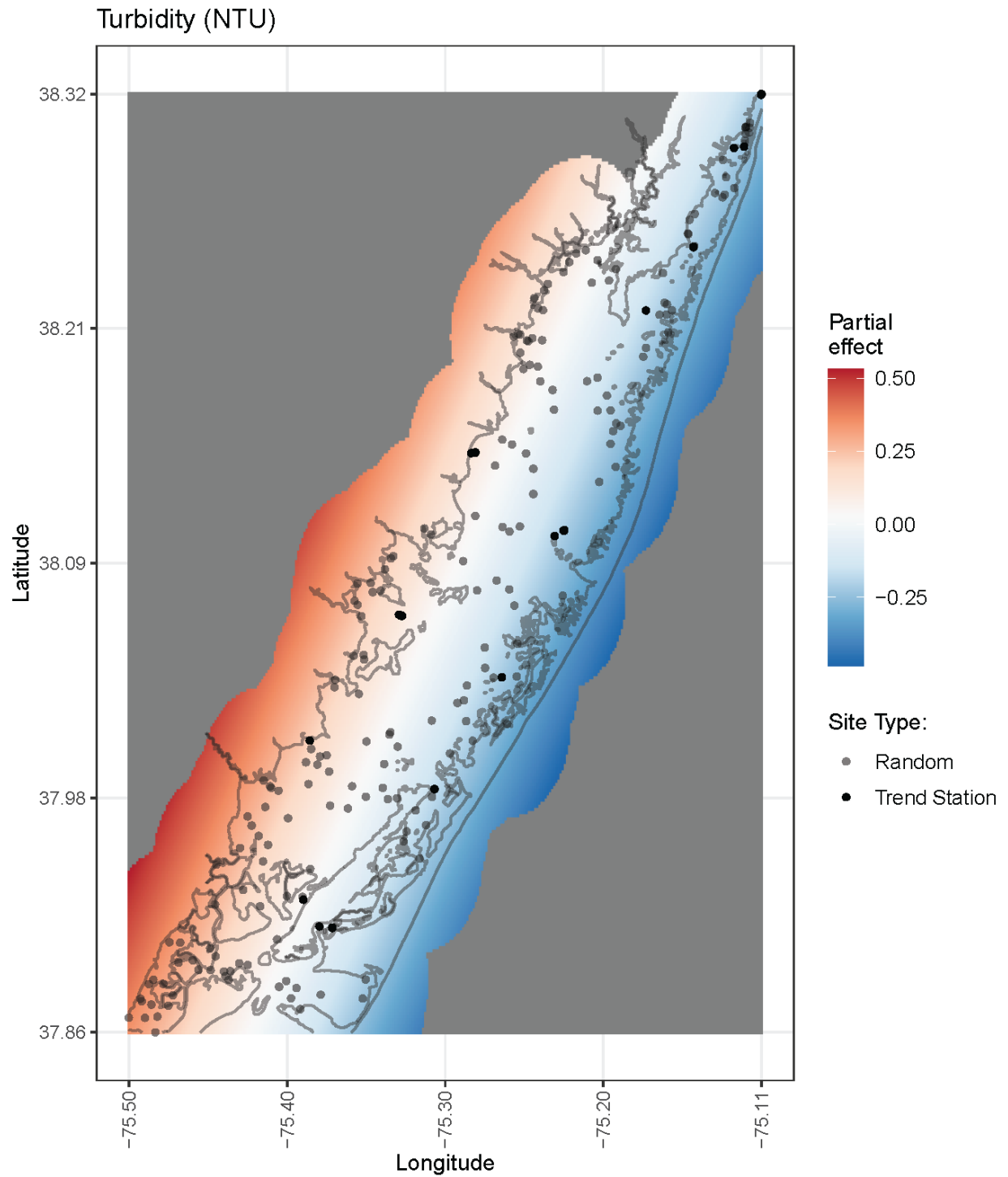


**Figure 2-13.** Mean surface for the generalized additive model latitude/longitude smooth of surface turbidity (NTU) within Assateague Island National Seashore during 2005-2020.

## 2.5 Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there is statistical evidence of a decreasing monotonic trend in PAR attenuation ( $p$ -value = 0.086) and a statistically significant ( $\alpha = 0.05$ ) decreasing monotonic trend in surface turbidity ( $p$ -value = 0.042) during the index periods of 2005 to 2020 (Table 2-14).

**Table 2-14.** Summary of multivariate Mann-Kendall test for monotonic trend for each 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      | -0.34    | 0.734      |
| Dissolved oxygen (mg/L)                      | Bottom       | 0.83     | 0.409      |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | Water Column | -1.72    | 0.086      |
| Salinity (psu)                               | Surface      | 0.28     | 0.780      |
| Temperature ( $^{\circ}\text{C}$ )           | Surface      | 0.54     | 0.590      |
| Turbidity (NTU)                              | Surface      | -2.03    | 0.042      |

## 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 Assateague Island National Seashore trend stations. [SD = standard deviation]

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

**Table 3-2.** Yearly summary statistics for bottom dissolved oxygen concentration ( $\text{mg/L}$ ) at Assateague Island National Seashore trend stations. [SD = standard deviation]

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

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

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

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

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

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

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

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

| Station | Statistic | Sampling Year |       |       |       |       |       |       |       |       |
|---------|-----------|---------------|-------|-------|-------|-------|-------|-------|-------|-------|
|         |           | 2005          | 2006  | 2008  | 2010  | 2012  | 2014  | 2016  | 2018  | 2020  |
| 6       | Mean      | 16.05         | 15.03 | 10.20 | 19.95 | 15.45 | 26.05 | 14.50 | 9.94  | 10.51 |
| 6       | SD        | 8.17          | 7.02  | 2.52  | 4.19  | 4.32  | 16.26 | 4.01  | 2.61  | 0.91  |
| 6       | n         | 4             | 4     | 3     | 4     | 4     | 4     | 4     | 4     | 4     |
| 14      | Mean      | 25.55         | 27.25 | 18.32 | 25.33 | 9.22  | 8.22  | 9.40  | 10.01 | 7.20  |
| 14      | SD        | 11.10         | 7.33  | 10.68 | 16.04 | 1.65  | 6.45  | 4.58  | 7.36  | 1.29  |
| 14      | n         | 4             | 4     | 4     | 4     | 4     | 4     | 4     | 4     | 4     |
| 18      | Mean      | 9.68          | 23.20 | 5.75  | 13.28 | 8.88  | 7.18  | 9.00  | 5.20  | 4.51  |
| 18      | SD        | 0.98          | 17.40 | 2.21  | 5.54  | 3.45  | 7.16  | 3.88  | 1.27  | 1.00  |
| 18      | n         | 4             | 4     | 4     | 4     | 4     | 4     | 4     | 4     | 4     |
| 19      | Mean      | 27.16         | 25.50 | 17.12 | 29.38 | 16.73 | 17.40 | 29.35 | 13.47 | 8.18  |
| 19      | SD        | 4.38          | 6.30  | 5.06  | 25.86 | 4.34  | 24.23 | 23.41 | 11.05 | 1.33  |
| 19      | n         | 4             | 3     | 4     | 4     | 4     | 4     | 4     | 4     | 4     |
| 27      | Mean      | 13.73         | NA    | 8.28  | 21.45 | 10.03 | 5.18  | 11.30 | 10.33 | 8.88  |
| 27      | SD        | 4.42          | NA    | 1.88  | 9.18  | 1.58  | 1.85  | 2.59  | 0.99  | 1.52  |
| 27      | n         | 4             | NA    | 4     | 4     | 4     | 4     | 4     | 4     | 4     |
| 30      | Mean      | 7.38          | 12.10 | 7.82  | 13.95 | 7.55  | 8.58  | 6.73  | 8.31  | 7.76  |
| 30      | SD        | 6.91          | 3.16  | 3.58  | 10.09 | 2.40  | 3.54  | 4.05  | 4.03  | 3.39  |
| 30      | n         | 4             | 4     | 4     | 4     | 4     | 4     | 4     | 4     | 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 bottom dissolved oxygen (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 highly non-linear and differ by station (Figure 3-1). The most notable trend is the sharp decrease in chlorophyll-*a* concentration at the hexagon 14 and 19 stations during the period of 2012-2014. Periods of significant temporal change were also observed at the station within hexagon 18.

#### **3.3.2 Dissolved Oxygen (near bottom)**

There is no temporal trend in the bottom dissolved oxygen concentrations measured at each trend station (Figure 3-2). The yearly average concentrations are all above the 5 mg/L threshold (i.e., good quality category) except for hexagon 19 in 2010.

#### **3.3.3 PAR Attenuation $K_d$ (SAV standard)**

Temporal trends for the stations located within hexagons 14 and 19 exhibit decreasing trends, with relatively high within year variability (Figure 3-3). There is a lack of any trend at the other stations and no periods of significant temporal change were identified.

#### **3.3.4 Salinity (near surface)**

Temporal trends for stations within hexagons 14, 18, and 19 indicate a slight increase in salinity until approximately 2012, after which salinity has been slightly decreasing until 2018 (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 decrease in surface water temperature until approximately 2012, after which temperatures have been slightly increasing (Figure 3-5). No periods of significant temporal change were identified.

#### **3.3.6 Turbidity (near surface)**

Statistically significant linearly decreasing trends in surface turbidity were observed at the station within hexagon 14 (Figure 3-6). There is a lack of any trend at the other stations.

**Table 3-7.** Approximate significance of the generalized additive model smooth terms for each 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  $\alpha$  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) | 43.00 (52)        | 5.73       | <0.001     |
| Dissolved oxygen (mg/L)                      | Bottom       | s(year,hex) | 0.67 (52)         | 0.02       | 0.307      |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | Water Column | s(year,hex) | 11.46 (52)        | 1.79       | <0.001     |
| Salinity (psu)                               | Surface      | s(year,hex) | 18.43 (52)        | 1.70       | <0.001     |
| Temperature ( $^{\circ}\text{C}$ )           | Surface      | s(year,hex) | 15.90 (52)        | 2.51       | <0.001     |
| Turbidity (NTU)                              | Surface      | s(year,hex) | 11.56 (52)        | 1.65       | <0.001     |

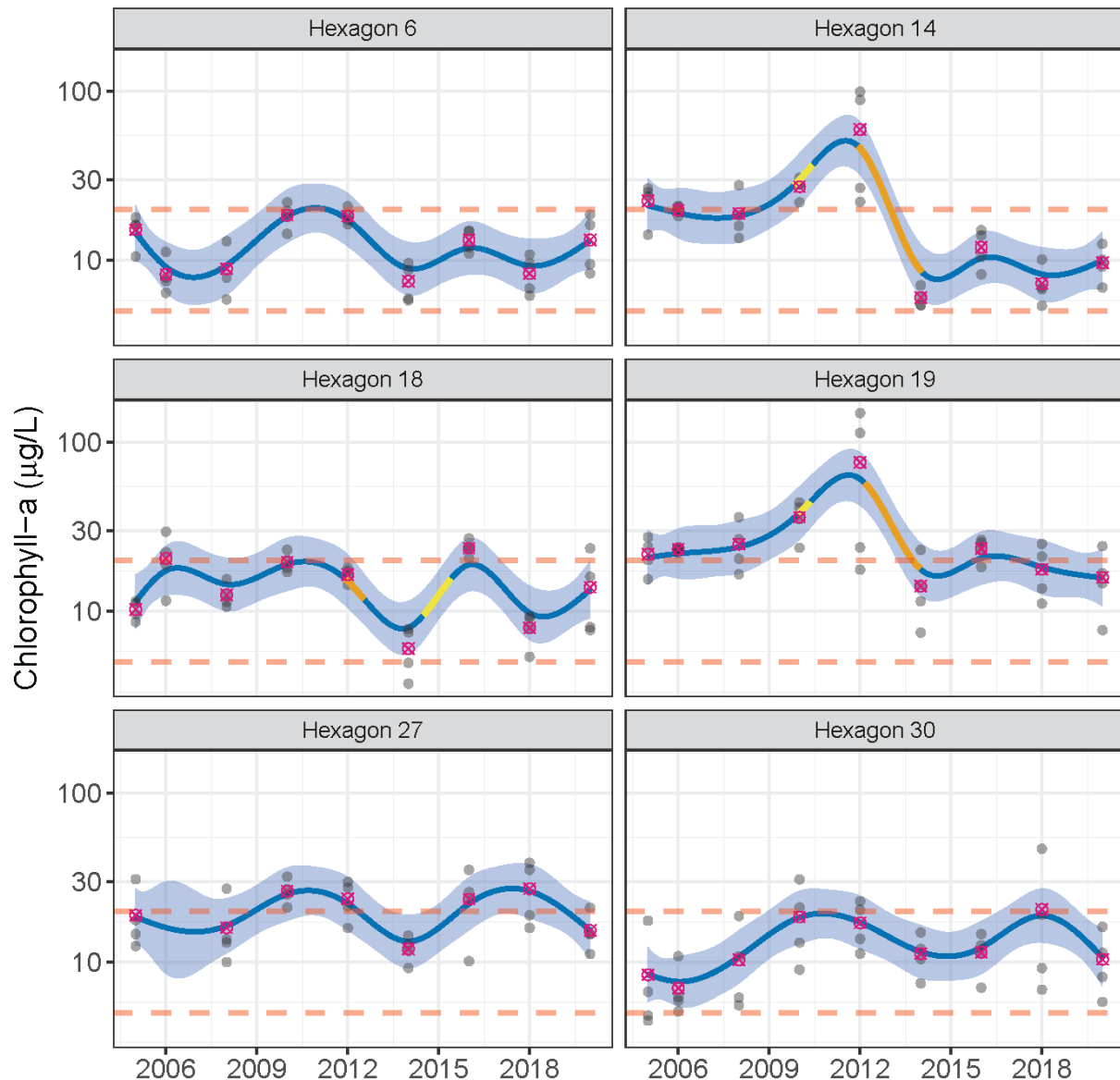


**Figure 3-1.** Mean surface chlorophyll-a concentration trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Within each year, individual measurements and the average are plotted in gray and magenta, respectively. Note: the y-axis is transformed to the log<sub>10</sub> scale to better visualize the estimated trend. Estuarine quality category thresholds (Table 2-1) are plotted as red dashed lines.

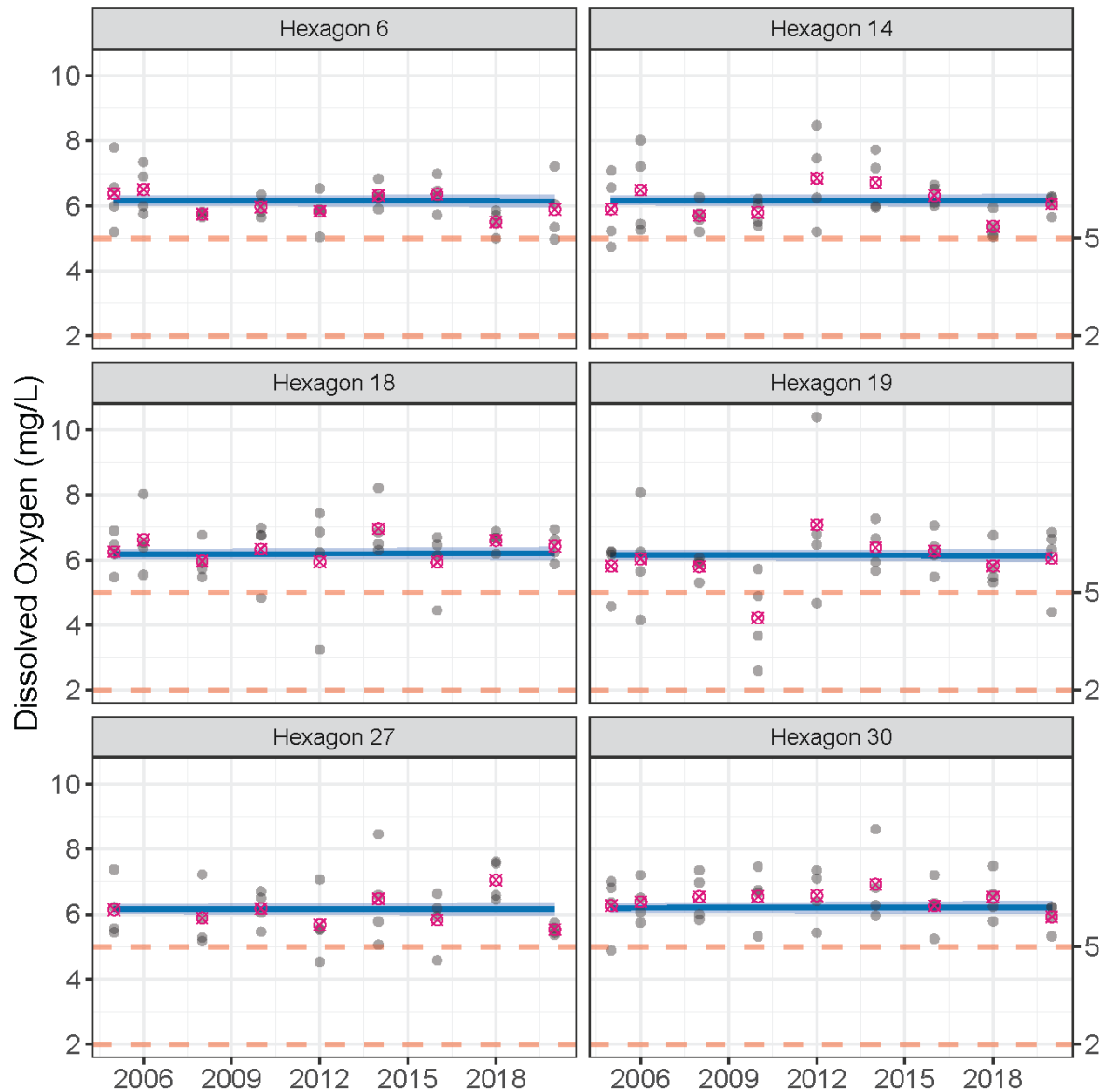


**Figure 3-2.** Mean bottom dissolved oxygen concentration trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases),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

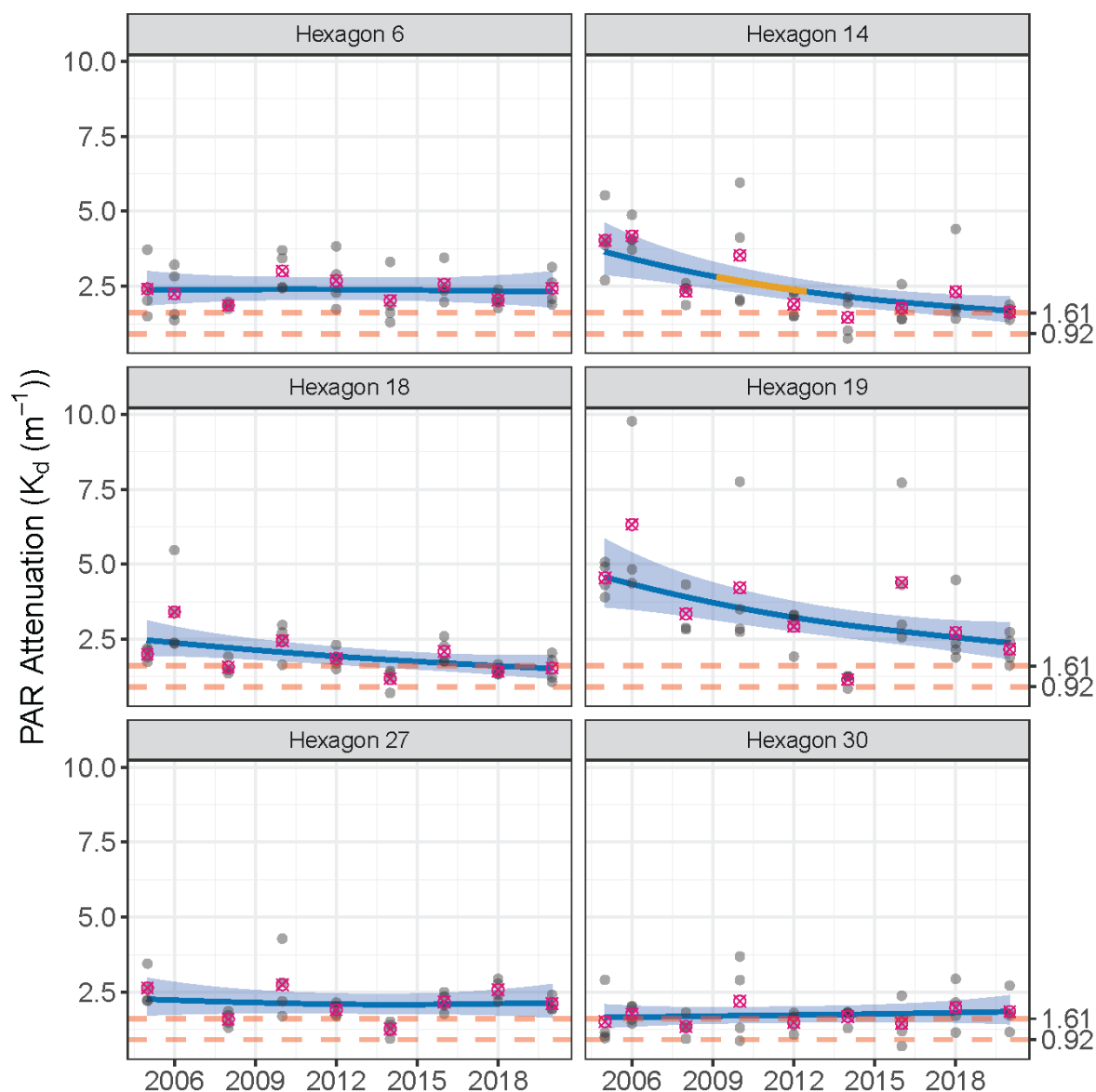


**Figure 3-3.** Mean PAR attenuation trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are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

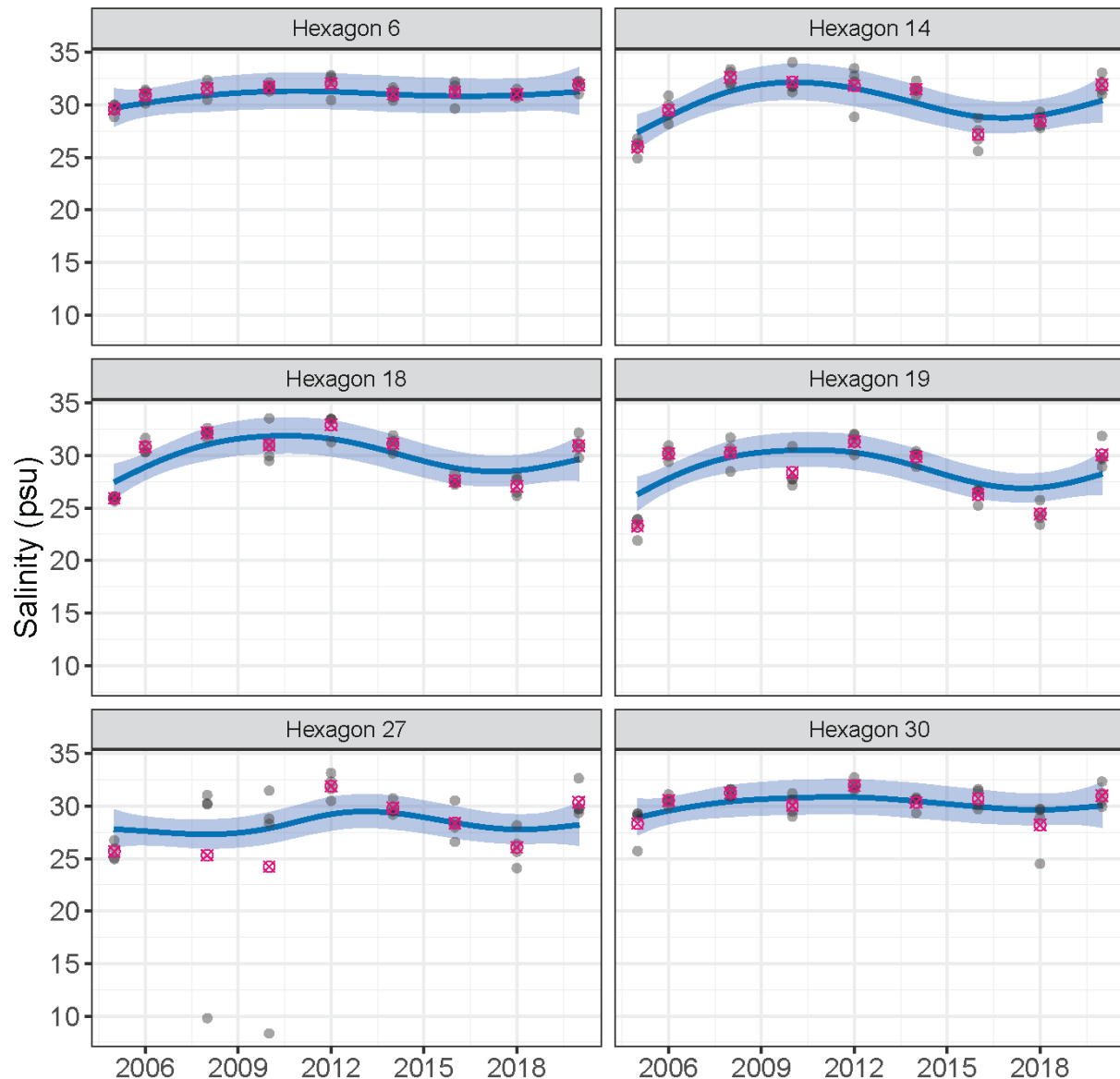


**Figure 3-4.** Mean surface salinity trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present, are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

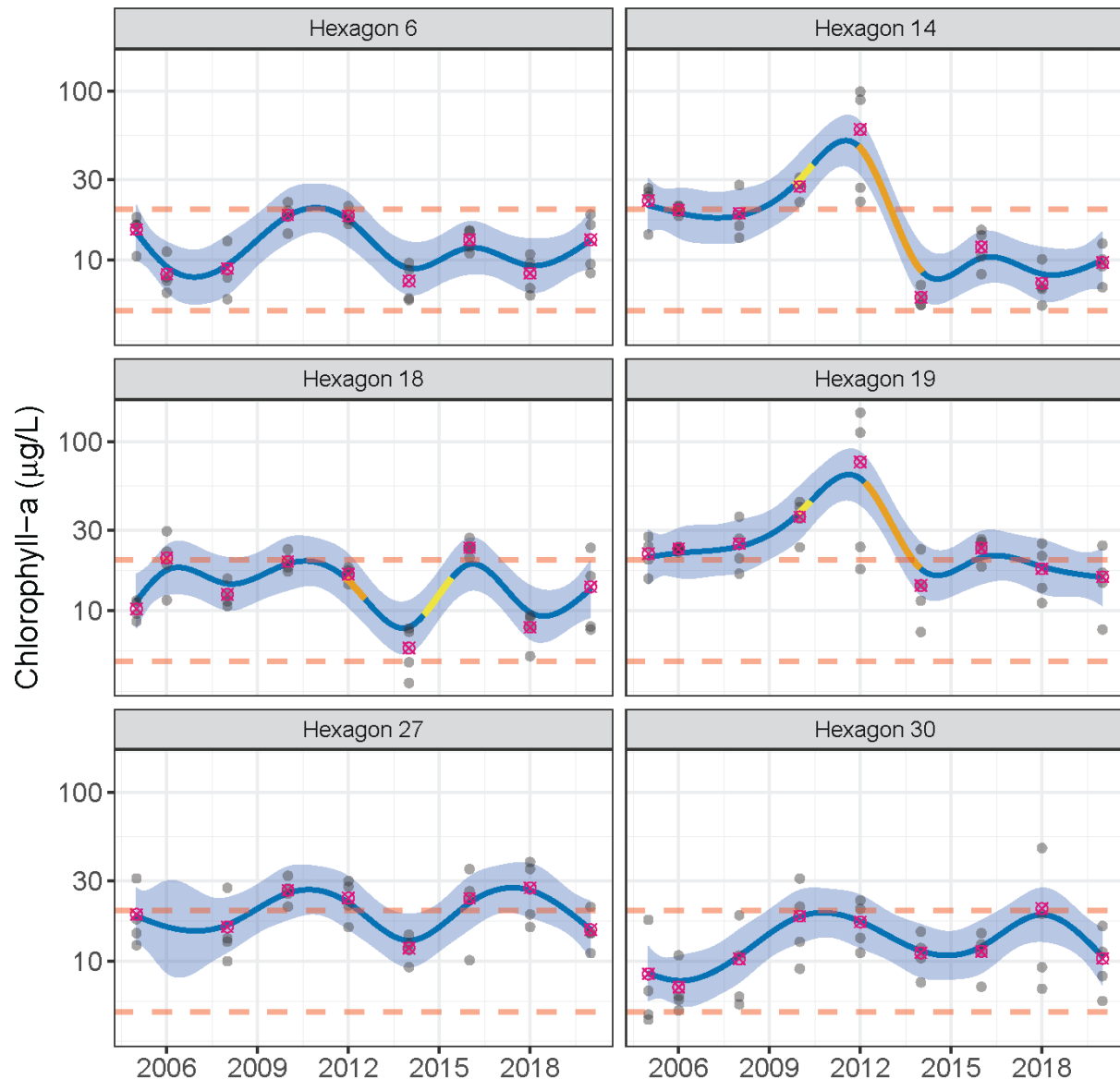


**Figure 3-5.** Mean surface temperature trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present,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

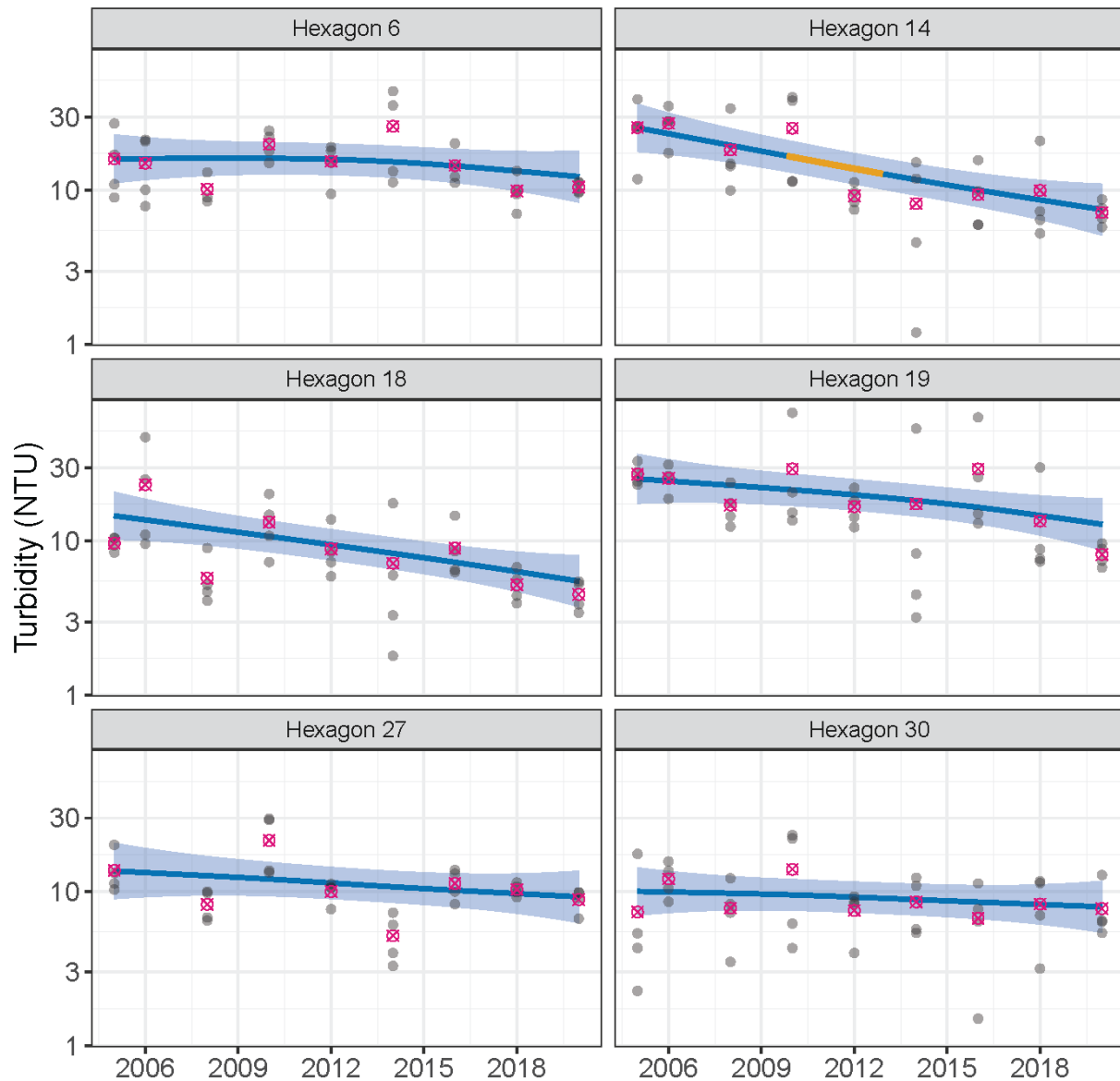


**Figure 3-6.** Mean surface turbidity trend at each Assateague Island National Seashore trend station based on generalized additive model smooths. The fitted smooth is plotted in dark blue with shaded 95% confidence interval. Periods of significant temporal change (increases/decreases), if present,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

### 3.4 Multivariate Mann-Kendall Trend Test Results

The multivariate Mann-Kendall test results indicate there is no statistical evidence (assuming a significance level of 0.05) of a monotonic trend in any of the measures measured at the trend stations during the index periods of 2005 to 2020 (Table 3-8).

**Table 3-8.** Summary of multivariate Mann-Kendall test for monotonic trend in each trend station 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      | 0.56     | 0.578      |
| Dissolved oxygen (mg/L)                      | Bottom       | 0.81     | 0.415      |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | Water Column | -0.46    | 0.648      |
| Salinity (psu)                               | Surface      | 1.23     | 0.218      |
| Temperature ( $^{\circ}\text{C}$ )           | Surface      | 1.11     | 0.267      |
| Turbidity (NTU)                              | Surface      | -1.27    | 0.202      |

## 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.

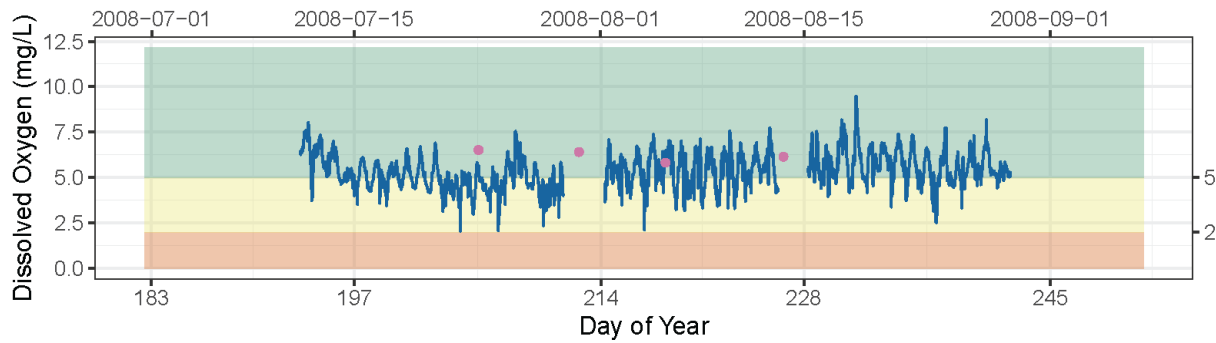


**Figure 4-1.** Continuous dissolved oxygen readings from sonde deployed at Assateague Island National Seashore logging station in 2008. Magenta points represent discrete grab samples collected every week for quality assurance. Estuarine quality category thresholds (Table 2-1) are delineated by the background 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 doym for the  $i$ th year,  $f(\text{hour})$  is a rank 24 cyclic cubic spline. The doym smoother is known as a factor-smoother and assumes that all factors (i.e., years) have the same smoothness, but may differ in shape over time. The smooth for hour is included to account for intra-day trends since many of the 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 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 4-2) and the associated distribution of measurements tends to also be highly skewed most years (Figure 4-2). Chlorophyll-*a* condition is generally 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 conditions are 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 ( $2.67 \text{ m}^{-1}$ ) was observed in 2012 and was followed by the lowest observed ( $0.75 \text{ m}^{-1}$  in 2014 (Table 4-1). Years 2005, 2006, 2012, 2016, and 2020 exhibited more highly non-linear mean trends compared to the other years (Figure 4-2). The distribution of measurements in 2012 and 2020 is highly right skewed compared to other years (Figure 4-3). For years where PAR attenuation conditions were poor (i.e., 2005, 2006 and 2012), a majority of each day was in poor condition (Figure 4-10).

#### **4.3.4 pH**

Measurements of pH obtained in 2020 were much more periodic and stationary compared to 2018. Both years exhibited a non-linear intra-annual mean trend (Figure 4-6).

#### **4.3.5 Salinity**

Intra-annual mean trends in salinity are non-linear and there are a few cases of increasing (2010 and 2018) or decreasing (2012, which appears to be somewhat anomalous) trends (Figure 4-4). Salinity measurements within each year typically span approximately 2-3 psu (Figure 4-5).

#### **4.3.6 Temperature**

Intra-annual mean trends in water temperature are highly non-linear with an overall decreasing trend from July to August (Figure 4-4). Water temperature measurements within each year typically span approximately  $6^\circ\text{C}$  (Figure 4-5), and temperatures don't decrease below  $28^\circ\text{C}$  until the first week of August.

#### **4.3.7 Turbidity**

Intra-annual mean trends in turbidity were generally fairly smooth except for the 2005, 2006, 2008, and 2012 (Figure 4-4). Turbidity measurements in 2008 were more left-skewed than other years (Figure 4-5). The distribution of turbidity in 2014 also appears somewhat anomalous compared to the other years.

**Table 4-1.** Yearly summary statistics for measures collected at the Assateague Island National Seashore logging station. Note: new logging station location for 2018. [SD = standard deviation]

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

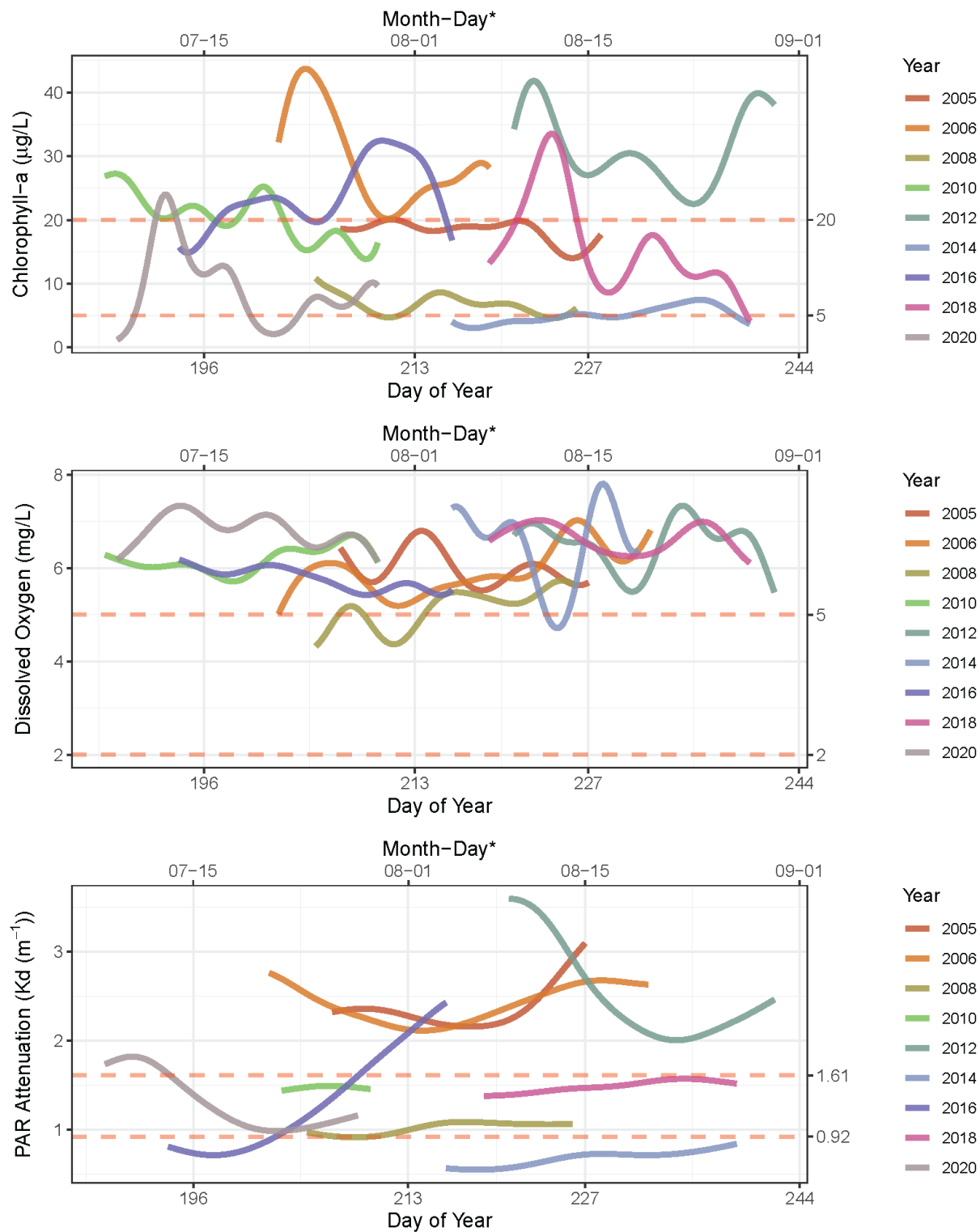


**Figure 4-2.** Intra-annual trends in surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Assateague Island National Seashore logging station based on generalized additive model smooths. Estuarine quality category thresholds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

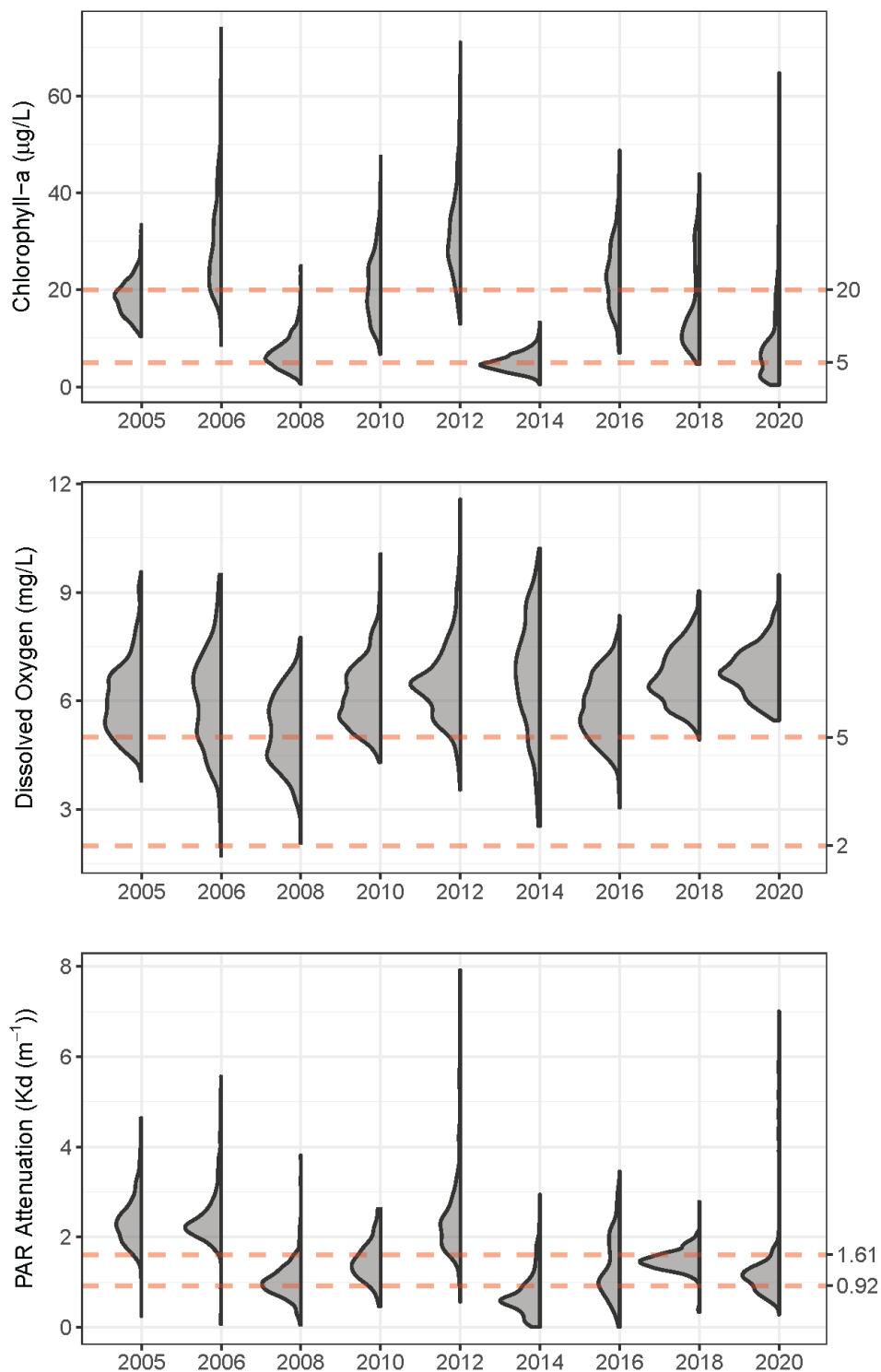


**Figure 4-3.** Distribution of index period time series values for surface chlorophyll-a concentration (top), bottom dissolved oxygen concentration (middle), and PAR attenuation (bottom) at the Assateague Island National Seashore logging station. Estuarine quality category thresholds (Table 2-1) are plotted as red dashed lines.

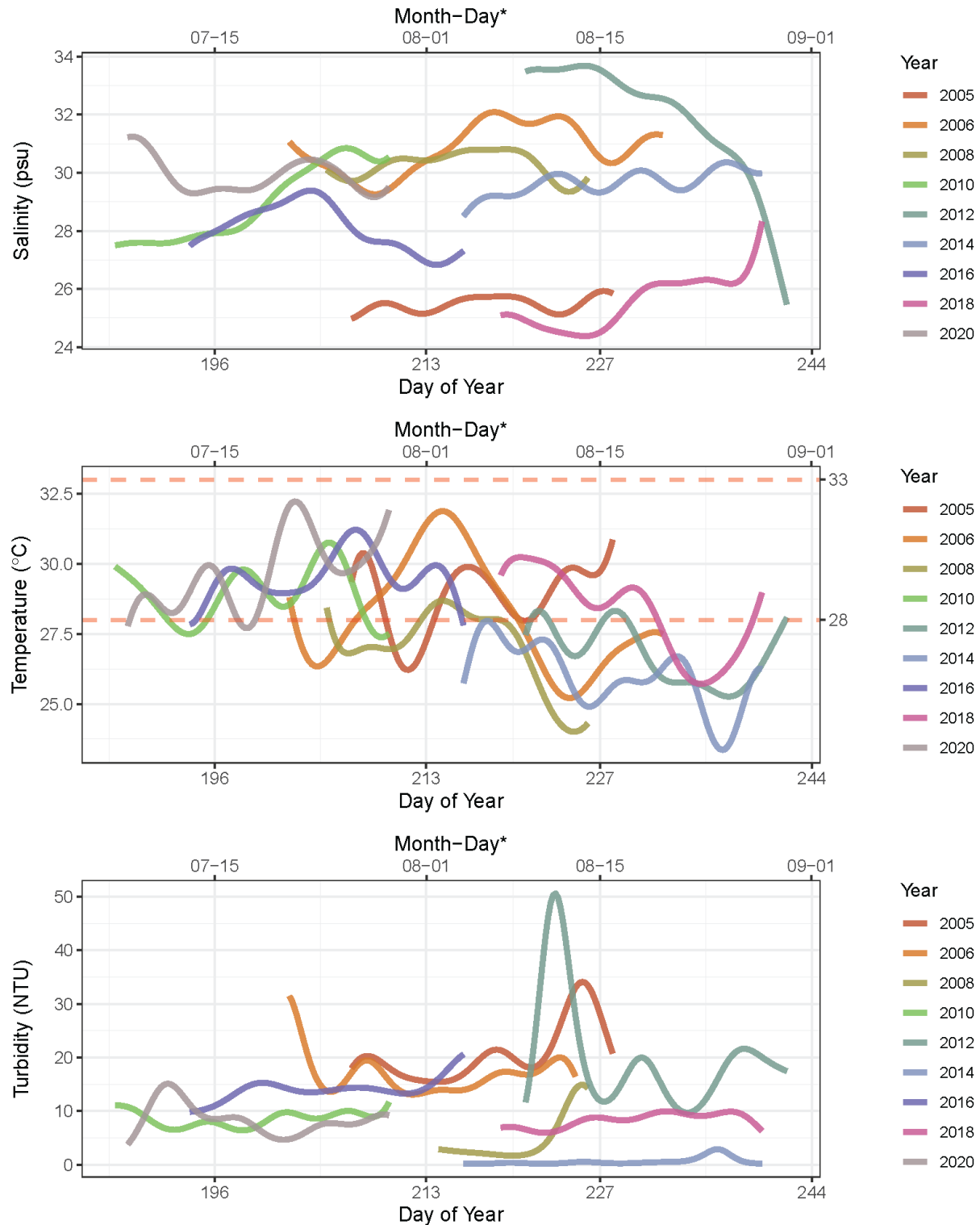


**Figure 4-4.** Intra-annual trends in surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Assateague Island National Seashore logging station based on generalized additive model smooths. Estuarine quality category thresholds (Table 2-1) are plotted as red dashed lines.

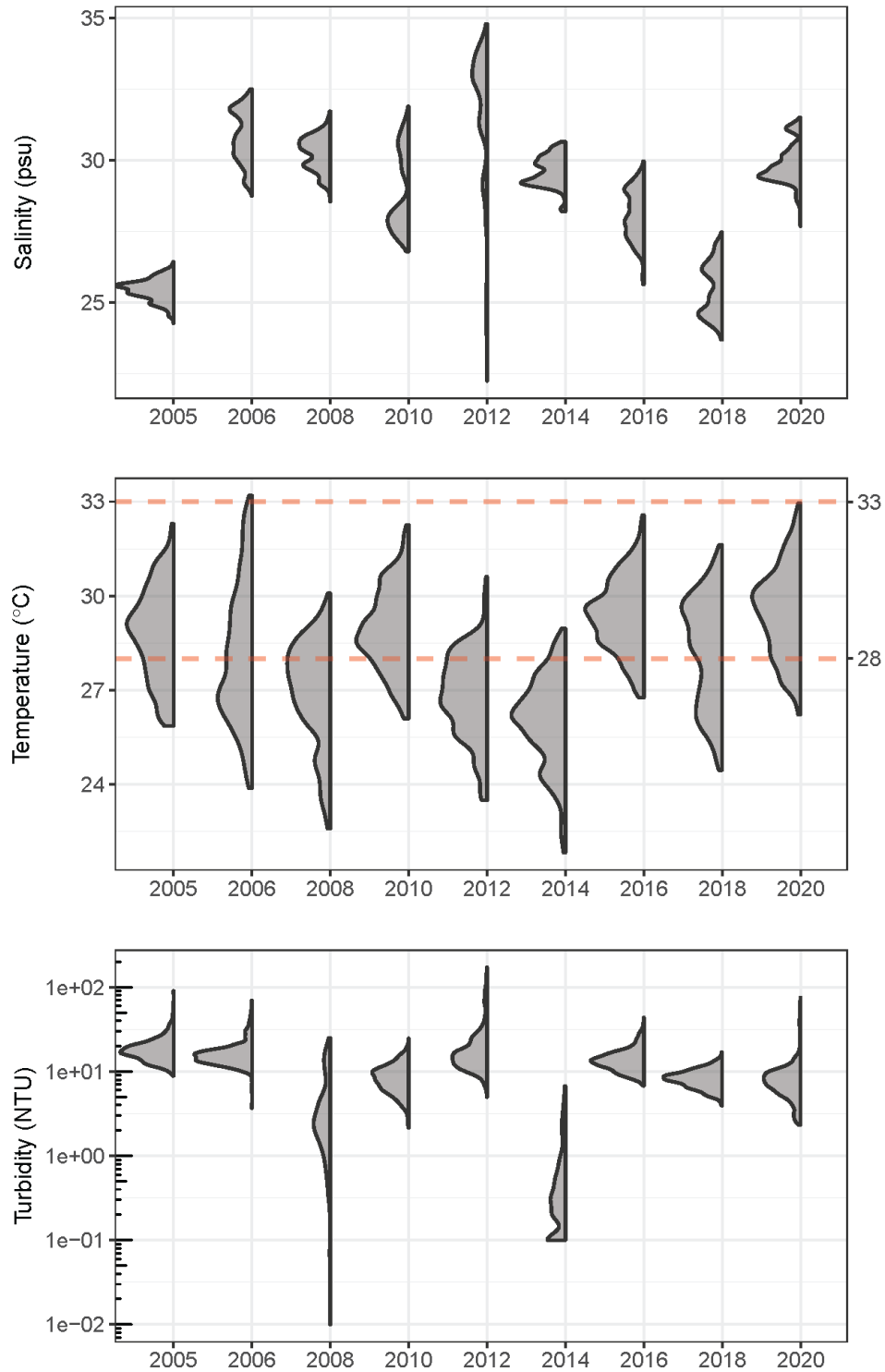


**Figure 4-5.** Distribution of index period time series values for surface salinity (top), surface temperature (middle), and surface turbidity (bottom) at the Assateague Island National Seashore logging station. Note: the surface turbidity y-axis is transformed to the  $\log_{10}$  scale to better visualize the estimated distributions. Estuarine quality category thresholds (Table 2-1) are plotted as red dashed lines.

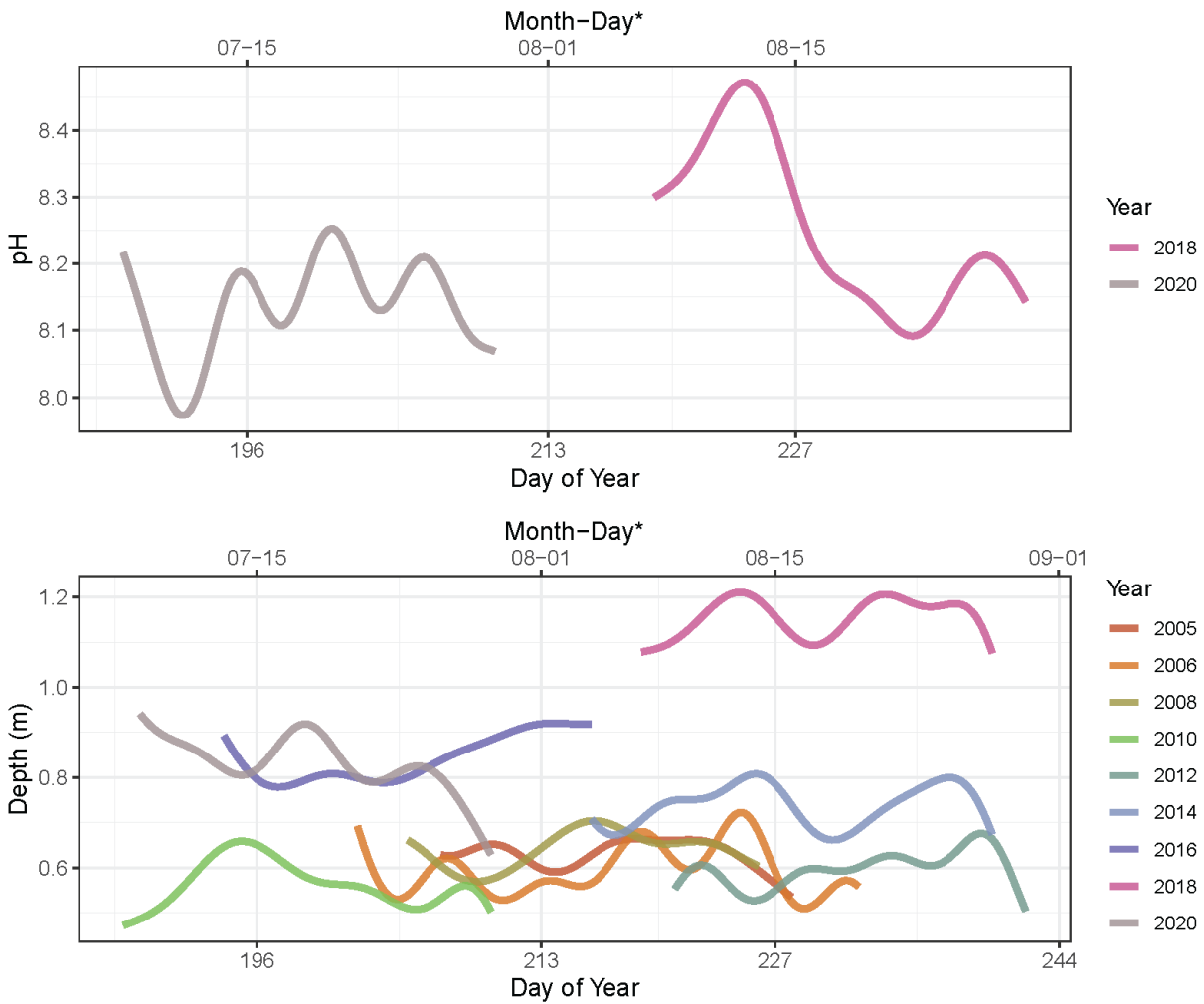


**Figure 4-6.** Intra-annual trends in pH (top) and depth (bottom) at the Assateague Island National Seashore logging station based on generalized additive model smooths.

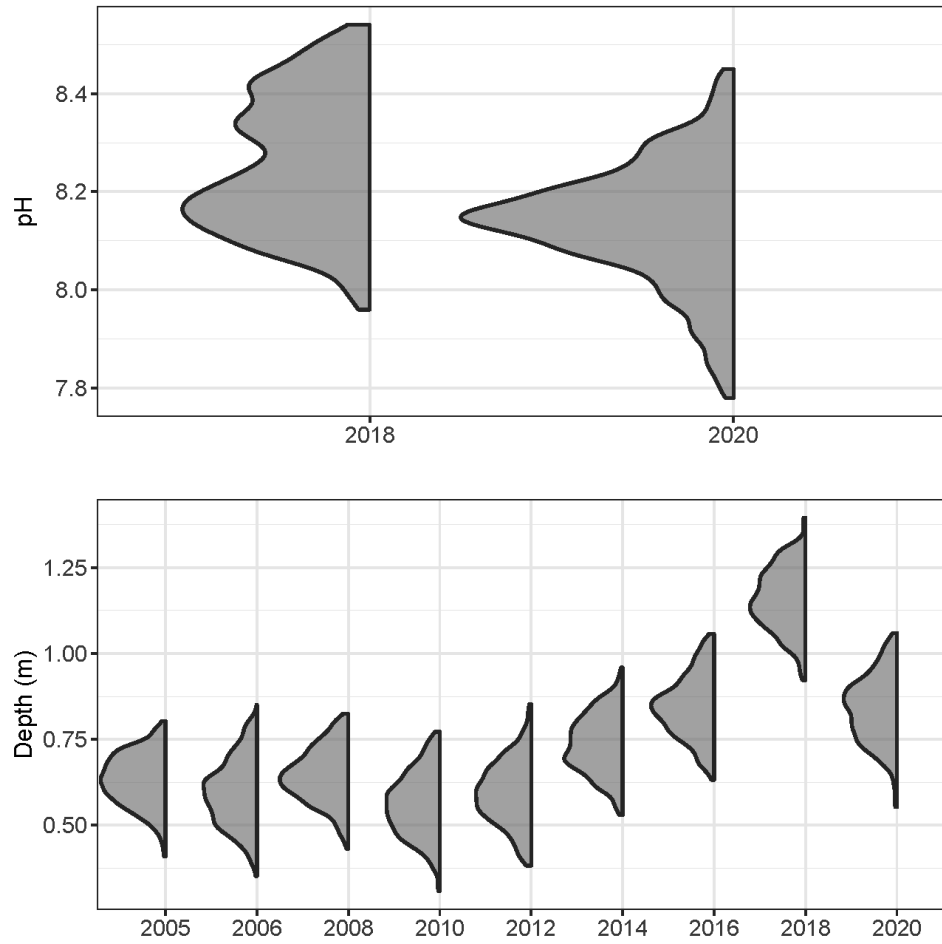


**Figure 4-7.** Distribution of index period time series values for pH (top) and depth (bottom) at the Assateague Island National Seashore logging station.

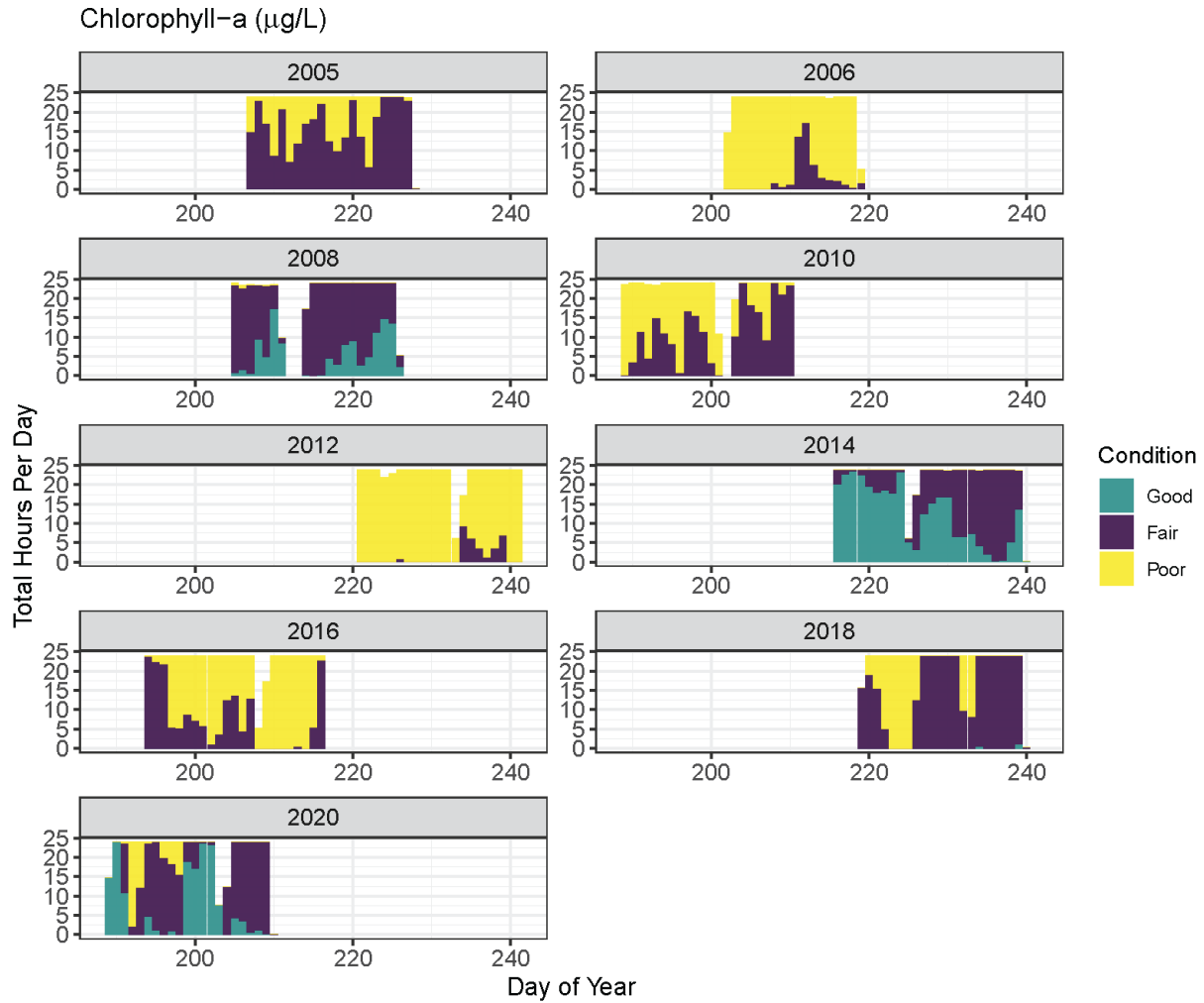


**Figure 4-8.** Total hours per day that surface chlorophyll-a concentration was observed within each condition category at the Assateague Island National Seashore logging station.

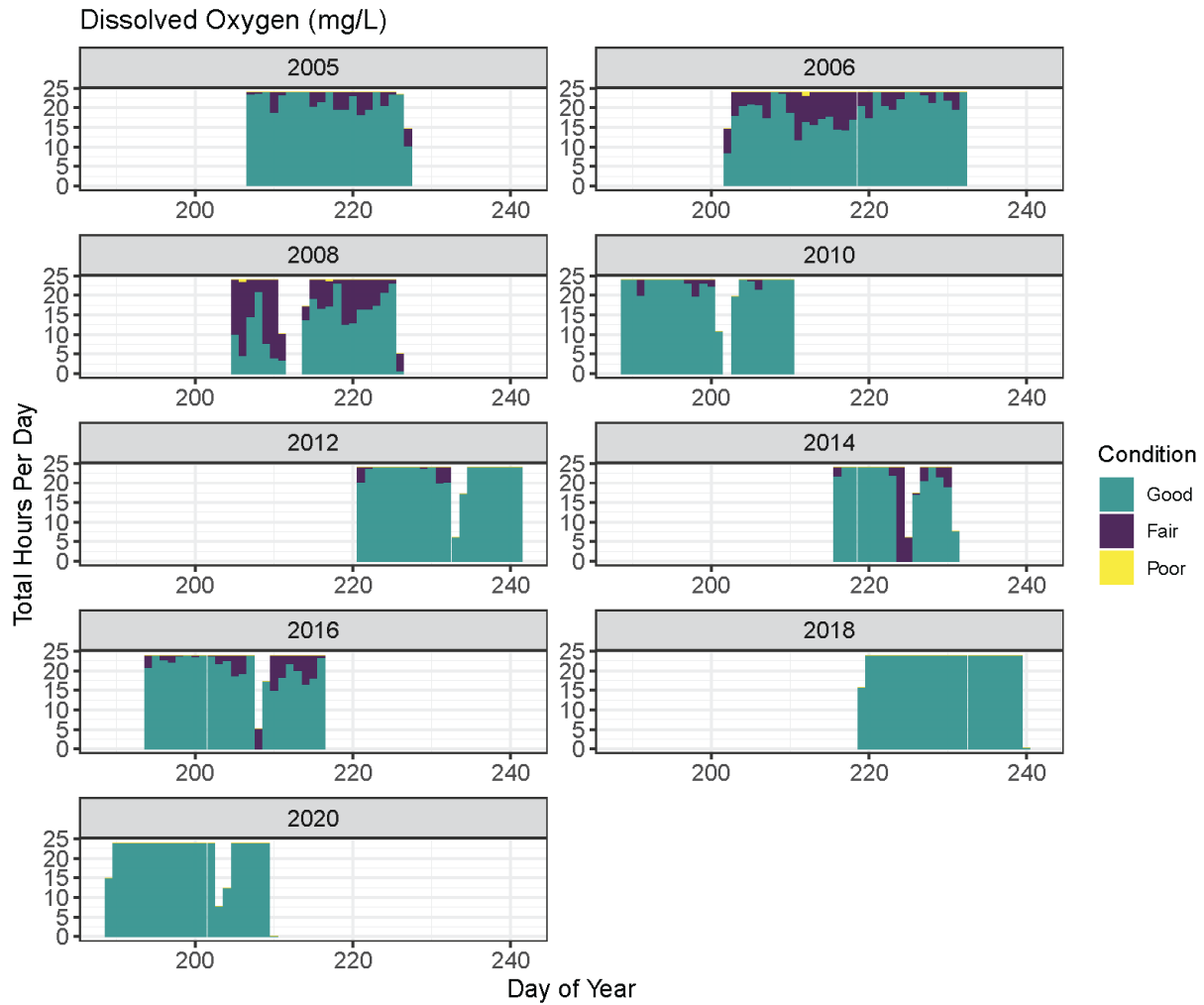


**Figure 4-9.** Total hours per day that bottom dissolved oxygen concentration was observed within each condition category at the Assateague Island National Seashore logging station.

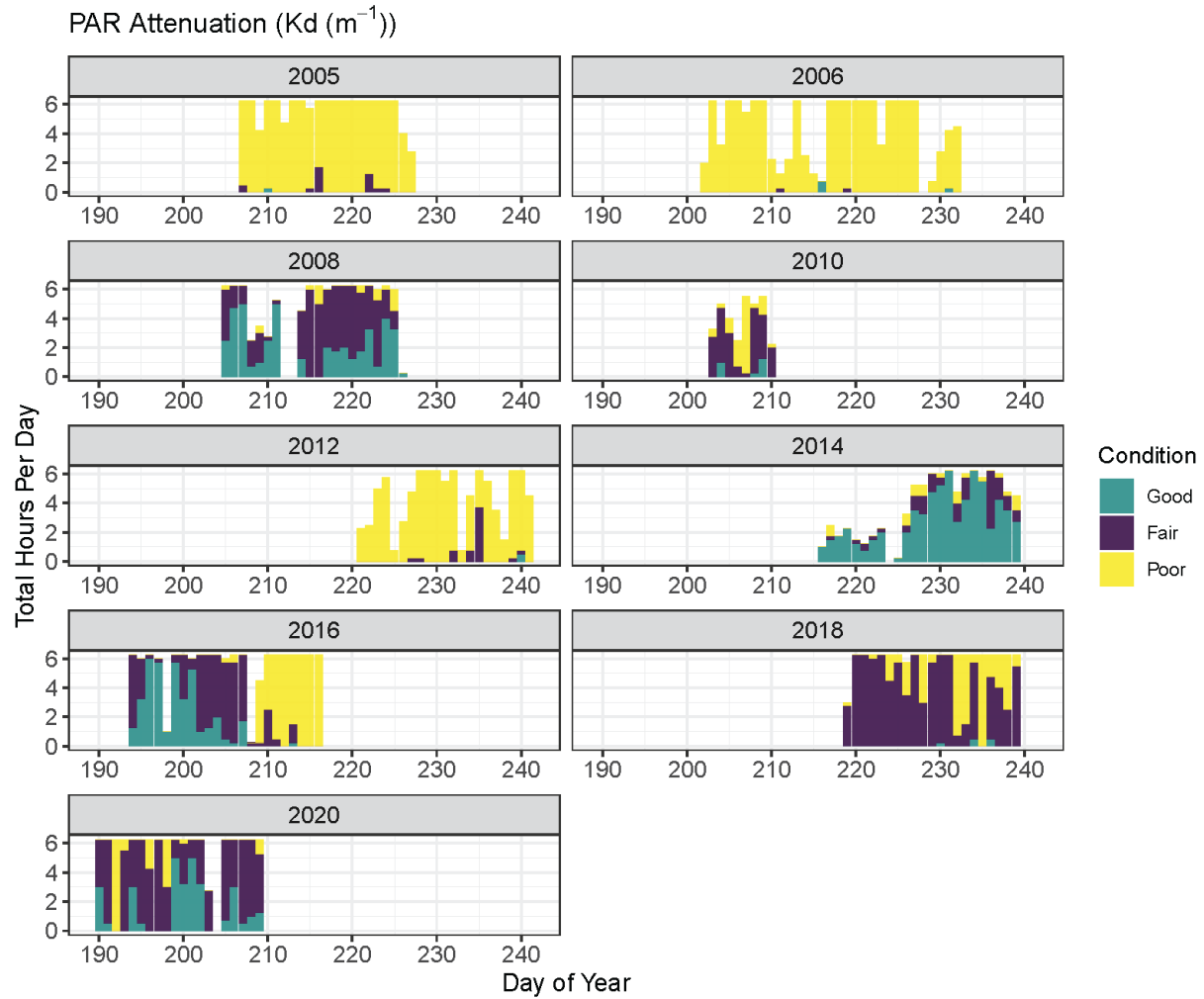


**Figure 4-10.** Total hours per day that PAR attenuation was observed within each condition category at the Assateague Island National Seashore logging station.

## 5. Seagrass Condition

### 5.1 Background

Seagrass monitoring data has been collected at the SeagrassNet monitoring site since 2009 following the standardized monitoring protocol outlined in Short et al. (2004). The 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 m<sup>2</sup> 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 m<sup>2</sup> 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  $f_{\text{transect}_i}$  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  $\phi$  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 m<sup>2</sup> or 0.0625 m<sup>2</sup> subplot within a quadrat. A negative binomial distribution was used instead of a Poisson to allow for

overdispersion<sup>6</sup>. 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 distribution<sup>7</sup>.
- 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.

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).

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<sup>6</sup> 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.

<sup>7</sup> 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 Summary Statistics

Yearly and monthly (if applicable) summary statistics are provided for both *Zostera marina* and *Ruppia maritima* (where applicable) 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 1m<sup>2</sup>) at Assateague Island National Seashore. [SD = standard deviation]

| Date    | Shallow Transect |       |    | Mid-Depth Transect |       |    | Deep Transect |       |    |
|---------|------------------|-------|----|--------------------|-------|----|---------------|-------|----|
|         | Mean             | SD    | n  | Mean               | SD    | n  | Mean          | SD    | n  |
| 2009-06 | 165.7            | 204.2 | 12 | 706.7              | 222.6 | 12 | 72.7          | 114.3 | 12 |
| 2009-10 | 19.3             | 24.6  | 12 | 291.0              | 126.3 | 12 | 28.0          | 82.4  | 12 |
| 2010-01 | 27.0             | 34.2  | 12 | 355.7              | 93.7  | 12 | 65.3          | 172.6 | 12 |
| 2010-04 | 30.3             | 46.0  | 12 | 560.0              | 159.3 | 12 | 67.7          | 169.6 | 12 |
| 2010-06 | 16.7             | 28.7  | 12 | 817.3              | 332.0 | 12 | 121.3         | 322.3 | 12 |
| 2010-10 | 4.7              | 11.0  | 12 | 143.0              | 127.5 | 12 | 3.0           | 10.4  | 12 |
| 2011-04 | 25.3             | 51.1  | 12 | 464.0              | 267.3 | 12 | 11.7          | 36.8  | 12 |
| 2011-06 | 120.0            | 287.7 | 12 | 382.7              | 225.0 | 12 | 6.0           | 20.8  | 12 |
| 2011-10 | 35.0             | 109.3 | 12 | 173.7              | 143.8 | 12 | 0.0           | 0.0   | 12 |
| 2012-04 | 141.0            | 290.2 | 12 | 275.3              | 202.0 | 12 | 6.7           | 11.6  | 12 |
| 2012-06 | 140.0            | 315.0 | 12 | 322.0              | 221.2 | 12 | 7.3           | 17.1  | 12 |
| 2012-10 | 0.3              | 1.2   | 12 | 9.7                | 15.1  | 12 | 0.0           | 0.0   | 12 |
| 2013-04 | 21.3             | 21.8  | 12 | 69.7               | 52.0  | 12 | 27.3          | 11.7  | 12 |
| 2013-06 | 141.3            | 94.8  | 12 | 147.3              | 103.3 | 12 | 132.0         | 81.4  | 12 |
| 2013-10 | 175.7            | 192.6 | 12 | 221.3              | 204.2 | 12 | 259.3         | 235.5 | 12 |
| 2014-04 | 249.7            | 276.9 | 12 | 272.7              | 184.7 | 12 | 242.3         | 185.1 | 12 |
| 2014-06 | 268.3            | 255.2 | 12 | 316.7              | 152.8 | 12 | 324.0         | 212.9 | 12 |
| 2014-10 | 21.3             | 34.0  | 12 | 54.7               | 57.2  | 12 | 95.7          | 84.2  | 12 |
| 2015-04 | 33.3             | 33.0  | 12 | 35.7               | 38.2  | 12 | 53.3          | 42.7  | 12 |
| 2015-06 | 36.3             | 23.7  | 12 | 37.7               | 61.6  | 12 | 45.7          | 46.6  | 12 |
| 2015-10 | 0.0              | 0.0   | 12 | 1.7                | 3.2   | 12 | 7.7           | 18.7  | 12 |
| 2016-04 | 0.0              | 0.0   | 12 | 3.7                | 8.9   | 12 | 28.3          | 47.1  | 12 |
| 2016-06 | 0.3              | 1.2   | 12 | 2.3                | 6.0   | 12 | 23.7          | 64.3  | 12 |
| 2016-10 | 0.0              | 0.0   | 12 | 0.0                | 0.0   | 12 | 0.0           | 0.0   | 12 |
| 2017-04 | 1.3              | 4.6   | 12 | 22.7               | 33.0  | 12 | 3.3           | 5.9   | 12 |
| 2017-06 | 3.0              | 8.2   | 12 | 56.7               | 51.8  | 12 | 1.3           | 4.6   | 12 |
| 2017-10 | 2.7              | 9.2   | 12 | 42.7               | 46.8  | 12 | 0.0           | 0.0   | 12 |
| 2018-04 | 12.3             | 35.6  | 12 | 150.7              | 176.4 | 12 | 0.0           | 0.0   | 12 |
| 2018-06 | 21.3             | 69.0  | 12 | 147.3              | 127.6 | 12 | 0.0           | 0.0   | 12 |
| 2018-10 | 29.7             | 101.5 | 12 | 168.3              | 126.9 | 12 | 0.0           | 0.0   | 12 |
| 2019-04 | 55.7             | 140.1 | 12 | 396.3              | 283.2 | 12 | 1.0           | 3.5   | 12 |
| 2019-06 | 57.0             | 109.2 | 12 | 298.0              | 184.1 | 12 | 0.0           | 0.0   | 12 |
| 2019-10 | 19.7             | 43.1  | 12 | 101.7              | 62.1  | 12 | 0.0           | 0.0   | 12 |

**Table 5-3.** Yearly (monthly within year, if applicable) summary statistics for percent cover (per 0.25m<sup>2</sup>) of *Ruppia maritima* and *Zostera marina* at Assateague Island National Seashore. [SD = standard deviation]

| Date    | <i>Ruppia maritima</i> |      |    |                    |      |    |               |      |    | <i>Zostera marina</i> |      |    |                    |      |    |               |      |    |
|---------|------------------------|------|----|--------------------|------|----|---------------|------|----|-----------------------|------|----|--------------------|------|----|---------------|------|----|
|         | Shallow Transect       |      |    | Mid-Depth Transect |      |    | Deep Transect |      |    | Shallow Transect      |      |    | Mid-Depth Transect |      |    | Deep Transect |      |    |
|         | Mean                   | SD   | n  | Mean               | SD   | n  | Mean          | SD   | n  | Mean                  | SD   | n  | Mean               | SD   | n  | Mean          | SD   | n  |
| 2009-06 | 23.7                   | 28.7 | 12 | 0.4                | 1.4  | 12 | 32.7          | 25.8 | 12 | 20.2                  | 26.5 | 12 | 88.3               | 18.9 | 12 | 8.2           | 12.8 | 12 |
| 2009-10 | 9                      | 19.5 | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 2.3                   | 3.2  | 12 | 35                 | 14.9 | 12 | 3.2           | 8.6  | 12 |
| 2010-01 | 5.8                    | 8.1  | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 3.5                   | 5    | 12 | 29.2               | 10.8 | 12 | 3.6           | 8.8  | 12 |
| 2010-04 | 19.8                   | 24.6 | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 4.8                   | 7.7  | 12 | 72.5               | 11.6 | 12 | 7.7           | 18.6 | 12 |
| 2010-06 | 59                     | 32.5 | 12 | 0                  | 0    | 12 | 0.2           | 0.6  | 12 | 1                     | 1.9  | 12 | 85.8               | 9    | 12 | 9.4           | 24.7 | 12 |
| 2010-10 | 0.7                    | 2.3  | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 0.6                   | 1.5  | 12 | 19.6               | 14.7 | 12 | 0.4           | 1.4  | 12 |
| 2011-04 | 2.4                    | 6.9  | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 1.8                   | 4.2  | 12 | 42.1               | 25.9 | 12 | 1.3           | 4.3  | 12 |
| 2011-06 | 11.6                   | 15.8 | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 10.8                  | 21.9 | 12 | 52.5               | 31.2 | 12 | 0.4           | 1.4  | 12 |
| 2011-10 | 14.9                   | 16.8 | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 2.2                   | 7.2  | 12 | 24.4               | 25.8 | 12 | 0             | 0    | 12 |
| 2012-04 | 44.6                   | 41.6 | 12 | 0                  | 0    | 12 | 0.2           | 0.9  | 12 | 15.1                  | 33   | 12 | 48.3               | 35.6 | 12 | 0.8           | 1.5  | 12 |
| 2012-06 | 59.6                   | 44.9 | 12 | 0                  | 0    | 12 | 4.6           | 14.4 | 12 | 17.5                  | 33.7 | 12 | 55                 | 33   | 12 | 1.2           | 3.1  | 12 |
| 2012-10 | 0                      | 0    | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 0.1                   | 0.3  | 12 | 1                  | 1.3  | 12 | 0             | 0    | 12 |
| 2013-04 | 0.2                    | 0.4  | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 1.8                   | 1.8  | 12 | 9.4                | 8.7  | 12 | 2.3           | 1.3  | 12 |
| 2013-06 | 3.8                    | 8    | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 15                    | 11.1 | 12 | 19.6               | 12.7 | 12 | 18.8          | 12.5 | 12 |
| 2013-10 | 4.2                    | 7    | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 16.6                  | 15.6 | 12 | 20.1               | 15.4 | 12 | 20.8          | 16.4 | 12 |
| 2014-04 | 15.9                   | 21.8 | 12 | 0.4                | 1.4  | 12 | 0             | 0    | 12 | 15.8                  | 15.1 | 12 | 19.3               | 13.9 | 12 | 13.3          | 8.9  | 12 |
| 2014-06 | 26.7                   | 24.2 | 12 | 1.2                | 3.1  | 12 | 0             | 0    | 12 | 33.8                  | 29.7 | 12 | 39.2               | 23.2 | 12 | 39.6          | 21.8 | 12 |
| 2014-10 | 1.1                    | 2.9  | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 3.2                   | 4.7  | 12 | 5.5                | 5.7  | 12 | 8.5           | 7.3  | 12 |
| 2015-04 | 0.8                    | 2.6  | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 3.8                   | 5.9  | 12 | 5.2                | 7.7  | 12 | 8.1           | 7.6  | 12 |
| 2015-06 | 2.1                    | 3.3  | 12 | 0.1                | 0.3  | 12 | 0             | 0    | 12 | 10.4                  | 11.3 | 12 | 8.7                | 14.5 | 12 | 9.1           | 11   | 12 |
| 2015-10 | 0.2                    | 0.4  | 12 | 0.1                | 0.3  | 12 | 0             | 0    | 12 | 0                     | 0    | 12 | 0.2                | 0.5  | 12 | 0.7           | 1.5  | 12 |
| 2016-04 | 1.8                    | 4.4  | 12 | 1.4                | 2    | 12 | 0             | 0    | 12 | 0                     | 0    | 12 | 0.5                | 1.4  | 12 | 4.3           | 7.2  | 12 |
| 2016-06 | 9.1                    | 15.7 | 12 | 19.1               | 24.7 | 12 | 0             | 0    | 12 | 0.1                   | 0.3  | 12 | 0.5                | 1.4  | 12 | 4.3           | 11.6 | 12 |
| 2016-10 | 19.8                   | 26.7 | 12 | 22.7               | 26.8 | 12 | 0.1           | 0.3  | 12 | 0                     | 0    | 12 | 0                  | 0    | 12 | 0             | 0    | 12 |
| 2017-04 | 27.8                   | 23.4 | 12 | 21.8               | 25.8 | 12 | 1.5           | 2    | 12 | 0.1                   | 0.3  | 12 | 2.8                | 3.8  | 12 | 0.4           | 0.5  | 12 |
| 2017-06 | 41.3                   | 32   | 12 | 32.2               | 27.3 | 12 | 1.8           | 3.2  | 12 | 0.5                   | 1.4  | 12 | 6.9                | 6.9  | 12 | 0.1           | 0.3  | 12 |

| Date    | <i>Ruppia maritima</i> |      |    |                    |      |    |               |     |    | <i>Zostera marina</i> |      |    |                    |      |    |               |     |    |
|---------|------------------------|------|----|--------------------|------|----|---------------|-----|----|-----------------------|------|----|--------------------|------|----|---------------|-----|----|
|         | Shallow Transect       |      |    | Mid-Depth Transect |      |    | Deep Transect |     |    | Shallow Transect      |      |    | Mid-Depth Transect |      |    | Deep Transect |     |    |
|         | Mean                   | SD   | n  | Mean               | SD   | n  | Mean          | SD  | n  | Mean                  | SD   | n  | Mean               | SD   | n  | Mean          | SD  | n  |
| 2017-10 | 14.6                   | 14.4 | 12 | 62.2               | 23.3 | 12 | 0.4           | 0.5 | 12 | 0.4                   | 1.4  | 12 | 7                  | 8.1  | 12 | 0             | 0   | 12 |
| 2018-04 | 11.8                   | 15.9 | 12 | 35.8               | 14.6 | 12 | 0             | 0   | 12 | 1.8                   | 4.4  | 12 | 16.3               | 13.7 | 12 | 0             | 0   | 12 |
| 2018-06 | 27.4                   | 27.2 | 12 | 54.1               | 21.1 | 12 | 0.1           | 0.3 | 12 | 2.2                   | 7.2  | 12 | 23.4               | 19.9 | 12 | 0             | 0   | 12 |
| 2018-10 | 43.7                   | 33.5 | 12 | 19.2               | 11.2 | 12 | 0             | 0   | 12 | 3.4                   | 11.5 | 12 | 17.9               | 11.8 | 12 | 0             | 0   | 12 |
| 2019-04 | 32.5                   | 28.5 | 12 | 8.4                | 5.6  | 12 | 0.2           | 0.5 | 12 | 7.1                   | 20.1 | 12 | 35.8               | 23.7 | 12 | 0.1           | 0.3 | 12 |
| 2019-06 | 32.3                   | 26.9 | 12 | 5.3                | 4.3  | 12 | 0             | 0   | 12 | 10.6                  | 22.2 | 12 | 38.8               | 26.9 | 12 | 0             | 0   | 12 |
| 2019-10 | 0                      | 0    | 12 | 0                  | 0    | 12 | 0             | 0   | 12 | 2.2                   | 5    | 12 | 12.5               | 8.7  | 12 | 0             | 0   | 12 |

**Table 5-4.** Yearly (monthly within year, if applicable) summary statistics for *Ruppia maritima* and *Zostera marina* canopy height (cm) at Assateague Island National Seashore. [SD = standard deviation]

| Date    | <i>Ruppia maritima</i> |     |    |                    |     |    |               |     |    | <i>Zostera marina</i> |     |    |                    |     |    |               |     |    |
|---------|------------------------|-----|----|--------------------|-----|----|---------------|-----|----|-----------------------|-----|----|--------------------|-----|----|---------------|-----|----|
|         | Shallow Transect       |     |    | Mid-Depth Transect |     |    | Deep Transect |     |    | Shallow Transect      |     |    | Mid-Depth Transect |     |    | Deep Transect |     |    |
|         | Mean                   | SD  | n  | Mean               | SD  | n  | Mean          | SD  | n  | Mean                  | SD  | n  | Mean               | SD  | n  | Mean          | SD  | n  |
| 2009-06 | 9.1                    | 1.6 | 9  | 20                 | —   | 1  | 11.9          | 3.5 | 11 | 9.9                   | 1.9 | 11 | 20.2               | 2.8 | 12 | 12            | 3.4 | 11 |
| 2009-10 | 12                     | 4.7 | 6  | —                  | —   | 0  | —             | —   | 0  | 12.4                  | 4.4 | 7  | 13.8               | 3.7 | 12 | 12.8          | 5.6 | 5  |
| 2010-01 | 11.5                   | 5.8 | 8  | —                  | —   | 0  | —             | —   | 0  | 14.9                  | 3.2 | 7  | 9.6                | 1.6 | 12 | 10.2          | 0.4 | 5  |
| 2010-04 | 8.4                    | 5.3 | 9  | —                  | —   | 0  | —             | —   | 0  | 11.8                  | 7.3 | 6  | 15.6               | 3.3 | 12 | 14.3          | 2.1 | 3  |
| 2010-06 | 12                     | 7.2 | 10 | —                  | —   | 0  | 17            | —   | 1  | 15.5                  | 11  | 4  | 17                 | 2.4 | 12 | 15            | 2.8 | 2  |
| 2010-10 | 13                     | —   | 1  | —                  | —   | 0  | —             | —   | 0  | 11.5                  | 2.1 | 2  | 18.8               | 2.3 | 10 | 13            | —   | 1  |
| 2011-04 | 9.5                    | 0.7 | 2  | —                  | —   | 0  | —             | —   | 0  | 9.4                   | 2.1 | 8  | 13.3               | 1.3 | 11 | 9.5           | 4.9 | 2  |
| 2011-06 | 9.4                    | 5.2 | 5  | —                  | —   | 0  | —             | —   | 0  | 10.3                  | 3.3 | 7  | 14.6               | 1.6 | 10 | 14            | —   | 1  |
| 2011-10 | 8.9                    | 1.7 | 8  | —                  | —   | 0  | —             | —   | 0  | 11                    | 1.4 | 2  | 12.9               | 2   | 10 | —             | —   | 0  |
| 2012-04 | 10.5                   | 5.2 | 10 | —                  | —   | 0  | 9             | —   | 1  | 14.2                  | 4.9 | 5  | 15.1               | 2.6 | 10 | 13.8          | 3.9 | 4  |
| 2012-06 | 18                     | 7.4 | 9  | —                  | —   | 0  | 7             | 1.4 | 2  | 18.2                  | 4.7 | 4  | 20.2               | 2.8 | 10 | 14            | 0   | 2  |
| 2012-10 | —                      | —   | 0  | —                  | —   | 0  | —             | —   | 0  | 5                     | —   | 1  | 6.8                | 1.8 | 8  | —             | —   | 0  |
| 2013-04 | 6                      | 1.4 | 2  | —                  | —   | 0  | —             | —   | 0  | 7.9                   | 2   | 10 | 12.3               | 2.7 | 11 | 10.1          | 3.6 | 12 |
| 2013-06 | 9.7                    | 3.2 | 3  | —                  | —   | 0  | —             | —   | 0  | 11.2                  | 1.5 | 10 | 13.4               | 1.3 | 11 | 15.2          | 1.5 | 12 |
| 2013-10 | 19.4                   | 4   | 7  | —                  | —   | 0  | —             | —   | 0  | 18.7                  | 4.3 | 11 | 22                 | 4   | 11 | 20.9          | 3.8 | 11 |
| 2014-04 | 9.6                    | 2.4 | 8  | 14                 | —   | 1  | —             | —   | 0  | 9                     | 3.4 | 11 | 14.6               | 0.7 | 11 | 11.4          | 3.9 | 12 |
| 2014-06 | 16.5                   | 5.2 | 11 | 17                 | 1.4 | 2  | —             | —   | 0  | 17.7                  | 4.1 | 10 | 17.3               | 1.2 | 11 | 17.6          | 3.5 | 11 |
| 2014-10 | 20.3                   | 0.6 | 3  | —                  | —   | 0  | —             | —   | 0  | 17.7                  | 4.6 | 7  | 10.6               | 1.9 | 8  | 12.4          | 2.6 | 9  |
| 2015-04 | 5                      | —   | 1  | —                  | —   | 0  | —             | —   | 0  | 6.6                   | 1.5 | 9  | 7.7                | 2.4 | 10 | 11.4          | 3.2 | 11 |
| 2015-06 | 8.8                    | 4.3 | 4  | 10                 | —   | 1  | —             | —   | 0  | 8.7                   | 2.6 | 10 | 9.1                | 1.7 | 9  | 10.8          | 2.5 | 10 |
| 2015-10 | 9                      | 0   | 2  | 10                 | —   | 1  | —             | —   | 0  | —                     | —   | 0  | 8.3                | 1.5 | 3  | 11            | 3.6 | 3  |
| 2016-04 | 5.3                    | 0.6 | 3  | 6.7                | 5.6 | 6  | —             | —   | 0  | —                     | —   | 0  | 15.5               | 3.5 | 2  | 13.4          | 2.6 | 7  |
| 2016-06 | 10.6                   | 3   | 5  | 8.9                | 3   | 7  | —             | —   | 0  | 15                    | —   | 1  | 12.5               | 0.7 | 2  | 15.2          | 4   | 4  |
| 2016-10 | 15.6                   | 5.6 | 10 | 13.8               | 3   | 8  | 10            | —   | 1  | —                     | —   | 0  | —                  | —   | 0  | —             | —   | 0  |
| 2017-04 | 5.7                    | 0.7 | 10 | 9.6                | 3.8 | 7  | 5             | 1.3 | 7  | 6                     | —   | 1  | 10.3               | 2.9 | 7  | 6.8           | 1.8 | 5  |
| 2017-06 | 19.4                   | 6   | 11 | 12.9               | 3   | 11 | 7             | 1.2 | 5  | 17                    | 4.2 | 2  | 13.4               | 2.8 | 11 | 17            | —   | 1  |
| 2017-10 | 13.7                   | 4   | 11 | 16.8               | 3.4 | 12 | 7.6           | 3.2 | 5  | 18                    | —   | 1  | 17.3               | 2.9 | 10 | —             | —   | 0  |

| Date    | <i>Ruppia maritima</i> |     |    |                    |     |    |               |     |   | <i>Zostera marina</i> |     |   |                    |     |    |               |    |   |
|---------|------------------------|-----|----|--------------------|-----|----|---------------|-----|---|-----------------------|-----|---|--------------------|-----|----|---------------|----|---|
|         | Shallow Transect       |     |    | Mid-Depth Transect |     |    | Deep Transect |     |   | Shallow Transect      |     |   | Mid-Depth Transect |     |    | Deep Transect |    |   |
|         | Mean                   | SD  | n  | Mean               | SD  | n  | Mean          | SD  | n | Mean                  | SD  | n | Mean               | SD  | n  | Mean          | SD | n |
| 2018-04 | 7.4                    | 2.8 | 11 | 9.8                | 1.8 | 12 | –             | –   | 0 | 10.7                  | 3.8 | 3 | 10.2               | 1.5 | 10 | –             | –  | 0 |
| 2018-06 | 9.7                    | 2.7 | 10 | 14.6               | 2.8 | 12 | 5             | –   | 1 | 14                    | 2.8 | 2 | 14.7               | 2.9 | 11 | –             | –  | 0 |
| 2018-10 | 12.3                   | 2.3 | 11 | 13.8               | 1.7 | 12 | –             | –   | 0 | 14                    | 2.8 | 2 | 13.8               | 1.7 | 12 | –             | –  | 0 |
| 2019-04 | 7.5                    | 2.8 | 11 | 10                 | 2.4 | 11 | 6.3           | 1.5 | 3 | 10.7                  | 4   | 3 | 10.5               | 1.8 | 11 | 12            | –  | 1 |
| 2019-06 | 8.4                    | 3.3 | 11 | 11.8               | 2.4 | 9  | –             | –   | 0 | 10.2                  | 3.5 | 6 | 11.6               | 2.2 | 12 | –             | –  | 0 |
| 2019-10 | –                      | –   | 0  | –                  | –   | 0  | –             | –   | 0 | 8.3                   | 0.6 | 3 | 8.5                | 1.4 | 11 | –             | –  | 0 |

**Table 5-5.** Yearly (monthly within year, if applicable) summary statistics for total biomass (g/m<sup>2</sup>) of *Ruppia maritima* and *Zostera marina* at Assateague Island National Seashore. [SD = standard deviation]

| Date    | <i>Ruppia maritima</i> |       |    |                    |      |    |               |      |    | <i>Zostera marina</i> |      |    |                    |      |    |               |      |    |
|---------|------------------------|-------|----|--------------------|------|----|---------------|------|----|-----------------------|------|----|--------------------|------|----|---------------|------|----|
|         | Shallow Transect       |       |    | Mid-Depth Transect |      |    | Deep Transect |      |    | Shallow Transect      |      |    | Mid-Depth Transect |      |    | Deep Transect |      |    |
|         | Mean                   | SD    | n  | Mean               | SD   | n  | Mean          | SD   | n  | Mean                  | SD   | n  | Mean               | SD   | n  | Mean          | SD   | n  |
| 2009-06 | 54.7                   | 50.6  | 12 | 6.5                | 21.8 | 12 | 43            | 20.6 | 8  | 19.9                  | 29.3 | 9  | 93.3               | 37.3 | 12 | 13.8          | 18.1 | 5  |
| 2009-10 | 20.1                   | 28.6  | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 1.5                   | 2.1  | 9  | 18.1               | 9.7  | 12 | 1.1           | 2.7  | 12 |
| 2010-01 | 6.4                    | 8.1   | 7  | 0                  | 0    | 12 | 0             | 0    | 12 | 0.1                   | 0.2  | 6  | 7.8                | 4.9  | 11 | 1.8           | 4.2  | 9  |
| 2010-04 | 20.3                   | 21.9  | 11 | 0                  | 0    | 12 | 0             | 0    | 12 | 4.8                   | 8.4  | 10 | 27.4               | 10.6 | 12 | 2.9           | 7.3  | 12 |
| 2010-06 | 151.5                  | 96.4  | 12 | 0                  | 0    | 12 | 0             | 0    | 11 | 0.2                   | 0.6  | 9  | 60.3               | 26.8 | 12 | 11.3          | 33   | 12 |
| 2010-10 | 0                      | 0     | 11 | 0                  | 0    | 12 | 0             | 0    | 12 | 0.2                   | 0.5  | 11 | 4.7                | 3.8  | 11 | 0.1           | 0.3  | 12 |
| 2011-04 | 1.8                    | 4.1   | 11 | 0                  | 0    | 12 | 0             | 0    | 12 | 0.2                   | 0.2  | 9  | 15.7               | 9.6  | 10 | 0.2           | 0.7  | 11 |
| 2011-06 | 27.8                   | 37.4  | 10 | 0                  | 0    | 12 | 0             | 0    | 12 | 8.8                   | 21.7 | 11 | 30.6               | 20.1 | 12 | 0.6           | 2    | 12 |
| 2011-10 | 72                     | 86    | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 1.3                   | 3.8  | 12 | 8.7                | 8.4  | 12 | 0             | 0    | 12 |
| 2012-04 | 33.4                   | 30    | 11 | 0.1                | 0.4  | 12 | 0             | 0    | 11 | 9.5                   | 18.5 | 11 | 17.9               | 14.6 | 12 | 0.3           | 0.6  | 12 |
| 2012-06 | 128.3                  | 135.5 | 12 | 0                  | 0    | 12 | 8.4           | 20.3 | 12 | 19.5                  | 45.7 | 11 | 31.3               | 21.7 | 12 | 0.4           | 1.4  | 11 |
| 2012-10 | 0                      | 0     | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 0                     | 0    | 11 | 0                  | 0    | 4  | 0             | 0    | 12 |
| 2013-04 | 0.8                    | 2.6   | 11 | 0                  | 0    | 12 | 0             | 0    | 12 | 0.3                   | 0.3  | 12 | 2.7                | 3    | 11 | 0.8           | 0.4  | 12 |
| 2013-06 | 8.6                    | 19.2  | 11 | 0                  | 0    | 12 | 0             | 0    | 12 | 5.8                   | 6.2  | 11 | 9.4                | 10.1 | 11 | 6.1           | 3.6  | 12 |
| 2013-10 | 29.6                   | 39.3  | 9  | 6.8                | 22.9 | 12 | 0             | 0    | 12 | 9.2                   | 10.6 | 12 | 15                 | 12.7 | 11 | 19.2          | 19.2 | 12 |
| 2014-04 | 20.7                   | 27.4  | 9  | 8.5                | 20.2 | 12 | 0             | 0    | 12 | 9.7                   | 11   | 10 | 15.4               | 10.7 | 11 | 12.9          | 15.2 | 12 |
| 2014-06 | 50.6                   | 32    | 11 | 5.6                | 13.1 | 12 | 0             | 0    | 12 | 19.9                  | 23.8 | 10 | 27.4               | 18.5 | 12 | 28.3          | 20   | 12 |
| 2014-10 | 1.2                    | 3.7   | 10 | 4.8                | 11.6 | 12 | 0             | 0    | 12 | 1.1                   | 1.9  | 12 | 3.4                | 4.7  | 11 | 4.3           | 3.4  | 12 |
| 2015-04 | 0.8                    | 2.6   | 12 | 0                  | 0    | 12 | 0             | 0    | 12 | 0.8                   | 0.8  | 8  | 1.5                | 1.8  | 12 | 2             | 2.5  | 12 |
| 2015-06 | 13.8                   | 24.7  | 10 | 1.5                | 5.1  | 12 | 0             | 0    | 12 | 1.9                   | 1.8  | 11 | 2.4                | 4.2  | 12 | 3.2           | 3.9  | 12 |
| 2015-10 | 0.2                    | 0.7   | 11 | 0                  | 0    | 11 | 0             | 0    | 12 | 0                     | 0    | 12 | 0                  | 0.1  | 10 | 0.3           | 0.7  | 12 |
| 2016-04 | 7.4                    | 13.6  | 12 | 8                  | 15.1 | 8  | 0             | 0    | 12 | 0                     | 0    | 12 | 0.2                | 0.6  | 12 | 1.5           | 3    | 11 |
| 2016-06 | 20.2                   | 30.8  | 11 | 34                 | 35.2 | 12 | 0             | 0    | 12 | 0                     | 0    | 11 | 0                  | 0    | 10 | 1.8           | 5.2  | 12 |
| 2016-10 | 25.8                   | 24.2  | 12 | 14.5               | 14.5 | 12 | 0.5           | 1.8  | 12 | 0                     | 0    | 12 | 0                  | 0    | 12 | 0             | 0    | 12 |
| 2017-04 | 30.2                   | 21    | 12 | 15                 | 15.4 | 12 | 3.5           | 3.5  | 12 | 0                     | 0    | 11 | 0.4                | 0.7  | 8  | 0.1           | 0.1  | 11 |
| 2017-06 | 22.5                   | 18.3  | 12 | 24.7               | 20.1 | 11 | 4.1           | 5.4  | 12 | 0.1                   | 0.2  | 11 | 4.2                | 2.9  | 8  | 0.1           | 0.3  | 12 |
| 2017-10 | 12.7                   | 11.3  | 12 | 47.3               | 20.7 | 12 | 0.5           | 1.2  | 9  | 0                     | 0    | 11 | 3.7                | 3.5  | 5  | 0             | 0    | 12 |

| Date    | <i>Ruppia maritima</i> |      |    |                    |      |    |               |     |    | <i>Zostera marina</i> |      |    |                    |      |    |               |    |    |
|---------|------------------------|------|----|--------------------|------|----|---------------|-----|----|-----------------------|------|----|--------------------|------|----|---------------|----|----|
|         | Shallow Transect       |      |    | Mid-Depth Transect |      |    | Deep Transect |     |    | Shallow Transect      |      |    | Mid-Depth Transect |      |    | Deep Transect |    |    |
|         | Mean                   | SD   | n  | Mean               | SD   | n  | Mean          | SD  | n  | Mean                  | SD   | n  | Mean               | SD   | n  | Mean          | SD | n  |
| 2018-04 | 22.3                   | 13   | 11 | 44.2               | 23.5 | 11 | 0             | 0   | 12 | 0.4                   | 1.2  | 11 | 10.5               | 15.4 | 10 | 0             | 0  | 12 |
| 2018-06 | 51.7                   | 42.5 | 12 | 77.5               | 53.5 | 11 | 1.3           | 4.5 | 12 | 1.1                   | 3.6  | 12 | 10.9               | 9.4  | 10 | 0             | 0  | 12 |
| 2018-10 | 35.8                   | 25.7 | 12 | 16.8               | 8.1  | 12 | 0             | 0   | 12 | 0                     | 0    | 10 | 7.3                | 5.7  | 9  | 0             | 0  | 12 |
| 2019-04 | 34.2                   | 20.8 | 11 | 6.4                | 4.6  | 5  | 0.6           | 1.4 | 11 | 4.6                   | 12.3 | 11 | 33.7               | 40.7 | 12 | 0             | 0  | 11 |
| 2019-06 | 64.9                   | 28.2 | 12 | 13.7               | 11   | 11 | 0             | 0   | 12 | 0.9                   | 2.5  | 7  | 44.7               | 59.3 | 12 | 0             | 0  | 12 |
| 2019-10 | 0                      | 0    | 12 | 0                  | 0    | 12 | 0             | 0   | 12 | 0.4                   | 1    | 11 | 4.7                | 3.7  | 12 | 0             | 0  | 12 |

**Table 5-6.** Yearly (monthly within year, if applicable) summary statistics for ratio of above to below ground biomass of *Ruppia maritima* and *Zostera marina* at Assateague Island National Seashore. [SD = standard deviation]

| Date    | <i>Ruppia maritima</i> |     |    |                    |     |    |               |     |   | <i>Zostera marina</i> |     |    |                    |     |    |               |     |    |
|---------|------------------------|-----|----|--------------------|-----|----|---------------|-----|---|-----------------------|-----|----|--------------------|-----|----|---------------|-----|----|
|         | Shallow Transect       |     |    | Mid-Depth Transect |     |    | Deep Transect |     |   | Shallow Transect      |     |    | Mid-Depth Transect |     |    | Deep Transect |     |    |
|         | Mean                   | SD  | n  | Mean               | SD  | n  | Mean          | SD  | n | Mean                  | SD  | n  | Mean               | SD  | n  | Mean          | SD  | n  |
| 2009-06 | 1.5                    | 1   | 11 | 11.3               | 7.5 | 2  | 1.8           | 0.9 | 8 | 2.4                   | 2.1 | 8  | 0.6                | 0.3 | 12 | 1.9           | 1.5 | 5  |
| 2009-10 | 1.2                    | 0.4 | 9  | —                  | —   | 0  | —             | —   | 0 | 2.9                   | 2.1 | 4  | 1                  | 0.3 | 12 | 1.3           | 0.3 | 5  |
| 2010-01 | —                      | —   | 0  | —                  | —   | 0  | —             | —   | 0 | 0.4                   | —   | 1  | 0.8                | 0.5 | 11 | 0.6           | 0.2 | 2  |
| 2010-04 | 1.1                    | 0.2 | 7  | —                  | —   | 0  | —             | —   | 0 | 2.2                   | 0.4 | 4  | 2.8                | 1.6 | 12 | 1.3           | 0.3 | 3  |
| 2010-06 | 2.1                    | 0.8 | 10 | —                  | —   | 0  | —             | —   | 0 | 2.7                   | —   | 1  | 1.9                | 0.6 | 12 | 3.3           | 0.7 | 2  |
| 2010-10 | —                      | —   | 0  | —                  | —   | 0  | —             | —   | 0 | 3.9                   | —   | 1  | 1.5                | 0.4 | 9  | 0.4           | —   | 1  |
| 2011-04 | 1.6                    | 0.7 | 2  | —                  | —   | 0  | —             | —   | 0 | 1.8                   | 0.3 | 5  | 2.6                | 1.8 | 9  | 2.2           | —   | 1  |
| 2011-06 | 5.9                    | 9.4 | 5  | —                  | —   | 0  | —             | —   | 0 | 2.5                   | 2.6 | 8  | 2.8                | 1.3 | 10 | 1.4           | —   | 1  |
| 2011-10 | 1.5                    | 0.8 | 8  | —                  | —   | 0  | —             | —   | 0 | 2.4                   | 1.1 | 3  | 1.6                | 1.4 | 10 | —             | —   | 0  |
| 2012-04 | 1.2                    | 0.5 | 9  | 1.5                | —   | 1  | —             | —   | 0 | 5.4                   | 4.8 | 4  | 2.6                | 1.4 | 10 | 2.5           | 0.6 | 4  |
| 2012-06 | 2.3                    | 0.9 | 10 | —                  | —   | 0  | 1.8           | 0.4 | 2 | 2.9                   | 1.7 | 4  | 2                  | 0.8 | 10 | 1.1           | 0.7 | 2  |
| 2012-10 | —                      | —   | 0  | —                  | —   | 0  | —             | —   | 0 | —                     | —   | 0  | —                  | —   | 0  | —             | —   | 0  |
| 2013-04 | 0.5                    | —   | 1  | —                  | —   | 0  | —             | —   | 0 | 2.6                   | 1.3 | 10 | 3.4                | 2.1 | 10 | 2.9           | 1   | 11 |
| 2013-06 | 1.4                    | 0   | 2  | —                  | —   | 0  | —             | —   | 0 | 1.5                   | 1   | 9  | 2.4                | 1.5 | 10 | 1.9           | 0.7 | 12 |
| 2013-10 | 1.8                    | 0.8 | 4  | 1.2                | 0.2 | 2  | —             | —   | 0 | 3.4                   | 2.9 | 11 | 2.9                | 2.7 | 10 | 2.3           | 0.9 | 11 |
| 2014-04 | 1.2                    | 0.2 | 5  | 0.7                | 0.3 | 2  | —             | —   | 0 | 1.7                   | 1.3 | 9  | 3.5                | 3.9 | 10 | 1.7           | 1.9 | 12 |
| 2014-06 | 1.5                    | 0.8 | 10 | 2.7                | 2.9 | 3  | —             | —   | 0 | 1.9                   | 1.3 | 10 | 1.5                | 0.9 | 11 | 1.7           | 0.5 | 11 |
| 2014-10 | 1.3                    | —   | 1  | 1.3                | 1.2 | 2  | —             | —   | 0 | 1.2                   | 0.6 | 7  | 0.9                | 0.5 | 7  | 0.9           | 0.8 | 9  |
| 2015-04 | —                      | —   | 0  | —                  | —   | 0  | —             | —   | 0 | 1.6                   | 1.1 | 6  | 1.9                | 1.6 | 10 | 2.2           | 1.3 | 11 |
| 2015-06 | 1.3                    | 0.4 | 3  | 2.2                | —   | 1  | —             | —   | 0 | 1.2                   | 0.6 | 9  | 1.2                | 0.5 | 9  | 3.1           | 4.4 | 10 |
| 2015-10 | 1.1                    | —   | 1  | —                  | —   | 0  | —             | —   | 0 | —                     | —   | 0  | 2.7                | —   | 1  | 0.7           | 0   | 3  |
| 2016-04 | 0.9                    | 0.4 | 3  | 1.7                | 0.2 | 2  | —             | —   | 0 | —                     | —   | 0  | 1.8                | 1.2 | 6  | 1.2           | 0.4 | 6  |
| 2016-06 | 1.6                    | 0.8 | 4  | 1.6                | 0.5 | 7  | —             | —   | 0 | 0.6                   | —   | 1  | —                  | —   | 0  | 3.1           | 1.7 | 4  |
| 2016-10 | 1.4                    | 0.7 | 10 | 1.1                | 0.3 | 8  | 2.4           | —   | 1 | —                     | —   | 0  | —                  | —   | 0  | —             | —   | 0  |
| 2017-04 | 0.7                    | 0.2 | 10 | 0.8                | 0.1 | 7  | 1.4           | 0.7 | 7 | —                     | —   | 0  | 1.8                | 0.4 | 3  | 1.9           | 0.8 | 4  |
| 2017-06 | 2.9                    | 3.7 | 11 | 1.5                | 0.6 | 10 | 2             | 0.6 | 5 | 2.5                   | —   | 1  | 1.2                | 0.7 | 7  | 1.9           | —   | 1  |
| 2017-10 | 2.5                    | 4.8 | 11 | 1.4                | 0.6 | 12 | 1.1           | 0.7 | 2 | —                     | —   | 0  | 2.9                | 3.4 | 3  | 11.7          | —   | 1  |

| Date    | <i>Ruppia maritima</i> |     |    |                    |     |    |               |     |   | <i>Zostera marina</i> |     |   |                    |     |    |               |    |   |
|---------|------------------------|-----|----|--------------------|-----|----|---------------|-----|---|-----------------------|-----|---|--------------------|-----|----|---------------|----|---|
|         | Shallow Transect       |     |    | Mid-Depth Transect |     |    | Deep Transect |     |   | Shallow Transect      |     |   | Mid-Depth Transect |     |    | Deep Transect |    |   |
|         | Mean                   | SD  | n  | Mean               | SD  | n  | Mean          | SD  | n | Mean                  | SD  | n | Mean               | SD  | n  | Mean          | SD | n |
| 2018-04 | 1.1                    | 0.3 | 10 | 1.1                | 0.5 | 11 | –             | –   | 0 | 1.2                   | 0.9 | 3 | 2.8                | 1.8 | 8  | –             | –  | 0 |
| 2018-06 | 1.6                    | 0.4 | 10 | 2                  | 0.6 | 11 | 2.6           | –   | 1 | 1.5                   | 0.5 | 2 | 2.2                | 0.9 | 9  | –             | –  | 0 |
| 2018-10 | 1.2                    | 0.7 | 11 | 1.7                | 1.5 | 12 | –             | –   | 0 | –                     | –   | 0 | 3.3                | 4.5 | 10 | –             | –  | 0 |
| 2019-04 | 1.2                    | 0.5 | 10 | 1.1                | 1   | 5  | 0.7           | 0.5 | 2 | 3.3                   | 2.3 | 4 | 2.1                | 2.2 | 12 | –             | –  | 0 |
| 2019-06 | 2.1                    | 0.7 | 11 | 1.7                | 0.6 | 10 | –             | –   | 0 | 1.2                   | –   | 1 | 1.3                | 0.6 | 12 | –             | –  | 0 |
| 2019-10 | –                      | –   | 0  | –                  | –   | 0  | –             | –   | 0 | 1.3                   | 0.7 | 2 | 1.1                | 0.6 | 11 | –             | –  | 0 |

## 5.5 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), all *Ruppia maritima* measures (Table 5-8), and ancillary sediments (Table 5-9). Notable observations from the fitted smooths for each measure are as follows:

### 5.5.1 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 after 2015 is minimal for both the shallow and deep transects. Shoot density within the mid-depth transect has generally been decreasing with a slight increase occurring since 2016.

### 5.5.2 Percent Cover

*Zostera marina* experienced a decline in percent cover within the mid-depth transect from 2009 to 2016 but has since been on the increase (Figure 5-2). There was a statistically significant increase in percent cover around 2013 within the deep transect.

Percent cover of *Ruppia maritima* is generally highest within the shallow transect, where measurements are also the most variable. Increased cover within the mid-depth transect occurred during the period of 2016-2018, but dropped off in 2019 (Figure 5-3).

### 5.5.3 Canopy Height

The trend in *Zostera marina* canopy height is cyclical in nature with a slight overall decline within the mid-depth transect (Figure 5-4).

There is generally a lack of trend for *Ruppia maritima* canopy height. There has been a recent decline within the shallow transect during the period of 2017 to 2019 (Figure 5-5).

### 5.5.4 Total Biomass

*Zostera marina* experienced a decline in total biomass within the mid-depth transect from 2009 to 2016 but has since been on the increase (Figure 5-6). There was a statistically significant increase in total biomass around 2013 within the deep transect.

Total biomass of *Ruppia maritima* is generally highest within the shallow transect and the trend is cyclical in nature during the period of 2009 to 2015 (Figure 5-7). There was increased biomass within the mid-depth transect during the period of 2016-2018, but measurements decreased the following year in 2019.

### 5.5.5 Above to Below Ground Biomass Ratio

There has been an overall slight decline in the *Zostera marina* above to below ground biomass ratio during the period of 2011 to 2015 within the mid-depth and shallow transects (Figure 5-8). A similar decline was observed within the shallow transect for *Ruppia maritima* (Figure 5-9).

### 5.5.6 Percent Fine Sediment

Percent fine sediment within the transects is low and temporal trends differ by transect (Figure 5-10).

### 5.5.7 Percent Organic Material

Percent organic material within the transects is very low. Temporal trends differ by transect (Figure 5-11) and mirror the trends in percent fine sediment.

**Table 5-7.** Approximate significance of the generalized additive model smooth terms for each Assateague Island National Seashore *Zostera marina* model. Each respective  $p$ -value corresponds to the test of the hypotheses:  $H_0: f(x) = 0$  versus  $H_1: f(x) \neq 0$ . Note:  $p$ -values are computed without considering uncertainty in the smoothing parameter estimates and may need to be interpreted with caution when near the  $\alpha$  level. [edf = effective degrees of freedom]

| Measure                    | Model Term        | edf   | $p$ -value |
|----------------------------|-------------------|-------|------------|
| Shoot density              | s(year, transect) | 23.80 | < 0.001    |
| Percent cover              | s(year, transect) | 21.53 | < 0.001    |
| Canopy height              | s(year, transect) | 26.23 | < 0.001    |
| Total biomass              | s(year, transect) | 24.90 | < 0.001    |
| Above:below ground biomass | s(year, transect) | 11.39 | < 0.001    |

**Table 5-8.** Approximate significance of the generalized additive model smooth terms for each Assateague Island National Seashore *Ruppia maritima* model. Each respective  $p$ -value corresponds to the test of the hypotheses:  $H_0: f(x) = 0$  versus  $H_1: f(x) \neq 0$ . Note:  $p$ -values are computed without considering uncertainty in the smoothing parameter estimates and may need to be interpreted with caution when near the  $\alpha$  level. [edf = effective degrees of freedom]

| Measure                    | Model Term        | edf   | $p$ -value |
|----------------------------|-------------------|-------|------------|
| Shoot density              | —                 | —     | —          |
| Percent cover              | s(year, transect) | 14.07 | < 0.001    |
| Canopy height              | s(year, transect) | 8.16  | < 0.001    |
| Total biomass              | s(year, transect) | 24.35 | < 0.001    |
| Above:below ground biomass | s(year, transect) | 9.86  | 0.020      |

**Table 5-9.** Approximate significance of the generalized additive model smooth terms for each Assateague Island National Seashore ancillary sediment model. Each respective  $p$ -value corresponds to the test of the hypotheses:  $H_0: f(x) = 0$  versus  $H_1: f(x) \neq 0$ . Note:  $p$ -values are computed without considering uncertainty in the smoothing parameter estimates and may need to be interpreted with caution when near the  $\alpha$  level. [edf = effective degrees of freedom]

| Measure                  | Model Term        | edf  | $p$ -value |
|--------------------------|-------------------|------|------------|
| Percent fine sediment    | s(year, transect) | 8.54 | < 0.001    |
| Percent organic material | s(year, transect) | 7.97 | < 0.001    |

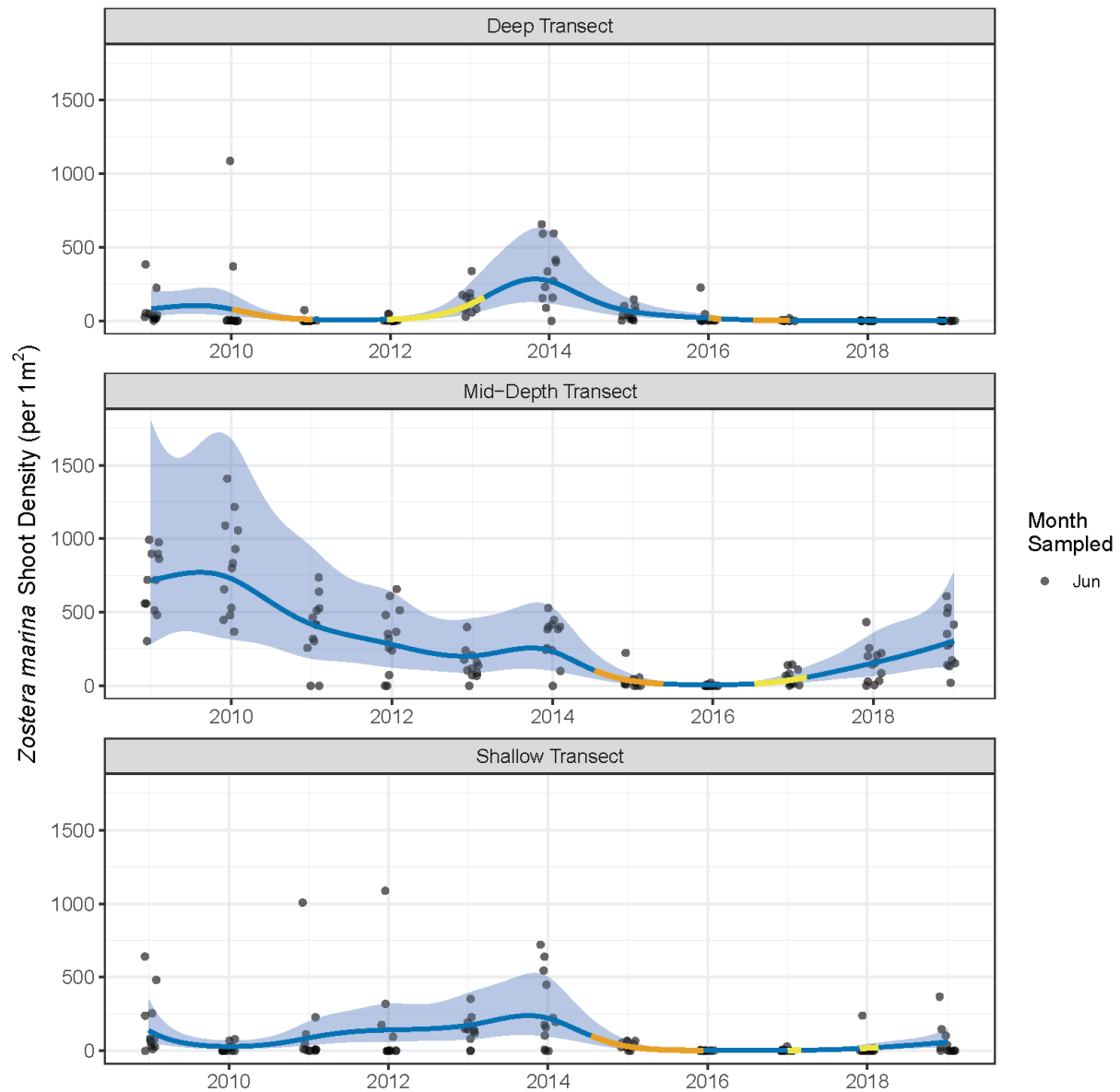


**Figure 5-1.** Trend in *Zostera marina* shoot density (per 1-m<sup>2</sup>) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

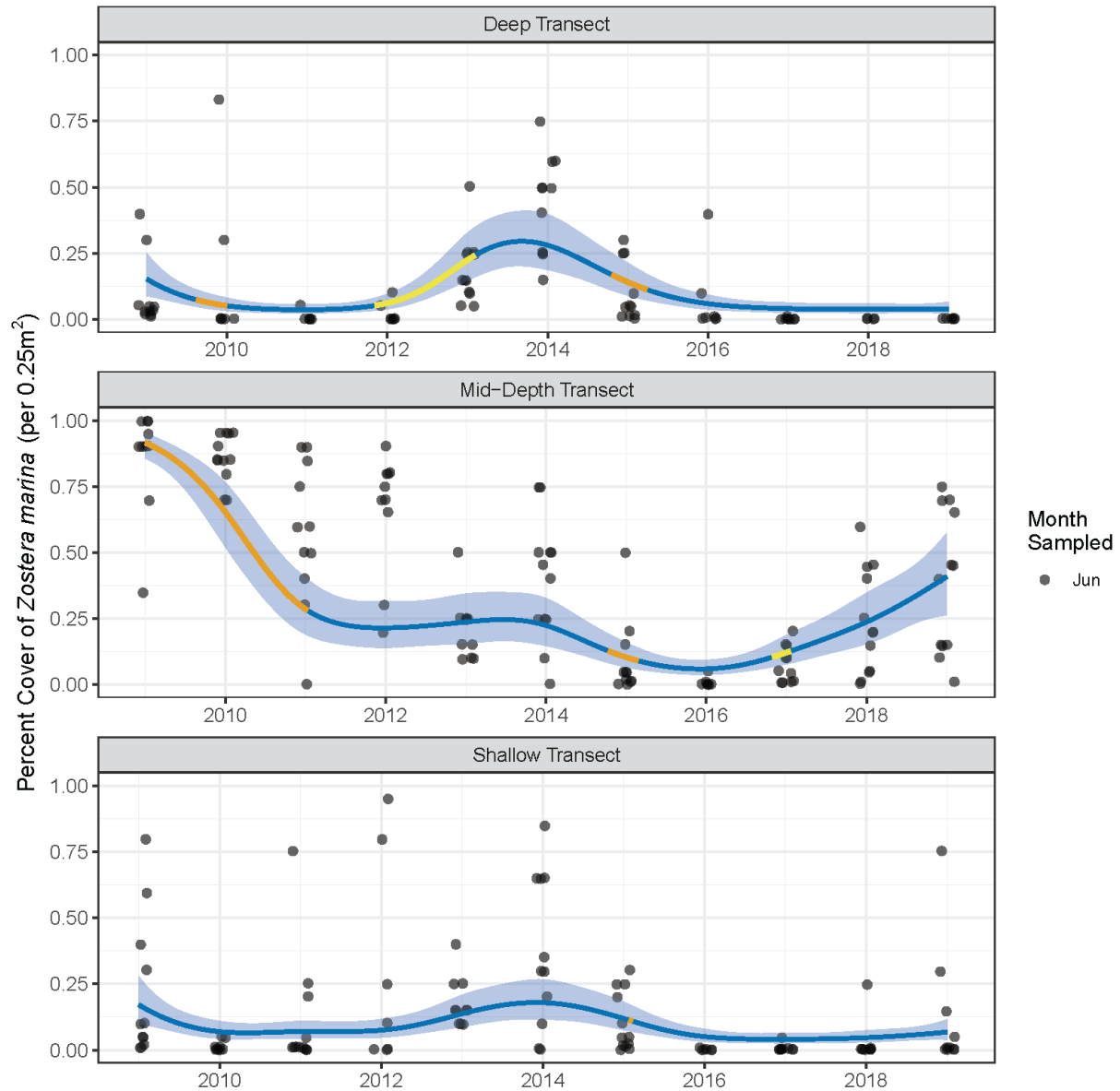


**Figure 5-2.** Trend in percent cover of *Zostera marina* (per 0.25-m<sup>2</sup>) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval.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

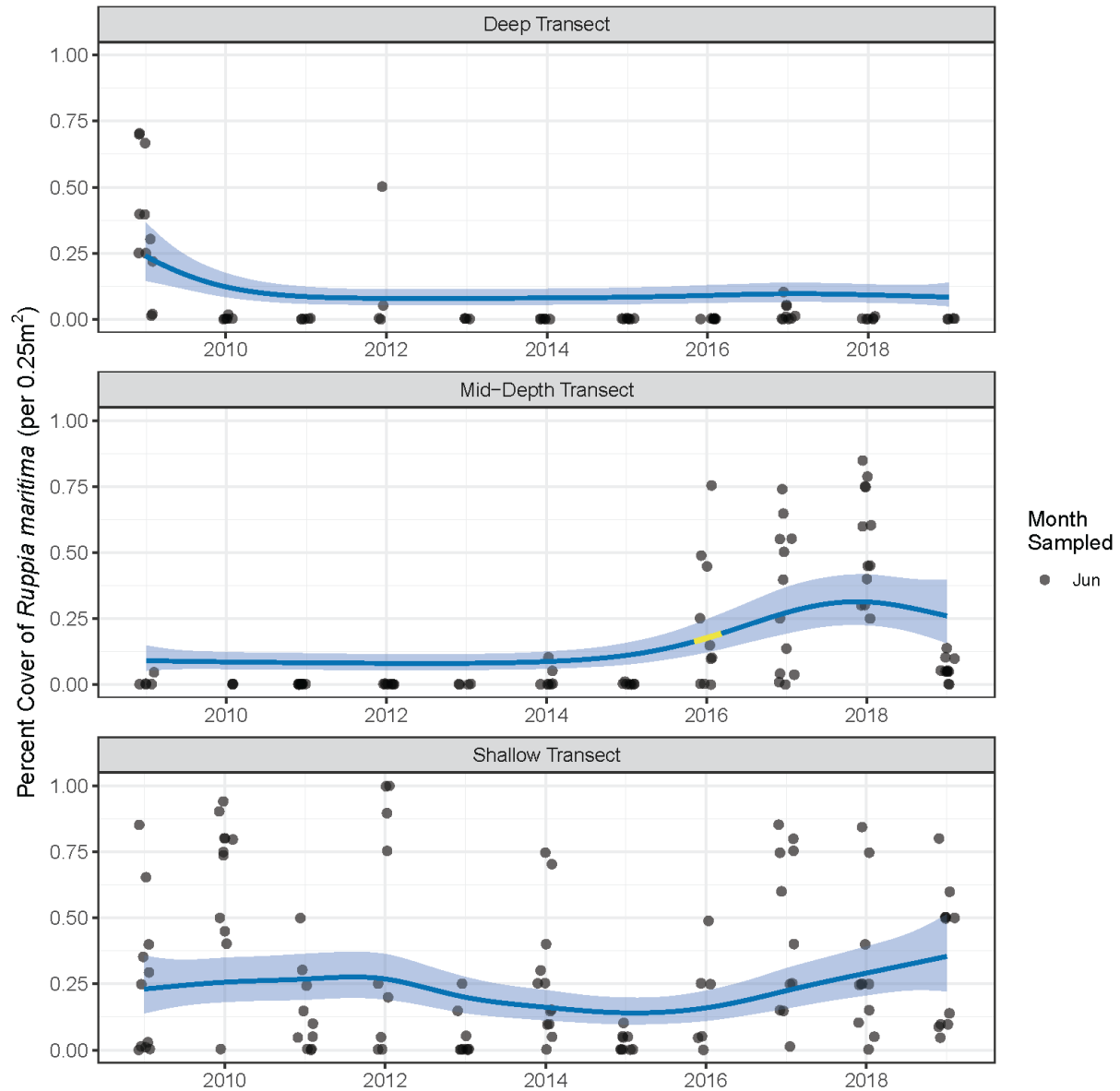


**Figure 5-3.** Trend in percent cover of *Ruppia maritima* (per 0.25-m<sup>2</sup>) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

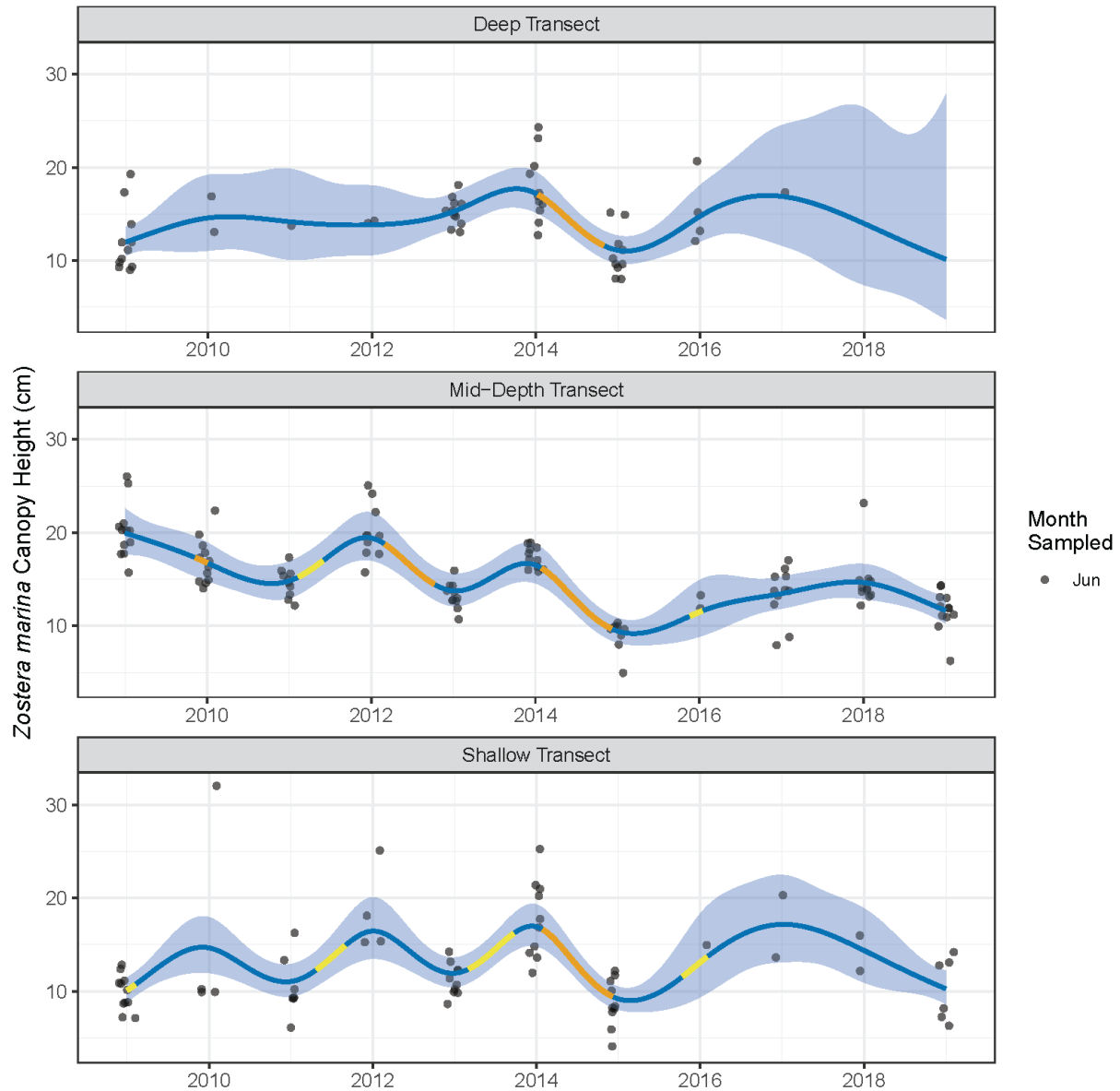


**Figure 5-4.** Trend in *Zostera marina* canopy height by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange

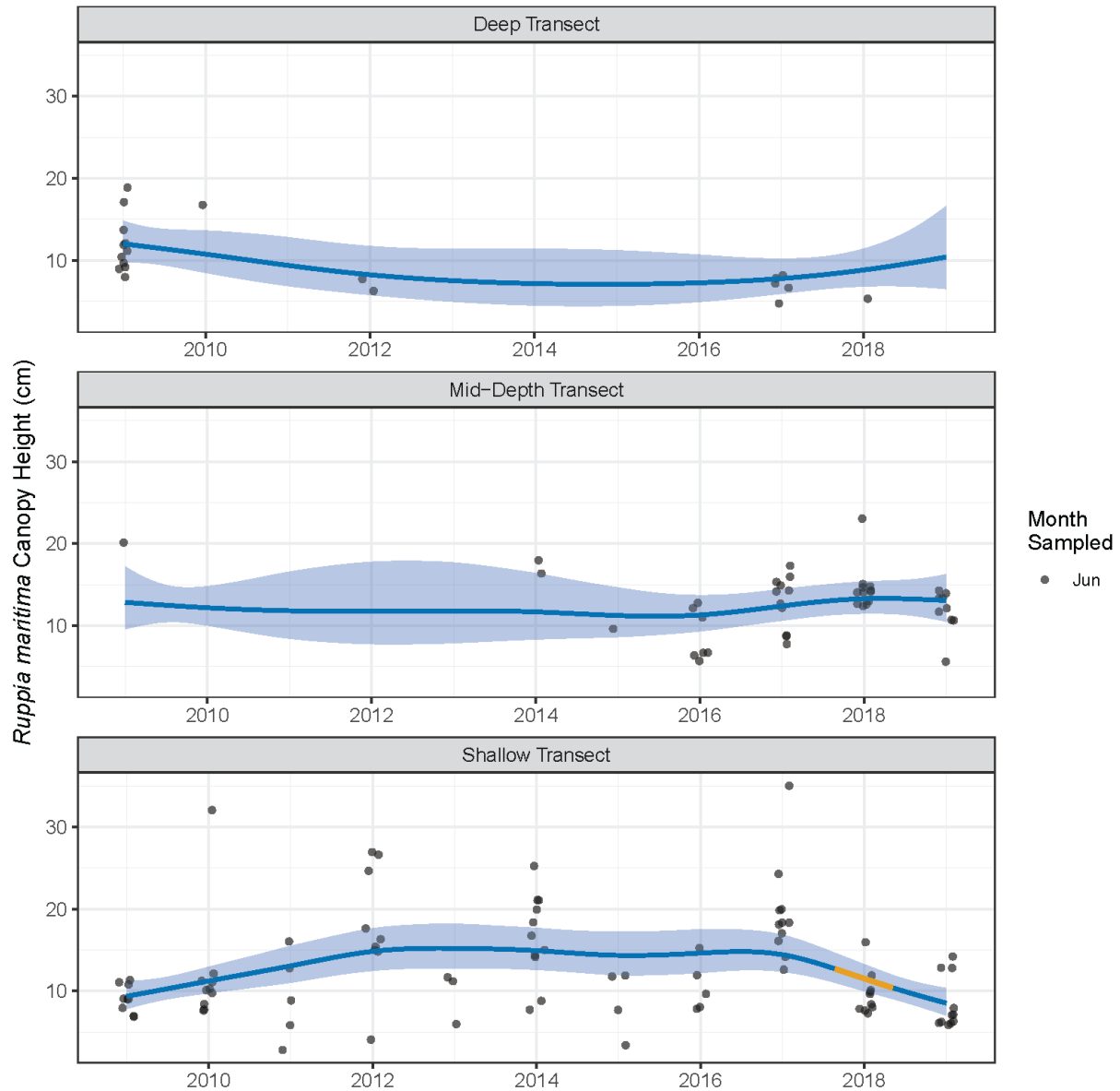


**Figure 5-5.** Trend in *Ruppia maritima* canopy height by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

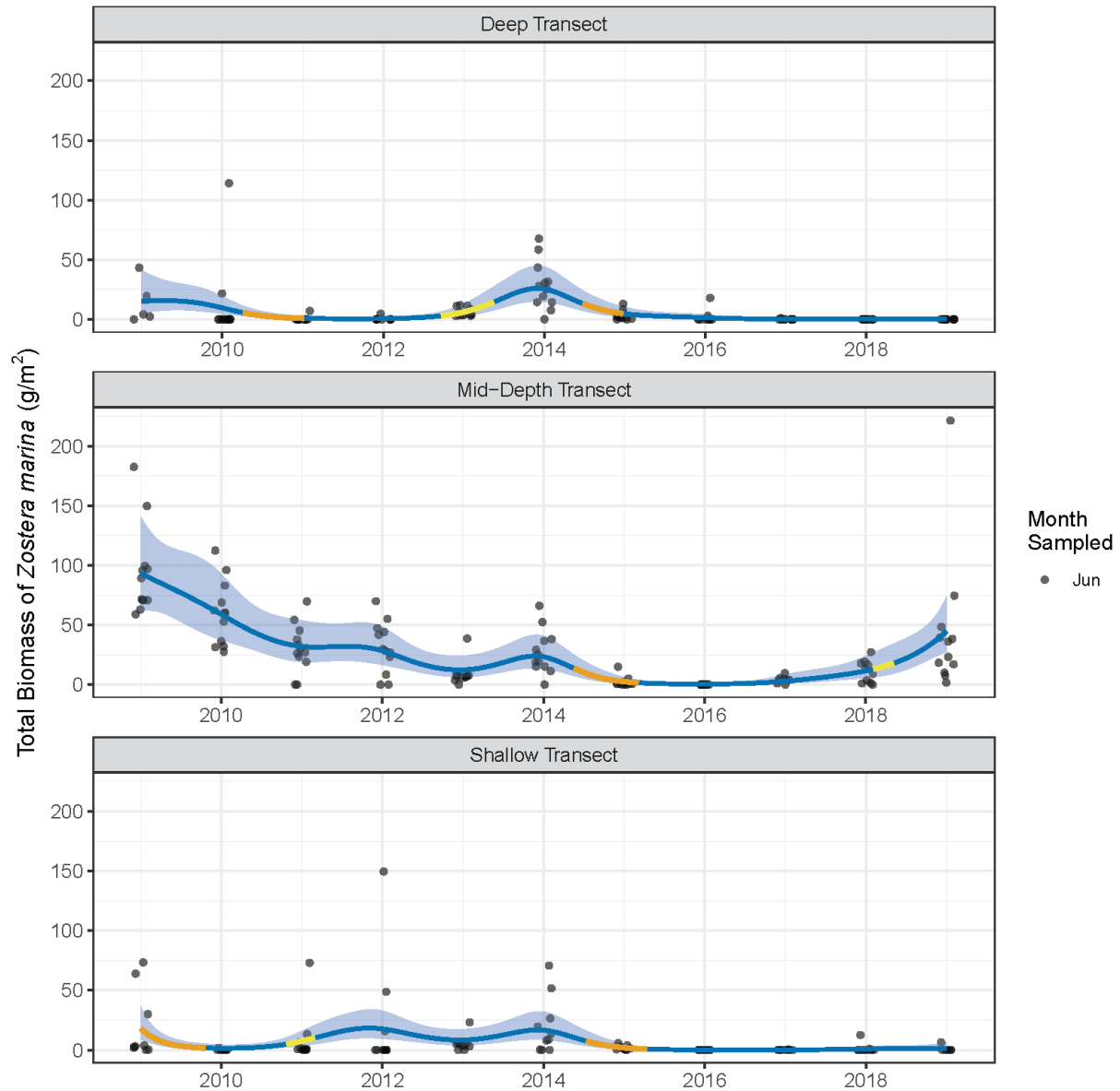


**Figure 5-6.** Trend in *Zostera marina* total biomass (g/m<sup>2</sup>) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

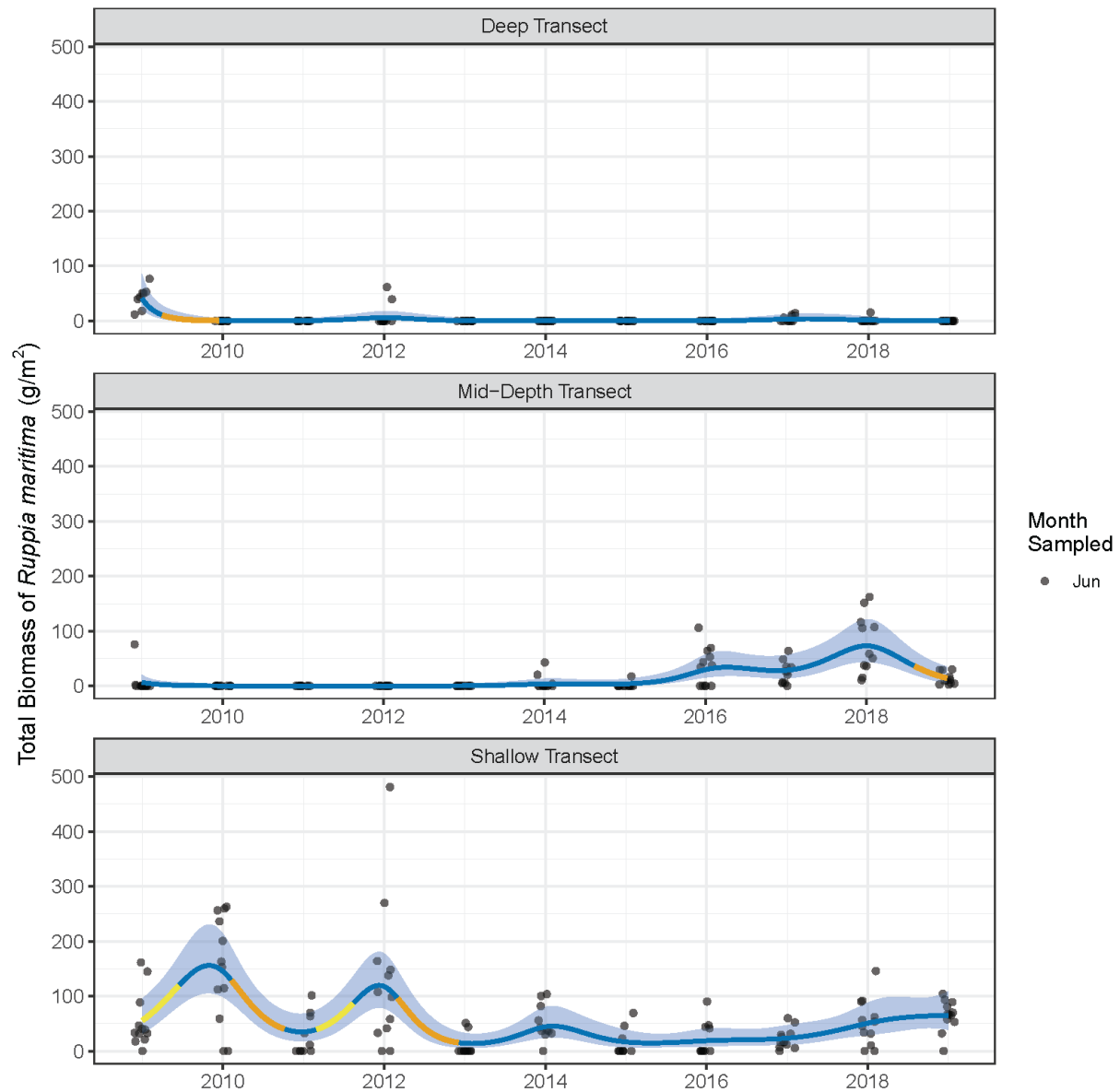


**Figure 5-7.** Trend in *Ruppia maritima* total biomass (g/m<sup>2</sup>) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

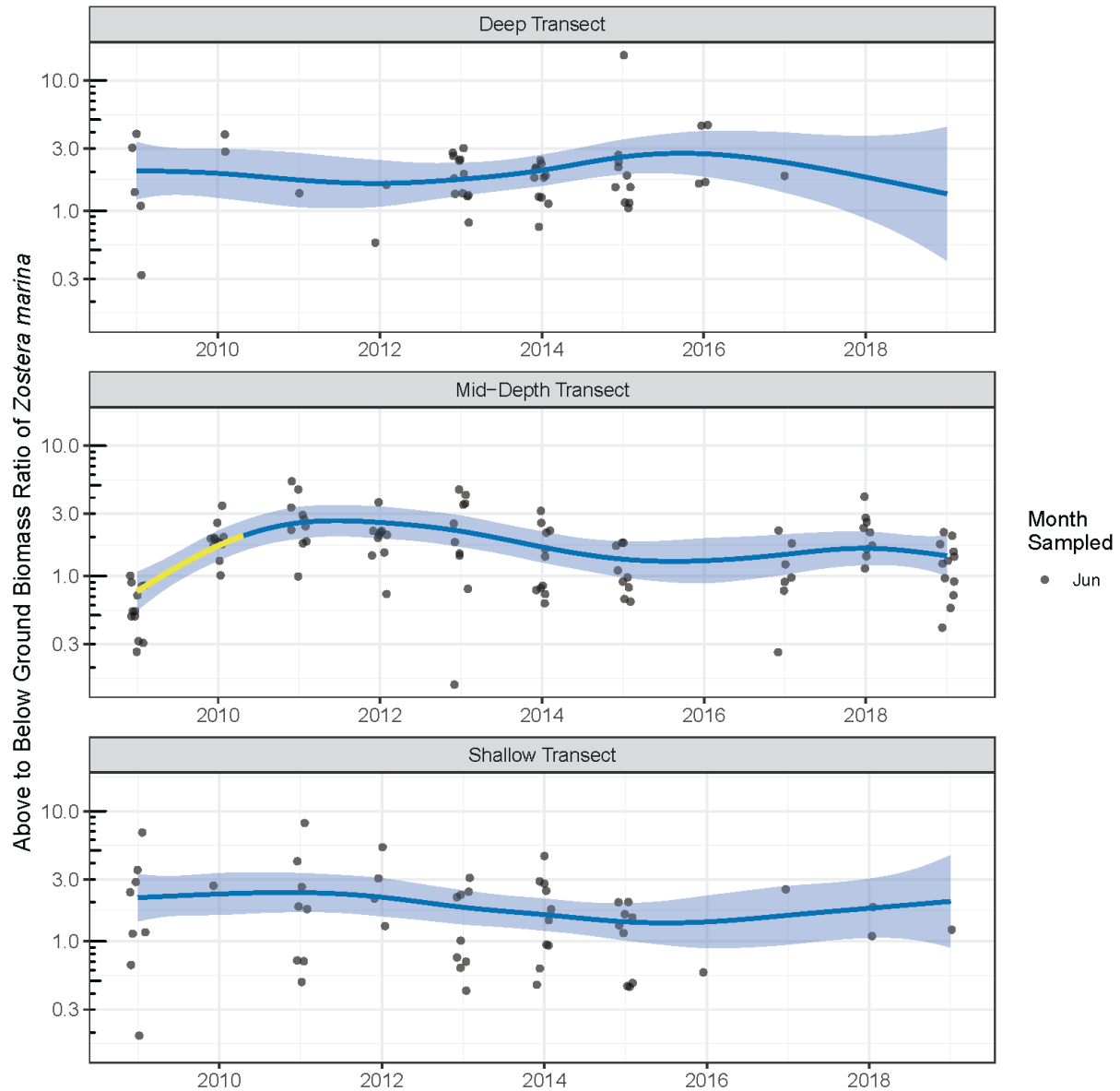


**Figure 5-8.** Trend in above to below ground biomass ratio of *Zostera marina* by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: y-axes are transformed to the log<sub>10</sub> scale to better visualize the estimated trends.

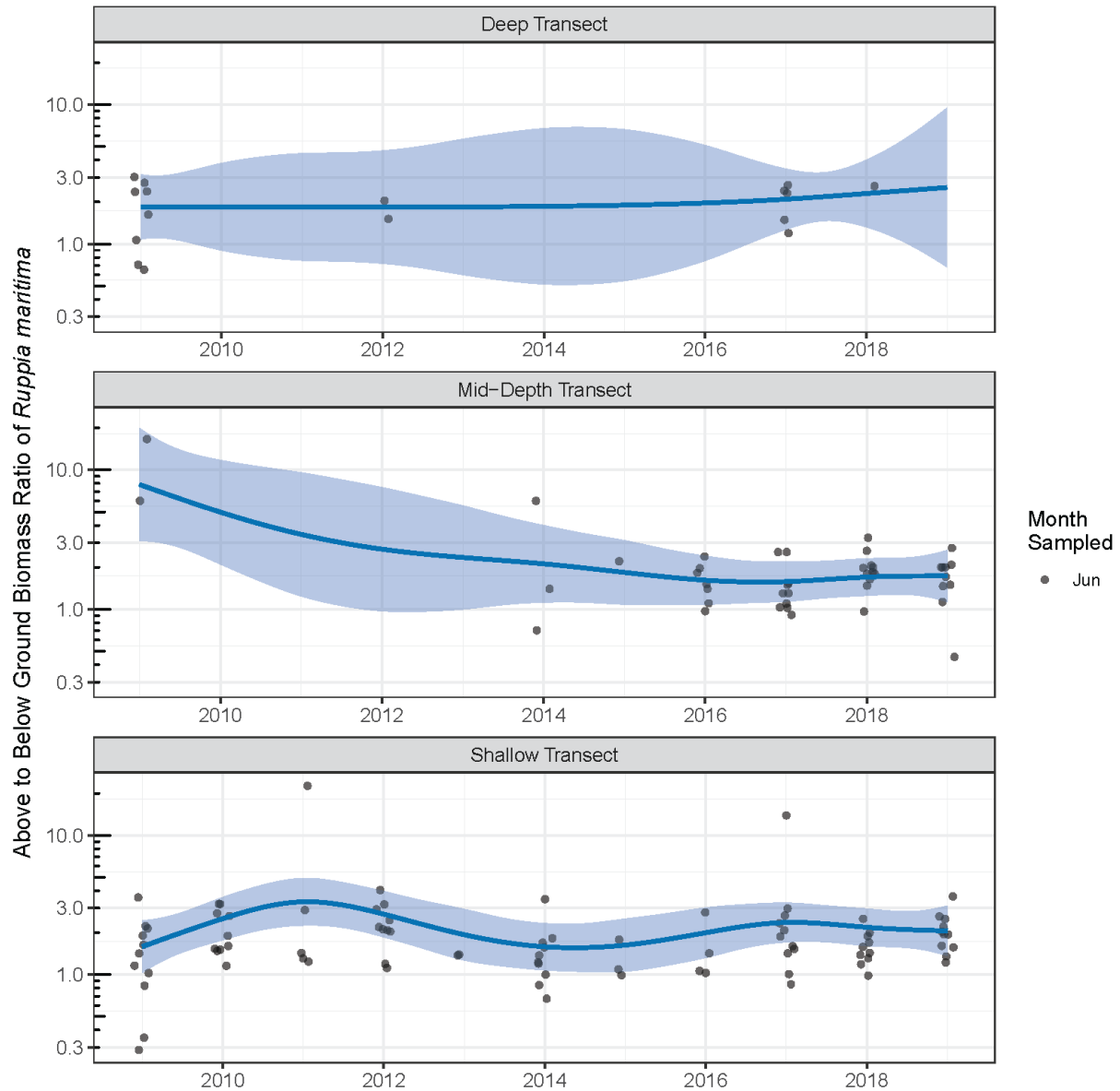


**Figure 5-9.** Trend in above to below ground biomass ratio of *Ruppia maritima* by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange. Note: y-axes are transformed to the log<sub>10</sub> scale to better visualize the estimated trends.

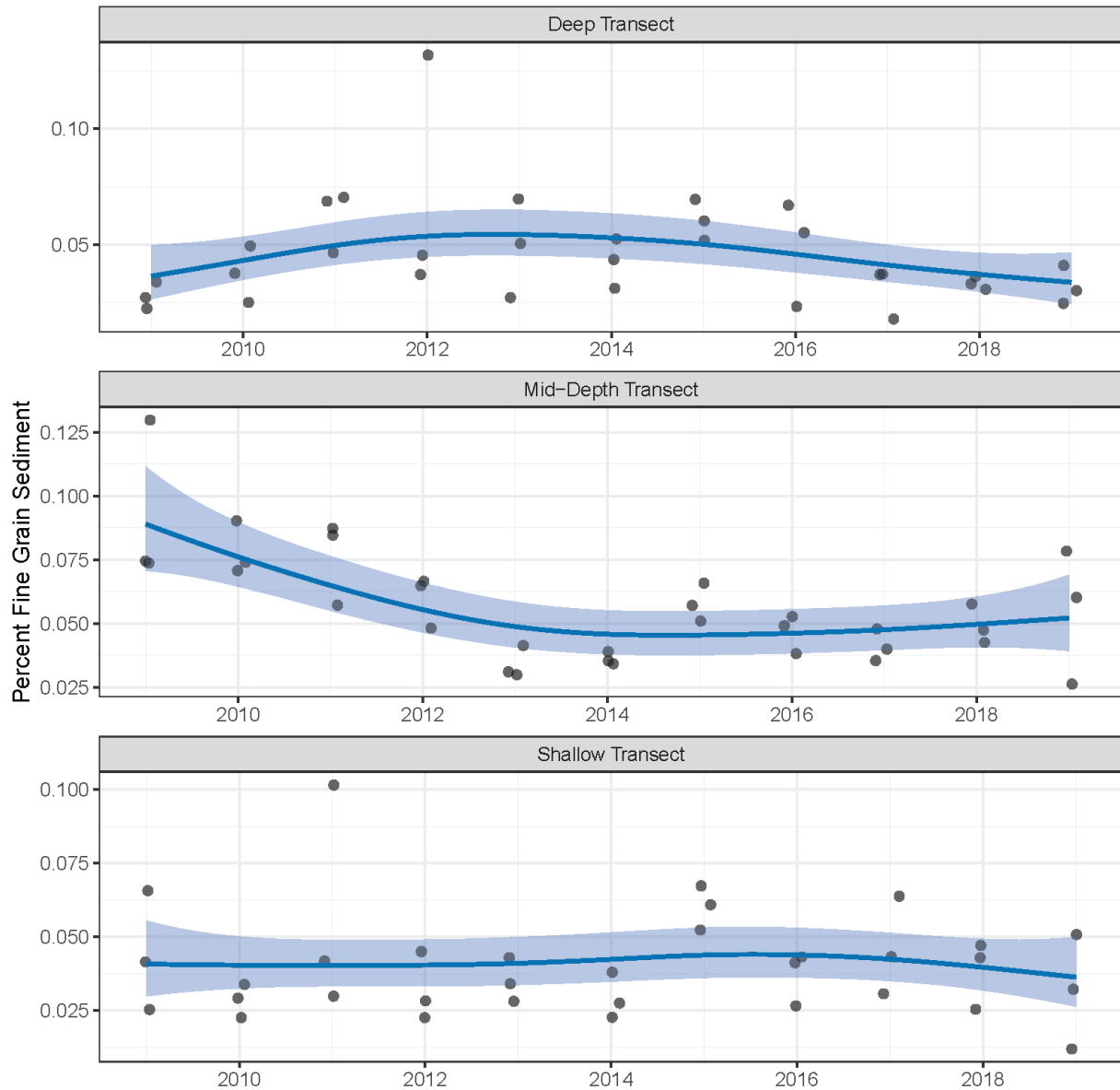


**Figure 5-10.** Trend in percent fine sediment (i.e., clay and silt) by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

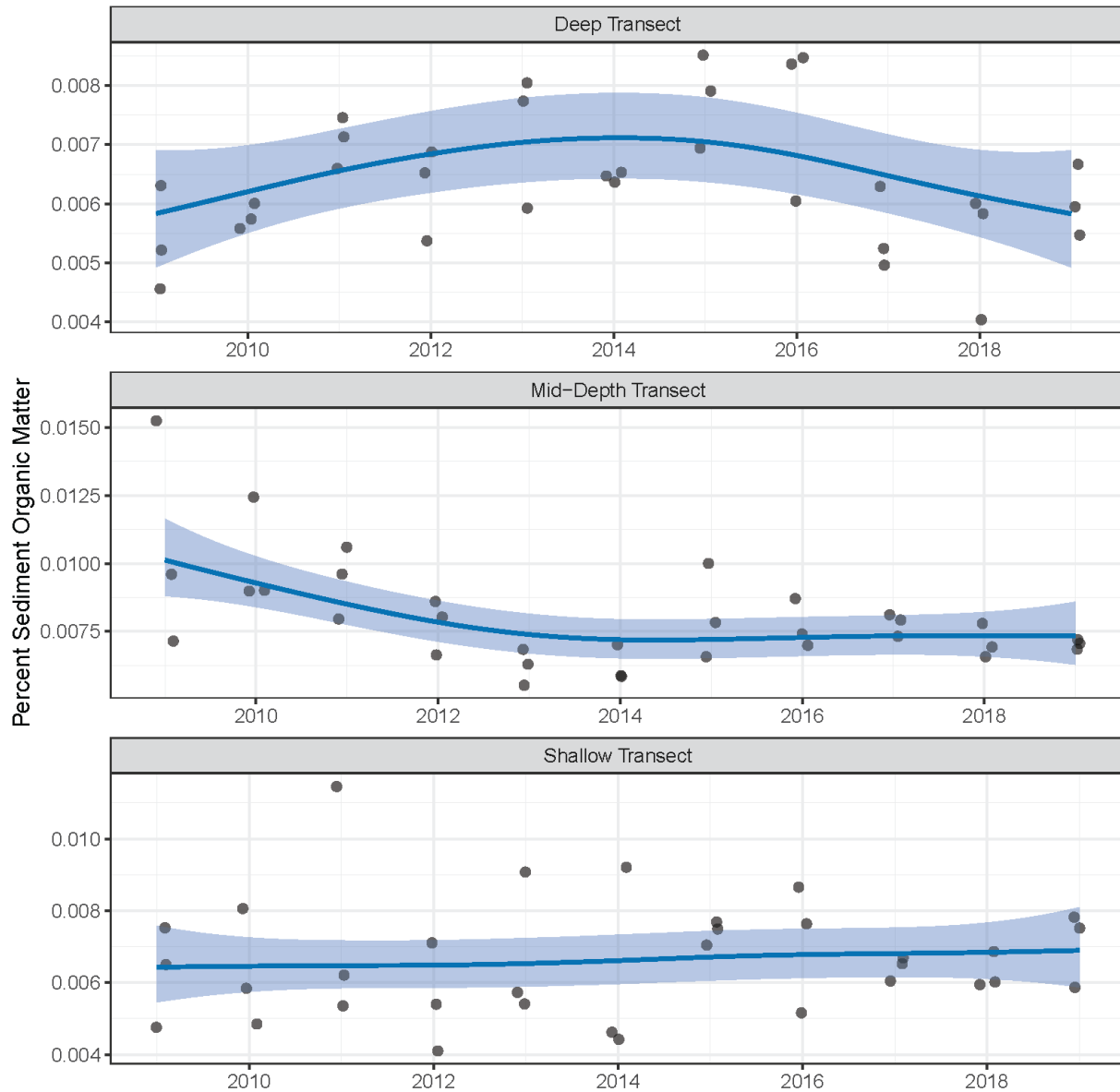


**Figure 5-11.** Trend in percent sediment organic material by transect at the Assateague Island National Seashore Tingles Island reference seagrass bed based on generalized additive model smooths. Fitted spline is plotted in dark blue with shaded 95% point-wise confidence interval. Periods of significant temporal change (increases/decreases), if present, are plotted in yellow/orange.

## 5.6 Water Temperature Summaries

The distribution of observed water temperatures within transect A (shallow) is comparable to transect C (deep) (Figure 5-13). Temperature quantiles within transect A are generally slightly higher than in transect C (Figure 5-12). Days wherein the daily average temperature exceeds 28 °C generally occurs during the months of June to August, with a few years extending into September for both transects (Figure 5-14).

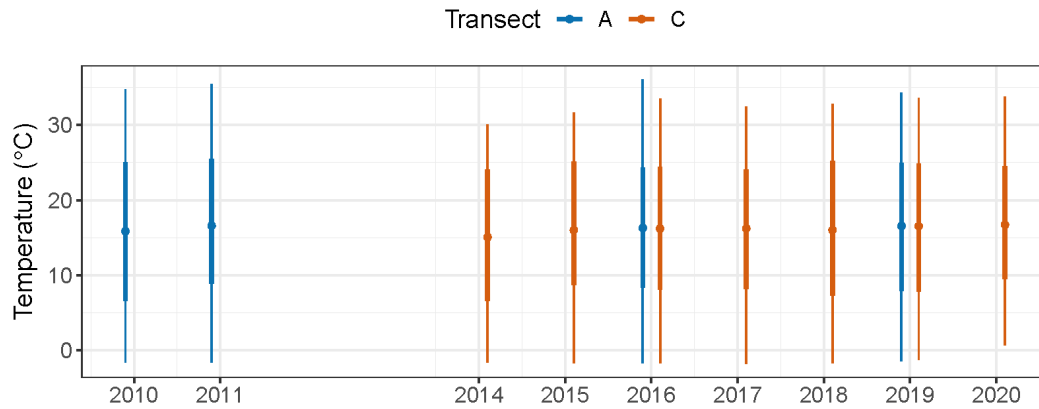


**Figure 5-12.** Dot and whisker plots depicting the mean (dot), range (thin line) and middle 50% of observed water temperatures (°C) (thick line) within each transect at the Assateague Island National Seashore Tingles Island reference seagrass bed.

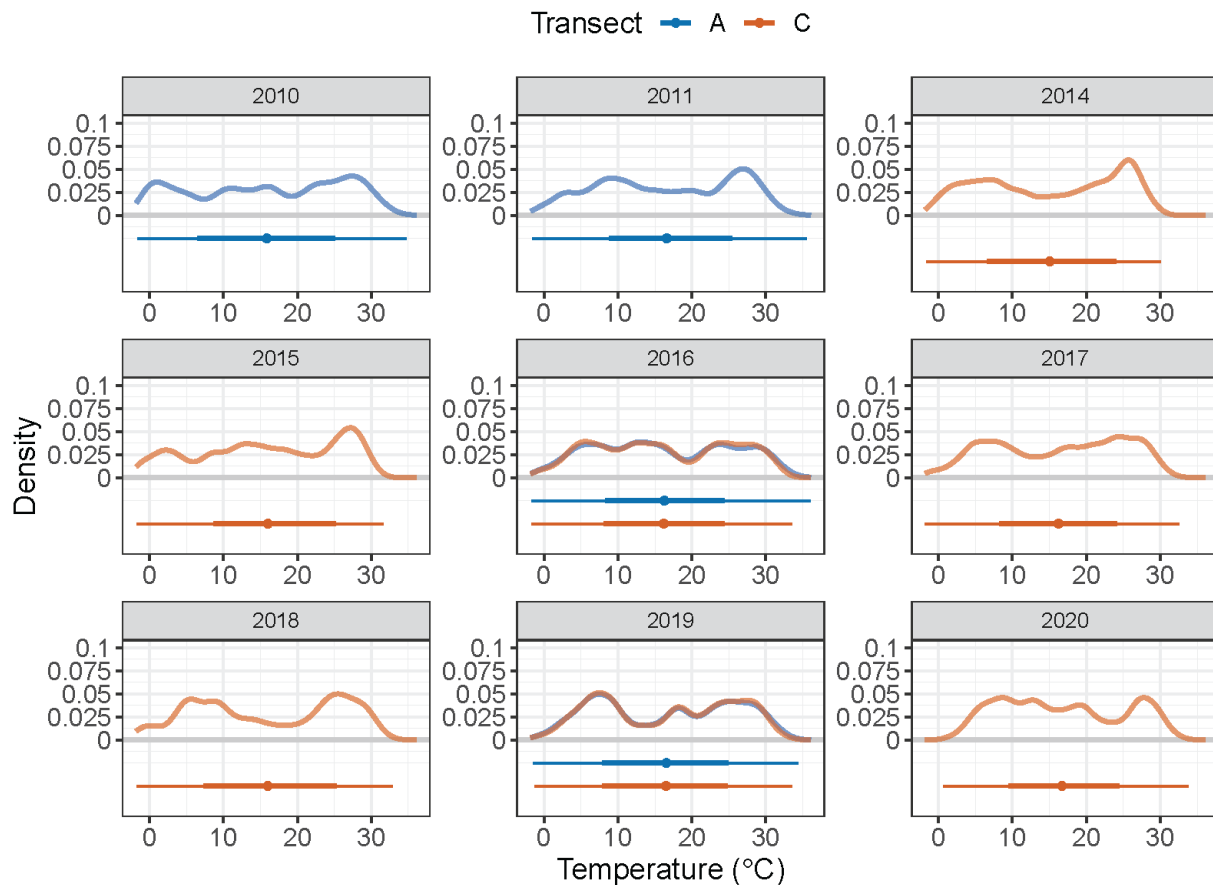


**Figure 5-13.** Distribution of water temperature (°C ) within each transect at the Assateague Island National Seashore Tingles Island reference seagrass bed. Dot and whisker plots below the density plots depict the mean (dot), range (thin line) and middle 50% of observed water temperatures (thick line).

**(a) Daily Average Temperature > 28°C (Days/Month)**

Shallow Transect (A)

|      |       |   |   |   |    |    |    |   |    |    |    |
|------|-------|---|---|---|----|----|----|---|----|----|----|
| 2020 | 0     | 0 | 0 | 0 | 5  | 28 | 13 |   |    |    |    |
| 2019 | 0     | 0 | 0 | 0 | 5  | 23 | 17 | 0 | 0  | 0  | 0  |
| 2018 | 0     | 0 | 0 | 0 | 5  | 11 | 23 | 8 | 0  | 0  | 0  |
| 2017 | 0     | 0 | 0 | 0 | 1  | 21 | 7  | 0 | 0  |    | 0  |
| 2016 | 0     | 0 | 0 | 0 | 0  | 26 | 25 | 0 | 0  | 0  | 0  |
| 2015 | 0     | 0 | 0 | 0 | 11 | 14 | 9  | 4 | 0  | 0  | 0  |
| 2014 |       | 0 | 0 | 0 | 4  | 3  | 0  | 4 | 0  |    | 0  |
| 2013 |       | 0 | 0 | 0 | 3  | 16 | 3  | 0 |    |    |    |
| 2012 | 0     | 0 | 0 | 0 | 7  | 21 | 11 | 0 |    |    |    |
| 2011 | 0     | 0 | 0 | 1 | 9  | 23 | 11 | 0 | 0  | 0  | 0  |
| 2010 | 0     | 0 | 0 | 0 | 12 | 21 | 15 | 2 | 0  | 0  | 0  |
| 2009 |       |   |   |   |    | 3  | 23 | 0 | 0  | 0  | 0  |
|      | 1     | 3 | 4 | 5 | 6  | 7  | 8  | 9 | 10 | 11 | 12 |
|      | Month |   |   |   |    |    |    |   |    |    |    |

**(b) Daily Average Temperature > 28°C (Days/Month)**

Deep Transect (C)

|      |       |   |   |   |    |    |    |   |    |    |    |
|------|-------|---|---|---|----|----|----|---|----|----|----|
| 2020 | 0     | 0 | 0 | 0 | 4  | 27 | 12 | 2 | 0  | 0  | 0  |
| 2019 | 0     | 0 | 0 | 0 | 4  | 22 | 15 | 0 | 0  | 0  | 0  |
| 2018 | 0     | 0 | 0 | 0 | 4  | 11 | 20 | 8 | 0  | 0  | 0  |
| 2017 | 0     | 0 | 0 | 0 | 2  | 20 | 4  | 0 | 0  | 0  | 0  |
| 2016 | 0     | 0 | 0 | 0 | 0  | 24 | 22 | 0 | 0  | 0  | 0  |
| 2015 | 0     | 0 | 0 | 0 | 10 | 16 | 9  | 3 | 0  | 0  | 0  |
| 2014 | 0     | 0 | 0 | 0 | 3  | 2  | 0  | 5 | 0  | 0  | 0  |
| 2013 |       | 0 | 0 | 0 | 3  | 15 | 3  | 0 | 0  | 0  | 0  |
| 2012 | 0     | 0 | 0 | 0 | 5  | 22 | 6  | 1 |    |    |    |
| 2011 | 0     |   |   | 0 |    |    |    |   |    | 0  | 0  |
| 2010 | 0     | 0 | 0 | 0 | 11 | 18 | 13 | 1 | 0  | 0  | 0  |
| 2009 |       |   |   |   |    | 1  | 19 | 0 | 0  | 0  | 0  |
|      | 1     | 3 | 4 | 5 | 6  | 7  | 8  | 9 | 10 | 11 | 12 |
|      | Month |   |   |   |    |    |    |   |    |    |    |

**Figure 5-14.** Number of days per month wherein average daily water temperature exceeded 28 °C for the (a) shallow and (b) deep transects at the Assateague Island National Seashore Tingles Island 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 framework<sup>8</sup> 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  $\beta_1$  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  $\phi$  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 ( $\beta_1$ ) 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

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<sup>8</sup> 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 of  $H_0: \beta_1 = 0$  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  $\beta_1$  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 ( $\exp(0.05) \approx 1.051$ ).

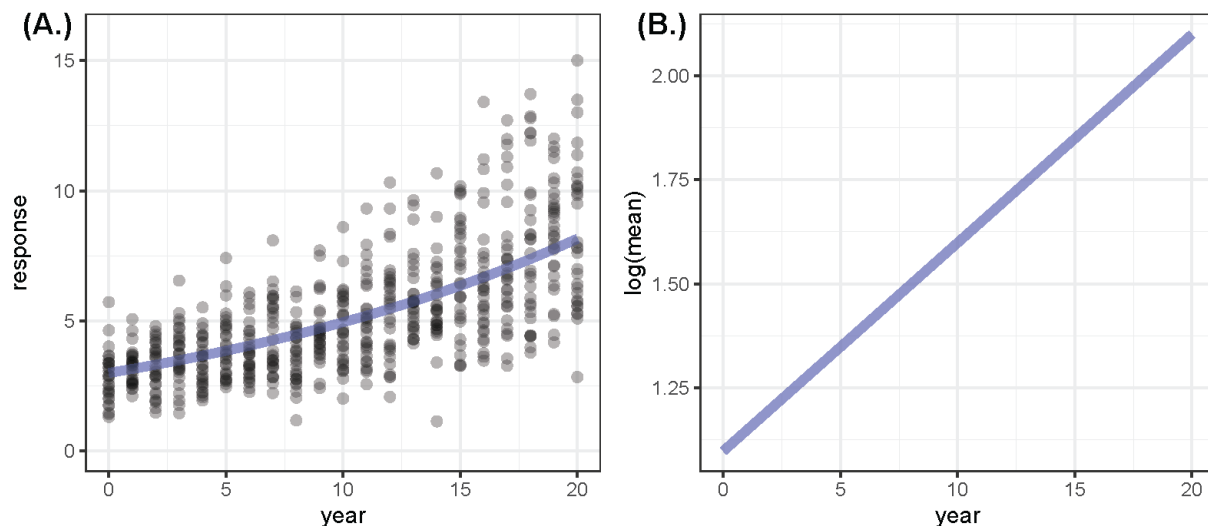


**Figure 6-1.** (A.) Process model realizations (black dots) representing samples from 30 sites within a hypothetical estuary. The  $i$ th hexagon's response value is simulated from  $\text{Gamma}(\mu_i, 0.1)$ , where  $\ln(\mu_i) = 3 + 0.05 \cdot \text{year}_i$ . The blue curve represents the true underlying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

**Table 6-1.** Process model dispersion ( $\phi$ ) used to simulate trends in each water quality measure.

| Measure                                      | $\phi$ |
|----------------------------------------------|--------|
| Chlorophyll <i>a</i> ( $\mu\text{g/L}$ )     | 0.336  |
| Dissolved oxygen (mg/L)                      | 0.048  |
| PAR attenuation ( $K_d$ ( $\text{m}^{-1}$ )) | 0.162  |

## 6.2 Simulation Results

Estimated power for detecting a linear trend 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).

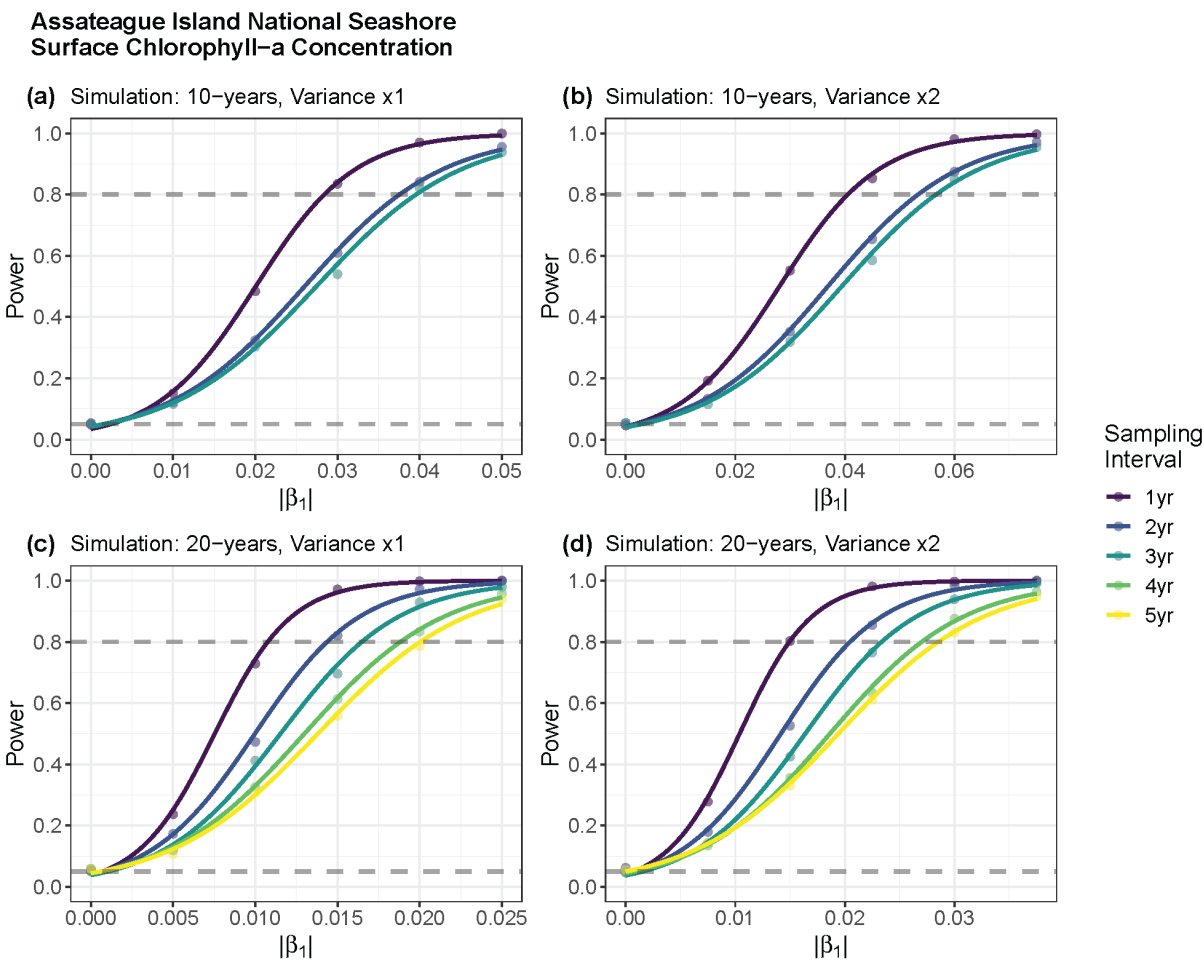


**Figure 6-2.** Estimated power to detect a linear trend in mean surface chlorophyll-*a* concentration ( $\mu\text{g/L}$ ) within Assateague Island National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates 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 ( $\beta_1$ ) 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 ( $\mu\text{g/L}$ ) large enough to cross both quality thresholds within Assateague Island National Seashore. The  $\beta_1$  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 is provided in the table footnotes.

| Period | Variance   | Threshold | $\beta_1$ | Power by Sampling Interval |      |      |      |      |
|--------|------------|-----------|-----------|----------------------------|------|------|------|------|
|        |            |           |           | 1yr                        | 2yr  | 3yr  | 4yr  | 5yr  |
| 10 yrs | $\times 1$ | 5         | -0.113    | 1.00                       | 1.00 | 1.00 | NA   | NA   |
| 10 yrs | $\times 1$ | 20        | 0.026     | 0.71                       | 0.49 | 0.45 | NA   | NA   |
| 10 yrs | $\times 2$ | 5         | -0.113    | 1.00                       | 1.00 | 1.00 | NA   | NA   |
| 10 yrs | $\times 2$ | 20        | 0.026     | 0.43                       | 0.28 | 0.25 | NA   | NA   |
| 20 yrs | $\times 1$ | 5         | -0.057    | 1.00                       | 1.00 | 1.00 | 1.00 | 1.00 |
| 20 yrs | $\times 1$ | 20        | 0.013     | 0.91                       | 0.71 | 0.59 | 0.49 | 0.44 |
| 20 yrs | $\times 2$ | 5         | -0.057    | 1.00                       | 1.00 | 1.00 | 1.00 | 1.00 |
| 20 yrs | $\times 2$ | 20        | 0.013     | 0.67                       | 0.42 | 0.33 | 0.28 | 0.27 |

# **Assateague Island National Seashore Bottom Dissolved Oxygen Concentration**

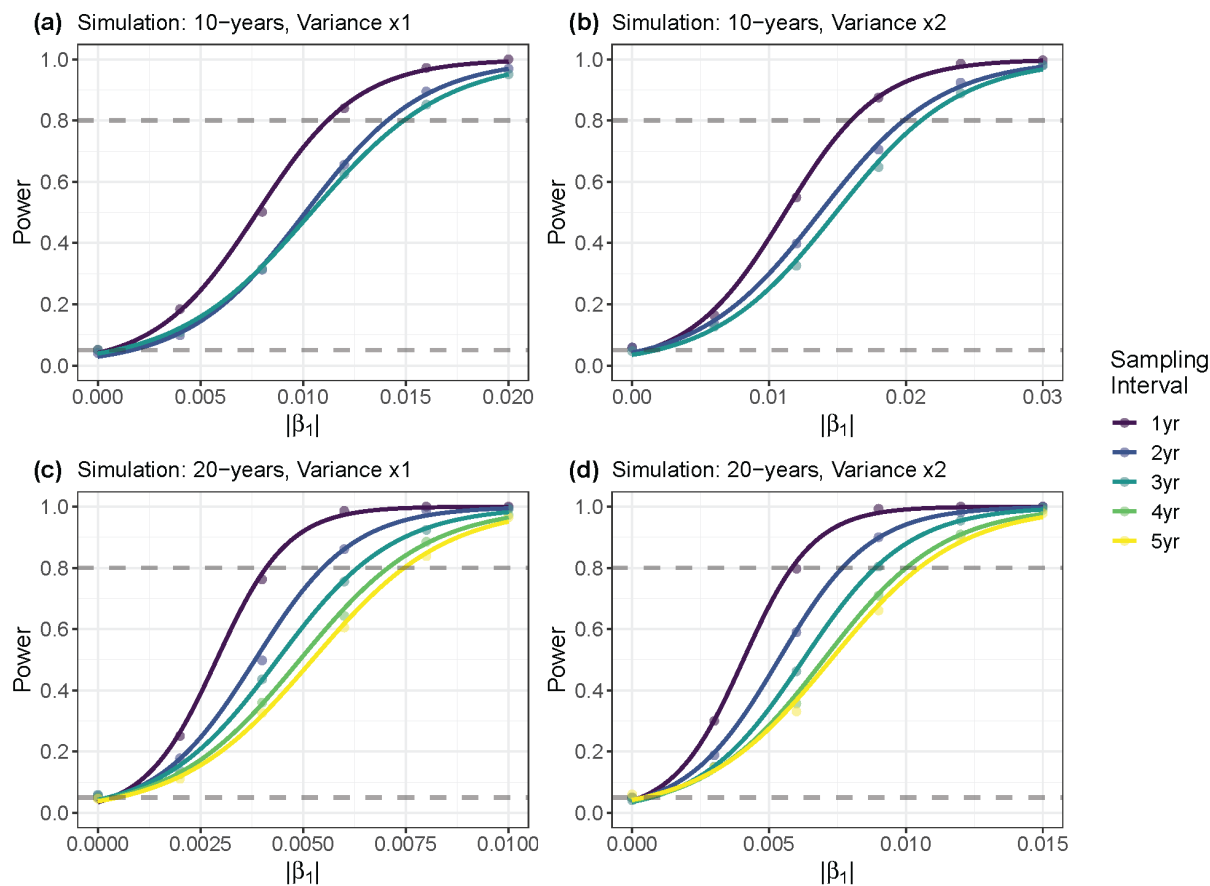


**Figure 6-3.** Estimated power to detect a linear trend in mean bottom dissolved oxygen concentration (mg/L) within Assateague Island National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) 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 ( $\beta_1$ ) 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 (mg/L) large enough to cross both quality thresholds within Assateague Island National Seashore. The  $\beta_1$  column value corresponds to the magnitude of trend that would result in the mean equalling 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 is provided in the table footnotes.

| Period | Variance | Threshold | $\beta_1$ | Power by Sampling Interval |      |      |      |      |
|--------|----------|-----------|-----------|----------------------------|------|------|------|------|
|        |          |           |           | 1yr                        | 2yr  | 3yr  | 4yr  | 5yr  |
| 10 yrs | ×1       | 2         | −0.115    | 1.00                       | 1.00 | 1.00 | NA   | NA   |
| 10 yrs | ×1       | 5         | −0.023    | 1.00                       | 0.99 | 0.98 | NA   | NA   |
| 10 yrs | ×2       | 2         | −0.115    | 1.00                       | 1.00 | 1.00 | NA   | NA   |
| 10 yrs | ×2       | 5         | −0.023    | 0.97                       | 0.89 | 0.86 | NA   | NA   |
| 20 yrs | ×1       | 2         | −0.057    | 1.00                       | 1.00 | 1.00 | 1.00 | 1.00 |
| 20 yrs | ×1       | 5         | −0.012    | 1.00                       | 1.00 | 0.99 | 0.99 | 0.98 |
| 20 yrs | ×2       | 2         | −0.057    | 1.00                       | 1.00 | 1.00 | 1.00 | 1.00 |
| 20 yrs | ×2       | 5         | −0.012    | 1.00                       | 0.98 | 0.94 | 0.89 | 0.86 |

# Assateague Island National Seashore PAR Attenuation

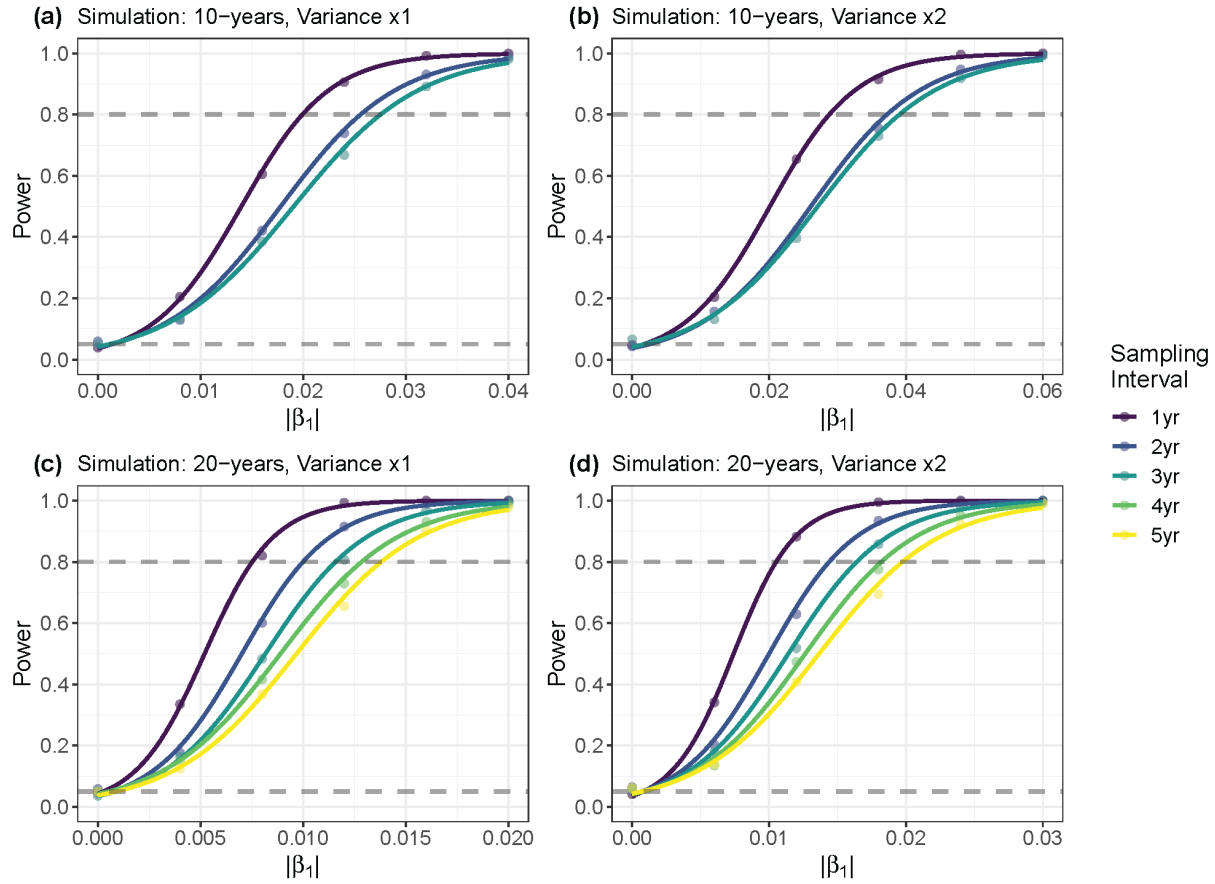


**Figure 6-4.** Estimated power to detect a linear trend in mean PAR attenuation ( $K_d$  ( $m^{-1}$ )) within Assateague Island National Seashore. Power estimates vary based on the assumed sampling interval (see legend) and duration: (a) 10-year period, (c) 20-year period. Power estimates in (b) and (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 ( $\beta_1$ ) 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 ( $K_d$  ( $m^{-1}$ )) large enough to cross both quality thresholds within Assateague Island National Seashore. The  $\beta_1$  column value corresponds to the magnitude of trend that would result in the mean equalling 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 is provided in the table footnotes.

| Period | Variance | Threshold | $\beta_1$ | Power by Sampling Interval |      |      |      |      |
|--------|----------|-----------|-----------|----------------------------|------|------|------|------|
|        |          |           |           | 1yr                        | 2yr  | 3yr  | 4yr  | 5yr  |
| 10 yrs | ×1       | 0.92      | −0.093    | 1.00                       | 1.00 | 1.00 | NA   | NA   |
| 10 yrs | ×1       | 1.61      | −0.037    | 1.00                       | 0.97 | 0.95 | NA   | NA   |
| 10 yrs | ×2       | 0.92      | −0.093    | 1.00                       | 1.00 | 1.00 | NA   | NA   |
| 10 yrs | ×2       | 1.61      | −0.037    | 0.94                       | 0.80 | 0.76 | NA   | NA   |
| 20 yrs | ×1       | 0.92      | −0.047    | 1.00                       | 1.00 | 1.00 | 1.00 | 1.00 |
| 20 yrs | ×1       | 1.61      | −0.019    | 1.00                       | 1.00 | 0.99 | 0.97 | 0.95 |
| 20 yrs | ×2       | 0.92      | −0.047    | 1.00                       | 1.00 | 1.00 | 1.00 | 1.00 |
| 20 yrs | ×2       | 1.61      | −0.019    | 0.99                       | 0.94 | 0.88 | 0.81 | 0.75 |

## 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  $\beta_1$  values are relatively small when interpreting change on a yearly basis, these changes are compounded over time. For example, a  $\beta_1$  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 ( $\beta_1$ ) 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  $\beta_1$  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 surface chlorophyll-*a* concentration (Table 6-2). From the table's footnotes, the estimated mean chlorophyll-*a* concentration in 2018 is 15.49  $\mu\text{g/L}$ . Looking across all simulation scenarios, we see that there is low power to detect changes from the fair to poor category (i.e., 20  $\mu\text{g/L}$  threshold) and high power to detect changes from fair to good category (i.e., 5  $\mu\text{g/L}$  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 poorer condition category are of interest (i.e., fair to poor), then the recommendation for each scenario would be to sample every year. Note: 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- <i>a</i> (fair) | 1 yr                                      | 1 yr        | 1 yr        | 1 yr        |
| Bottom dissolved oxygen (good)       | 3 yr                                      | 3 yr        | 5 yr        | 5 yr        |
| PAR attenuation (poor)               | 3 yr                                      | 2 yr        | 5 yr        | 4 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 bottom

dissolved oxygen, from 'fair' to 'poor' in surface chlorophyll-*a*, and from 'poor' to 'fair' in PAR attenuation.

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,  $\beta_0$ ,  $\beta_1$  and  $\beta_2$  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 functions<sup>9</sup>:

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

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  $\lambda$ ) controls the extent to which the penalty contributes to the likelihood function. Simpson (2018) recommends that  $\lambda$  be estimated via restricted maximum likelihood (REML) for best results. Since

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<sup>9</sup> 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  $\hat{f}(x)$ .

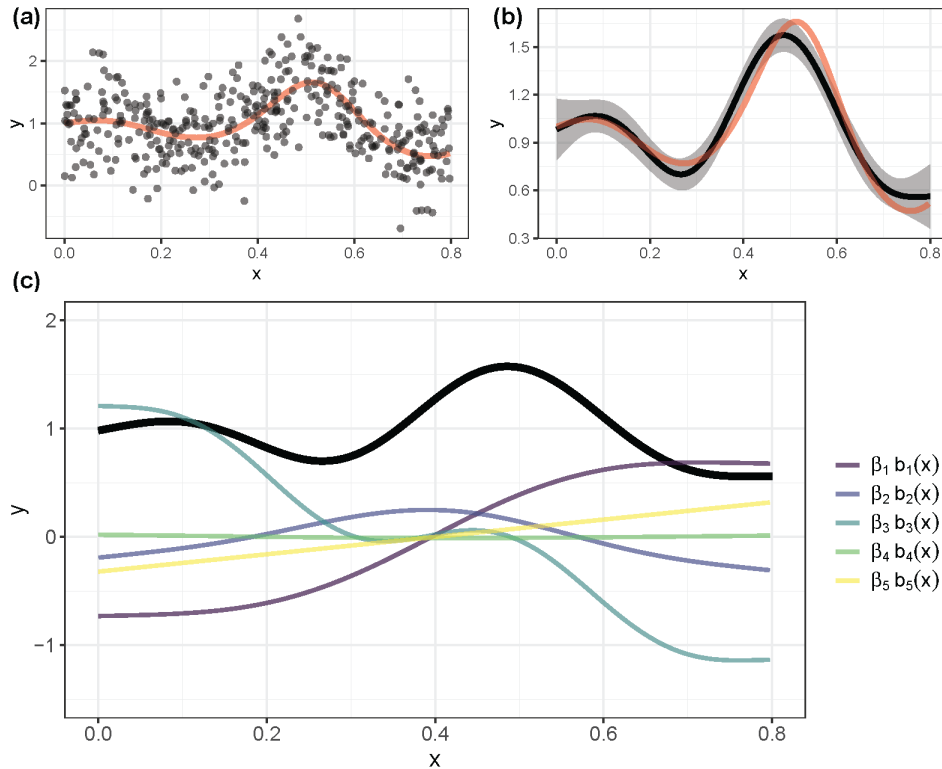


**Figure A-1.** (a) Data simulated from the nonlinear model given by Equation 2 and depicted in red. (b) Fitted generalized additive model smooth in black with corresponding 95% pointwise confidence interval in gray. True underlying curve provided in red for reference. (c) The six thin plate regression 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;  $\alpha$ ) 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, Assateague Island National Seashore has 9 years of monitoring data and therefore has 36 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 36 tests approximately 84% 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.