Hypoxia in Narragansett Bay

An Analysis of *Narragansett Bay Fixed Site Monitoring Network* Data

2001 to 2015

State of Rhode Island Department of Environmental Management
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ABSTRACT

The Narragansett Bay Fixed-Site Monitoring Network now has more than fifteen years of high-resolution temporal data and is growing in value with every additional season of data. These data are helping managers and researchers better understand the development of hypoxia in the bay and progress towards improving water quality.

We investigated hypoxia events and their relationship to possible explanatory variables, such as freshwater (i.e., river) flow to the bay, bottom water temperature, surface chlorophyll *a* (Chl *a*) abundance, and surface-bottom water stratification characterized by density differences. We focused on the summer months of June through September because hypoxia events are most likely to occur during this time period.

We found bottom water temperature and surface-bottom stratification to be positive explanatory variables for the probability of hypoxic days at several fixed-sites, while other explanatory variables, such as river flow and Chl *a* abundance, were both positive and negative, depending on the site and the threshold used to define hypoxia. Correlation of DO concentration among certain fixed-sites was high, but fractional overlap varied, suggesting further work is needed to better understand how the data from these sites can inform regional phenomena. Future work should focus on better understanding Chl *a* abundance and river flow as explanatory variables of hypoxia, and continued investigation of correlations of DO and hypoxia events among fixed-sites.

The tracking of seasonal hypoxic days shows some promise in identifying progress towards water quality goals. Additionally, hypoxia event deficit-duration characteristics, such as maximum duration and maximum deficit-duration, also have value in identifying progress and should be considered on a site-by-site basis. These metrics may be useful in first detecting changes before compliance with water quality standards has been achieved, allowing managers to better understand progress toward stated goals. Managers and researchers should continue to collaborate on data synthesis to support robust indicator reporting in the future.

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INTRODUCTION

Narragansett Bay is a medium-sized (196 mi^2) temperate estuary located in Rhode Island, USA, with a drainage area of ~ 1700 mi^2, of which about 60% is located in Massachusetts and the remaining 40% in Rhode Island. Land use within the watershed includes roughly 35% urban or urbanizing areas, 6% agriculture, 15% wetlands, with the remaining land in forest, open water or other undeveloped land (NBEP, 2017).

Dissolved oxygen in the water column and sediments sustains a healthy estuarine ecosystem. Periods of low dissolved oxygen, known as hypoxia events, stress marine life and threaten bay health. The complexity and variability inherent in estuaries such as Narragansett Bay (e.g., NBEP, 2017; Desbonnet and Costa-Pierce, 2008) challenge our ability to predict and manage hypoxia events. The severity of hypoxia events varies in time and space, but is characterized by dissolved oxygen deficit and the duration of the event.

It is well documented that portions of Narragansett Bay experience hypoxia (NBEP, 2017; Codiga et al., 2009; Saarman et al., 2008). The Rhode Island Department of Environmental Management assessments of water quality have resulted in about one-third of Narragansett Bay being designated as impaired due to low dissolved oxygen. (RI Department of Administration, 2016). Long-standing awareness of hypoxic conditions prompted a significant management response spanning two decades to reduce nitrogen pollutant loadings into Narragansett Bay through the upgrade of wastewater treatment facilities which discharge into the bay or its major tributaries. A comparison of nutrient budgets from 2000–2004 and 2013—2015 revealed a 55 percent decrease in total nitrogen from wastewater treatment facility loadings throughout the Narragansett Bay watershed (NBEP, 2017). Accordingly, water quality conditions relating to hypoxia are expected to be undergoing change in the bay.

Fifteen years of continuous monitoring of water quality parameters at fixed locations throughout the bay provides an opportunity to investigate hypoxia events and their relationship to possible explanatory variables, such as freshwater (i.e., river) flow to the bay, water temperature, chlorophyll *a* abundance, and surface-bottom water stratification. Here we focus on the summer months of June through September because hypoxia events are most likely to occur during this time period.

METHODS

DATA SOURCES

Data used in these analyses were obtained from the Narragansett Bay Fixed-Site Monitoring Network (NBFSMN; RI DEM, 2017; DEM map). The network is operated as a collaborative partnership among several organizations: The RI DEM and URI Graduate School of Oceanography deploy and maintain a majority of the NBFSMN sites. The Narragansett Bay Commission, Narragansett Bay National Estuarine Research Reserve and Massachusetts

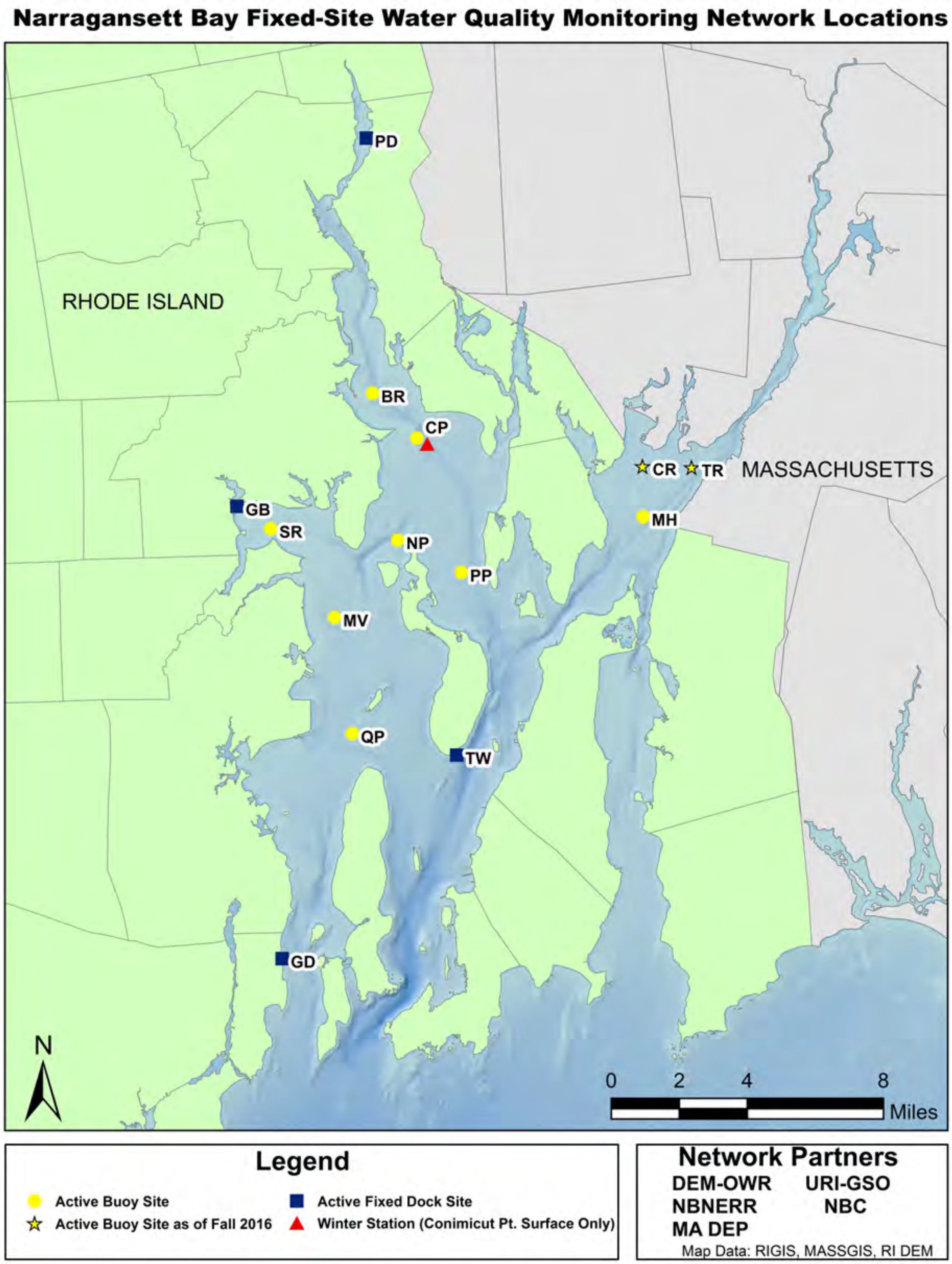


Figure 1. Locations of the fifteen Narragansett Bay Fixed Sites. Twelve sites provided data for this report: eight at buoys, the remaining four affixed to docks (Phillipsdale, T Wharf on Prudence Island, Greenwich Bay and GSO Dock). All locations have a "surface" sonde, located about a meter below the surface. All except GSO Dock have a "bottom" sonde, located about a meter above the bottom, and Bullock Reach also has a "mid" sonde. The three sites not included in this report are the CP Winter Station, Taunton River (TR) and Cole River (CR). TR and CR were added in 2016 while the CP Winter Station data are outside the seasonal time frame covered in this report. Map created by Elena Zanzarov (URI/GSO).

Department of Environmental Protection (MA DEP) also host sites in the network. Data from the network is compiled and processed by URI-GSO Marine Ecosystem Research Laboratory and made available via URI and DEM websites. There are currently 15 fixed-sites, 12 of which provided data used in this report (Figure 1, Table 1). Eight of the 12 sites are at buoys, with the remaining four affixed to docks (Phillipsdale, T Wharf on Prudence Island, Greenwich Bay, and GSO Dock). All locations have a "surface" sonde, located about a meter below the surface. All except GSO Dock have a "bottom" sonde, located about 0.5 m above the bottom, and Bullock Reach also has a "mid" sonde, located at approximately the midway point between the surface and bottom sondes. These sondes collect data every 15 minutes for a range of parameters: temperature, salinity, DO%, DO mg/L, depth, pH and surface Chl-*a*. The three fixed-sites not included in these analyses are the Conimicut Point Winter Station (also known as "Upper Bay (UB)"), excluded because we are focusing on June through September, and two new stations (CR and TR) in Mount Hope Bay recently deployed by MA DEP, excluded due to the short period of record.

Table 1. Fixed site locations and years each began collecting data. All locations have a surface and bottom sonde, unless otherwise noted.

Name	Code	Lat (dm)	Long (dm)	Start Year
Bullock Reach *	BR	41°43.980'	-71°22.130'	2001
Conimicut Point	CP	41°42.774'	-71°20.647'	2003
Greenwich Bay	GB	41°41.163'	-71°26.755'	2003
GSO Dock^{+}	GD	41°39.535'	-71°25.137'	2001
Mt. Hope Bay	MH	41°40.772'	-71°12.939'	2005
Mount View	MV	41°38.378'	-71°23.665'	2004
North Prudence	NP	41°40.238'	-71°21.340	2001
Phillipsdale Landing	PD	41°50.505'	-71°22.332'	2004
Poppasquash Point	PP	41°38.886'	-71°19.144'	2004
Quonset Point	QP	41°35.289'	-71°22.780'	2005
Sally Rock	SR	41°40.532'	-71°25.474'	2008
T Wharf, Prudence Island	TW	41°34.702'	-71°19.267'	2005
Also part of the network; data not included in this analysis				
Conimicut Point Winter Station	CP-WS	41°42.689'	-71°20.268'	2008
Cole River	CR	41°42.088'	-71°12.925'	2016
Taunton River	TR	41°42.064'	-71°11.261'	2016

* mid sonde added in 2014 $^{+}$ surface sonde only

The daily mean of the 15-minute data for the following parameters were used in this report: dissolved oxygen (DO) concentration [mg/L], water temperature [^{o}C], Chl *a* [μg/L], and density [g/cm^3]. The difference in density between the surface and bottom sondes was added to the data set for use in regression analyses to work with more uniform magnitudes of explanatory variables. For that purpose, the density difference was multiplied by 1000 [mg/cm^3].

There are a few stations, Phillipsdale (PD) and Greenwich Bay (GB) that experience high diurnal swings in DO due to high algae concentrations, identified by examining standard deviations in

DO. The daily mean is well correlated with the daily minimum (M. Brush, personal communication) and likely sufficient for these analyses. Using the daily mean will also facilitate future calculations and reporting. However, given that these stations are shallow and can experience 8 to 14 hours of low DO during the summer growing season (May through October), the daily mean DO at these stations should be viewed with some caution.

We used river flow data from USGS stream gages located within the Narragansett Bay drainage area (USGS, 2018). The long-term data from a subset of these stream gages were reported on in a companion report (Kellogg, in preparation).

DATA ORGANIZATION

Fixed site data were assembled through a months-long process that began with downloading all available data from narrbay.org. These data were then organized and catalogued, and missing years were obtained from Heather Stoffel at the URI MERL lab. All data started out as Excel files and were converted to .csv format because it is more stable than Excel and more reliably read into R. Separate .csv files were created for each site and sonde depth combination. Consistent file names and structure were created to allow for automated reading in R.

After data were read into R from .csv files, duplicates were removed, then checked for duplicate dates but different data values. When any discrepancies were identified, Heather Stoffel was consulted and the original data were amended and re-sent to me as Excel files. I then re-formatted as .csv and re-checked. “Tidy data” rules were followed such that the structure of the final complete data frame was one row per observation with the following columns:
Date: YYYY-MM-DD
param: possible values = Temp, Salinity, DO., DO.Conc, Depth, pH, Chl, Turb, SpCond, Density
measure: value of parameter at time of observation (in this case mean daily value)
site: possible values = BR, CP, GB, GD, MH, MV, NP, PD, PP, QP, SR, TW
depth: possible values = surface, mid, bottom

An associated data frame was created to keep fixed site long name and lat/long locations.

All coding and data are stored at https://github.com/qkellogg/narrbay_flow_hypoxia.

DATA ANALYSES

All analyses were performed using R (R Core Team, 2016) through the RStudio interface (RStudio Team, 2015). R is a free open-source code developed for statistical computing and graphics.

This report focuses on hypoxia in Narragansett Bay as recorded at the Narragansett Bay Fixed Sites from June 1 to September 30 for the years 2001 to 2015, using the mean daily data. Hypoxia was examined by asking the following general questions:

1. Can we identify any trends in hypoxic days with respect to frequency or severity from 2001 to 2015 at any of the fixed sites?
2. Can we characterize hypoxia events with a deficit-duration value using the Moving Window Trigger method (Codiga, 2008) applied to mean daily data?
3. Are the bottom water hypoxia events (deficit-duration values) correlated with conditions of potential explanatory variables that precede their onset?
4. Are the bottom water hypoxia days (distinct from "events") correlated with these same potential explanatory variables?
5. Is the DO at sites in the same region of the bay correlated? Sites to consider:
    a. In the northern region of the bay: Bullock Reach (BR), Conimicut Point (CP), and North Prudence (NP).
    b. In the West Passage: Mount View (MV), correlated with North Prudence (NP) and/or Sally Rock (SR).
6. Are hypoxia events at Quonset Point (QP) correlated with hypoxia events at Mount View (MV) or further north in the bay?
7. Are seasonal cumulative deficit durations correlated with total river flow over the season?

To answer these questions, we used two thresholds for mean daily DO concentration. These thresholds are intended to approximate DO concentrations at which organisms begin to be stressed (5 mg/L) and where they may begin to perish (2 mg/L). These are near, but not equal to, certain commonly referred to DO thresholds that are part of the Rhode Island Saltwater DO Criteria (RI DEM OWR, 2010). However, application of the state criteria to assess water quality conditions involves review of data over a growing season at various DO concentrations and time durations. The RI criteria are not intended to be applied to mean daily DO.

We define mean daily DO status categories as follows:

Oxic:	Dissolved oxygen concentrations $\geq$ 5 mg O_2/L
Hypoxic:	Dissolved concentrations > 2 mg O_2/L and < 5 mg O_2/L
Severely Hypoxic to Anoxic:	Dissolved oxygen concentrations $\leq$ 2 mg O_2/L

Analysis of Trends in Hypoxic Days

A simple analysis of trends was done by tallying the number of days within each DO status category at each site and depth over each season then normalizing by dividing by the total number of days of data for the season to arrive at percent of days at each DO status category for each season. If a trend was suspected, a linear regression was performed to explore a possible trend.

Hypoxia Events: Calculation of Deficit-Duration

The severity of hypoxia events was characterized using the Moving Window Trigger (MWT) method (Codiga, 2008). An MWT analysis is with respect to a DO threshold. It captures the *duration* of an event as seen through a "window" moving through time where the beginning and end of the event are defined by DO being at or below the threshold for at least the length of the "window." The *deficit* for an event is then the difference between the threshold and the mean DO during the event. The severity of the event is the product of the *deficit* and *duration* (called the deficit-duration, and represents the area between a time vs. DO curve and the defined threshold. This type of analysis has previously been used with a window of 9-hours on 15-minute data (e.g., Codiga et al., 2009). Here we used a one-day window on mean daily data and the thresholds of 2 mg O_2/L and 5 mg O_2/L. A deficit-duration was calculated for each hypoxic event as:

deficit = threshold DO concentration – event mean DO concentration [mg O_2/L]
duration = length of event [days]
deficit-duration = deficit * duration [mg O_2/L days].

In order to test the daily MWT method as compared to the hourly MWT, we used three different thresholds that were also used in Codiga et al. (2009): 4.8, 2.9, and 1.4 mg O_2/L. This allowed comparison of our event characterizations with those described in Codiga et al. (2009).

Hypoxia Events: Relationships Between Deficit-Duration and Potential Explanatory Variables
To explore relationships between deficit-duration of hypoxia events and the conditions preceding these events, we focused on hypoxia events recorded at each bottom sonde, and excluded any events that were adjacent to data gaps. We first explored possible correlations among potential explanatory variables for the formation, severity and duration of hypoxic conditions. These results were used to guide the final choice of variables to use in a linear regression model.

The pre-event conditions were summarized as the value on day zero (day of hypoxia onset), the mean for the 1 to 7 days preceding the onset, and the mean for the 8 to 14 days preceding the onset, with the aim of understanding if there is a significant time component to potential explanatory variables. Potential variables considered were bottom water temperature, density difference between surface and bottom waters, as surrogate for stratification, and the sum of freshwater flow as recorded at gages near the fixed site. We used flow data from gages considered most representative of river flow influencing each site (Table 2). We excluded flow at day zero assuming that any flow recorded at a stream gage would not have a same-day effect at a fixed site in the bay. In addition, we examined surface Chl *a* as an explanatory variable.

A correlation analysis showed that bottom water temperature was highly correlated over time. This was not unexpected because water temperature shifts relatively slowly as compared to air temperature. Similarly, density difference between the bottom and surface sondes was correlated over time, often strongly so. And finally, the sum of freshwater flow for days 1 to 7 was highly correlated to the sum of freshwater flow for days 8 to 14. Surface mean Chl *a* at these different intervals was not strongly correlated. We therefore pared down the potential explanatory variable list to the following:

Surface mean Chl *a* concentration at day 0, days 1 to 7, and days 8 to 14
Mean bottom water temperature for days 0 to 14

Mean density difference for days 0 to 14
Sum of freshwater flow for days 1 to 7

A regression analysis was then done with event deficit-duration as the dependent variable for all sites using both thresholds. Relationships were identified as statistically significant for $p < 0.05$.

Hypoxic Days: Correlation with Potential Explanatory Variables

The extent to which these possible variables may explain the presence/absence of hypoxic days, rather than hypoxic event onset and severity (described above), was investigated by using logistic regression on a binary factor of 0 or 1 on each date of the season to indicate whether a day was below a specified threshold (2 or 5 mg O_2/L). We calculated the same conditions listed above for each date of the season. The logistic regression took the general form of hypoxia represented by [0/1] ~ variable1 + variable2 + variable3…

The goodness of fit was tested using McFadden's pseudo R^2, also denoted as ρ^2, which is similar to the R^2 used in ordinary regression but uses log-likelihood to assess goodness of fit. While it falls between 0 and 1, the nature of the distribution is such that values between 0.2 and 0.4 for ρ^2 would represent an excellent fit (McFadden, 1978).

Table 2. Gages used to estimate river flow in the region of each fixed site.

Site	Flow Region	Gage No.	Gage Name
BR, CP	Providence River	01112500	Blackstone River @ Woonsocket, RI
		01114000	Moshassuck River
		01116500	Pawtuxet River @ Cranston, RI
		01109403	Ten Mile River
		01114500	Woonasquatucket River @ Centerdale, RI
PD	Blackstone River	01112500	Blackstone River @ Woonsocket, RI
MH	Mt. Hope Bay	01108000	Taunton River near Bridgewater, MA
		01109000	Wading River near Norton, MA
GB, SR	Greenwich Bay	01117000	Hunt River near E. Greenwich, RI
NP, MV, QP, PP, TW	Narragansett Bay		Using method in Kellogg (in preparation)

Correlations Among Sites in the Upper Bay and West Passage

To explore correlations in DO at Conimicut Point (CP) with DO at Bullock Reach (BR) and North Prudence (NP), we plotted mean daily DO at CP and BR throughout each season, and at CP and

NP throughout each season, and performed a linear regression to explore the degree to which DO at BR and NP could explain DO at CP.

Similarly, to explore correlations in DO at Mount View (MV) with DO at Sally Rock (SR) and T-Wharf (TW) we plotted mean daily DO at MV and SR throughout each season, and at MV and TW, and performed a linear regression to explore the degree to which DO at SR and TW could explain DO at MV.

To explore overlap of hypoxia events, we used the approach described in Codiga et al. (2009) where fractional overlap was defined as the number of days that a hypoxic event is occurring at both stations divided by the total number of days of hypoxic events for the station with fewer hypoxic event days. For example, a fractional overlap (FO) of 1 would mean that the station with fewer hypoxic event days completely overlapped with the station with more hypoxic event days. This was done for both sets of stations described above, at both thresholds.

To explore the correlation between QP hypoxia events and those at nearby sites, the fractional overlap as described above was calculated between QP and SR, MV, NP, and TW.

Correlating Seasonal Cumulative Deficit-Duration with Seasonal Cumulative River Flow
While this was not the original focus of this report, it is included as an introduction to the issues surrounding the characterization of seasonal river flow (“wet,” “dry,” “normal”) as it relates to seasonal cumulative hypoxia events. Several plots are used to show potential relationships.

Where appropriate, stations were associated with bay regions consistent with those described in Oviatt et al. (2017).

RESULTS

An important component of any data analysis is understanding existing data gaps over the period of analysis. To that end, data gaps have been identified and summarized for the parameters used in this report (Chl *a*, Density, DO Concentration and Temperature) (Appendix). Summary statistics for Chl *a*, Density, DO Concentration, and Temperature are shown in the Appendix. The data gaps were accounted for when characterizing hypoxia events using deficit-duration. We excluded any events that were adjacent to data gaps, which reduced the number of events that were included in any analyses that used deficit-duration numbers. We focused on bottom hypoxia events, and the maximum fraction of events that were excluded was 21 of a total of 111 events at the 5 mg O_2/L threshold at the bottom sonde at Bullock Reach (BR) and 1 of a total of 7 events at the 2 mg O_2/L threshold at Conimicut Point (CP). While it is possible that the exclusion of these hypoxia events affected the analyses, it is not considered likely.

TRENDS IN HYPOXIC DAYS

Given the significant management response to past hypoxic events through the reduction of nitrogen loadings to Narragansett Bay, it is of great interest to assess any possible trend in hypoxic days. With the exception of Greenwich Bay (GB), there are no obvious trends in the number of seasonal hypoxic days from 2001 to 2015 (Figure 2) as recorded at bottom sondes. Graphs representing data from the bottom sonde at each site are arranged north to south, starting at Phillipsdale at the mouth of the Seekonk River and going south down the West Passage of the bay (Figure 2A, over this and the following two pages), followed by Greenwich Bay (Figure 2B) and Mt. Hope Bay (Figure 2C).

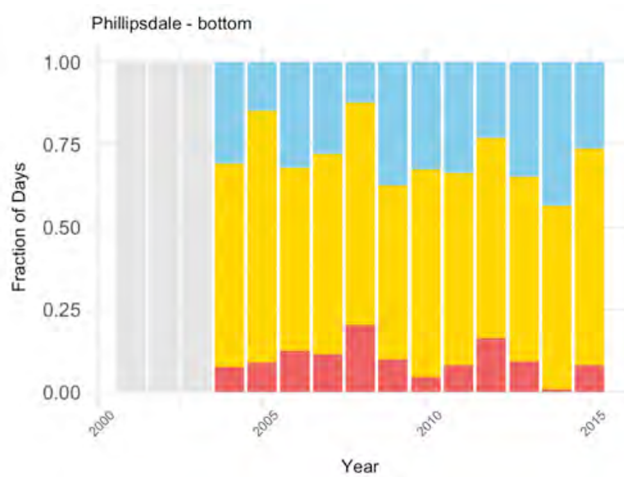
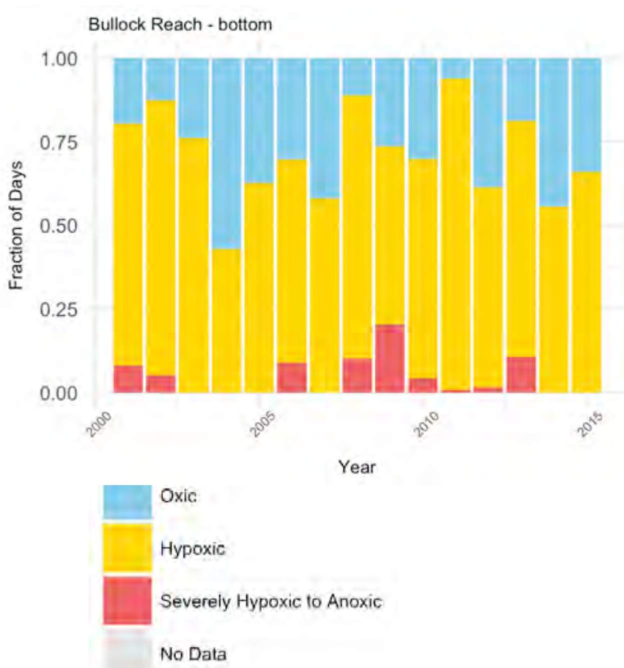
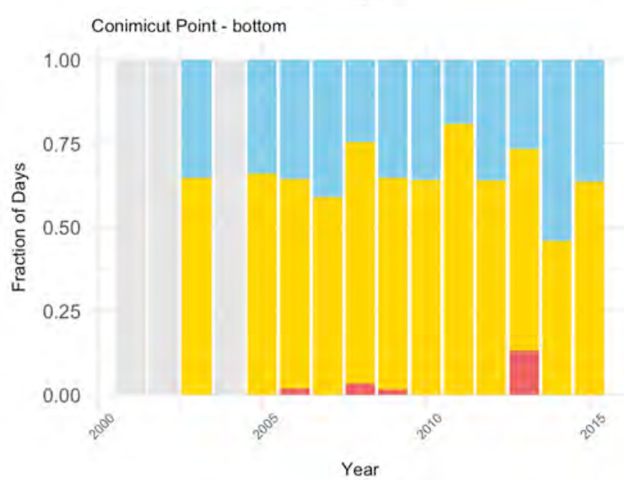


Figure 2A. Fraction of days with DO < 2 mg/L (Severely Hypoxic to Anoxic), 2 mg/L ≤ DO < 5 mg/L (Hypoxic), and DO ≥ 5 mg/L (Oxic). Data are from bottom sondes at each site. Graphs are arranged N to S.





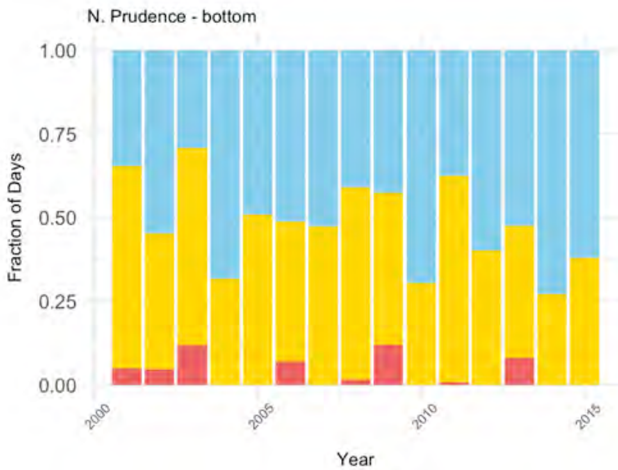
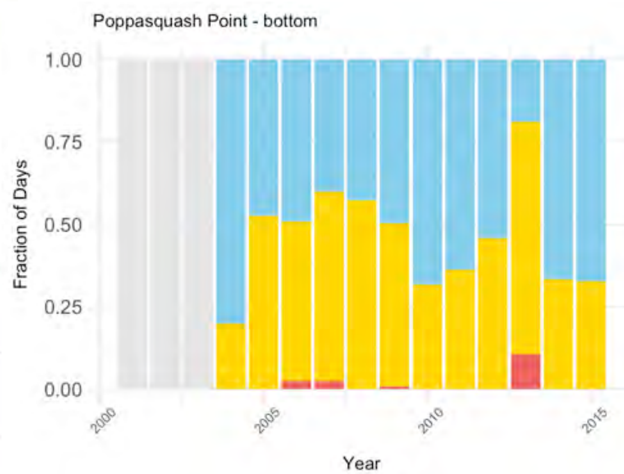
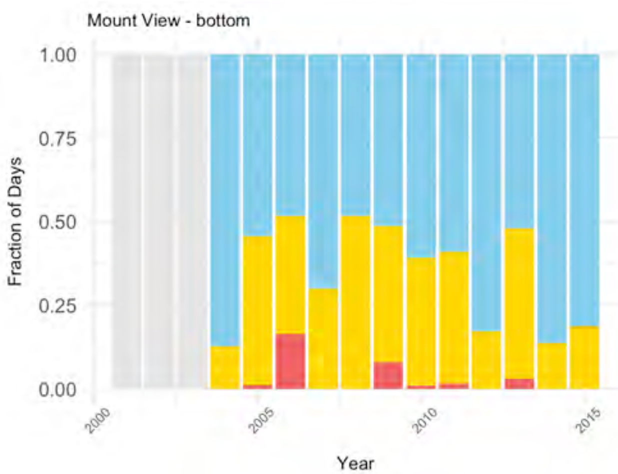
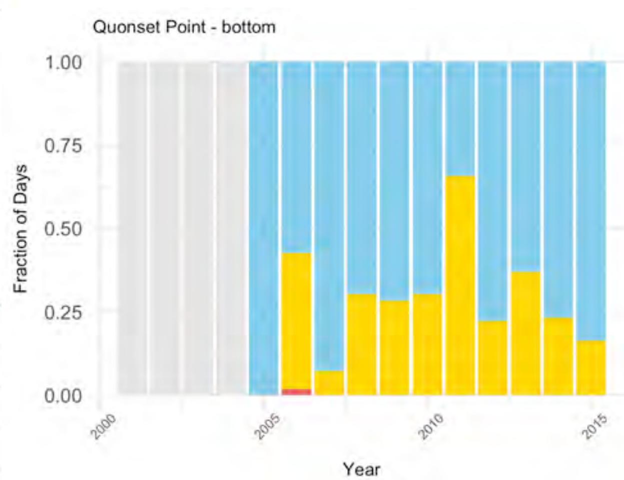
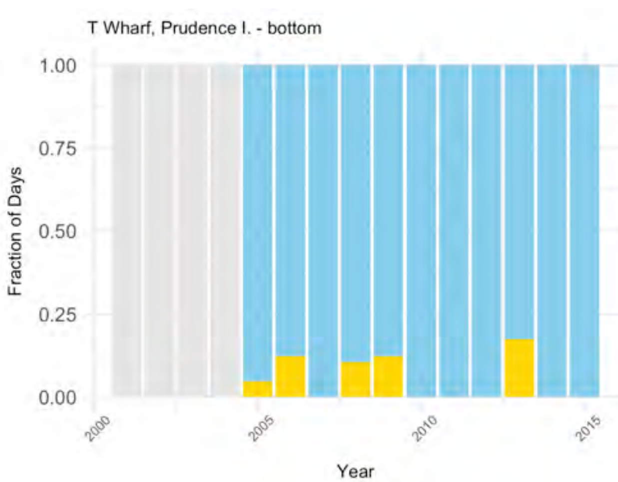


Figure 2A *continued*. Fraction of days with DO < 2 mg/L (Severely Hypoxic to Anoxic), 2 mg/L ≤ DO < 5 mg/L (Hypoxic), and DO ≥ 5 mg/L (Oxic). Data are from bottom sondes at each site. Graphs are arranged N to S; continued from previous page.









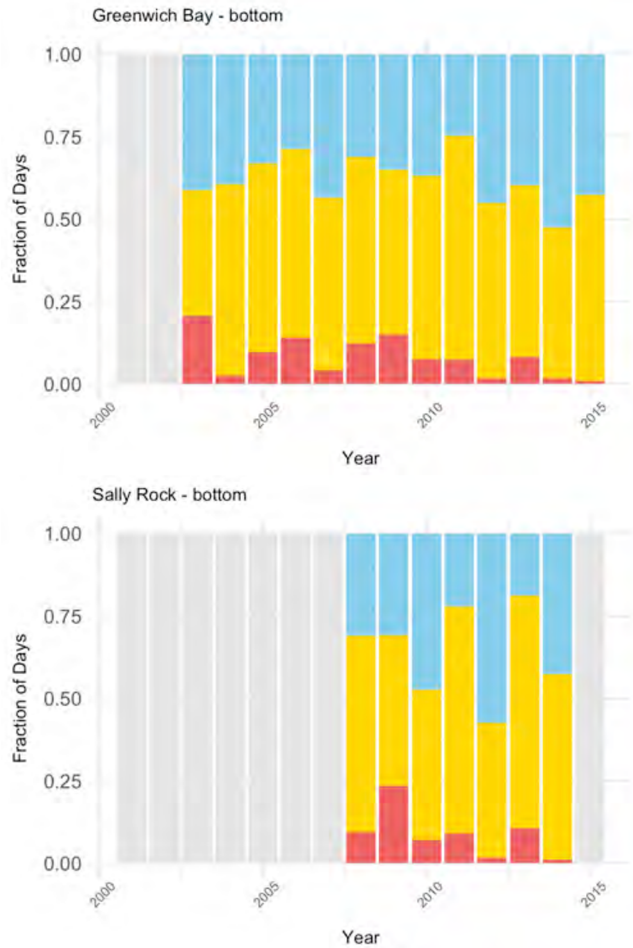


Figure 2B. Greenwich Bay and Sally Rock bottom sondes. Fraction of days with DO < 2 mg/L (Severely Hypoxic to Anoxic), 2 mg/L ≤ DO < 5 mg/L (Hypoxic), and DO ≥ 5 mg/L (Oxic). A statistically significant downward trend in "Severely Hypoxic to Anoxic" days was found at the Greenwich Bay bottom sonde.

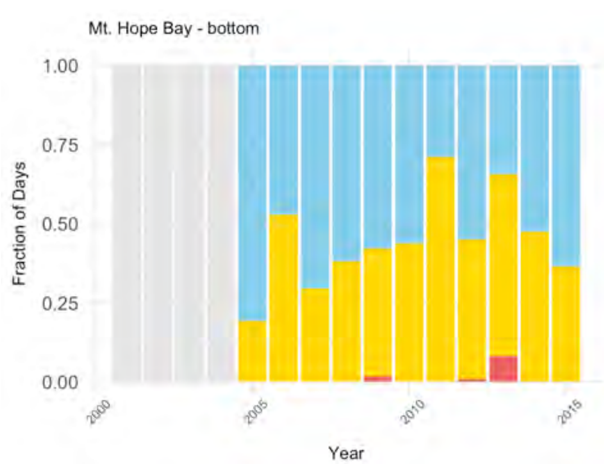


Figure 2C. Mt. Hope Bay bottom sonde. Fraction of days with DO < 2 mg/L (Severely Hypoxic to Anoxic), 2 mg/L ≤ DO < 5 mg/L (Hypoxic), and DO ≥ 5 mg/L (Oxic).

Seasons are represented by the proportion of days in each hypoxia status category out of the total number of days of data available during that season. Most recent years in the analysis show fewer severely hypoxic days, however given the variability in the longer data set the finding of few trends is not unexpected. Consistent with the findings of previous work (e.g., NBEP, 2017; Codiga et al., 2009; Oviatt, 2008), conditions improved from north to south. T-Wharf (TW) shows no severely hypoxic days between 2001 and 2015, and is noted by RI DEM as a site that is consistently in compliance with water quality standards (e.g., RI DEM, 2015). Again, the mean daily DO data from PD and GB may be underestimating the severity due to the wide swings in DO concentration during a 24-hour period.

As noted in the Methods Section, linear regressions were performed on data that visually suggested a trend over time. A linear regression of the GB “Severely Hypoxic to Anoxic” seasonal fraction of days against year showed a statistically significant downward trend between 2003 and 2015 at $p < 0.05$ and $R^2 = 0.3$, suggesting that about 30% of the variation in seasonal fraction of days with DO < 2 mg/L is explained by year. A similar analysis of “Hypoxic” fraction of days at GB showed no trend. The same regression analysis was performed on the data from Sally Rock (SR), but no statistically significant trend was found, likely due to fewer years of data collection. Graphs for data from surface sondes is presented in the Appendix (Section V).

HYPOXIA EVENTS: CALCULATION AND ANALYSIS OF DEFICIT-DURATION

As noted in the Methods Section, the modified MWT method that used daily data with a one-day window was compared to the MWT method that used 15-minute data and a 9-hour window by comparing identified events and their deficit-duration values.

Table 3. Summary statistics of seasonal hypoxia events from 2001 to 2015 for a threshold of 2 mg O_2/L. Season = June through September. Max and Min number of events in a season, event duration, event deficit and event deficit-duration are for all seasons within the monitoring period. Sites are color-coded by region consistent with accompanying graphs: Providence River (BR, PD), Upper Bay (CP, MH, NP), Greenwich Bay (GB, SR), Mid-Bay (MV, PP), and Lower Bay (QP, TW, GD).

Site*	# Years		# Events in a Season		Event Duration [day]		Event Deficit [mg O_2/L]		Event Deficit-Duration [mg O_2/L day]	
	With Events	Monitored	Min	Max	Min	Max	Min	Max	Min	Max
PD	11	12	1	9	1	9	0.04	1.15	0.04	10.35
BR	9	15	1	6	1	9	0.03	0.76	0.03	4.99
CP	4	12	1	2	1	4	0.11	0.62	0.11	2.49
MH	3	11	1	3	1	5	0.01	0.51	0.01	1.31
NP	7	15	1	5	1	6	0.03	1.06	0.03	5.29
GB	13	13	1	10	1	12	0.01	1.76	0.01	13.71
SR	7	7	1	8	1	7	0.04	1.65	0.04	7.55
MV	6	12	1	3	1	11	0.05	1.38	0.05	12.38
PP	4	12	1	4	1	7	0.05	0.85	0.05	4.99
QP	1	11	1	1	2	2	0.05	0.05	0.09	0.09

* TW and GD are not listed because they had no hypoxia events as defined by this threshold.

Deficit-duration values calculated with the daily MWT method with thresholds used in Codiga et al. (2009) were generally comparable to those presented in Tables 4 to 6 of that paper. Supporting materials are in the Appendix (Section III), along with tables similar to Tables 4 to 6 in Codiga et al. (2009), but using the 2 mg/L and 5 mg/L thresholds, and over the time period of 2001 to 2015.

Over the 15-year period from 2001 to 2015, the most frequent severely hypoxic events (< 2 mg O_2/L) occurred in Greenwich Bay (Tables 3), which also experienced the longest duration, deepest deficit and most severe deficit-duration. Greenwich Bay is an embayment on the west side of Narragansett Bay, with a densely developed watershed and limited exchange with the main stem of the bay, creating serious water quality challenges.

Another site with frequent severely hypoxic events is furthest north at Phillipsdale (PD), which is located in the Seekonk River, a little downstream of the mouth of the Blackstone River. It is a shallower site and experiences wide swings in salinity and dissolved oxygen. It is also located near the Bucklin Point wastewater treatment facility outfall, while the Blackstone River also receives treated wastewater from cities upstream, such as Woonsocket, RI and Worcester, MA. Severely hypoxic events decrease in frequency and severity from north to south.

Table 4. Summary statistics of seasonal hypoxia events from 2001 to 2015 for a threshold of 5 mg O_2/L. Season = June through September. The maximum and minimum number of events in a season, event duration, event deficit and event deficit-duration are for all seasons within the monitoring period. Sites are color-coded by region consistent with accompanying graphs: Providence River (BR, PD), Upper Bay (CP, MH, NP), Greenwich Bay (GB, SR), Mid-Bay (MV, PP), and Lower Bay (QP, TW, GD).

Site*	# Years		# Events per Season		Event Duration [day]		Event Deficit [mg O_2/L]		Event Deficit-Duration [mg O_2/L day]	
	With Events	Monitored	Min	Max	Min	Max	Min	Max	Min	Max
PD	11	12	5	13	1	52	0.05	3.01	0.05	130.9
BR	15	15	2	12	1	83	0.01	2.53	0.01	186.9
CP	12	12	2	10	1	77	0.0003	3.08	0.0003	113.2
MH	11	11	4	16	1	30	0.002	2.05	0.002	61.4
NP	15	15	3	14	1	37	0.003	2.55	0.003	94.5
GB	13	13	5	19	1	41	0.03	3.08	0.06	71.5
SR	7	7	3	17	1	58	0.003	2.70	0.003	113.5
MV	12	12	4	12	1	43	0.007	3.08	0.007	132.2
PP	12	12	3	16	1	58	0.008	1.90	0.008	110.2
QP	10	11	2	10	1	42	0.01	1.24	0.01	51.9
TW	5	11	2	8	1	12	0.03	1.00	0.03	11.5

* GD is not listed because it had no hypoxia events as defined by this threshold during this time period.

When the threshold was raised to 5 mg O_2/L there are many more hypoxia events identified, and less distinction among the sites with respect to frequency (Table 4). Maximum event durations were higher in the northern part of the bay, while maximum event deficits were similar throughout most of the bay, with the exception of the lower bay. Maximum event severity (as deficit-duration) was highest at BR, reflecting a high maximum duration. Maximum event severity at this higher threshold appears to be driven more by event duration rather than event deficit.

The year-to-year data (Figures 3 to 6) show high inter-annual variability and somewhat different phenomena between the 2 and 5 mg O_2/L thresholds. Total number of severely hypoxic events, by region, were highest in 2009, but with a lower relative number of events when the threshold is raised to 5 mg O_2/L (Figure 3), suggesting that the events that did occur in 2009 were more severe, as opposed to more frequent and less severe events.

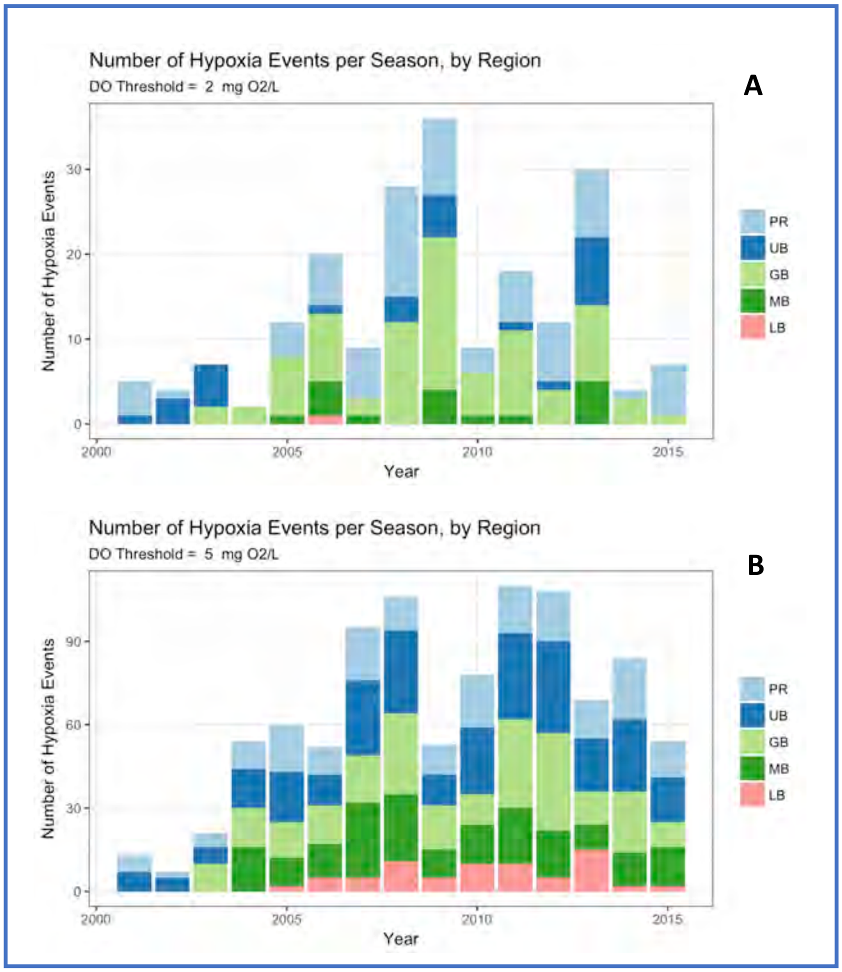


Figure 3. Number of hypoxia events for each season as defined by 2 mg O_2/L (A) and 5 mg O_2/L (B). PR = Providence River (PD, BR), UB = Upper Bay (CP, MH, NP), GB = Greenwich Bay (GB, SR), MB = Mid-Bay (MV, PP), and LB = Lower Bay (QP, TW, GD).

Maximum event durations appear to be nudging downward over time at the 2 mg O_2/L threshold (Figure 4A). At the 5 mg O_2/L threshold maximum event durations peaked in 2008, again with a slight downward trend over time (Figure 4B). Maximum event deficits also appear to be nudging downward over time at the 2 mg O_2/L threshold (Figure 5A). At the 5 mg O_2/L threshold there appears to be no such suggestion (Figure 5B). Maximum event deficit-duration at the 2 mg O_2/L threshold was highest in Greenwich Bay in 2003, the same year that a large fish kill was recorded there (Figure 6A). Greenwich Bay appears to have been uniquely low in oxygen that year, while 2009 saw a more widespread increase in maximum deficit-duration. Given the high variability in these natural systems, continued monitoring is necessary in order to more clearly discern trends over time.

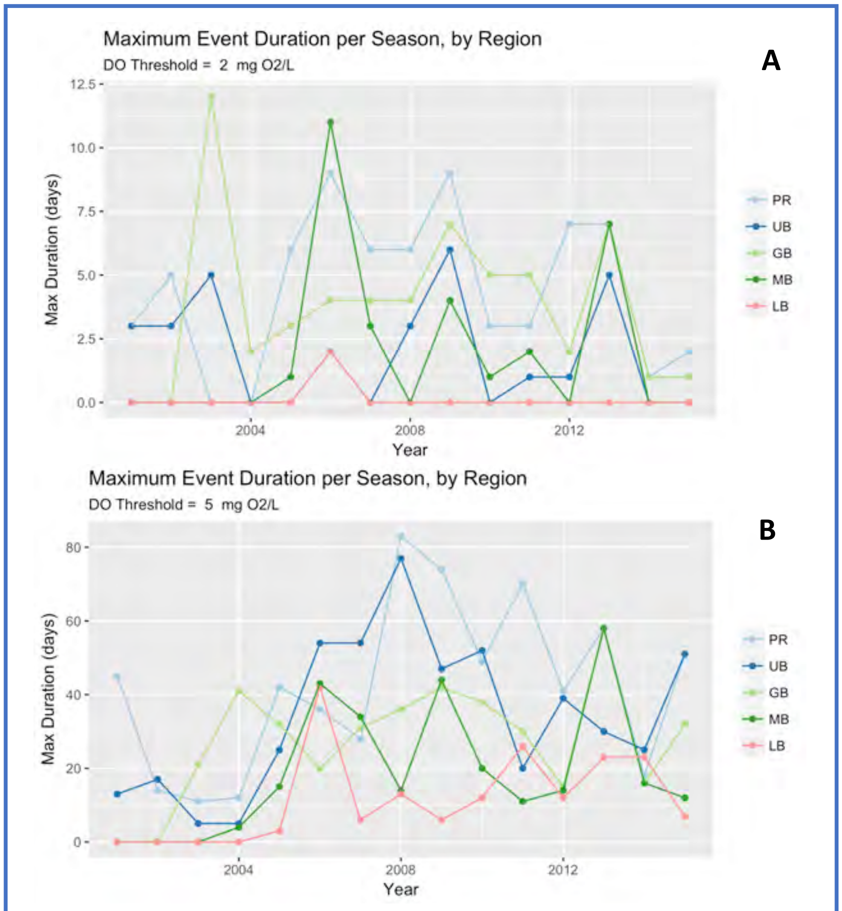


Figure 4. Maximum duration of hypoxia events for each season as defined by 2 mg O_2/L (A) and 5 mg O_2/L (B). PR = Providence River (PD, BR), UB = Upper Bay (CP, MH, NP), GB = Greenwich Bay (GB, SR), MB = Mid-Bay (MV, PP), and LB = Lower Bay (QP, TW, GD).

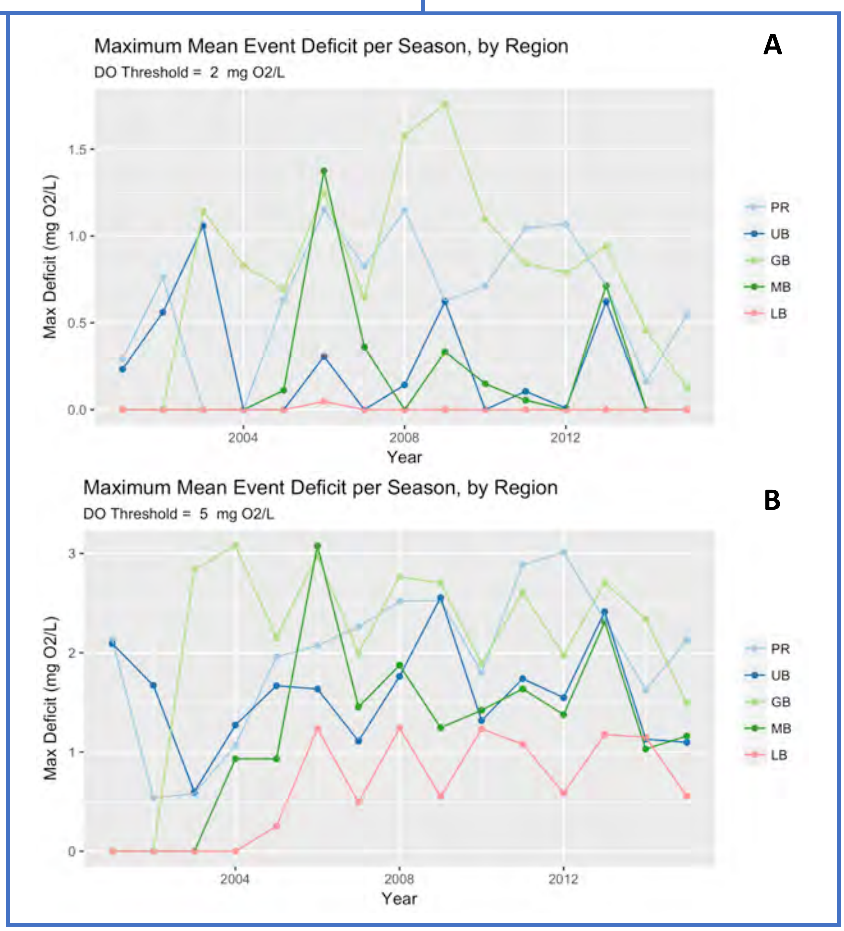


Figure 5. Maximum mean of event deficit during hypoxia events for each season as defined by 2 mg O_2/L (A) and 5 mg O_2/L (B). PR = Providence River (PD, BR), UB = Upper Bay (CP, MH, NP), GB = Greenwich Bay (GB, SR), MB = Mid-Bay (MV, PP), and LB = Lower Bay (QP, TW, GD).

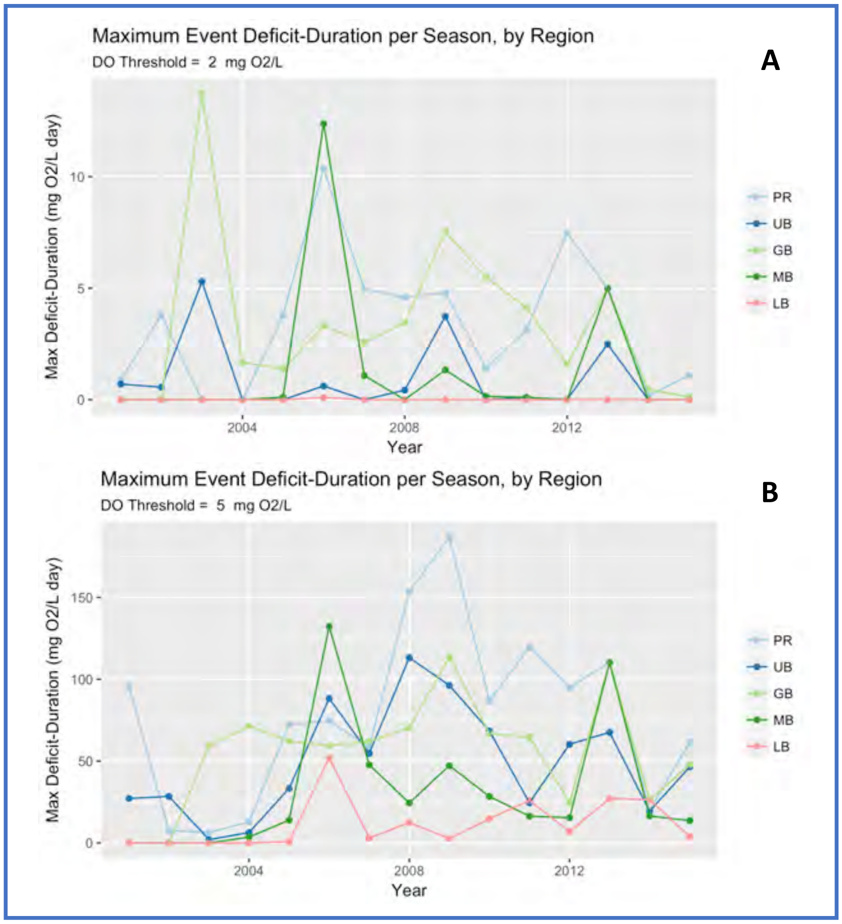


Figure 6. Maximum event deficit-duration of hypoxia events for each season as defined by 2 mg O_2/L (A) and 5 mg O_2/L (B). PR = Providence River (PD, BR), UB = Upper Bay (CP, MH, NP), GB = Greenwich Bay (GB, SR), MB = Mid-Bay (MV, PP), and LB = Lower Bay (QP, TW, GD).

Recent years show similarities with years before about 2008, suggesting that we need a longer timeframe to identify trends that are long-term and sustained.

LOGISTIC REGRESSION OF HYPOXIC DAYS WITH POTENTIAL EXPLANATORY VARIABLES

As mentioned in the Methods Section, a logistic regression was performed with hypoxic days as the response variable—represented as 0 or 1 to denote whether that day's mean dissolved oxygen fell below the threshold—and six potential explanatory variables: mean surface Chl *a* on day zero (day of onset), over the previous 1 to 7 days, and over the previous 8 to 14 days; mean bottom temperature over days 0 to 14 before the onset of the event; mean density difference between the surface and bottom sondes over days 0 to 14 before the onset of the event; and the sum of river flow over the previous 1 to 7 days before the onset of the event. Only those relationships that were significant at the $p < 0.05$ level were retained. The McFadden ρ^2 gives an indication of the goodness of fit, with a value between 0.2 and 0.4 considered an indication of an excellent fit (see the Methods Section for complete explanation). The coefficient is interpreted as indicating the change in the log of the odds of hypoxia occurring for one unit of change in the explanatory variable. A change in the positive direction suggests higher odds of hypoxia occurring, while a change in the negative direction suggests lower odds of hypoxia occurring.

At the 2 mg O_2/L threshold, sites that are within the same region produced very similar logistic regression models (Table 5). Mean Chl *a* appears to play a role at all sites where a model could be identified. Interestingly, there appears to be a negative relationship at day 0 (PD, CP, NP, PP), but a positive relationship with mean Chl *a* for the preceding 1 to 7 days at all but one site. Mean Chl *a* for the preceding 8 to 14 days is significant at PD (negative) and at GB and SR (positive). Mean bottom temperature for the preceding 0 to 14 days is a positive explanatory variable in the Providence River region (PD and BR) at GB and at MV, meaning that higher water temperatures increase the odds of hypoxic days.

The goodness of fit (ρ^2) of these models ranges from 0.12, good but not excellent, to 0.58, which is surprisingly high. Most are within the 0.2 to 0.4 range considered very good to excellent.

Table 5. Statistically significant ($p < 0.05$) logistic regression coefficients for hypoxic days below a threshold of 2 mg O_2/L.

Site	Mean surface Chl *a*			Mean bottom temp days 0 to 14 before date	Mean density diff days 0 to 14 before date	Sum of river flow days 1 to 7 before date	McFadden ρ^2
	Day 0	Days 1 to 7 before date	Days 8 to 14 before date				
PD	-0.05	0.02	-0.03	0.67	0.28	-0.0002	0.18
BR		0.09		0.67	0.69	-0.0001	0.31
CP	-0.20				0.90		0.33
NP	-0.20	0.18			0.99		0.28
GB		0.04	0.05	0.52	1.30	0.0027	0.22
SR		0.08	0.07			0.0022	0.12
MV		0.15		0.43	1.17		0.29
PP	-0.17	0.17			0.90	-0.0002	0.58

Mean density difference plays a role at all sites but SR, suggesting stratification is an important component in the development of severe hypoxia. Surprisingly, river flow is negatively related in the Providence River Region (PD and BR) and at PP, while positively related in the Greenwich

Bay region (GB). This is surprising because freshwater flow to the bay can contribute to density differences, promote stratification and hypoxia. Indeed, we see that mean density difference for the 0 to 14 days preceding a hypoxic day appears to play a positive role, as we would expect (greater density difference increasing the odds for hypoxia). The apparently negative influence of river flow appears to contradict this, but it may simply suggest a time lag where greater river flow initially increases mixing with higher fluxes in the short term, and later contributes to stratification as the less dense water settles closer to the surface. The positive influence of river flow during the previous 1 to 7 days to Greenwich Bay, on the other hand, is consistent with increased stratification and greater probability of hypoxia. Because Greenwich Bay is a smaller embayment it may be that there is less lag between higher river flow and increased stratification.

At the 5 mg O_2/L threshold, the mean density difference over the preceding 0 to 14 days plays a positive role at all sites and mean bottom temperature over the preceding 0 to 14 days plays a role at all but two sites (Table 6). This is similar to what was seen at the lower threshold. Again, river flow appears to play a negative role at all sites except in the Greenwich Bay region, where it appears to play a positive role. Mean Chl *a* shows up as both a positive and negative explanatory variable, suggesting complexity and localized phenomena. At this higher threshold, the models demonstrate slightly lower goodness of fit, ranging from 0.12 (good but not excellent) to 0.3 (very good to excellent).

Table 6. Statistically significant (p < 0.05) logistic regression coefficients for hypoxic days below a threshold of 5 mg O_2/L.

Site	Mean surface Chl *a*			Mean bottom temp days 0 to 14 before date	Mean density diff days 0 to 14 before date	Sum of river flow days 1 to 7 before date	McFadden ρ^2
	Day 0	Days 1 to 7 before date	Days 8 to 14 before date				
PD	-0.06			0.62	0.48	-0.00021	0.25
BR	0.05	0.07	0.03	0.47	0.62		0.26
CP	0.10	0.10	0.13	0.44	1.07	-0.00009	0.30
MH		-0.05		0.33	0.73		0.10
NP	0.03			0.31	1.28	0.00002	0.14
GB	-0.02		-0.02	0.39	0.85	0.00163	0.12
SR	0.11			0.29	1.30	0.00351	0.22
MV	0.04				1.24	-0.00002	0.12
PP		0.10		0.40	0.82		0.17
QP				0.16	0.94		0.13
TW			-1.24		1.21		0.13

RELATIONSHIP BETWEEN DEFICIT-DURATION OF HYPOXIA EVENTS AND PRECEDING CONDITIONS

As mentioned in the Methods Section, a linear regression was performed with hypoxia event deficit-duration as the dependent variable and the same set of explanatory variables as above, but taking the natural log of both the mean density difference and the sum of river flow to achieve a more normal distribution of these explanatory variables.

There were many fewer statistically significant relationships between deficit-duration of hypoxia events and the proposed explanatory variables than were found when looking at the daily occurrences of hypoxia (Table 7). In fact, there were no significant relationships found at the lower (2 mg O_2/L) threshold. A likely factor is the much lower number of hypoxia events, especially at the lower threshold, than hypoxic days.

Table 7. Statistically significant ($p < 0.05$) linear regression coefficients for hypoxic events identified using a threshold of 5 mg O_2/L.

Site	Mean surface Chl *a*			Mean bottom temp days 0 to 14 before event	Ln of mean density diff days 0 to 14 before event	Ln of sum of river flow days 1 to 7 before date	R^2
	Day 0	Days 1 to 7 before event	Days 8 to 14 before event				
BR	0.045						0.14
GB			-0.04	0.14	0.29		0.20
SR					0.60		0.33
MV				-0.19			0.21
PP		0.10					0.21

At the 5 mg O_2/L threshold, river flow appears to play no role in the severity of hypoxia events, as indicated by the deficit-duration. Mean density difference plays a positive role, but only in the Greenwich Bay region. Mean bottom temperature also plays a positive role in this region, but a seemingly weak but negative role out in the mid-bay (MV). Again, mean Chl *a* shows both positive and negative influences on deficit-duration. These results suggest the need for further analysis using more refined statistical methods given the relatively low number of hypoxic event data points available at most sites at this higher threshold.

CORRELATIONS AMONG SITES IN THE UPPER BAY AND WEST PASSAGE

Regression Analysis of bottom Dissolve Oxygen at CP, BR & NP and MV, GB & NP

Comparing bottom DO concentrations between Bullock Reach (BR) and Conimicut Point (CP) shows good agreement between the two sites, without a noticeable lag (Figure 7). Comparing bottom DO between Conimicut Point (CP) and North Prudence (NP) shows some agreement as well though, again, there is not an obvious lag (Figure 8). Linear regression with DO at CP as the dependent variable and DO at BR and NP as the explanatory variables produced a model that explained 70% (R^2 = 0.70, p < 0.001) of the variation in bottom dissolved oxygen at CP (Table 8). When either of the explanatory variables was removed, the model became either less explanatory (removing DO_{BR} gave R^2 = 0.47 (p < 0.001)), or less efficient (removing DO_{NP} produced a slightly higher value for the Aikake Information Criterion (AIC)).

Comparing bottom DO concentrations between Mount View (MV) and Greenwich Bay (GB) shows some rough agreement, without any noticeable lag (Figure 9). GB is more variable, but longer-term trends through the season are common between the two sites. Mount View (MV) and North Prudence (NP) also appear to be very similar, more so than MV with GB (Figure 10). Linear regression between MV and NP produced a model that explained 64% of the variation in bottom DO at MV ($R^2 = 0.64$, $p < 0.001$) and that between MV and GB produced a less explanatory model ($R^2 = 0.26$, $p < 0.001$). Using both GB and NP in the model produced a slightly more explanatory model than with NP alone ($R^2 = 0.66$, $p < 0.001$):

Table 8. Regression models explaining variability in DO at Conimicut Point (CP) and at Mount View (MV), using DO at nearby fixed-sites as independent variables.

Regression Model	R^2
$DO_{CP} = 1.135 + 0.699 * DO_{BR} + 0.088 * DO_{NP}$	0.70
$DO_{MV} = 1.032 + 0.126 * DO_{GB} + 0.729 * DO_{NP}$	0.66

DO_{CP} = bottom dissolved oxygen concentration at Conimicut Point,
DO_{BR} = bottom dissolved oxygen concentration at Bullock Reach,
DO_{NP} = bottom dissolved oxygen concentration at North Prudence
DO_{MV} = bottom dissolved oxygen concentration at Mount View
DO_{GB} = bottom dissolved oxygen concentration at Greenwich Bay

Fractional Overlap of Hypoxia Events

While variation in the daily mean of bottom dissolved oxygen (DO) at CP or MV can be explained by the variation in DO at nearby sites, the nature of hypoxia events as defined using the MWT method may not correlate to the same degree. To explore the degree to which hypoxia events overlap at these sites, the fractional overlap as described in the Methods Section was calculated for hypoxia events at CP, BR and NP; at MV, GB and NP; and at QP, SR, MV, and TW.

In both cases, the higher threshold resulted in higher fractional overlaps (Tables 9 and 10), suggesting a more diffuse distribution of these less severe hypoxia events. At the lower threshold, when hypoxia events are more severe, the lower fractional overlap suggests a more restricted spatial distribution, with local conditions prevailing. At Conimicut Point (CP), hypoxia events overlapped with BR 60% of the time, and with NP only 13% of the time at the lower threshold. At the higher threshold, hypoxia events at CP overlapped with BR 80% of the time while events at NP overlapped those at CP 58% of the time and those at BR 85% of the time (Table 9).

Table 9. Fractional overlap (FO) of hypoxia events at CP, BR and NP. The FO is with respect to the site with fewer hypoxia event days. The horizontal list is in descending order of number of days while the vertical list is in ascending order of number of days. The order is different at different thresholds.

Threshold = 2 mg/L		
	BR	NP
CP	0.6	0.13
NP	0.45	
Threshold = 5 mg/L		
	BR	CP
NP	0.85	0.58
CP	0.8	

Table 10. Fractional overlap (FO) of hypoxia events at MV, SR and NP. The FO is with respect to the site with fewer hypoxia event days. The horizontal list is in descending order of number of days while the vertical list is in ascending order of number of days. The order is different at different thresholds.

Threshold = 2 mg/L		
	SR	NP
MV	0.29	0.26
NP	0.4	
Threshold = 5 mg/L		
	NP	SR
MV	0.63	0.47
SR	0.64	

At Mount View (MV) at the lower threshold there was 29% overlap with hypoxia events at Sally Rock (SR), and 26% overlap with events at NP. Indeed, the fractional overlap of NP with SR is larger than any with MV, at 40%. At the higher threshold, there was higher overlap with 63% of hypoxia event days overlapping with those at NP and 47% overlapping with those at SR.

Finally, at Quonset Point (QP) at the higher threshold, the fractional overlap is roughly the same with respect to NP, SR and MV, with the highest FO occurring with NP, a surprising result because NP is furthest north from QP. There was only one hypoxia event at QP at the lower threshold.

These results highlight the spatial variability of hypoxia events and the importance of local conditions that are influenced by complex mixing patterns within the bay.

Table 11. Fractional overlap (FO) of hypoxia events at Quonset Point (QP) when compared to those at NP, SR and MV.

	Threshold = 5 mg/L		
	NP	SR	MV
QP	0.64	0.6	0.51

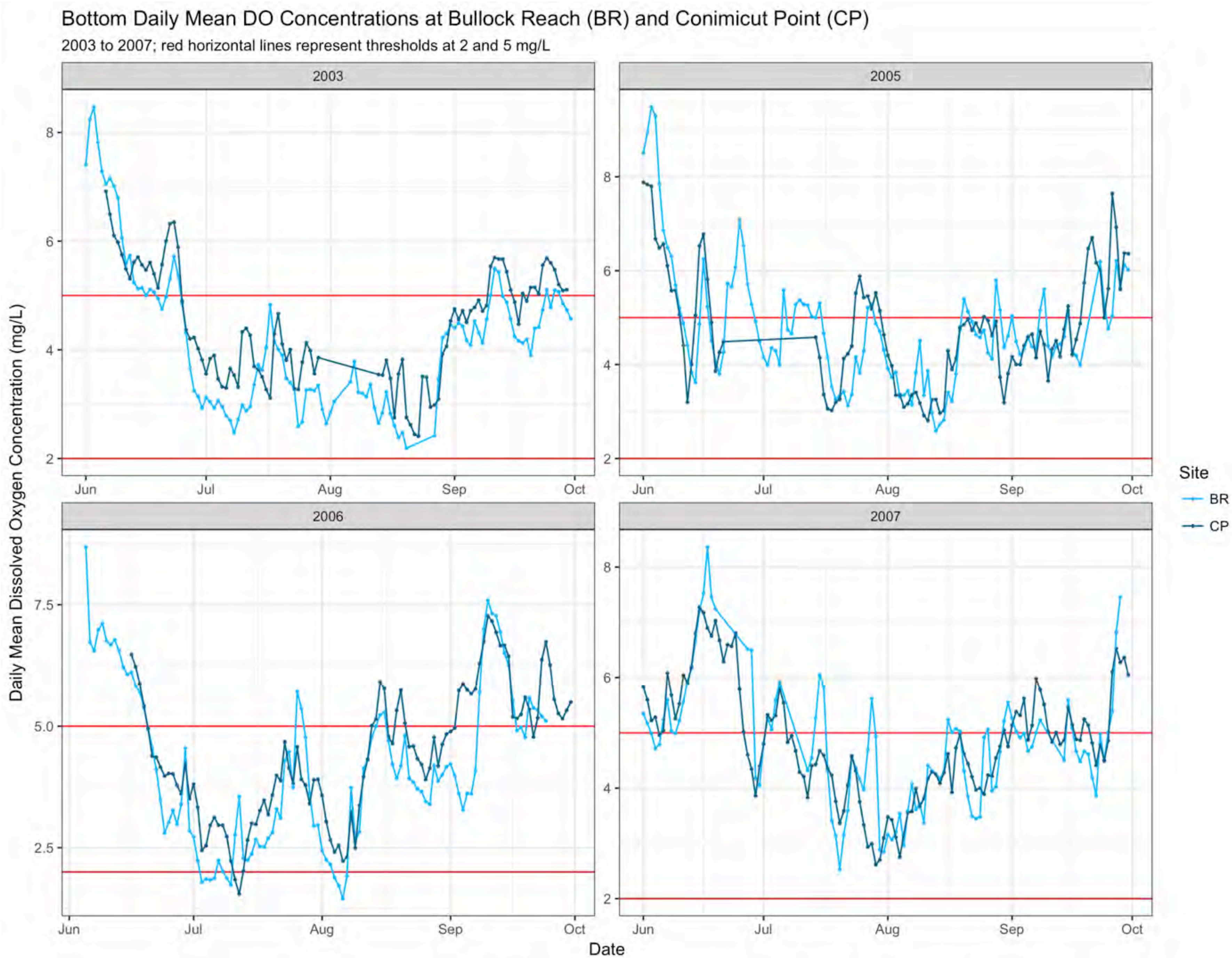


Figure 7a. Bottom dissolved oxygen concentrations (mg/L) at Bullock Reach (BR) and Conimicut Point (CP) from June 1 to September 30 for the years 2003 to 2007, omitting 2004 because data are missing at CP.

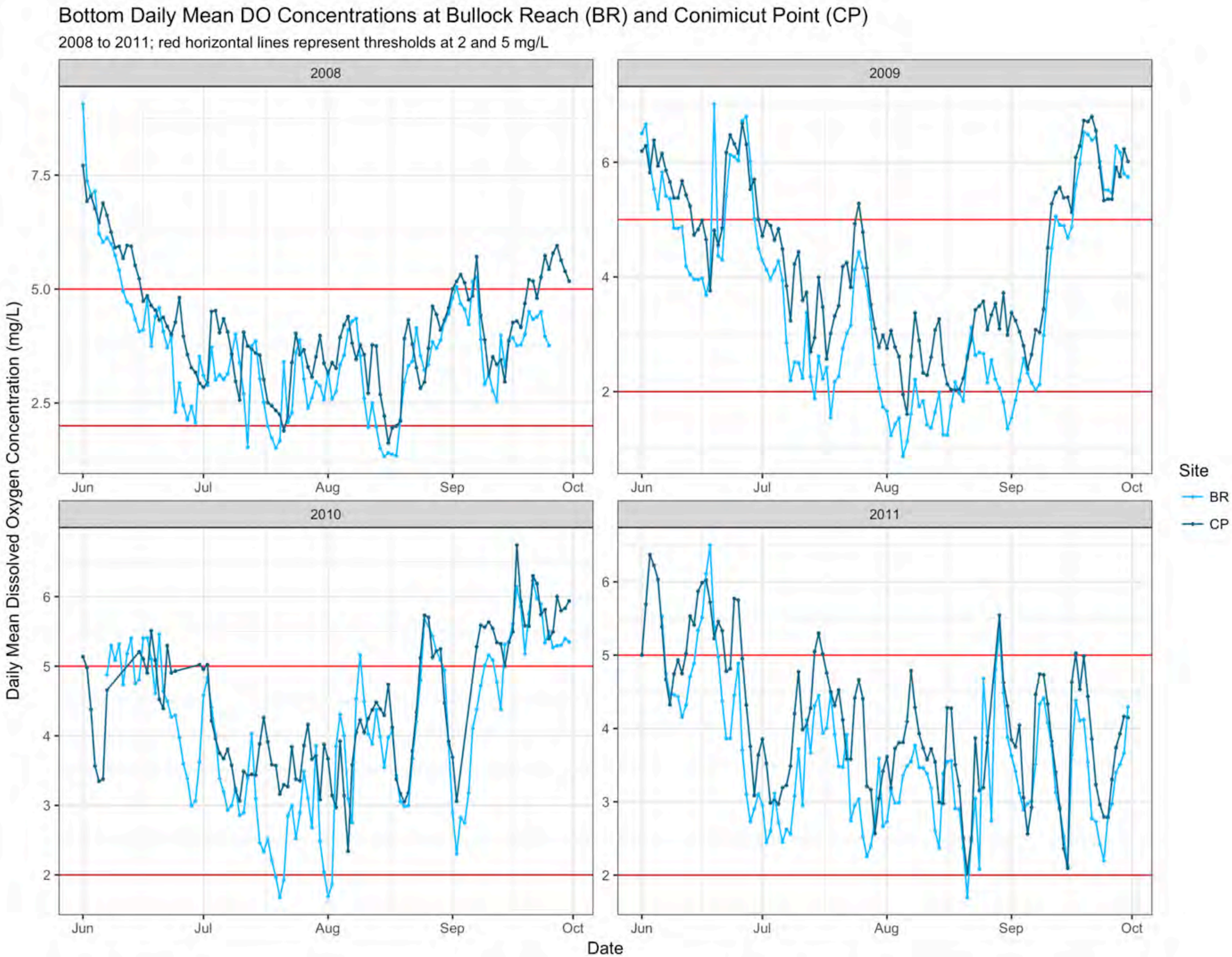


Figure 7b. Bottom dissolved oxygen concentrations (mg/L) at Bullock Reach (BR) and Conimicut Point (CP) from June 1 to September 30 for the years 2008 to 2011.

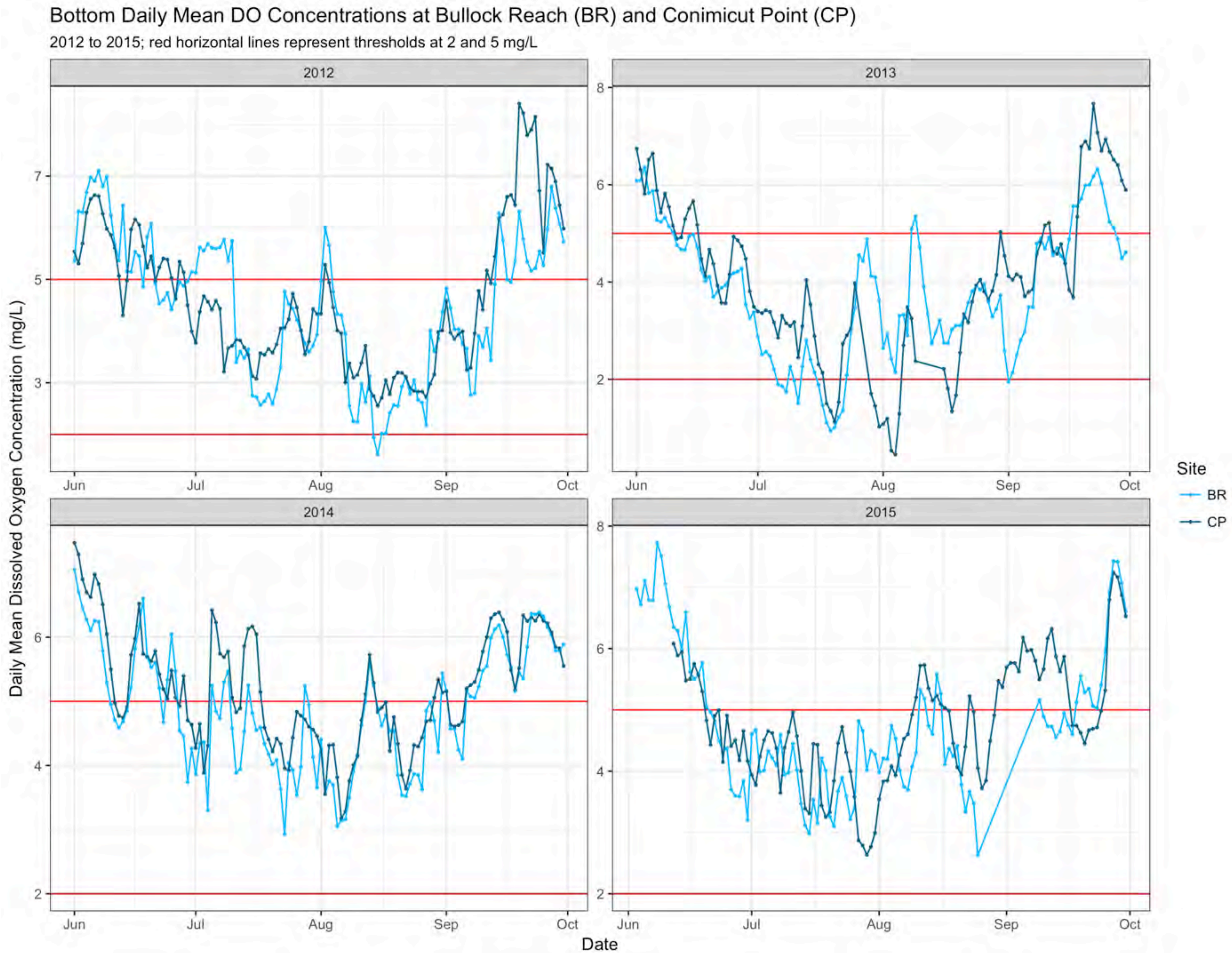


Figure 7c. Bottom dissolved oxygen concentrations (mg/L) at Bullock Reach (BR) and Conimicut Point (CP) from June 1 to September 30 for the years 2012 to 2015.

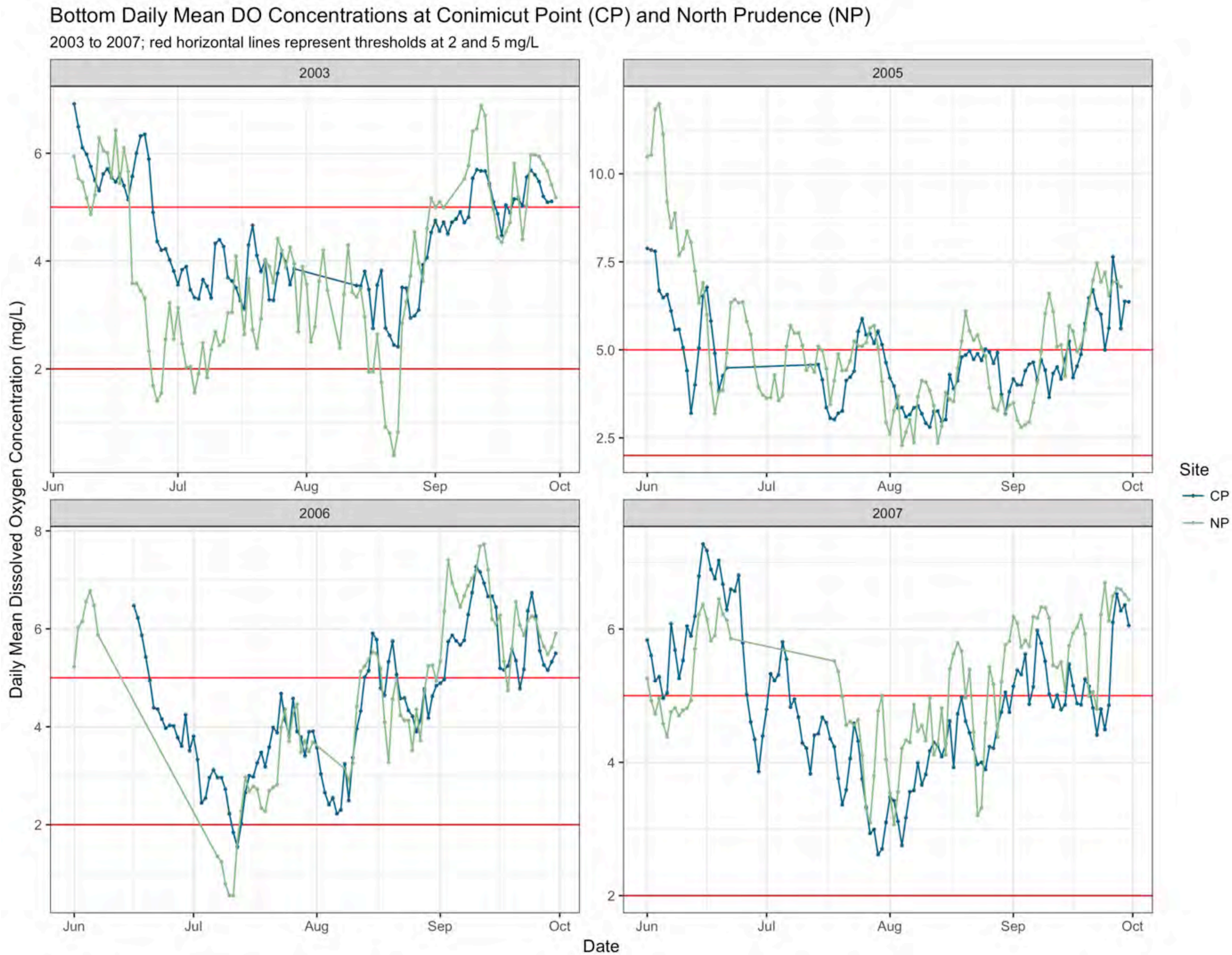


Figure 8a. Bottom dissolved oxygen concentrations (mg/L) at Conimicut Point (CP) and North Prudence (NP) from June 1 to September 30 for the years 2003 to 2007, omitting 2004 because data are missing at CP.

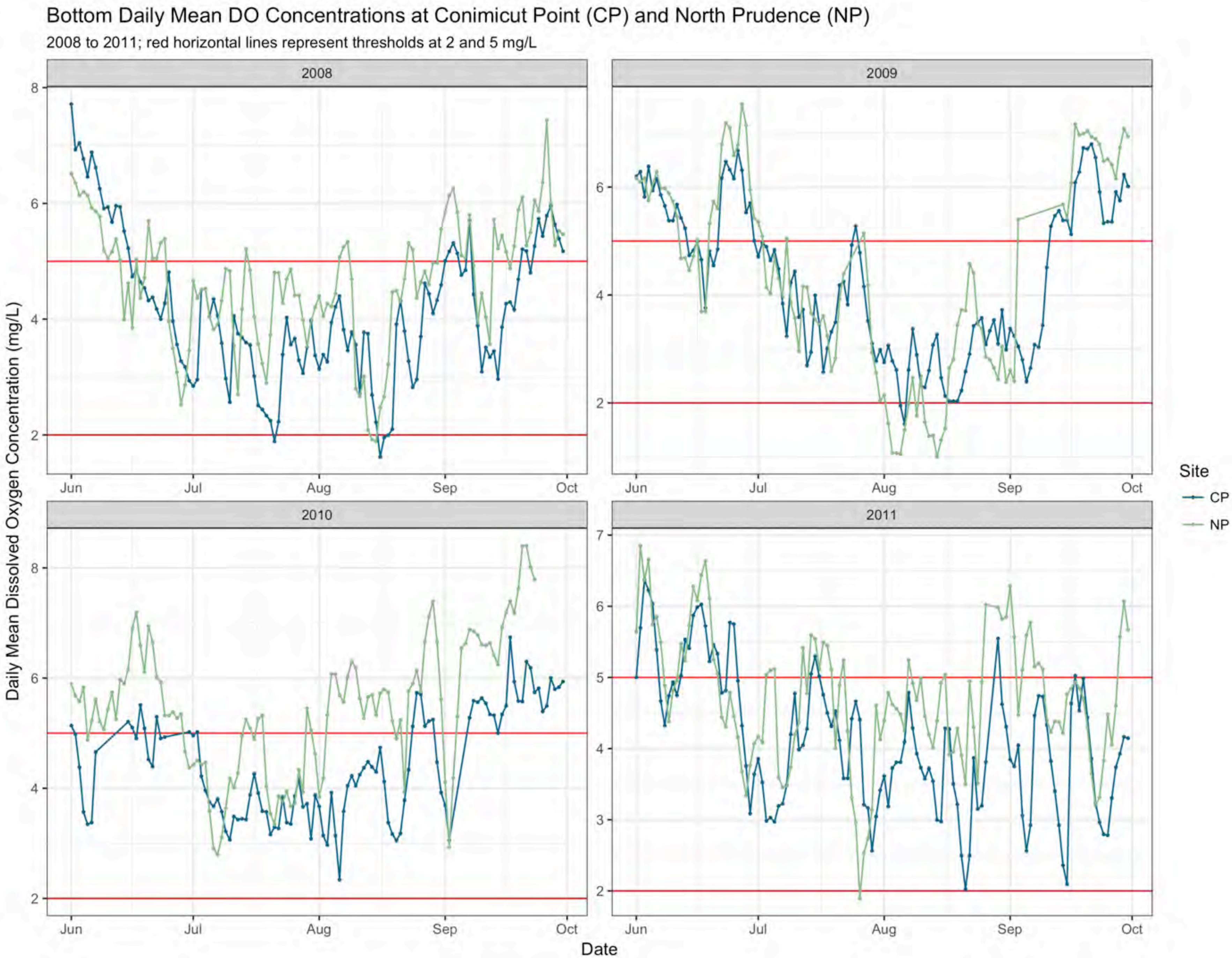


Figure 8b. Bottom dissolved oxygen concentrations (mg/L) at Conimicut Point (CP) and North Prudence (NP) from June 1 to September 30 for the years 2008 to 2011.

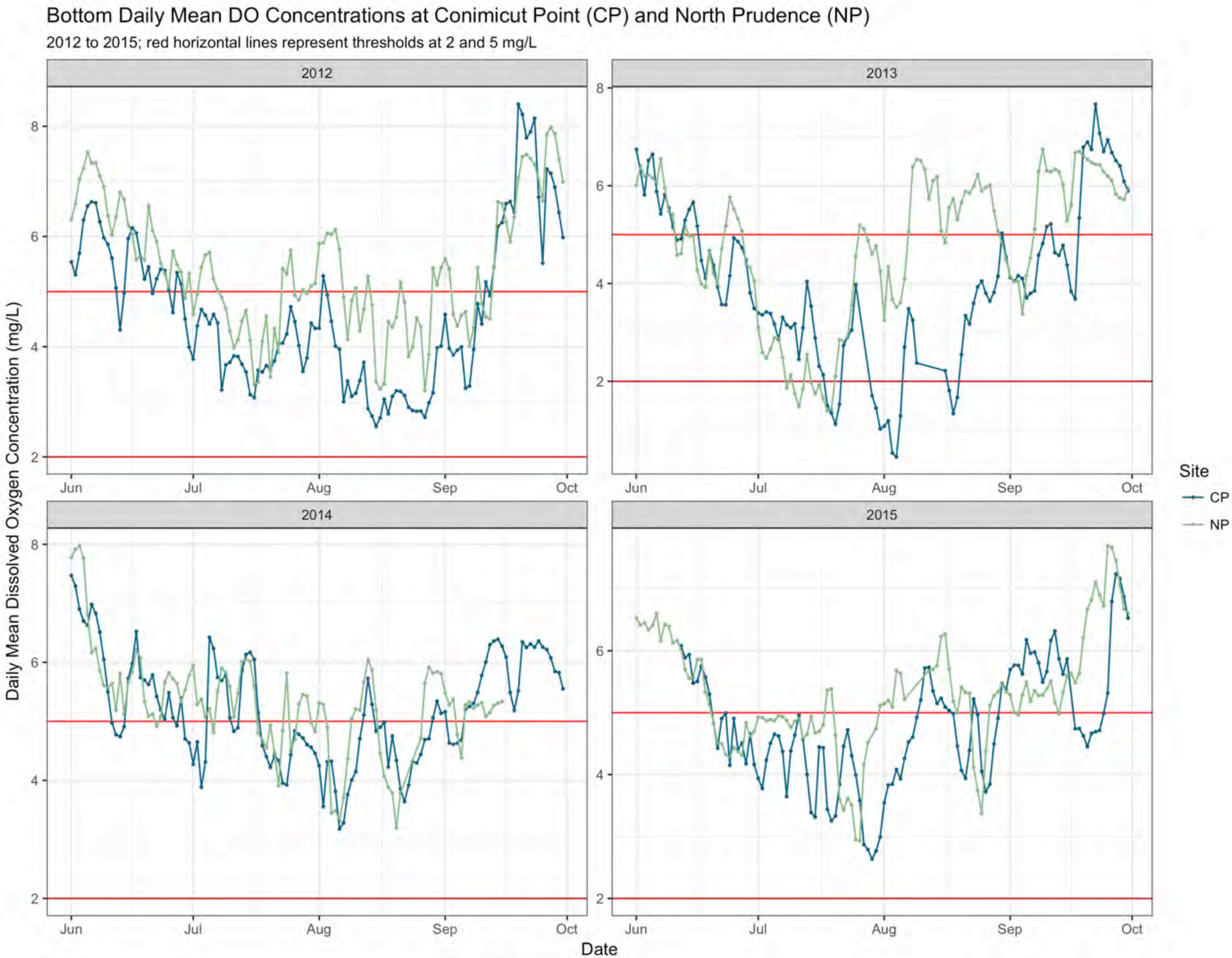


Figure 8c. Bottom dissolved oxygen concentrations (mg/L) at Conimicut Point (CP) and North Prudence (NP) from June 1 to September 30 for the years 2012 to 2015.

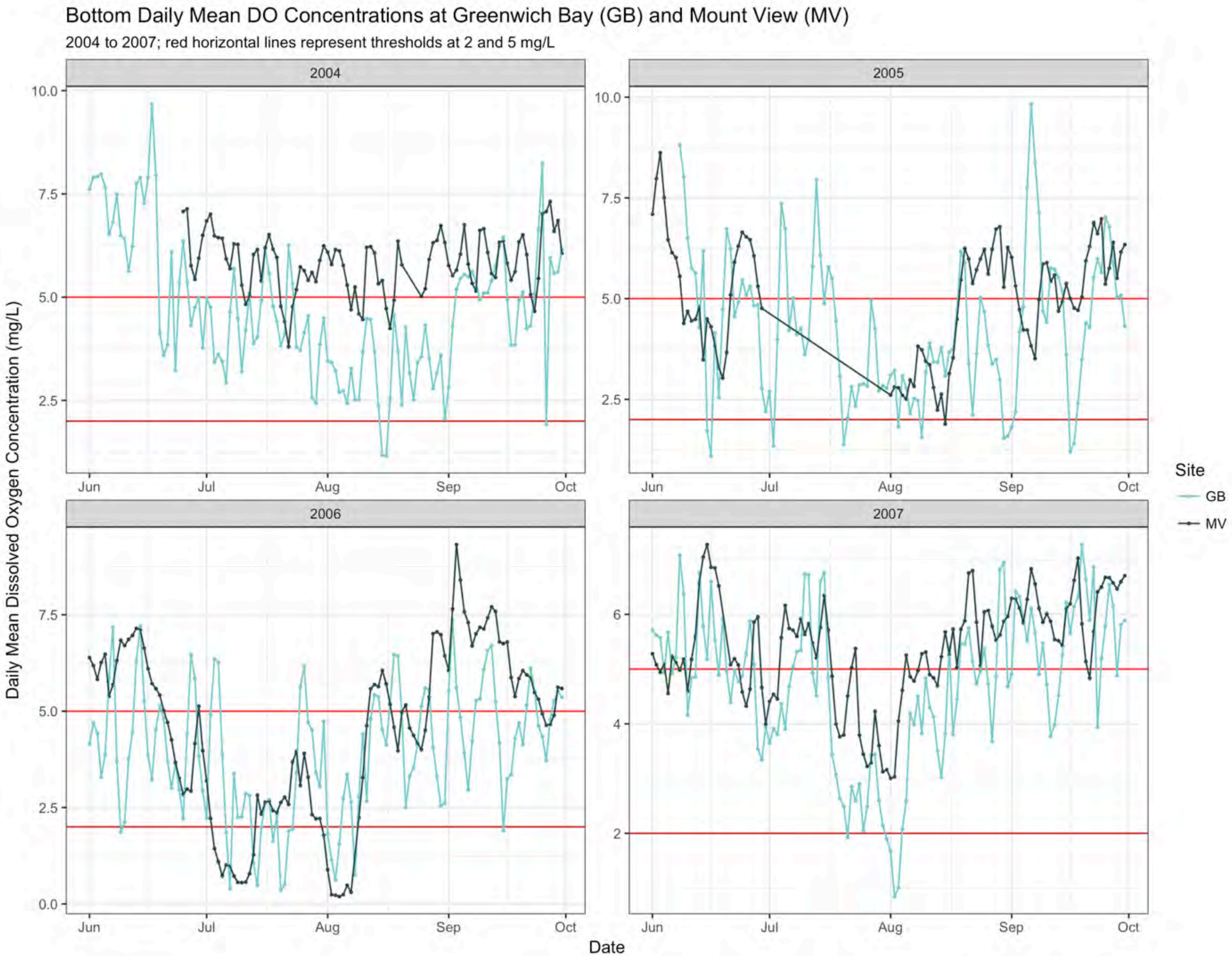


Figure 9a. Bottom dissolved oxygen concentrations (mg/L) at Greenwich Bay (GB) and Mount View (MV) from June 1 to September 30 for the years 2004 to 2007.

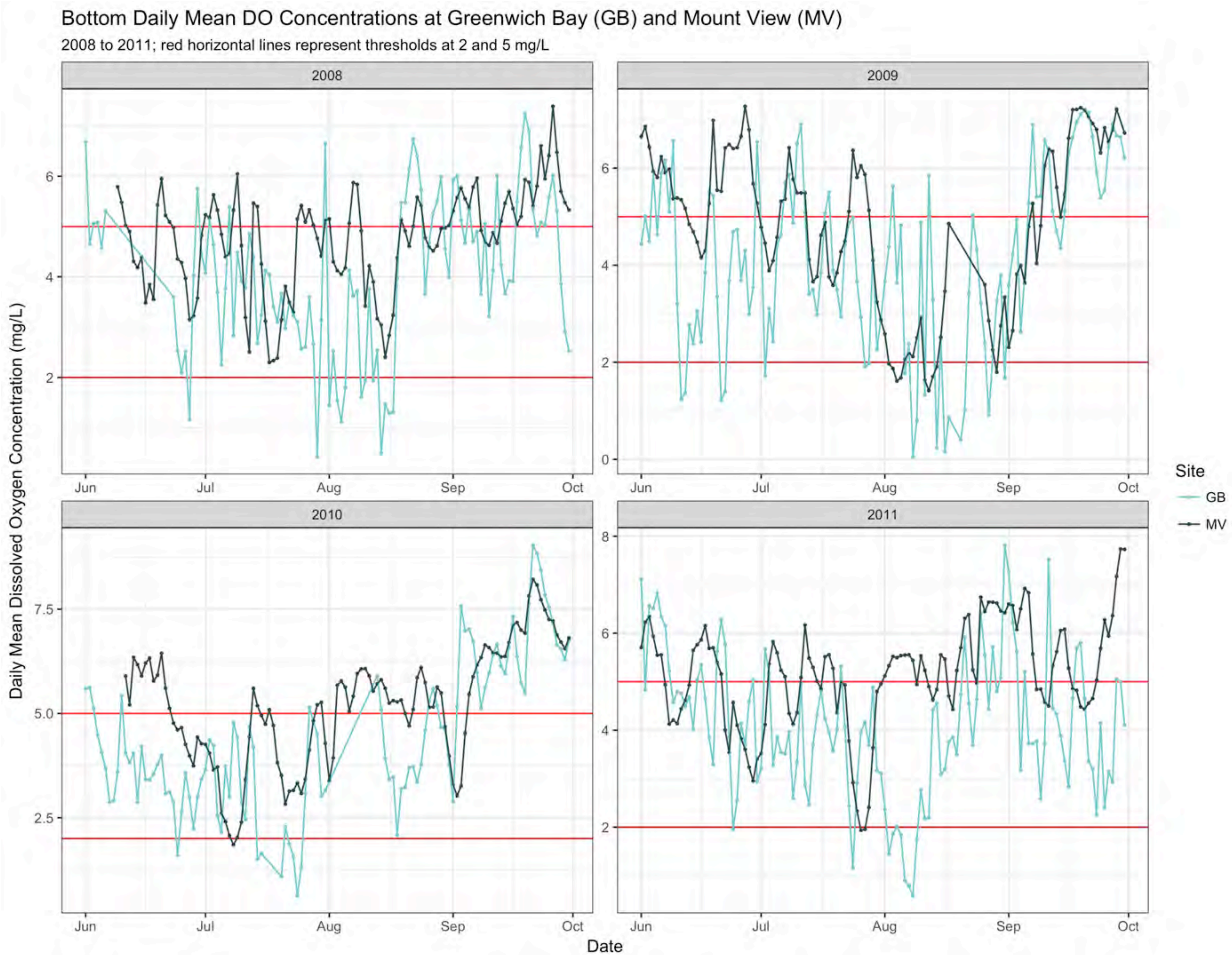


Figure 9b. Bottom dissolved oxygen concentrations (mg/L) at Greenwich Bay (GB) and Mount View (MV) from June 1 to September 30 for the years 2008 to 2011.

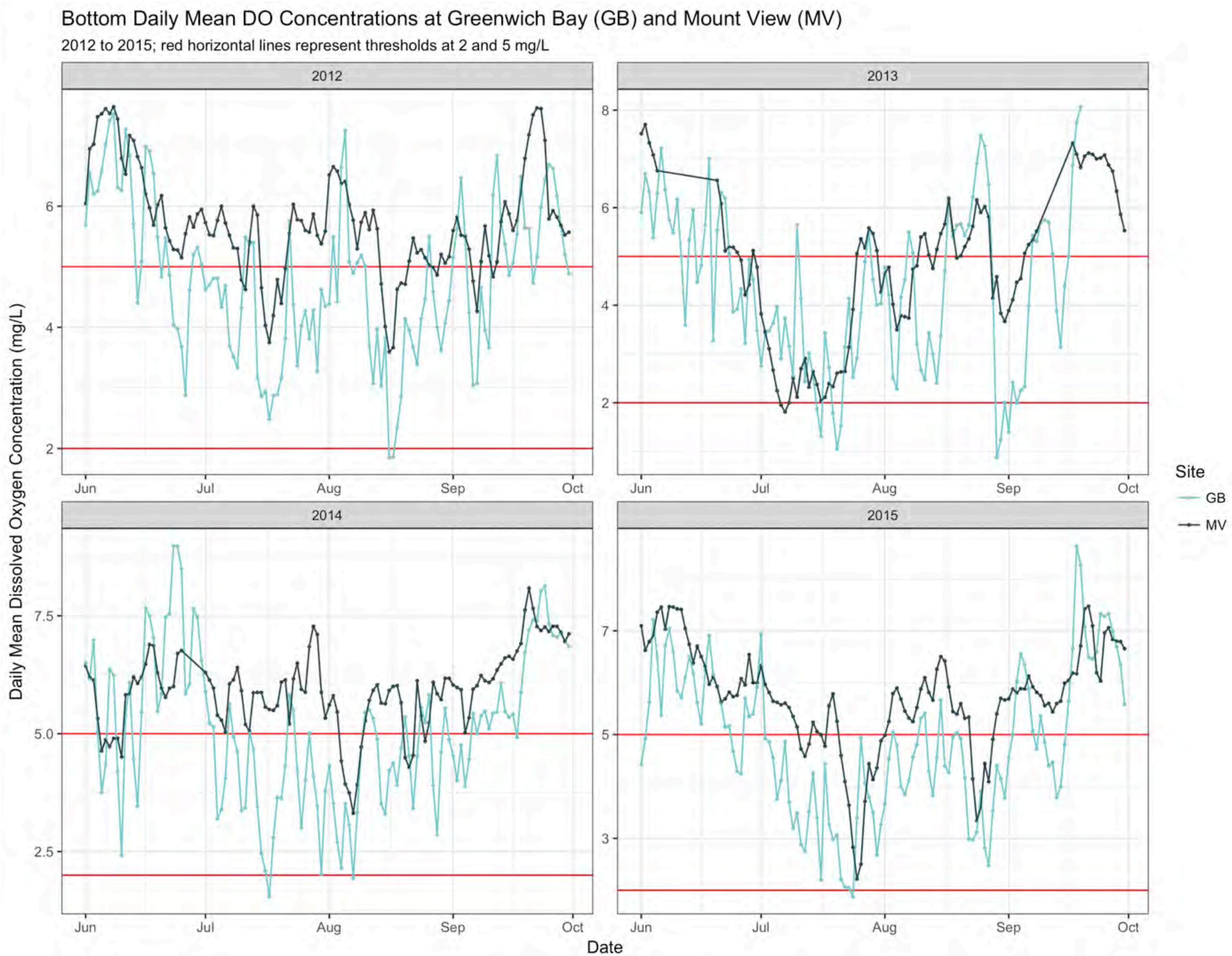


Figure 9c. Bottom dissolved oxygen concentrations (mg/L) at Greenwich Bay (GB) and Mount View (MV) from June 1 to September 30 for the years 2012 to 2015.

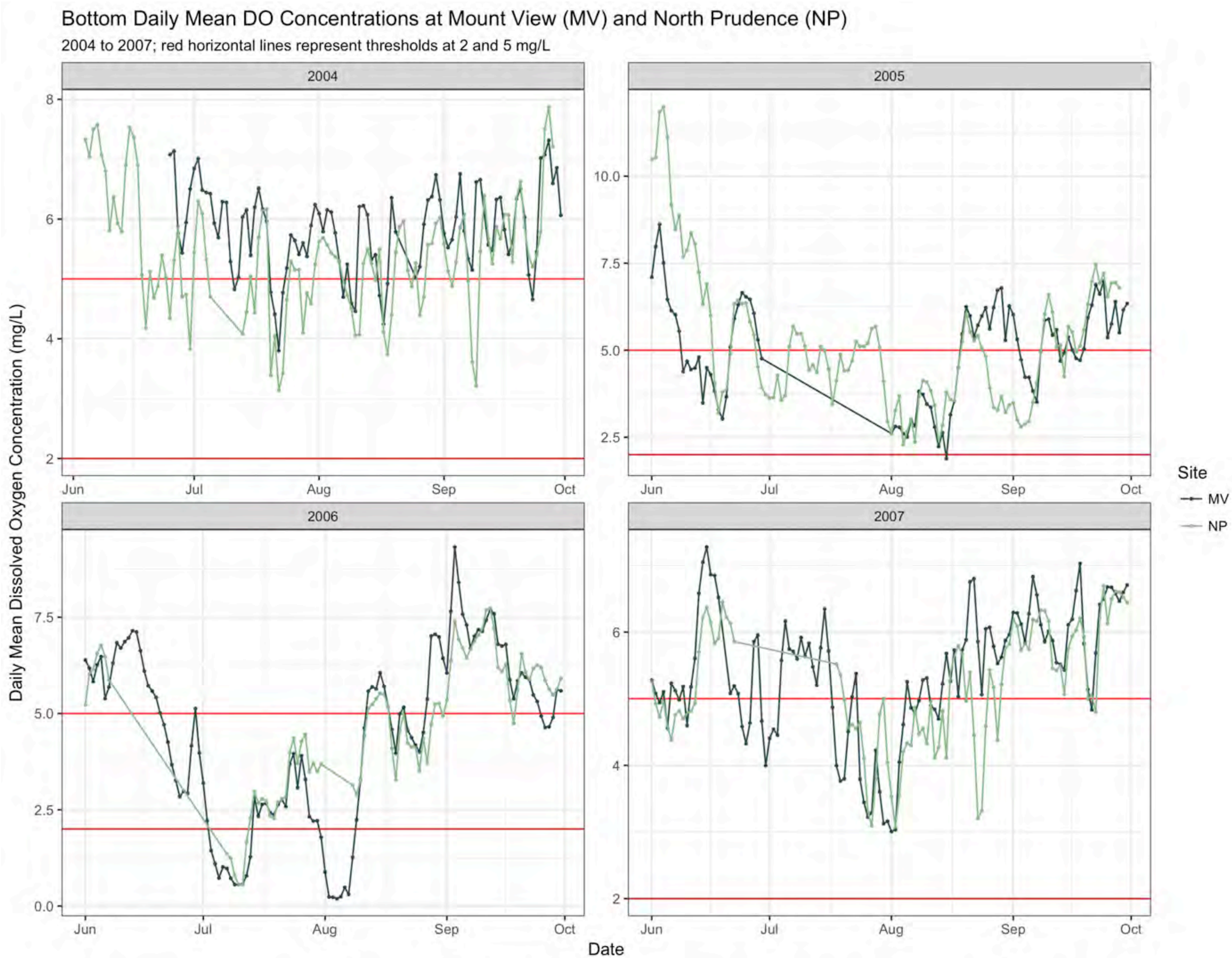


Figure 10a. Bottom dissolved oxygen concentrations (mg/L) at Mount View (MV) and North Prudence (NP) from June 1 to September 30 for the years 2004 to 2007.

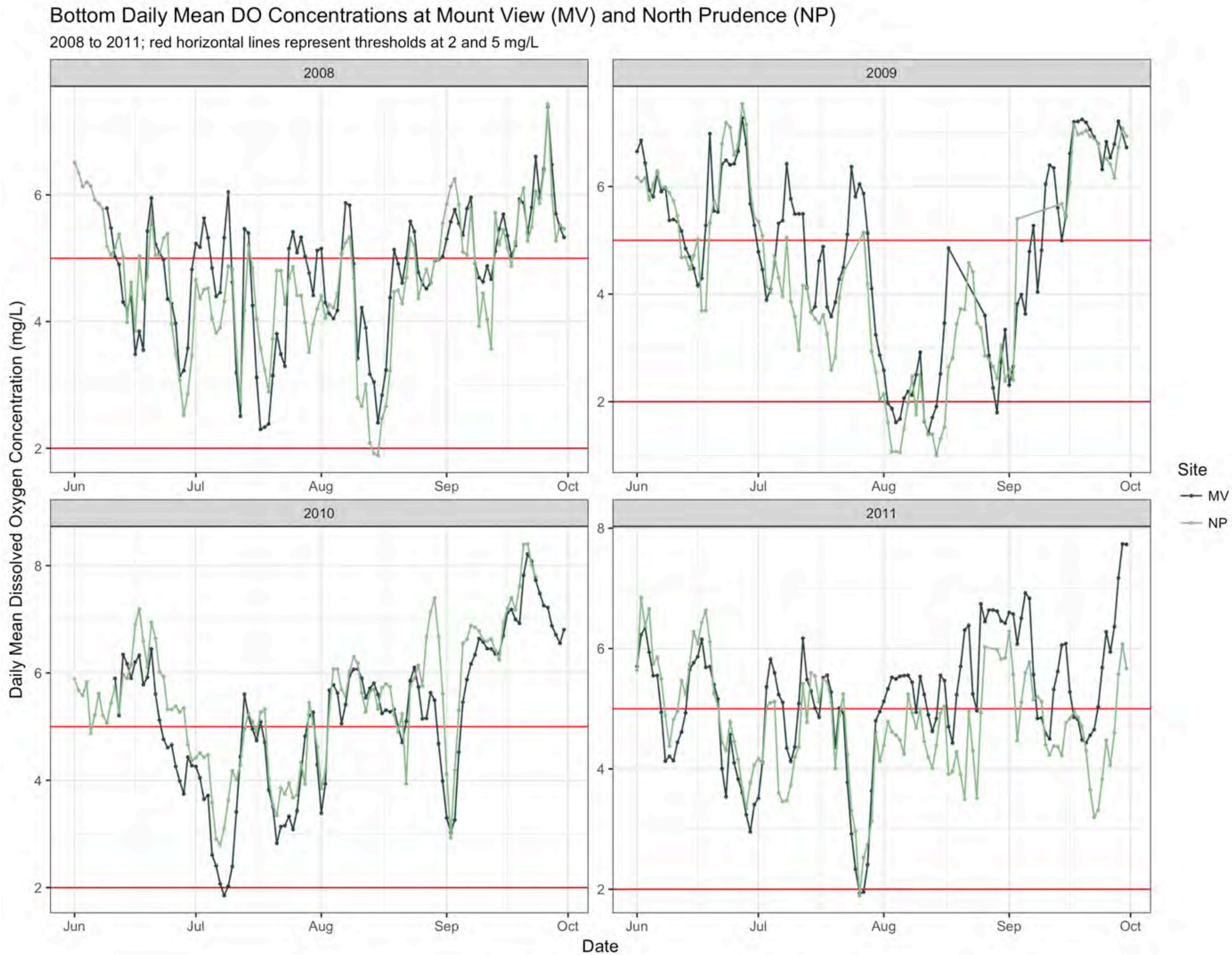


Figure 10b. Bottom dissolved oxygen concentrations (mg/L) at Mount View (MV) and North Prudence (NP) from June 1 to September 30 for the years 2008 to 2011.

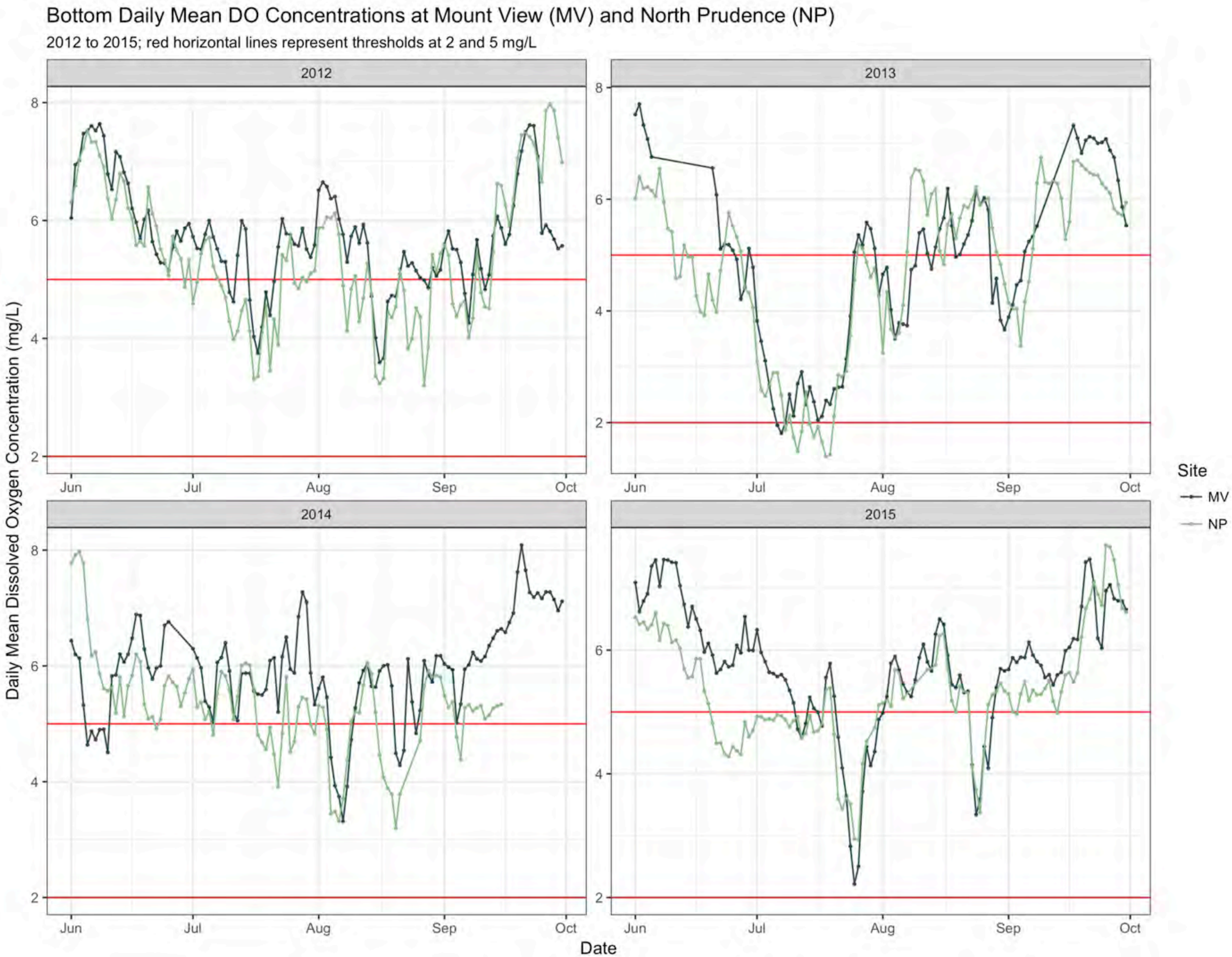


Figure 10c. Bottom dissolved oxygen concentrations (mg/L) at Mount View (MV) and North Prudence (NP) from June 1 to September 30 for the years 2012 to 2015.

CORRELATING SEASONAL CUMULATIVE DEFICIT-DURATION WITH SEASONAL CUMULATIVE RIVER FLOW

Work by URI MERL lab and others (Codiga et al., 2009; Stoffel, 2017) suggests that seasons (2001—2015) with the highest river flow are also the seasons with the highest severity and duration in hypoxia as measured using the RI DO Criteria System (RIDOCS). as “wet,” “dry,” or “normal” can be helpful in identifying which seasons are at highest risk for low oxygen conditions in the bay. A simple linear regression on the cumulative deficit-duration at all stations over each season, with the total river flow for the season as the explanatory variable produced a statistically significant relationship with $R^2 = 0.66$ ($p < 0.001$) at the 2 mg/L threshold (Figures 11 and 12) and $R^2 = 0.37$ ($p < 0.05$) at the 5 mg O_2/L threshold. Spearman’s Rank correlation test gave $\rho = 0.75$ ($p < 0.01$) at the 2 mg O_2/L threshold and $\rho = 0.53$ ($p < 0.05$) at the 5 mg O_2/L threshold.

Figure 11. Total seasonal flow (cubic feet) to Narragansett Bay vs. seasonal cumulative deficit-duration at all stations defined with a DO threshold of 2 mg O_2/L

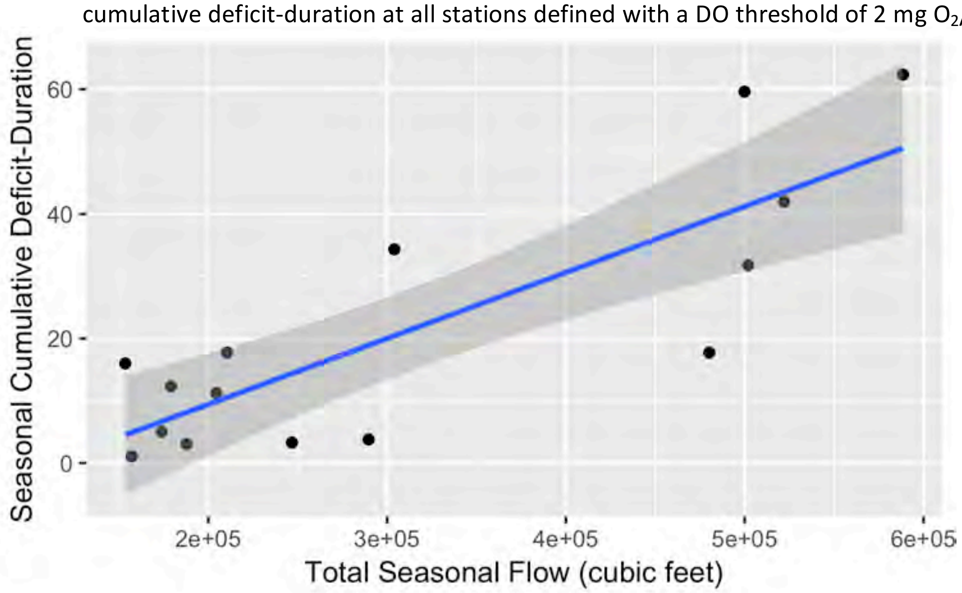
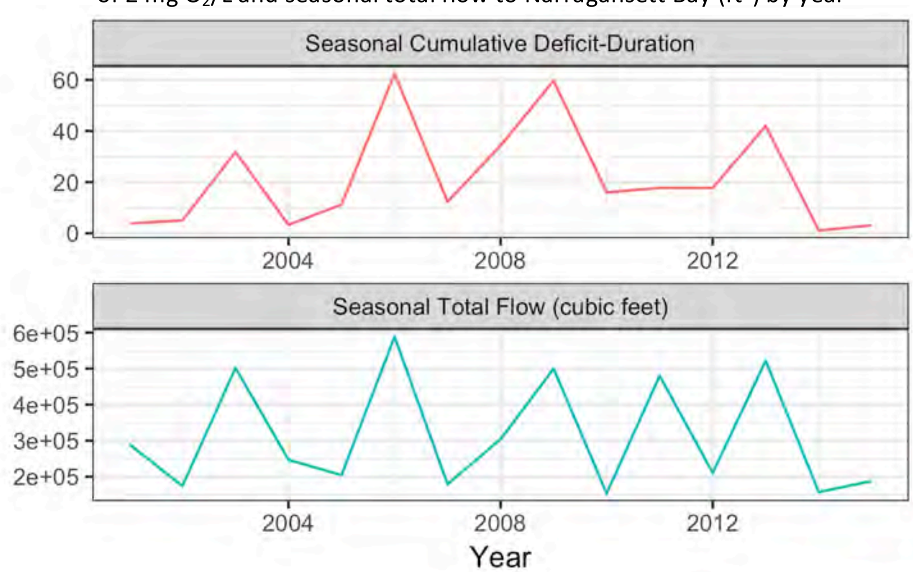


Figure 12. Seasonal cumulative deficit-duration defined with a DO threshold of 2 mg O_2/L and seasonal total flow to Narragansett Bay (ft^3) by year



The same analysis with June total river flow yielded no significant results. This latter result is inconsistent with the findings of Codiga et al. (2009) who found a significant correlation with June-mean river flow and cumulative seasonal deficit-duration at BR and NP. Note that while June total flow was used in this analysis, it is analogous to June mean flow, which is simply the total flow divided by the number of days. In addition, this analysis used bay-wide cumulative deficit-duration as compared to BR and NP alone. When only BR and NP were used, no significant relationship with June total flow was found at either threshold. This inconsistency may be due to the longer time frame for this analysis (2001—2015) as compared to Codiga et al. (2009), where their data covered 2001—2006. Another possible explanation for this inconsistency is that we used the MWT method applied to daily means with a one-day window as opposed to Codiga et al. (2009) using the MWT method applied to 15-minute data with a 9-hour window. This difference in method to calculate hypoxic event deficit-duration, while we assessed it to be small, may have also contributed to the inconsistency and warrants further exploration.

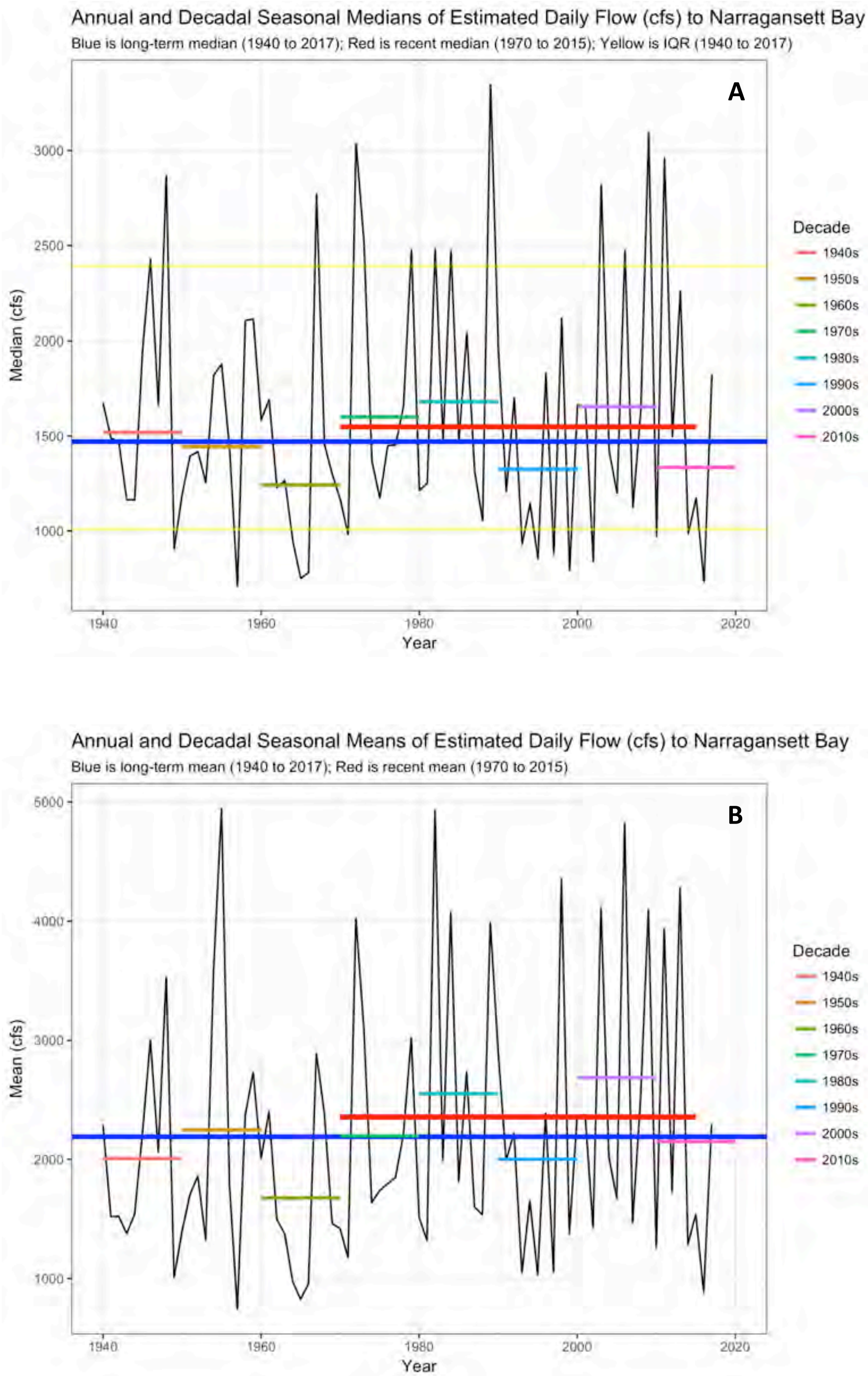
One challenge is how to define wet, dry and normal seasons using some measure of river flow. While median is the best measure of central tendency in river flow, mean is a surrogate for total flow. A similar regression and correlation analysis of cumulative deficit-duration and median flow yields a similar result to using total flow, though with slightly lower R^2 values.

If median flow were to be considered, the definition of “normal” would depend upon the period of time over which the median was calculated. Using the longest period of record (1940 to 2017) for seasonal (June 1 to September 30) flow to Narragansett Bay as estimated in Kellogg (in review), to determine the inter-quartile range, represented by yellow lines in Figure 13A, we see that seasons between 2001 and 2015 that fall above the 75% quartile and would be classified as “wet” are 2003, 2006, 2009 and 2011. Those that fall below the 25% quartile would be classified as “dry” and are 2002, 2010, 2014, and 2016. All others that fall between the 25% and 75% quartile would be classified as “normal.”

If mean flow were to be considered (Figure 13B), a similar pattern emerges for the decadal means, which fluctuate around the long-term mean but show a slight upward trend over time. Mean flow may be a better way to characterize seasonal flow because total flow may be the most relevant factor as opposed to central tendency, represented with the median. Mean flow is simply total (cumulative) flow divided by the number of days in the season. In this case, the range of normal seasonal cumulative flow cannot be characterized using standard deviation because flow data are skewed and need to be transformed using the natural log (for more details, see Kellogg, in review).

These examples illustrate the issues to be considered in characterizing wet and dry seasons. Further work is needed to identify the most promising approach.

Figure 13. Medians (A) and means (B) of seasonal river flow to Narragansett Bay over different time periods. Yellow lines show the inter-quartile range for 1940 to 2017. Note the increase in mean and median flow over the last several decades (Kellogg, in review).



DISCUSSION

Hypoxia in Narragansett Bay is often a localized phenomenon, complex and highly variable, influenced by a range of factors that are a function of location within the bay. Analysis of the 15-year record of data from the NBFSMN has allowed us to investigate possible trends in hypoxia events as well as the influence of preceding conditions, as characterized by a set of explanatory variables, on hypoxia events. As expected, hypoxia events were less frequent and less severe when compared along the north-to-south gradient of the West Passage of the bay.

When looking at trends in the fraction of days that are either "Severely Hypoxic to Anoxic" when mean daily DO < 2 mg/L or "Hypoxic" when mean daily DO < 5 mg/L and ≥ 2 mg/L, the Greenwich Bay (GB) site shows some statistically significant reduction in "Severely Hypoxic to Anoxic" days over the entire period of record (2003 to 2015). These data for GB, as well as for Phillipsdale (PD), should be viewed with caution because the daily mean may be under estimating the severity of hypoxia with these stations typically experiencing 8 to 14 hours of low DO during May to October. Other stations do not show a trend, but continued monitoring is necessary to continue tracking changes in hypoxia. This finding is similar to other recent reviews (e.g., NBEP, 2017).

The data also suggest recent decreasing maximum deficit-duration of hypoxic events with time, especially for severely hypoxic events (< 2 mg O_2/L) but, again, continued monitoring is necessary to identify suggested trends more clearly.

The proposed explanatory variables contributing to the development of hypoxia in the bay all showed some correlation with hypoxic days and/or hypoxia events.

Mean density difference for the preceding 0 to 14 days:
For hypoxic days below the 2 mg O_2/L threshold, mean density difference was a significant and positive explanatory variable for the probability of hypoxia at all stations except Sally Rock (SR) and the two southernmost stations where hypoxia has been observed, Quonset Point (QP) and T-Wharf (TW). For hypoxic days below the 5 mg O_2/L threshold, mean density difference was a significant and positive explanatory variable for the probability of hypoxia at all stations where hypoxia has been observed (i.e., excluding GSO Dock (GD)). Density difference is a measure of stratification and is influenced by freshwater inputs, wind, and tide ranges – lower tide ranges are less likely to promote mixing of bottom and surface waters. Consistent with these findings, earlier research has shown neap (low range) tides to be linked with the onset of hypoxia events (Bergondo et al., 2005). For hypoxia events defined using the 5 mg O_2/L threshold, the natural log of the mean density difference was a significant and positive explanatory variable for the deficit-duration of hypoxia events at the two stations in the Greenwich Bay region, GB and SR, suggesting not only a link to hypoxia onset but also hypoxia event severity in this shallow, sometimes poorly flushed embayment (Rogers, 2008).

Mean bottom water temperature for the preceding 0 to 14 days:
For hypoxic days below the 2 mg O_2/L threshold, mean bottom water temperature was a significant and positive explanatory variable for the probability of hypoxia at four sites: PD and BR in the Upper Bay, GB in Greenwich Bay, and MV in the Mid-Bay region. For hypoxic days below the 5 mg O_2/L threshold, mean bottom water temperature was a significant and positive

explanatory variable for the probability of hypoxia at all except two sites, the exceptions being MV and TW. This result is not unexpected – as water temperature increases, dissolved oxygen solubility decreases while biological activity increases, both factors contributing to lower bottom water oxygen concentrations.

Sum of river flow during the preceding 1 to 7 days:
The sum of river flow to the bay during the preceding 1 to 7 days was a significant and positive explanatory variable in the Greenwich Bay region (GB and SR) at both thresholds. This is consistent with what we would expect given our understanding of this embayment. River flow to Greenwich Bay would contribute nutrients and serve to intensify to stratification. Surprisingly, river flow is a negative explanatory variable in other regions of the bay at both thresholds. A possible explanation is that the initial effect of high river flow is increased mixing, with a longer time lag to the development of stratification in the more open and better mixed parts of the bay. The sum of river flow during the preceding 8 to 14 days is highly correlated to the sum of river flow during the preceding 1 to 7 days, but a longer time frame may be necessary to explore this further, and there may be different lag times in different regions of the bay.

Mean surface Chl *a* concentrations appeared to play a more complicated and less consistent role in explaining hypoxic days and the deficit-duration of hypoxia events.

The seasonal cumulative river flow appears to be well correlated with seasonal cumulative deficit-duration, supporting the hypothesis that river flow is an important positive explanatory variable for hypoxia events. However, because it relies on seasonal totals it does not currently appear to help with predicting the severity of seasonal hypoxia events before they occur.

The variability in DO at Bullock Reach (BR) and North Prudence (NP) explained 70% of the variability at Conimicut Point. Even with this high correlation, the fractional overlap of hypoxia events was variable and no higher than about 0.6 for Conimicut Point with respect to the other two stations. Similarly, the variability in DO at Greenwich Bay (GB) and North Prudence (NP) explained 66% of the variability in DO at Mt. View (MV), with fractional overlaps as high as 0.63. The fractional overlaps depended on the threshold used to define hypoxia. These correlations should be further explored to better understand how data from each of these nearby stations can inform regional phenomena.

This analysis effort was solely intended to explore the many possible explanatory variables related to hypoxia in Narragansett Bay. The complexity and variability of this ecosystem is evident in this analysis and any insights suggested here require further study. While the NBFSMN now has over 15 years of mostly continuous monitoring, the spatial and temporal variability of the bay indicate that continued monitoring is necessary to more clearly identify trends and better understand the factors contributing to hypoxia in the bay.

Implications for Environmental Indicators

The NBFSMN has high temporal resolution that supports trends analysis. However, high inter-annual variability requires evaluation over a longer period of record to identify and/or confirm long-term trends.

The tracking of seasonal hypoxic days shows some promise in identifying progress towards water quality goals. Additionally, hypoxia event deficit-duration characteristics, such as maximum duration and maximum deficit-duration, also have value in identifying progress and should be considered on a site-by-site basis. These metrics may be useful in first detecting changes before compliance with water quality standards has been achieved, allowing managers to better understand progress toward stated goals.

Managers and researchers should continue to collaborate on data synthesis to support robust indicator reporting in the future.

SUMMARY AND NEXT STEPS

The Narragansett Bay Fixed-Site Monitoring Network now has more than fifteen years of high-resolution temporal data and is growing in value with every additional season of data. These data are helping managers and researchers better understand the development of hypoxia in the bay and progress towards improving water quality.

We found bottom water temperature and surface-bottom stratification to be positive explanatory variables for the probability of hypoxic days at several fixed-sites, while other explanatory variables, such as river flow and Chl *a* abundance, were both positive and negative, depending on the site and the threshold used to define hypoxia. Correlation of DO concentration among certain fixed-sites was high, but fractional overlap varied, suggesting further work is needed to better understand how the data from these sites can inform regional phenomena.

Tracking hypoxic days and deficit-duration characteristics of hypoxia events show promise as possible indicators, or components of indicators, to identify trends in hypoxia. However, the identification of trends in hypoxic days and hypoxia events is complicated by high inter-annual variability. While we have seen some improvements in water quality over the last several years, coincident with upgrades to wastewater treatment facilities, recent years have also been somewhat drier than normal. We therefore need to continue monitoring in order to observe changes during wetter years. We expect to see river flows become more extreme with changing precipitation patterns (Kellogg, in review), and these changes are expected to affect hypoxia development in the bay.

These analyses suggest further directions to pursue to better understand how hypoxia is related to conditions in the bay that precede hypoxia, including further investigating the role of river flow as it relates to specific regions of the bay and specific periods of time. In addition, Chl *a* is understood to play a role through excessive productivity fueled by nutrient inputs followed by oxygen-consuming decomposition, but its role appears to be complex in the context of the many other factors contributing to bay hypoxia.

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APPENDIX A. Data Gaps

Table A1. Sum of days missing at fixed sites for the parameters used in this report over the season of June 1 to September 30. Greyed areas represent years before a site was active. Blanks indicate no data gap. Gaps of 122 days indicate an entire season missing.

Site	Depth	Parameter	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
BR	surface	Chl		7	36	14	4	5	37	5		6	5	2	3		17
		Density		6	8		4	5	37	5		6	5		3		19
		DO.Conc		6	20	11	4	5	37	5		9	5		3		17
		Temp		6			4	5	37	5		6	5		3		17
	mid	Chl														14	18
		Density														13	2
		DO.Conc														14	2
		Temp															2
	bottom	Density		26	6		4	10	44	5		6	5				16
		DO.Conc		26	9	17	4	10	22	5		6	5				16
		Temp		26	6		4	10	20	5		6	5				16
CP	surface	Chl			25	122	21	15			29	4	2				
		Density			25	122	20				7	4	2				
		DO.Conc			25	122	20		22		7	4	2				
		Temp			25	122	20				7	4	2				
	bottom	Density			20	122	22	15				16	2		9		12
		DO.Conc			20	122	22	15				16	2		9		12
		Temp			20	122	22	15				16	2		9		12

Table A1 *continued*. Sum of days missing at fixed sites for the parameters used in this report over the season of June 1 to September 30. Greyed areas represent years before a site was active. Blanks indicate no data gap. Gaps of 122 days indicate an entire season missing.

Site	Depth	Parameter	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
GB	surface	Chl			35	23	12		9	16	11	16	7	3			7
		Density			25	25	12		9	16	11	3					
		DO.Conc			56	12	12	12	20	16	11	10					
		Temp			25	15	12		9	16	11	3					
	bottom	Chl			28	26	7			16	2	122	8				
		Density			25		10			16	2	22			11		4
		DO.Conc			25		7			16	2	16			11		
		Temp			25		7			16	2	16					
GD	surface	Chl	122	122	122	26	34	8	16			9			5	122	7
		Density			22	26	34		16							122	
		DO.Conc	18	10	47	26	34		16		11	1				122	
		Temp				26	34		16							122	
MH	surface	Chl					31	50		9	1	10	8			10	
		Density					31	50	11	9	1	10		10			
		DO.Conc					31	50	11	9	1	10	36				
		Temp					31	50		9	1	10					
	bottom	Density					34	50		9	1	10	18				7
		DO.Conc					34	50		9	1	10	18				7
		Temp					34	50		9	1	10	18				7
MV	surface	Chl				27	32		46		1			17		5	
		Density				27	32		46		8		8	5	4	8	
		DO.Conc				27	32		46	8	1			5			
		Temp				27	32		46		8			5			
	bottom	Density				24	32		2	34	7	18			14	14	
		DO.Conc				28	32		2	8	9	10			22	5	
		Temp				24	32		2	8	1	16			14	5	

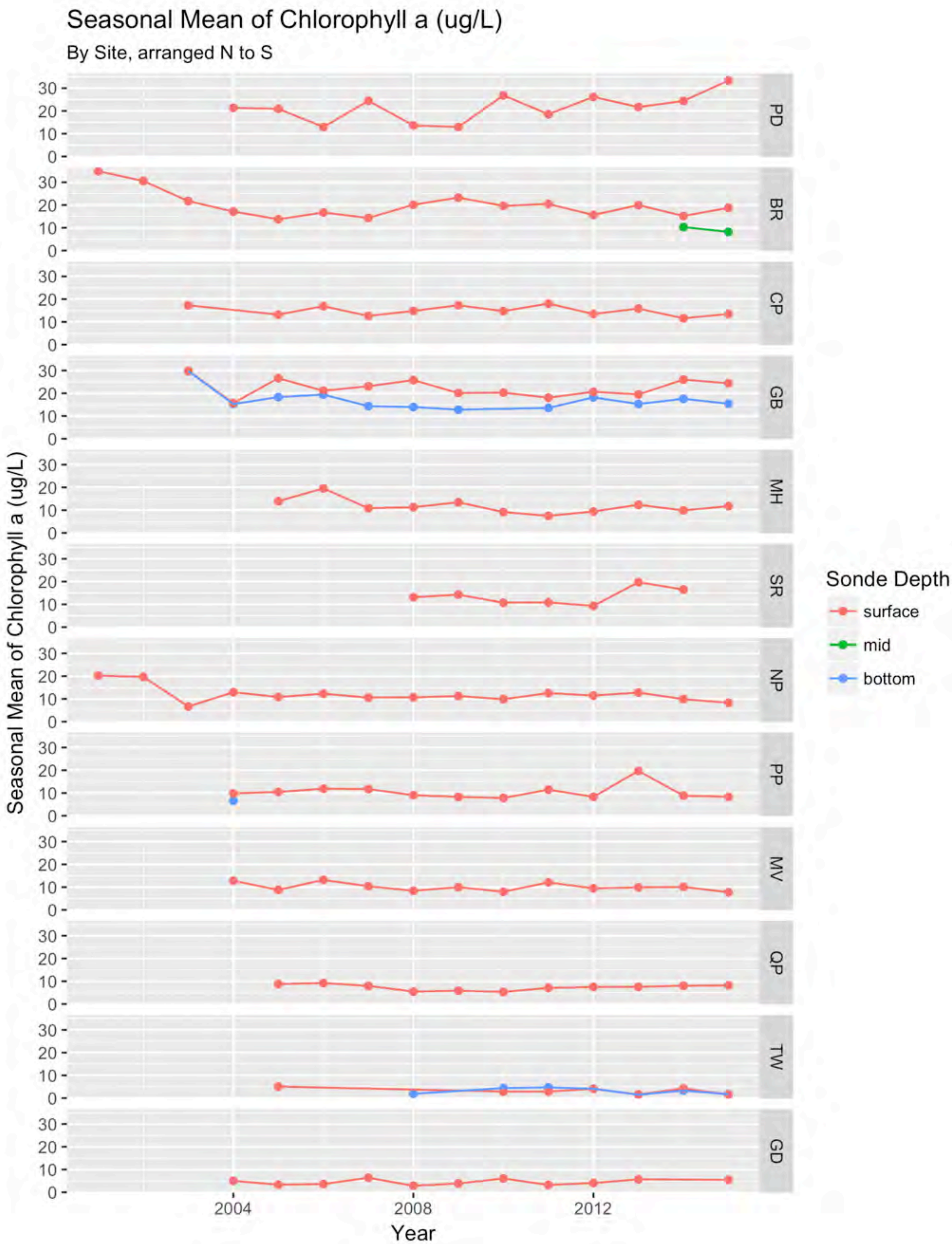
Table A1 *continued*. Sum of days missing at fixed sites for the parameters used in this report over the season of June 1 to September 30. Greyed areas represent years before a site was active. Blanks indicate no data gap. Gaps of 122 days indicate an entire season missing.

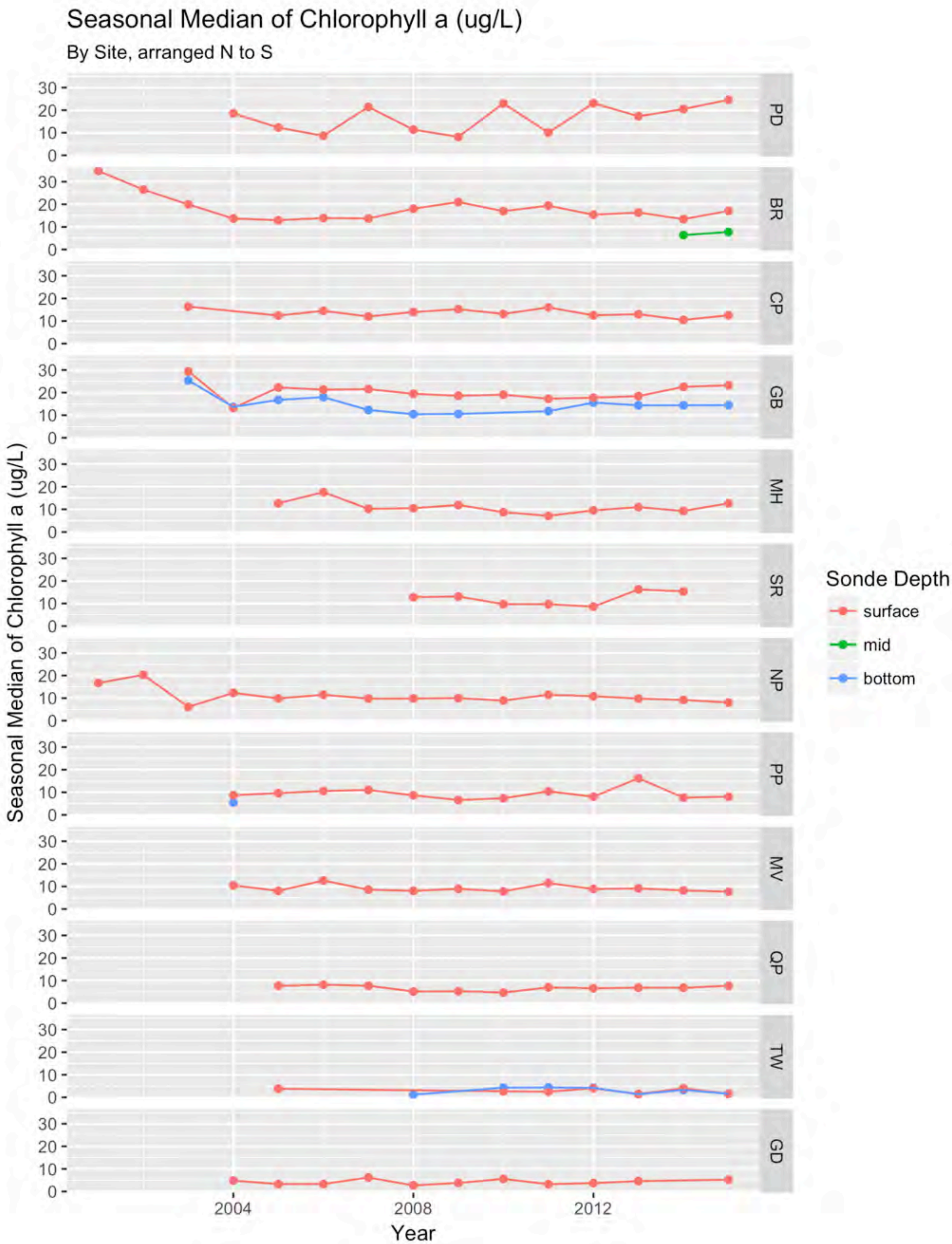
Site	**Depth**	**Parameter**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
NP	surface	Chl	29	27	17	5	9	44		8	8		2			15	2
		Density	28	16	5	5	4	44		8	8		2		6	15	2
		DO.Conc	28	16	5	5	4	44	18	8	8		2		6	20	2
		Temp	28	16	5	5	4	44		8	8		2		6	15	2
	bottom	Density	31	14	11	5	2	36	25		14	7	2			18	6
		DO.Conc	41	14	12	12	2	36	25		14	7	2			19	6
		Temp	31	14	11	5	2	36	25		14		2			18	6
PD	surface	Chl				109			2	2	28	59		5	4		
		Density				109			2	2	19	59			4	122	122
		DO.Conc				109			2	2	19	59			4		
		Temp				109			2	2	19	59			4		
	bottom	Density				109					12	36			4	122	122
		DO.Conc				109		3			12	36			4		
		Temp				109					12	36			4		
PP	surface	Chl				50	49	16			47	7	2				
		Density				37	65				6	7	2				
		DO.Conc				37	49				18	7	2			13	
		Temp				37	49				6	7	2				
	bottom	Chl				37	122	122	122	122	122	122	122	122	122	122	122
		Density				37	81			5		12	2			14	
		DO.Conc				37	65			5	5	12	12			14	
		Temp				37	65			5		12	2			14	

Table A1 *continued*. Sum of days missing at fixed sites for the parameters used in this report over the season of June 1 to September 30. Greyed areas represent years before a site was active. Blanks indicate no data gap. Gaps of 122 days indicate an entire season missing.

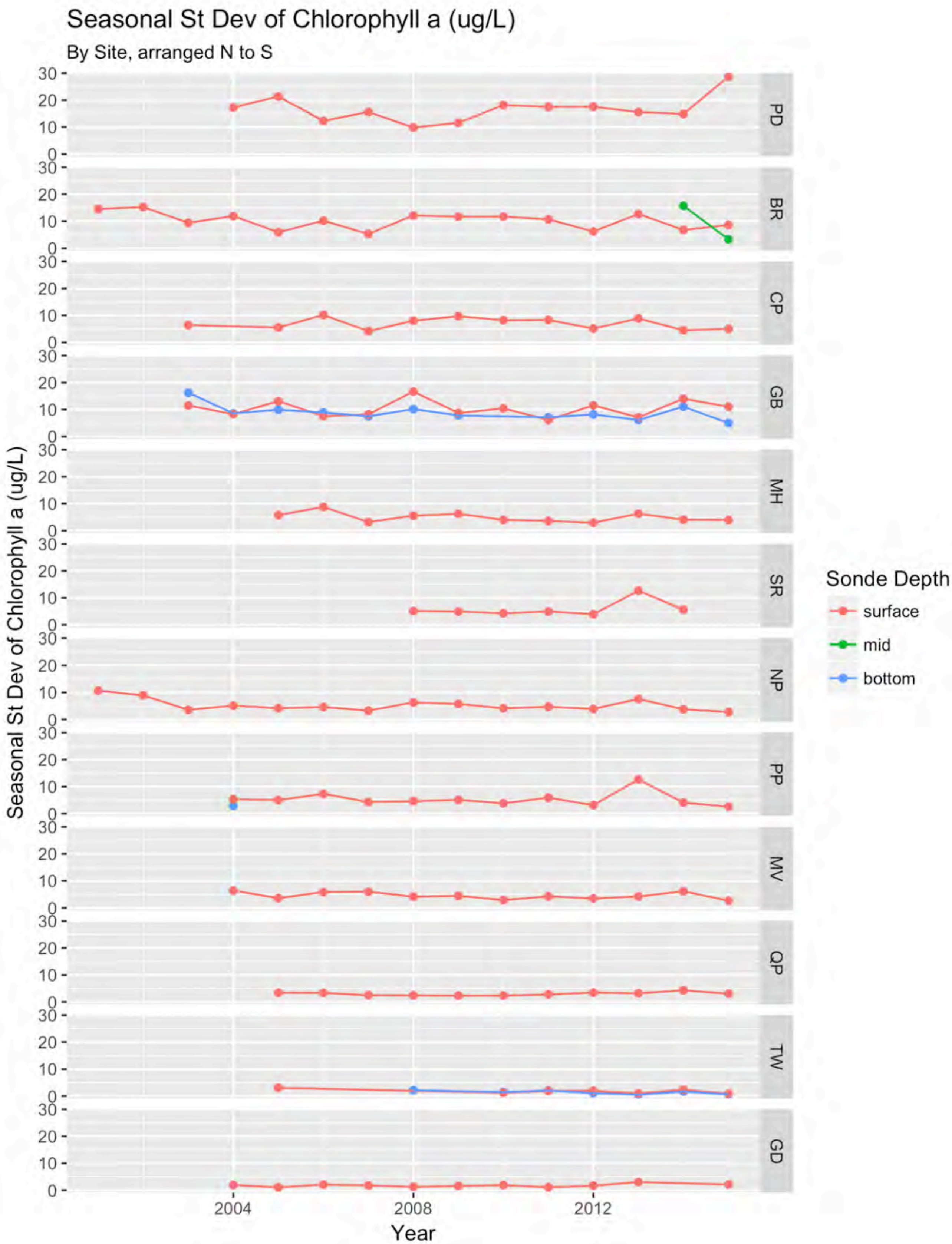
Site	**Depth**	**Parameter**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
QP	surface	Chl					58	34	23		10	3				33	
		Density					58	34	20			3	3			14	
		DO.Conc					58	34	20		4	11		13		14	
		Temp					58	34	20			3				14	
	bottom	Density					81	7	28		16		25	10	11	14	12
		DO.Conc					81	7	26		16		8	10	11	14	12
		Temp					81	7	26		16			10	11	14	12
SR	surface	Chl									13	8		5		43	122
		Density									27	8		5		43	122
		DO.Conc									13	8	13	5		43	122
		Temp									27	8		5		43	122
	bottom	Density								6	28	8				33	122
		DO.Conc								6	28	8				33	122
		Temp								6	28	8				33	122
TW	surface	Chl					16	122	122	122	122	4	34			5	
		Density					15	4		3	5	4	34			5	
		DO.Conc					15	4		3	5	4	34			5	
		Temp					15	4		3	5	4	34			5	
	bottom	Chl					122	122	122	5	122	4	37		2		
		Density					16		5	5	3	4	37		2		
		DO.Conc					16		9	18	16	4	37		2		
		Temp					16		5	5	3	4	37		2		

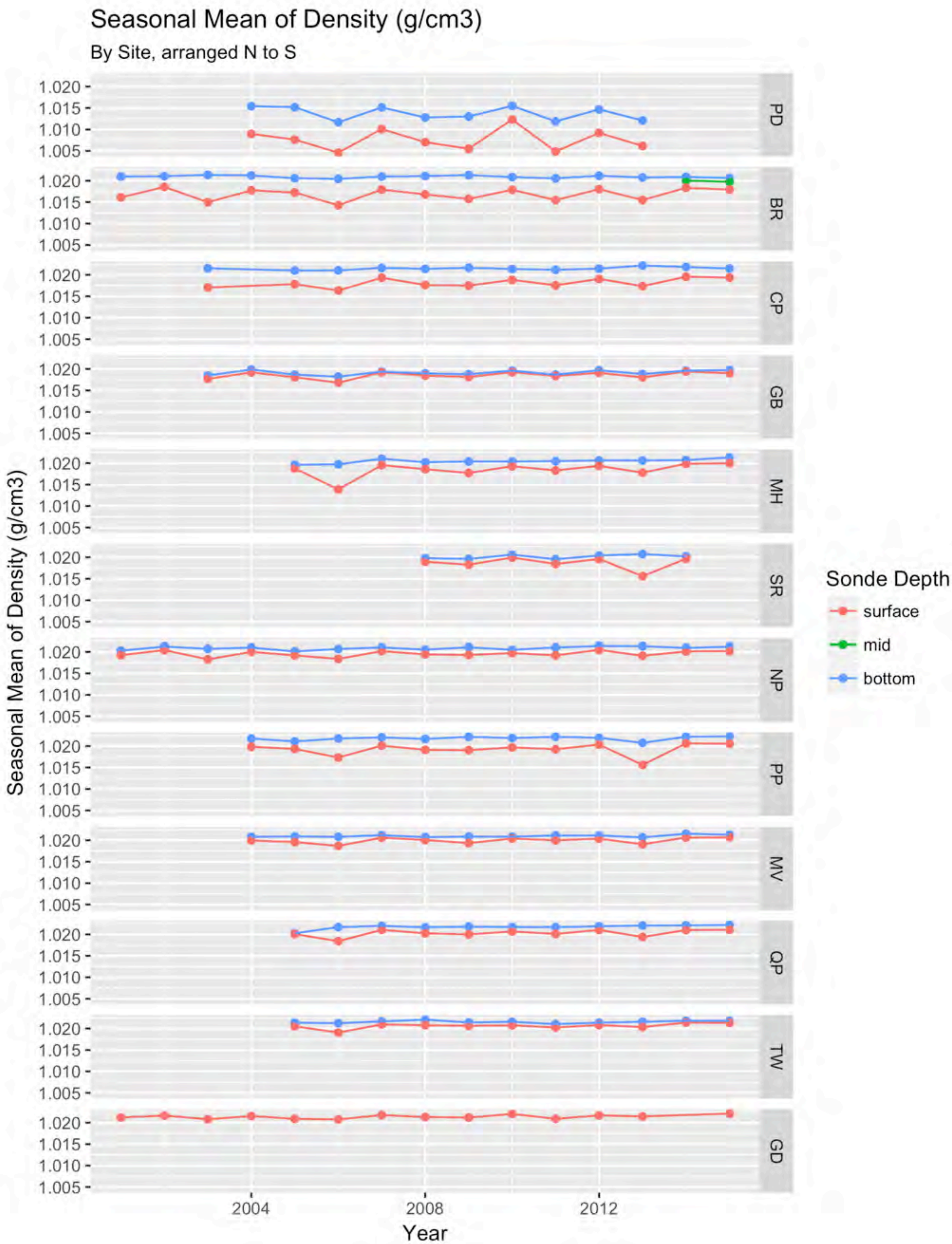
APPENDIX B. Seasonal (June through September) Summary Statistics for Chl *a*, Density, Dissolved Oxygen Concentration, Salinity, and Temperature at each fixed site, arranged N to S.



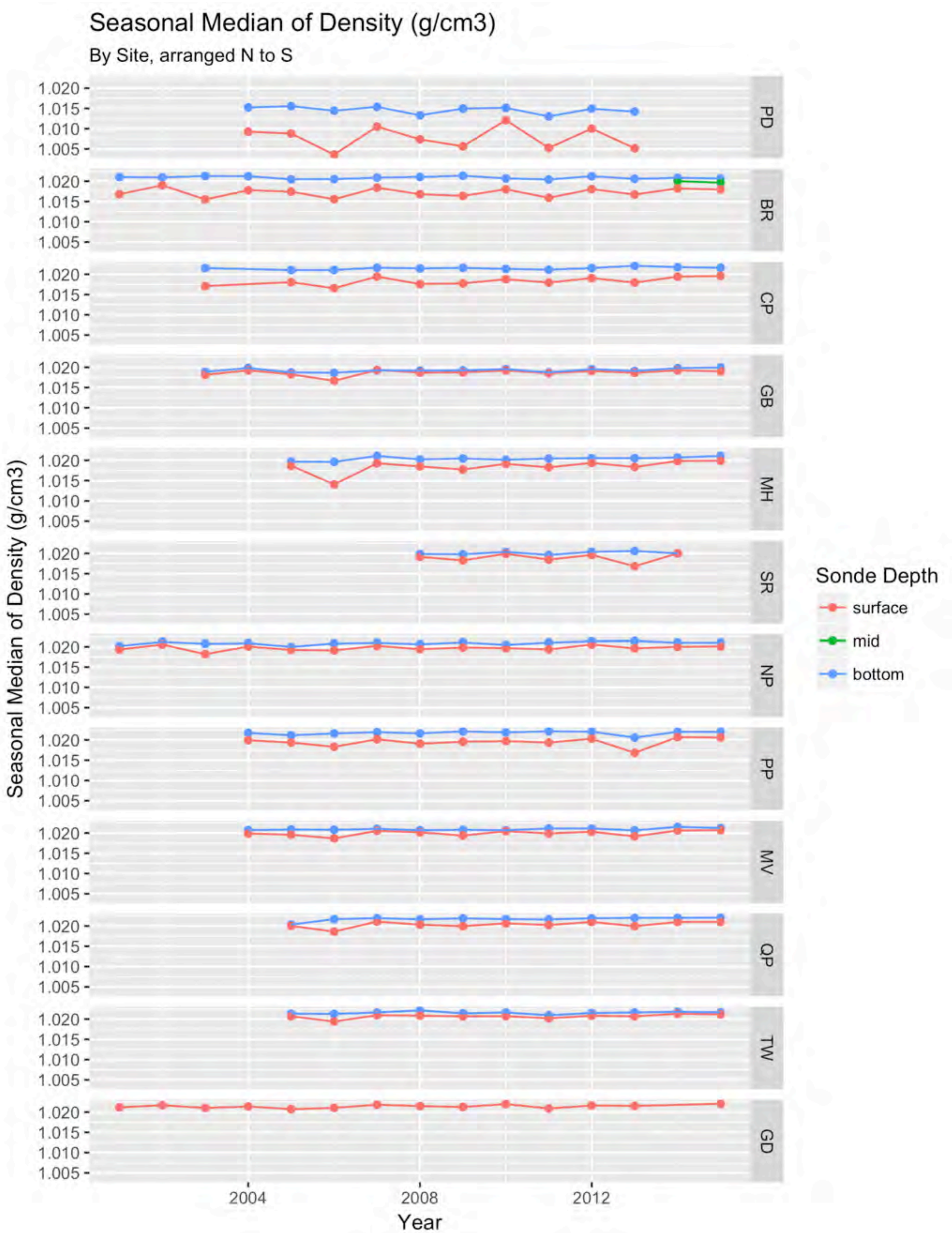


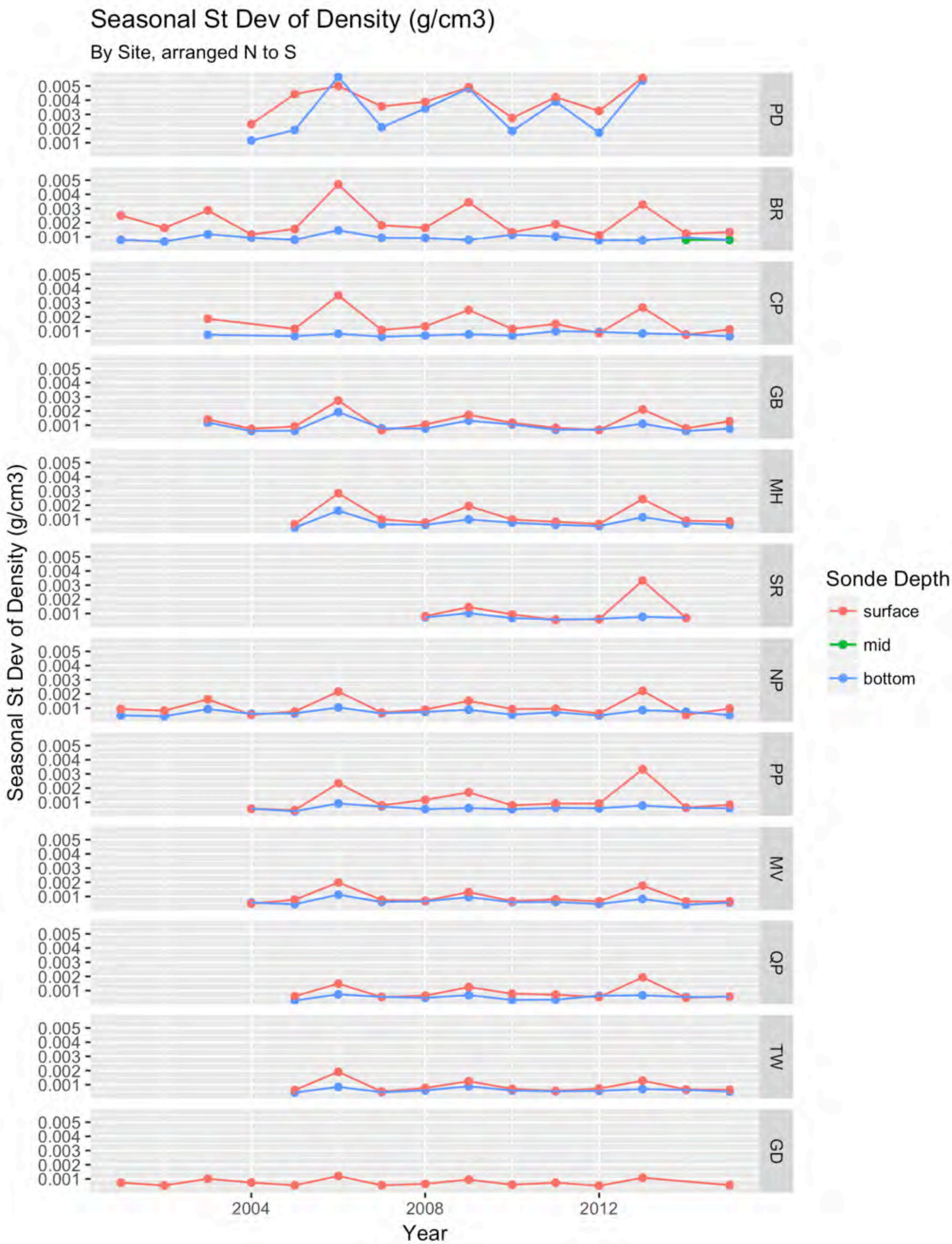
Seasonal Median of Chlorophyll a (ug/L)
By Site, arranged N to S
Seasonal Median of Chlorophyll a (ug/L)
Year
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
2004
2008
2012
0
10
20
30
Sonde Depth
surface
mid
bottom

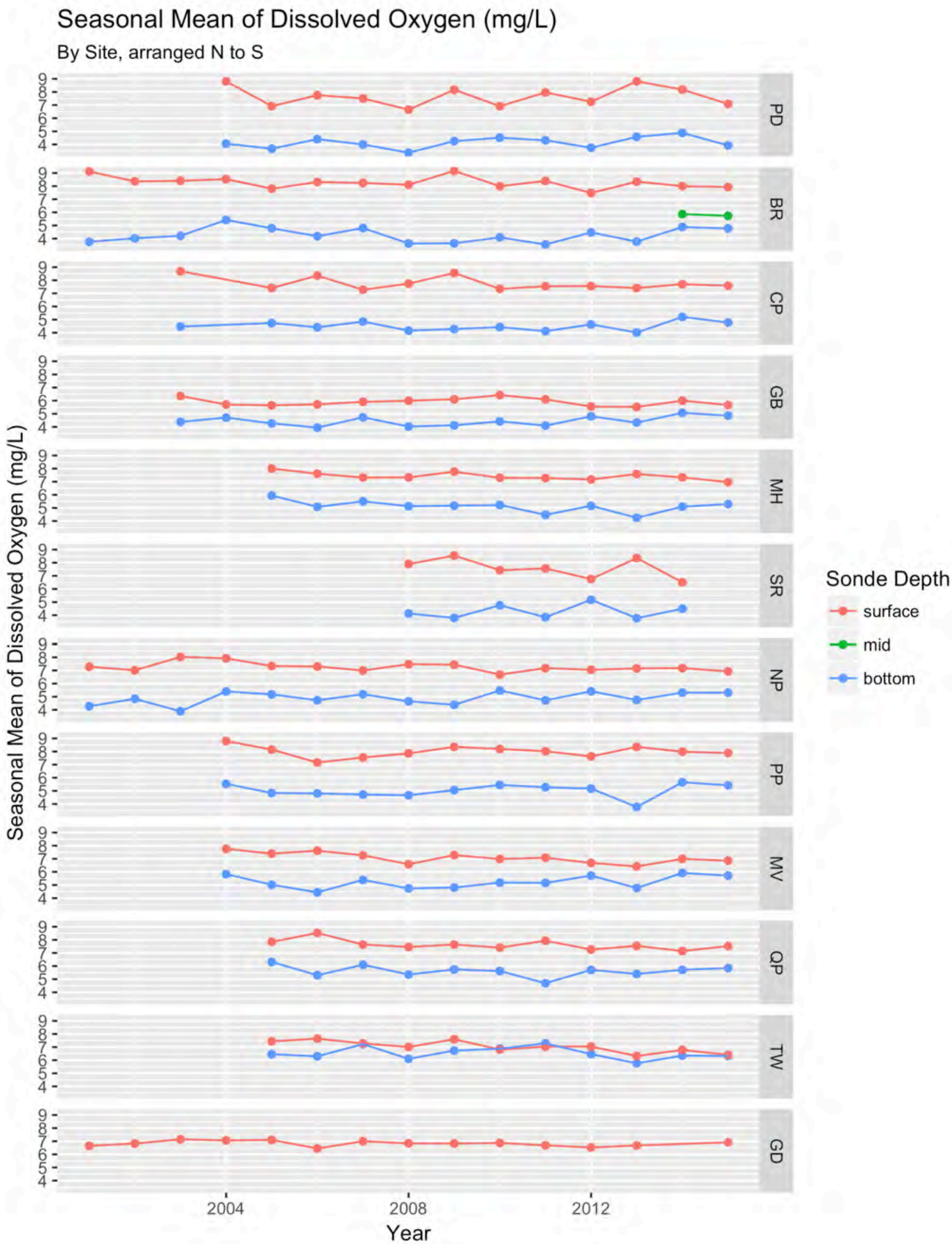

Seasonal St Dev of Chlorophyll a (ug/L)
By Site, arranged N to S
Seasonal St Dev of Chlorophyll a (ug/L)
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
0
10
20
30
2004
2008
2012
Year
Sonde Depth
surface
mid
bottom



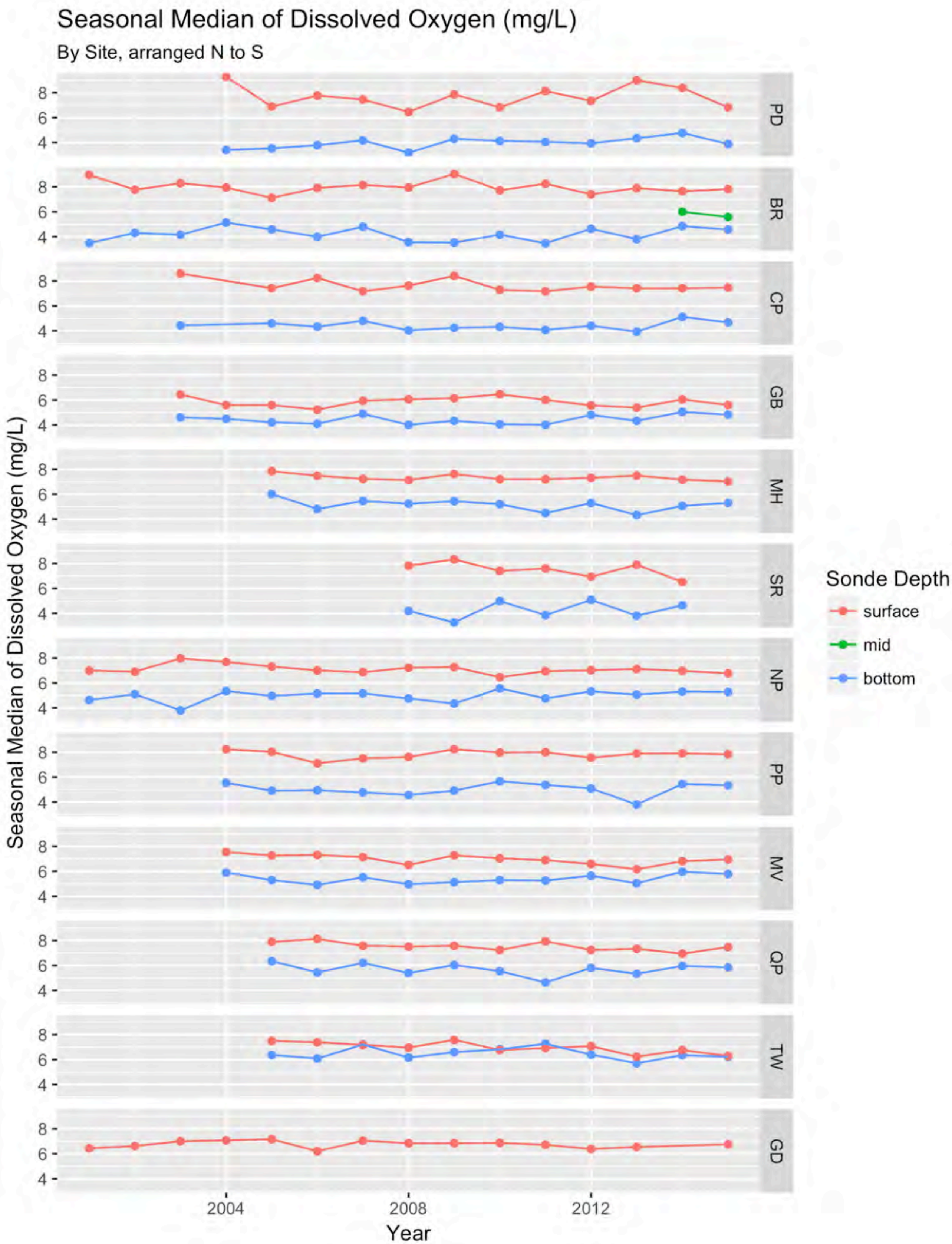
Seasonal Mean of Density (g/cm3)
By Site, arranged N to S
Seasonal Mean of Density (g/cm3)
Year
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
1.020
1.015
1.010
1.005
2004
2008
2012
Sonde Depth
surface
mid
bottom

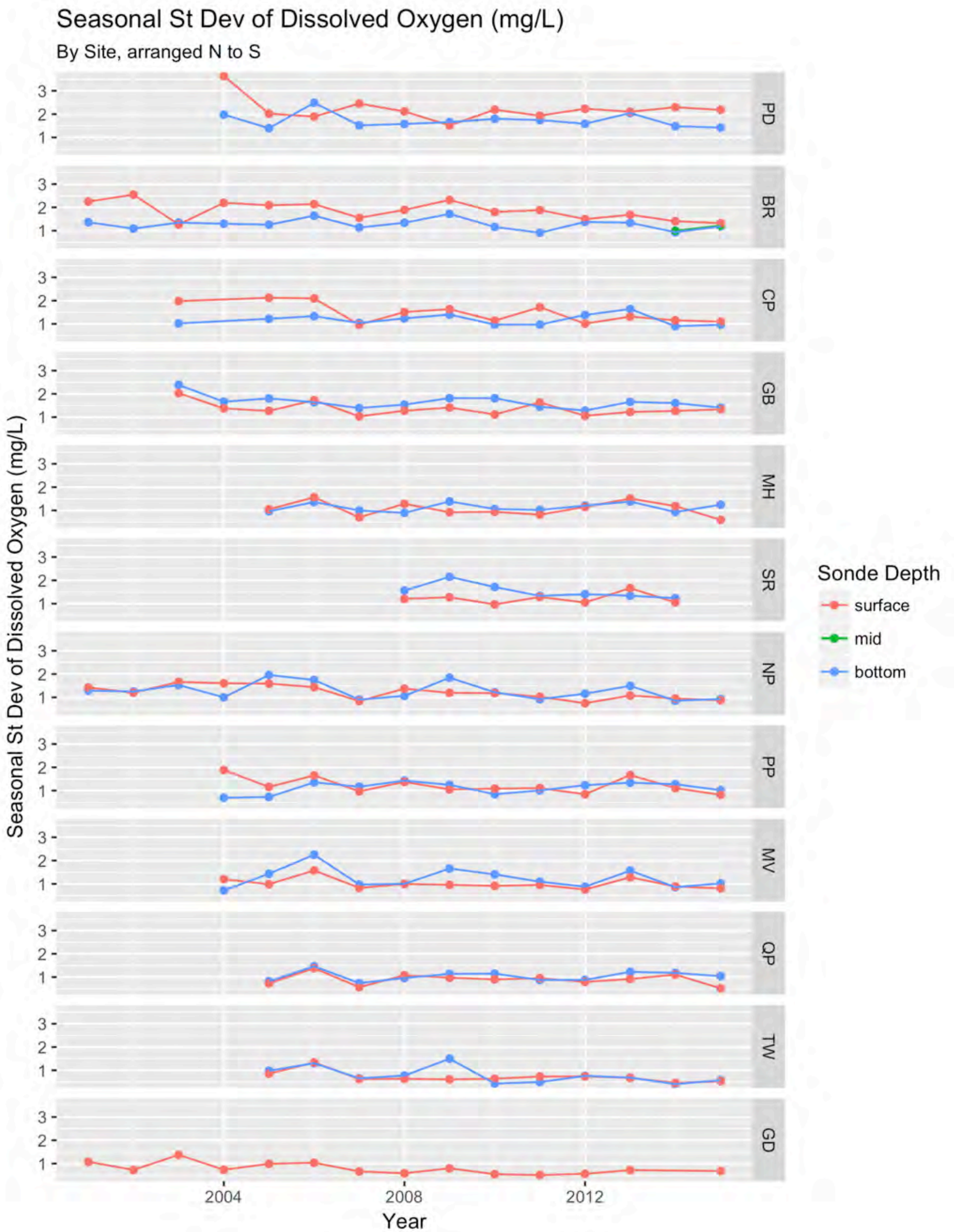

Seasonal Median of Density (g/cm3)
By Site, arranged N to S
Seasonal Median of Density (g/cm3)
1.020
1.015
1.010
1.005
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
2004
2008
2012
Year
Sonde Depth
surface
mid
bottom

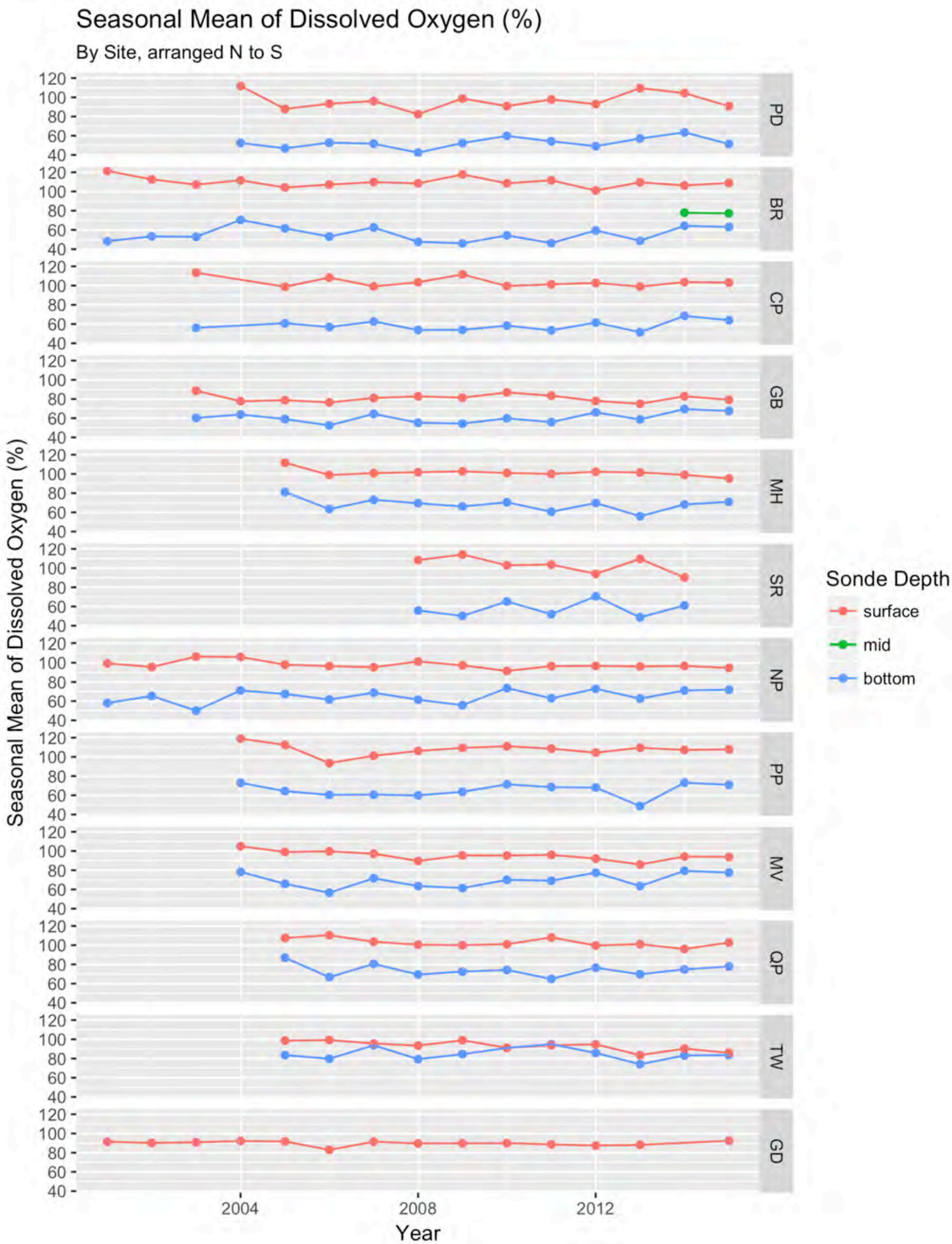

Seasonal St Dev of Density (g/cm3)
By Site, arranged N to S
Seasonal St Dev of Density (g/cm3)
0.005
0.004
0.003
0.002
0.001
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
2004
2008
2012
Year
Sonde Depth
surface
mid
bottom

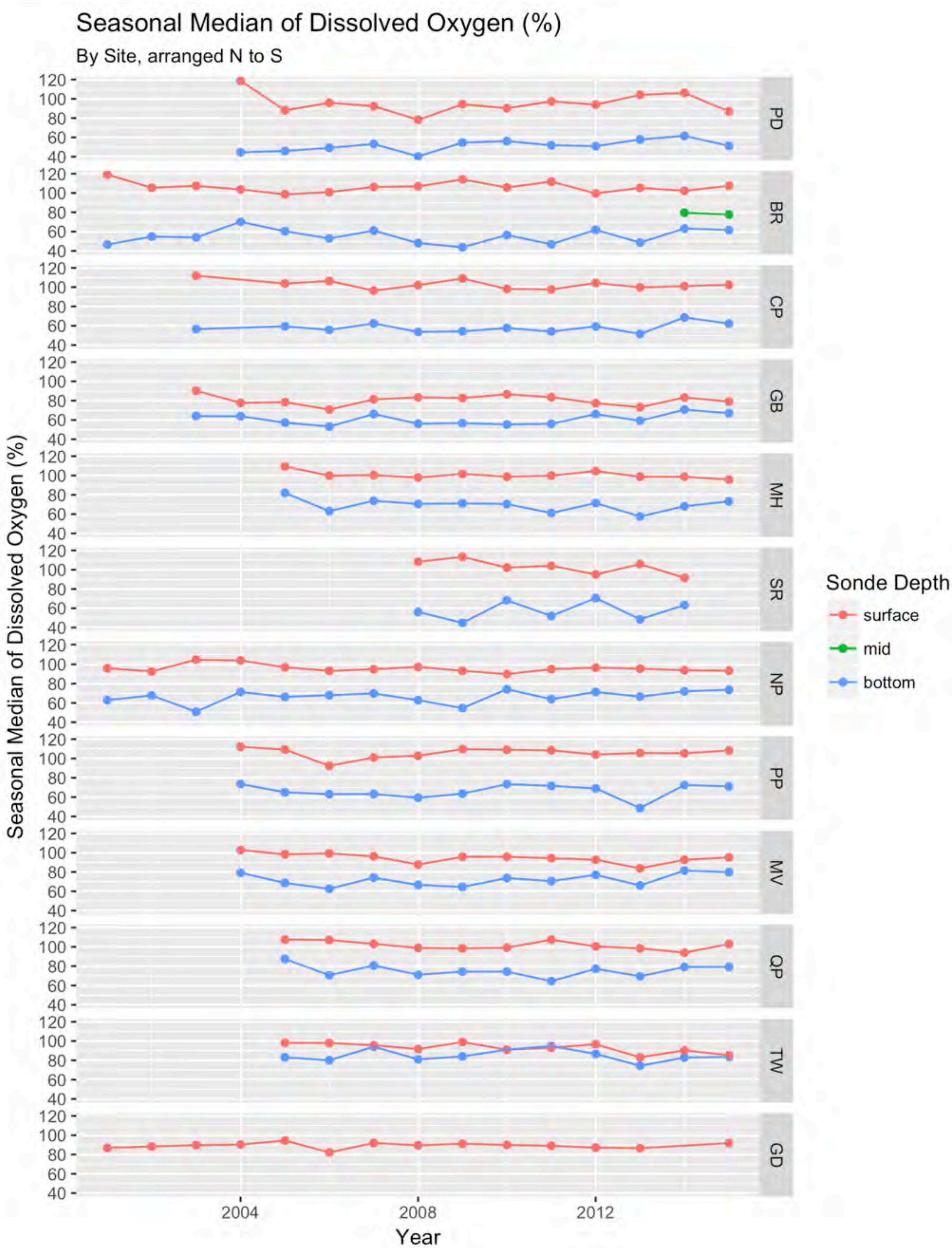


Seasonal Mean of Dissolved Oxygen (mg/L)
By Site, arranged N to S
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
Seasonal Mean of Dissolved Oxygen (mg/L)
Year
2004
2008
2012
Sonde Depth
surface
mid
bottom

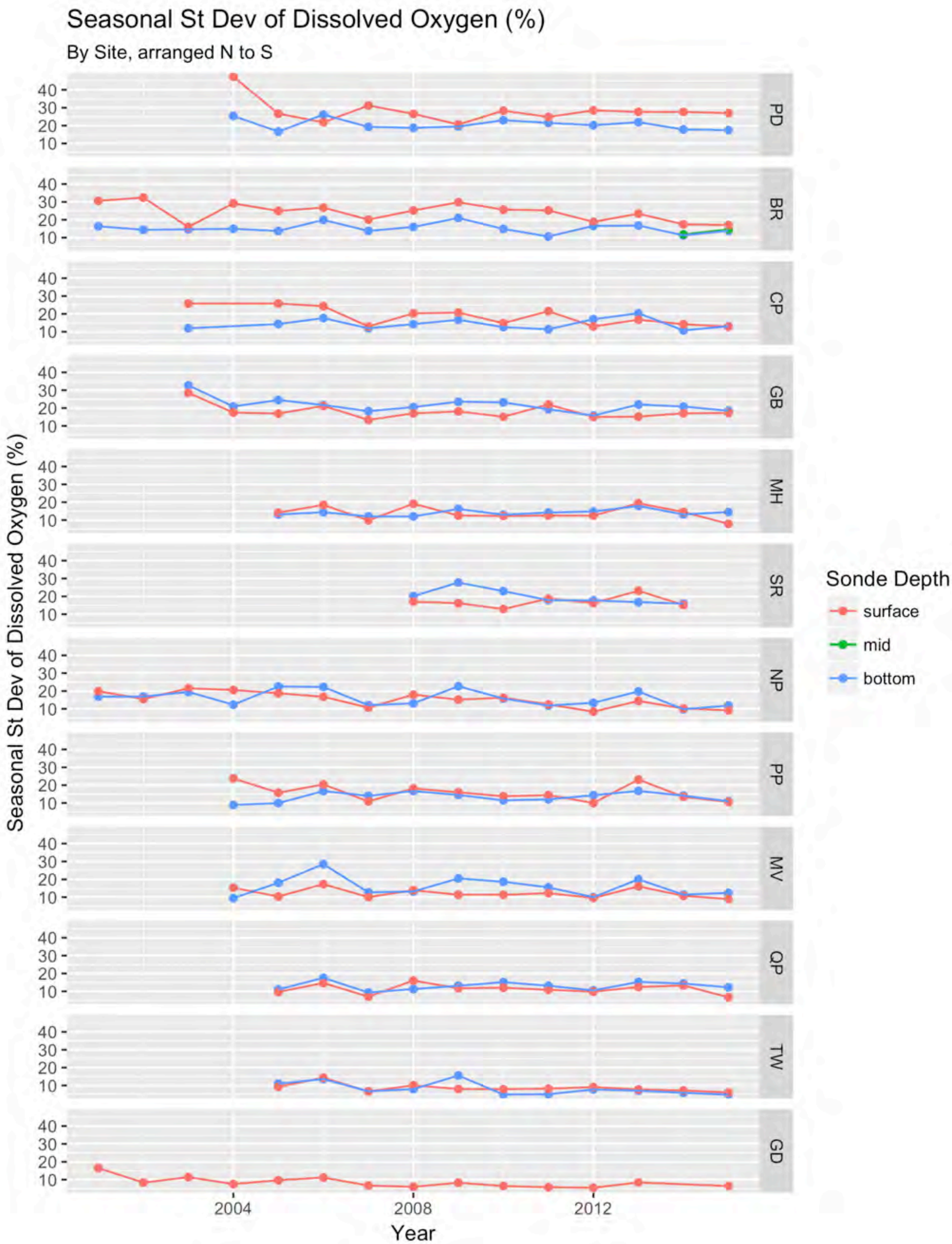

Seasonal Median of Dissolved Oxygen (mg/L)
By Site, arranged N to S
Seasonal Median of Dissolved Oxygen (mg/L)
Year
2004
2008
2012
8
6
4
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
Sonde Depth
surface
mid
bottom

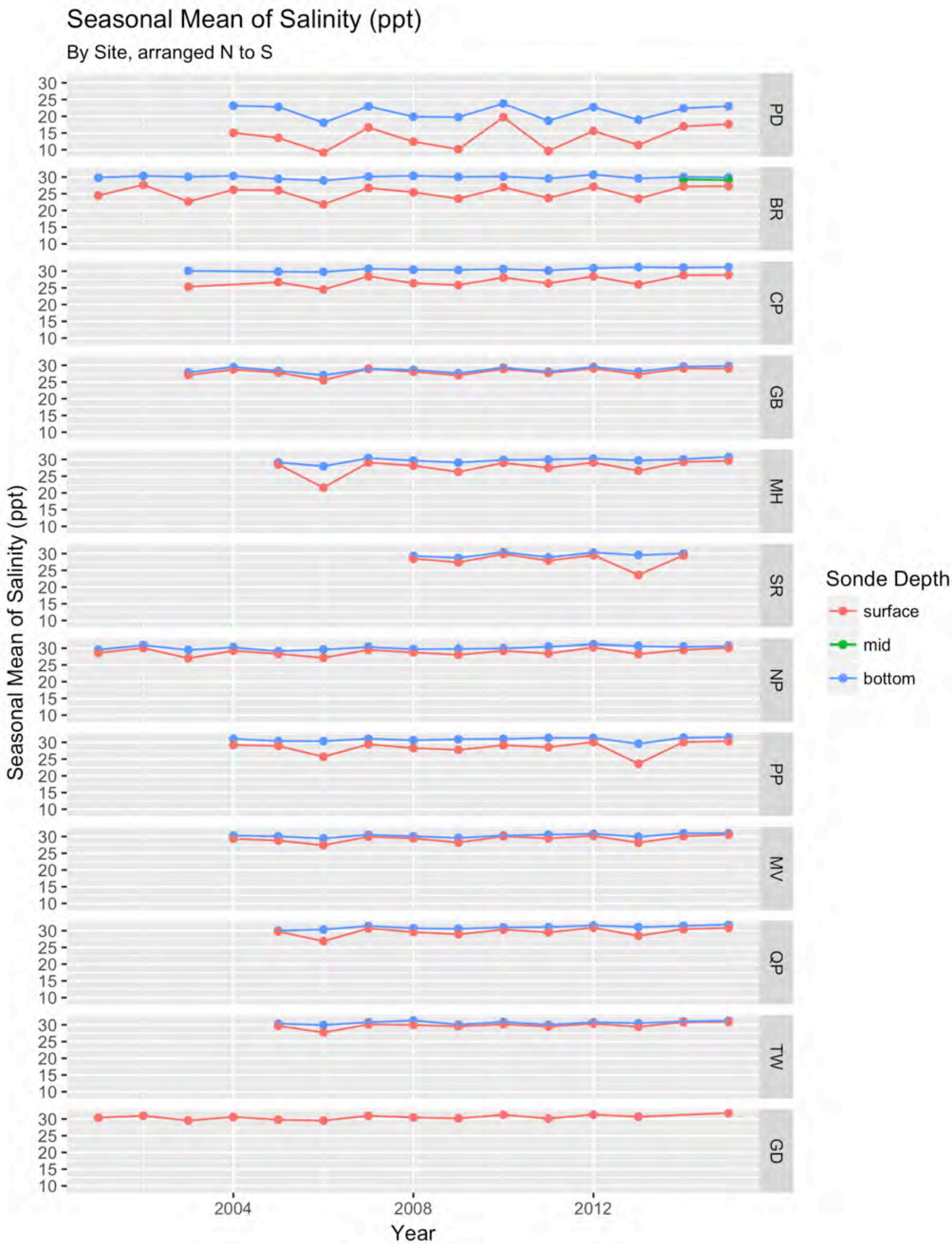

Seasonal St Dev of Dissolved Oxygen (mg/L)
By Site, arranged N to S
Seasonal St Dev of Dissolved Oxygen (mg/L)
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
1
2
3
2004
2008
2012
Year
Sonde Depth
surface
mid
bottom

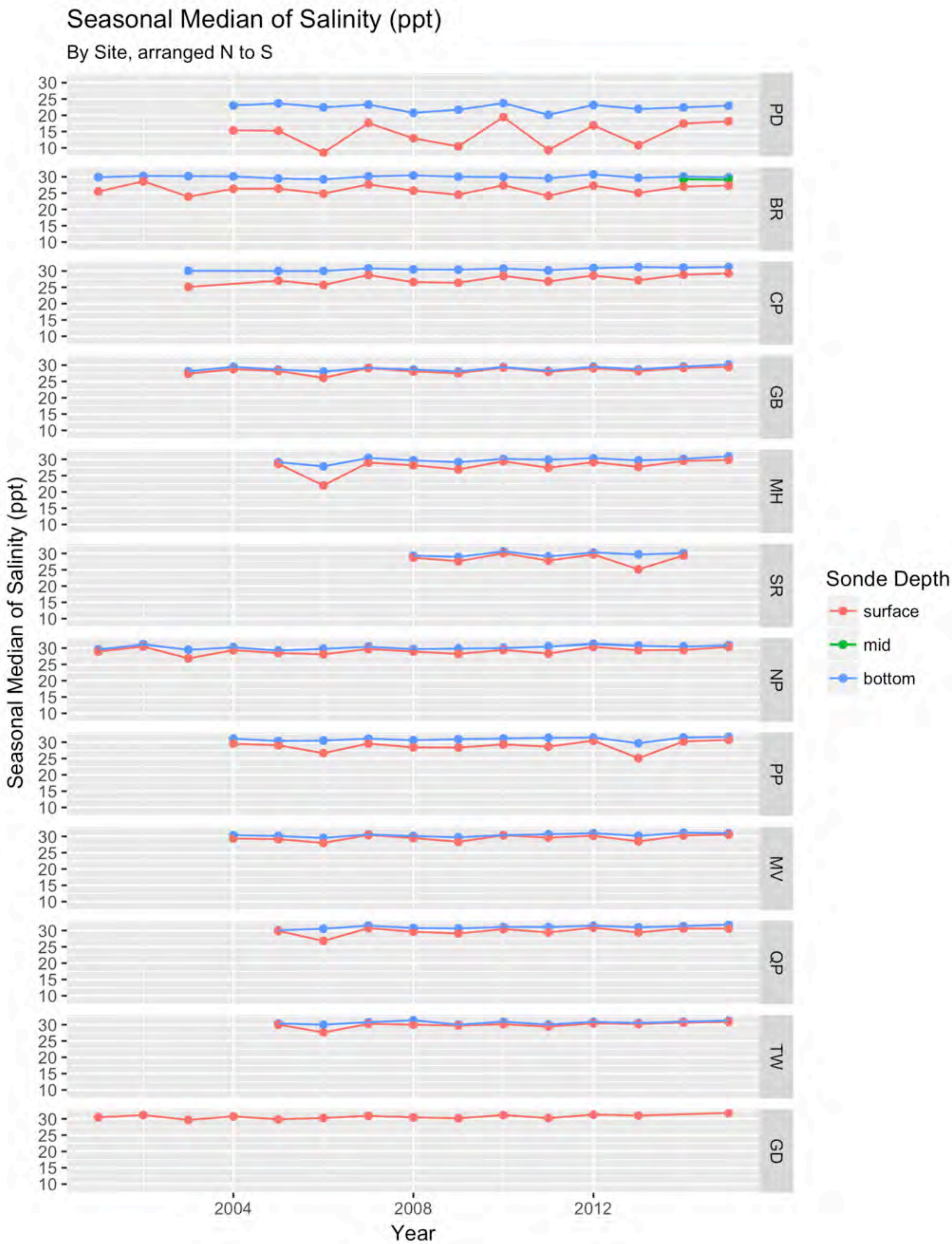

Seasonal Mean of Dissolved Oxygen (%)
By Site, arranged N to S
Seasonal Mean of Dissolved Oxygen (%)
Year
2004
2008
2012
40
60
80
100
120
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
Sonde Depth
surface
mid
bottom

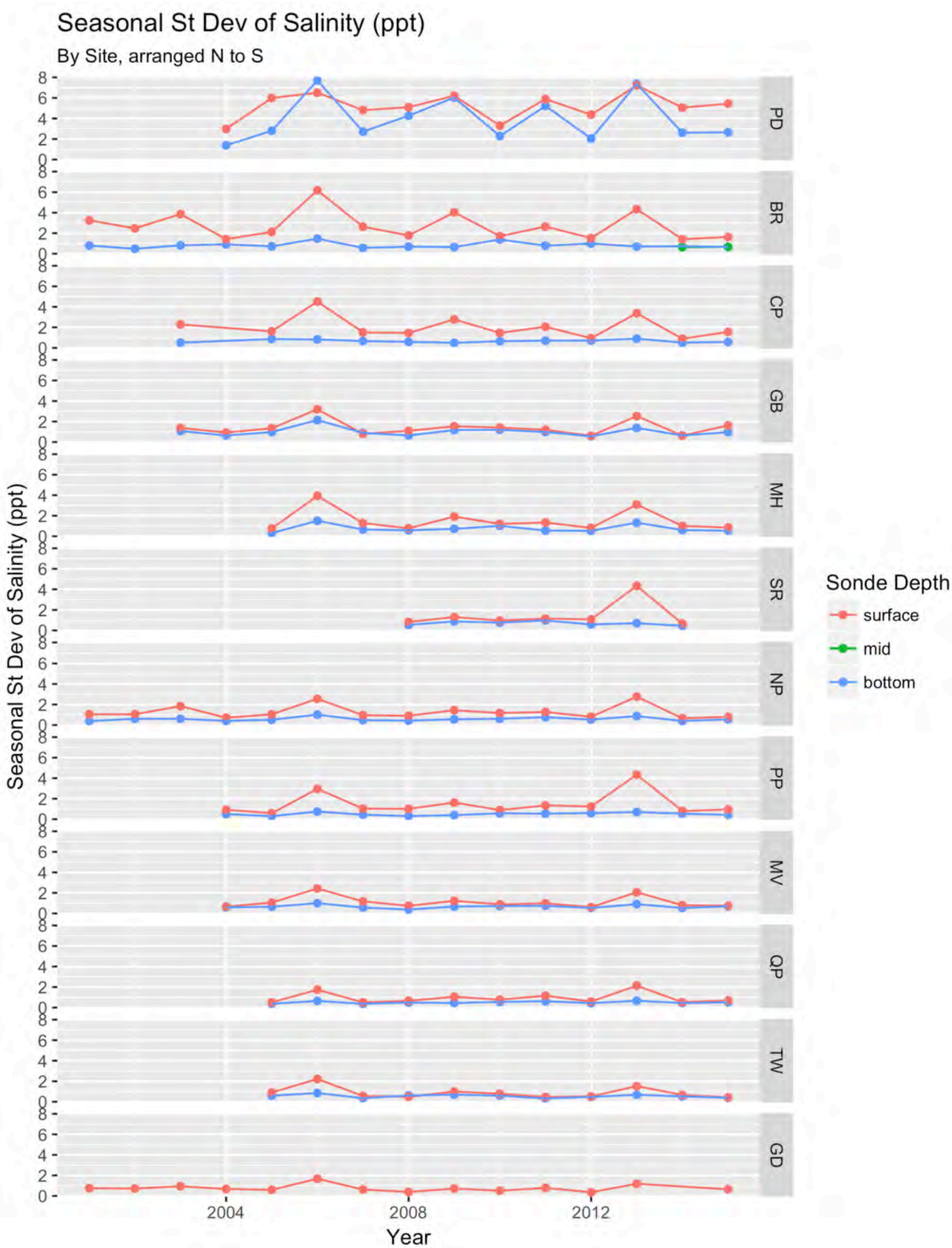


Seasonal Median of Dissolved Oxygen (%)
By Site, arranged N to S
Seasonal Median of Dissolved Oxygen (%)
120
100
80
60
40
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
2004
2008
2012
Year
Sonde Depth
surface
mid
bottom

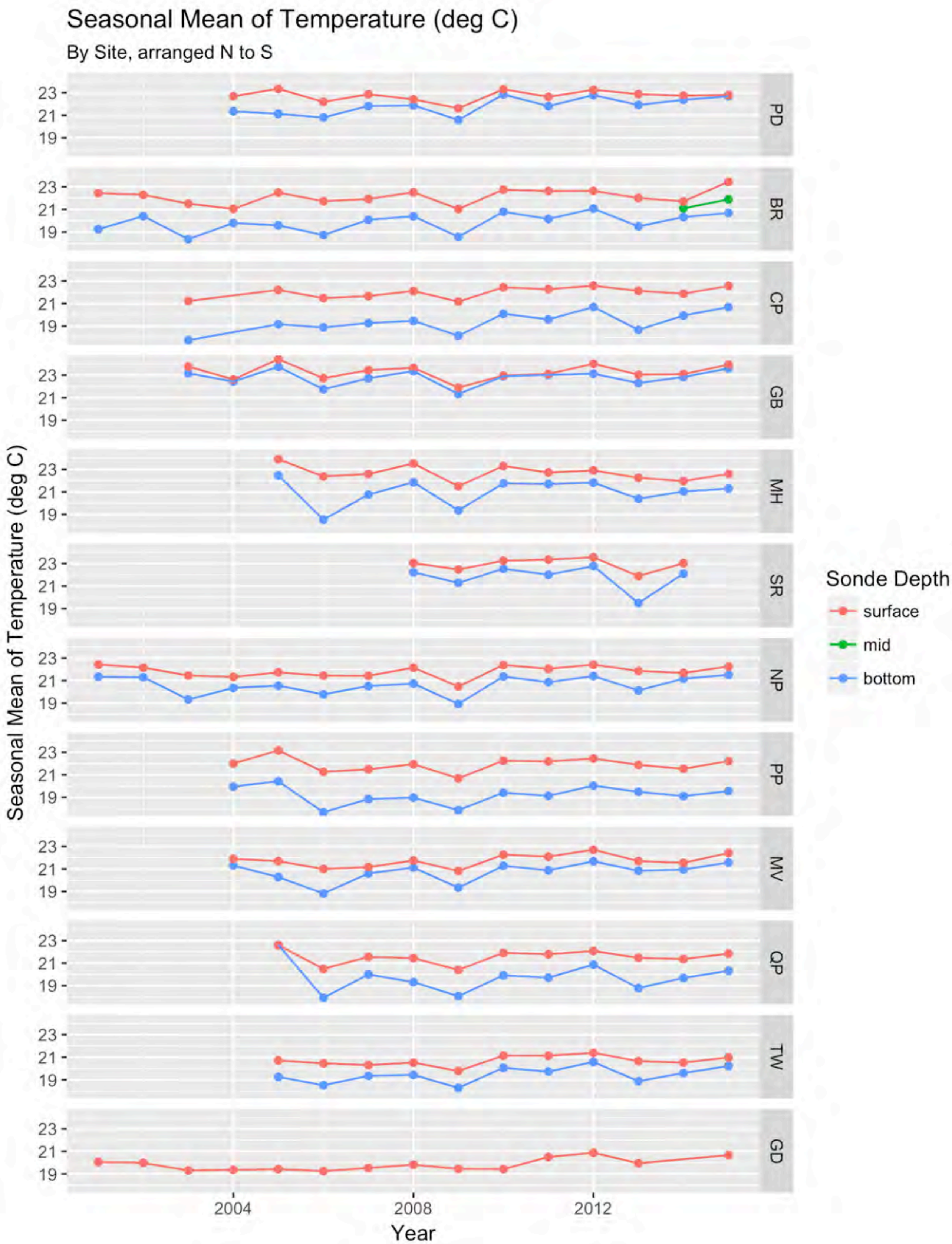

Seasonal St Dev of Dissolved Oxygen (%)
By Site, arranged N to S
Seasonal St Dev of Dissolved Oxygen (%)
40
30
20
10
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
2004
2008
2012
Year
Sonde Depth
surface
mid
bottom

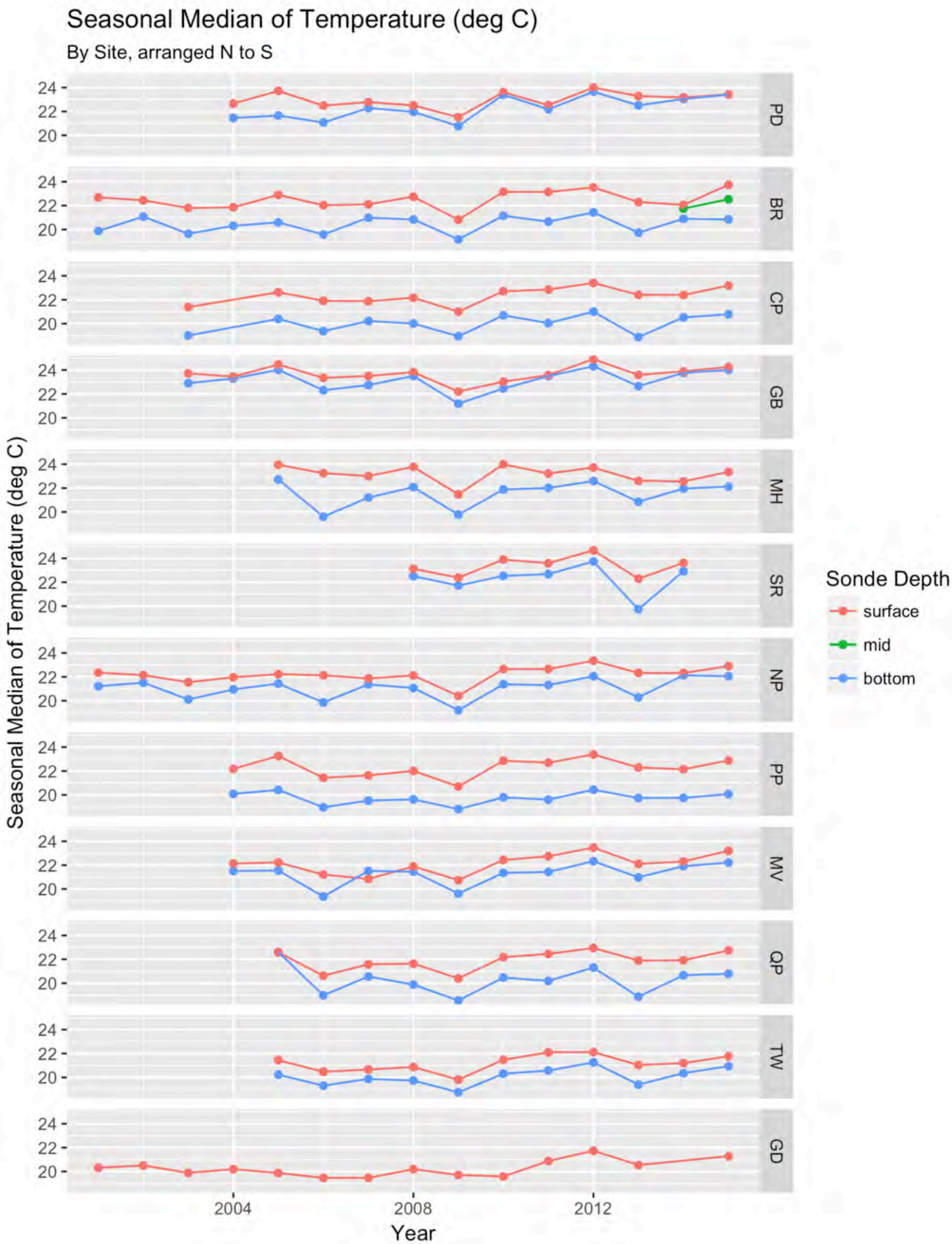

Seasonal Mean of Salinity (ppt)
By Site, arranged N to S
Seasonal Mean of Salinity (ppt)
30
25
20
15
10
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
2004
2008
2012
Year
Sonde Depth
surface
mid
bottom

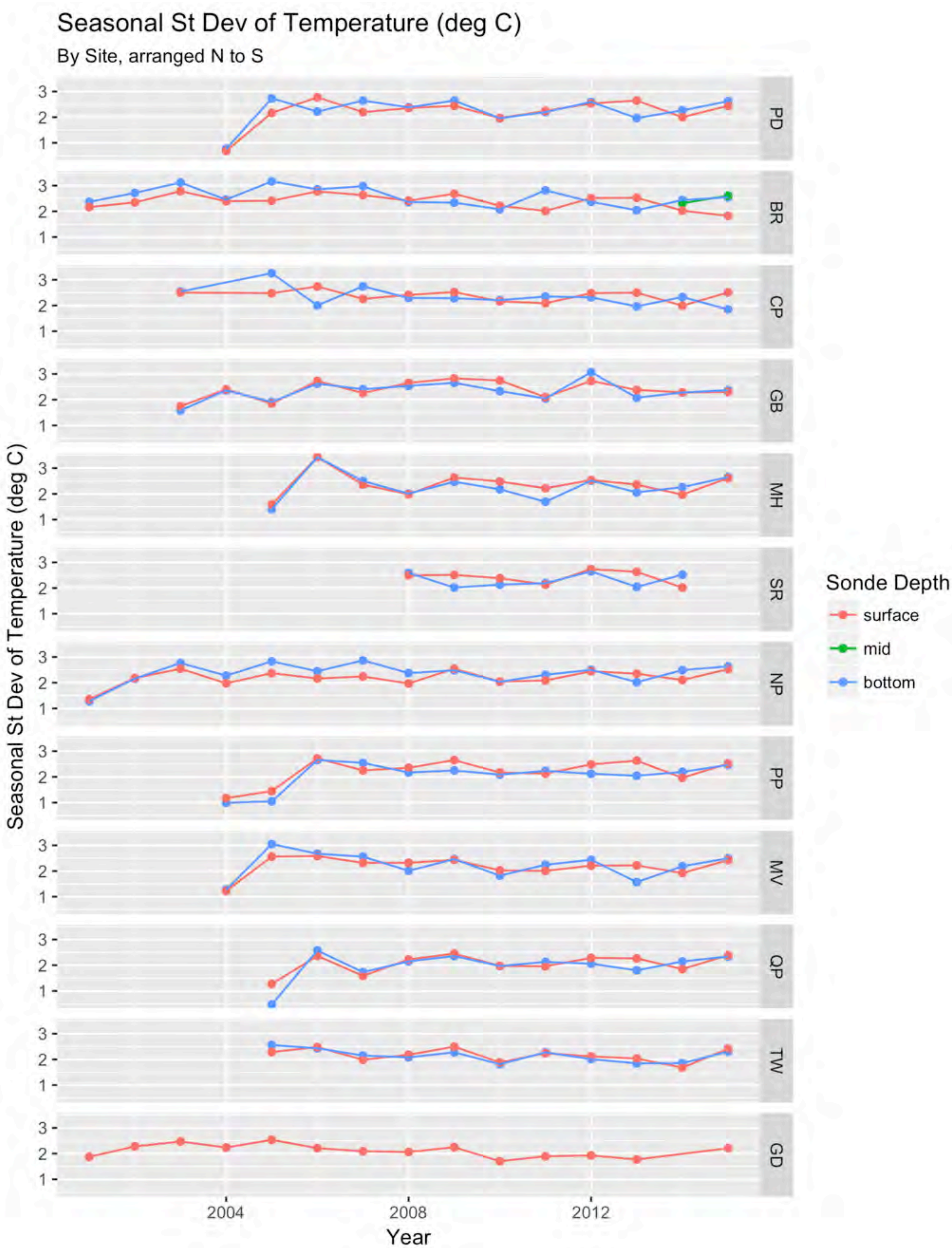

Seasonal Median of Salinity (ppt)
By Site, arranged N to S
Seasonal Median of Salinity (ppt)
Year
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
2004
2008
2012
30
25
20
15
10
Sonde Depth
surface
mid
bottom



Seasonal St Dev of Salinity (ppt)
By Site, arranged N to S
Seasonal St Dev of Salinity (ppt)
Year
2004
2008
2012
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
Sonde Depth
surface
mid
bottom

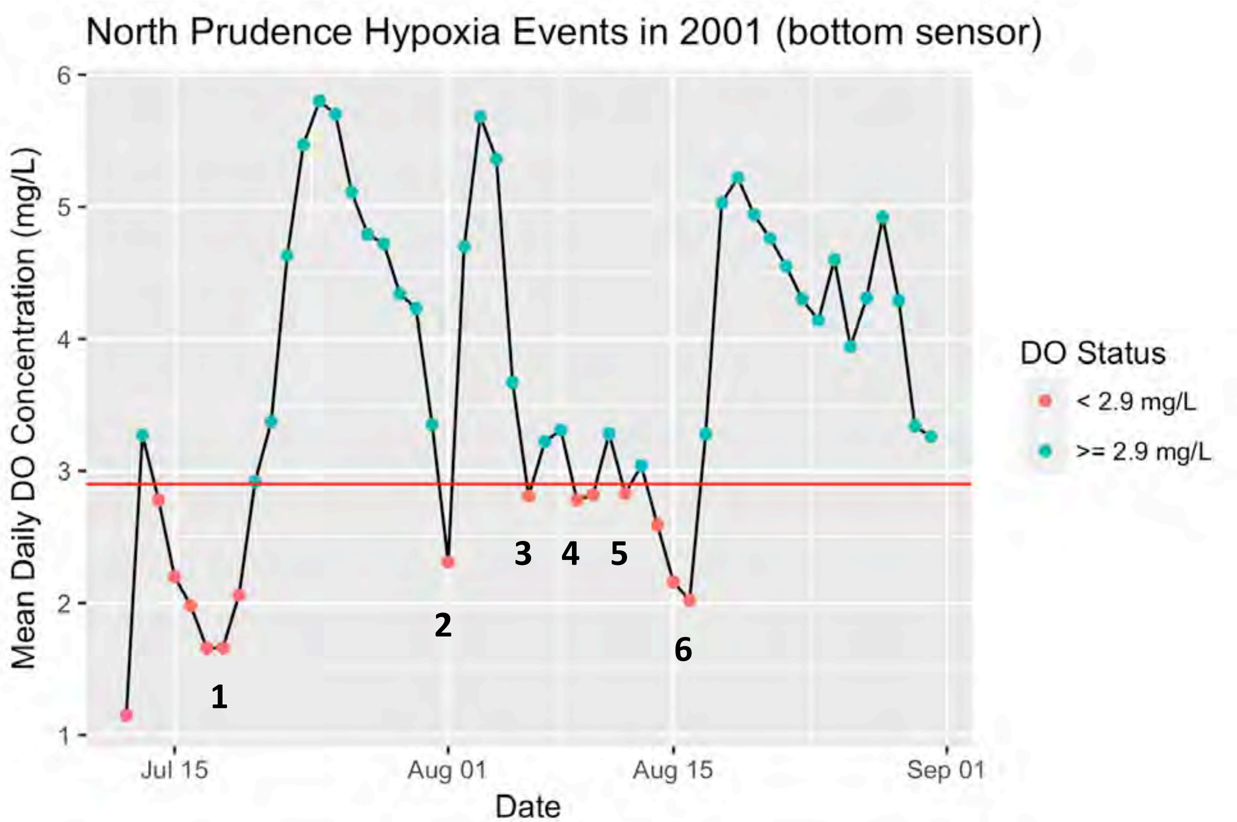

Seasonal Mean of Temperature (deg C)
By Site, arranged N to S
Seasonal Mean of Temperature (deg C)
Year
2004
2008
2012
23
21
19
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
Sonde Depth
surface
mid
bottom


Seasonal Median of Temperature (deg C)
By Site, arranged N to S
Seasonal Median of Temperature (deg C)
24
22
20
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
2004
2008
2012
Year
Sonde Depth
surface
mid
bottom


Seasonal St Dev of Temperature (deg C)
By Site, arranged N to S
Seasonal St Dev of Temperature (deg C)
Year
2004
2008
2012
PD
BR
CP
GB
MH
SR
NP
PP
MV
QP
TW
GD
Sonde Depth
surface
mid
bottom

APPENDIX C. Comparing hypoxia events as defined with the MWT method using mean daily DO data and a window of 1-day to those defined using 15-minute data and a 9-hour window as described in Codiga (2008).

Figure C1. Moving-Window Trigger method coded in R, using mean daily data, 1-day window and threshold = 2.9 mg O_2/L. Numbers correspond to events listed below graph.



Event 1
7/14 to 7/19
Duration: 6 days
Deficit-Duration: 5.1 mg/L-days

Event 2
8/1
Duration: 1 days
Deficit-Duration: 0.6 mg/L-days

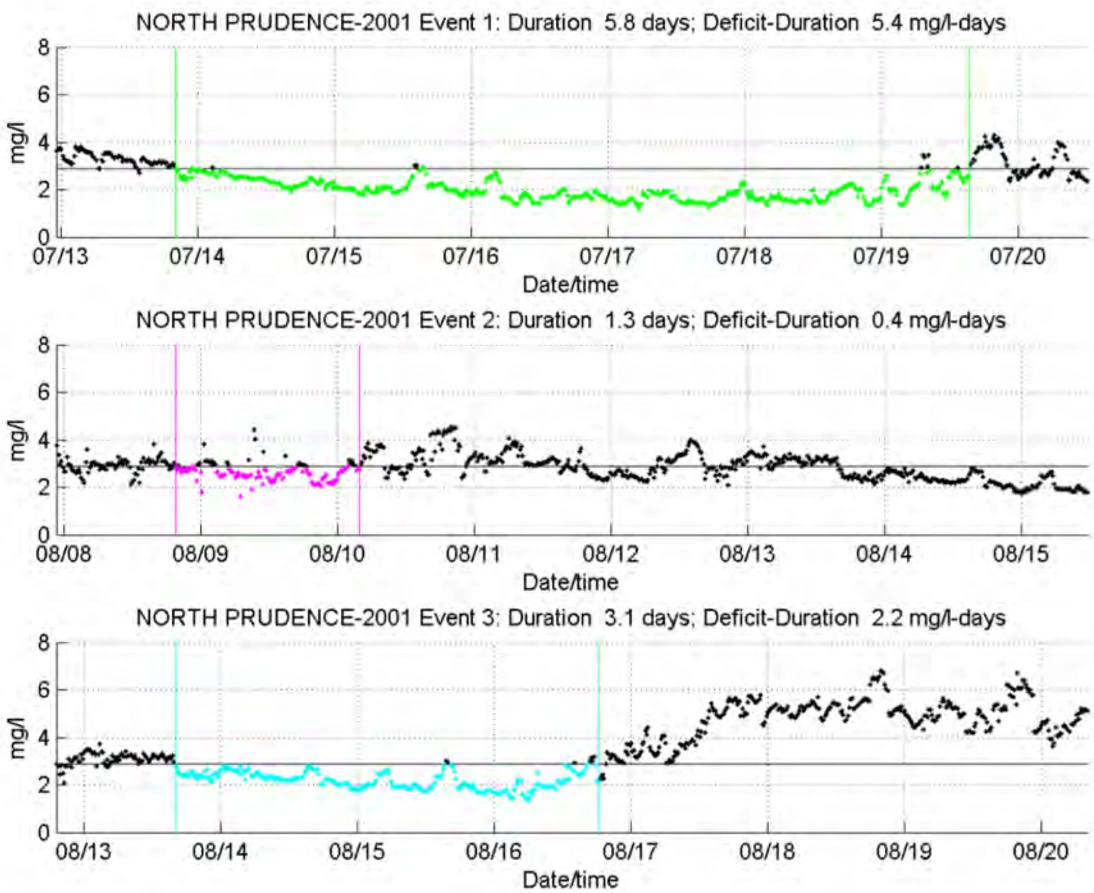
Event 3
8/6
Duration: 1 days
Deficit-Duration: 0.1 mg/L-days

Event 4
8/9 to 8/10
Duration: 2 days
Deficit-Duration: 0.2 mg/L-days

Event 5
8/12
Duration: 1 days
Deficit-Duration: 0.1 mg/L-days

Event 6
8/14 to 8/16
Duration: 3 days
Deficit-Duration: 1.9 mg/L-days

Figure C2. Moving-Window Trigger method coded in MatLab (from Codiga, 2008), using 15-minute data, 9-hour window, and threshold = 2.9 mg O_2/L. Event 1 corresponds to Event 1 in Figure C1. Event 2 corresponds to Event 4 in Figure C1. Event 3 corresponds to Event 6 in Figure C1.



APPENDIX D. MWT Statistics for Hypoxia Events, after Codiga et al. (2009), Tables 4 to 6. If a station is not listed no events were identified. Only events that are not adjacent to data gaps were included.

Table D1. MWT statistics for hypoxic events (threshold = 2 mg/L, trigger duration = 1 d). Note: CP, GB were added in 2003; MV, PD, PP were added in 2004; MH, QP, TW were added in 2005; SR added in 2008.

		No. of	**Duration [day]**			**Event-mean deficit [mg O_2/L]**			**Deficit-duration [mg O_2/L day]**		
Year	**Site**	**Events**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
2001	BR	4	1.0	2.5	3.0	0.0	0.2	0.3	0.0	0.6	0.9
	NP	1	3.0	3.0	3.0	0.2	0.2	0.2	0.7	0.7	0.7
2002	BR	1	5.0	5.0	5.0	0.8	0.8	0.8	3.8	3.8	3.8
	NP	3	1.0	1.7	3.0	0.1	0.3	0.6	0.3	0.4	0.6
2003	GB	2	1.0	6.5	12.0	0.2	0.7	1.1	0.2	7.0	13.7
	NP	5	1.0	2.6	5.0	0.1	0.4	1.1	0.1	1.5	5.3
2004	GB	2	1.0	1.5	2.0	0.1	0.5	0.8	0.1	0.9	1.7
2005	GB	7	1.0	1.6	3.0	0.2	0.5	0.7	0.2	0.8	1.4
	MV	1	1.0	1.0	1.0	0.1	0.1	0.1	0.1	0.1	0.1
	PD	4	1.0	2.8	6.0	0.1	0.4	0.6	0.1	1.4	3.8
2006	BR	3	2.0	3.3	4.0	0.2	0.2	0.3	0.4	0.7	1.0
	CP	1	2.0	2.0	2.0	0.3	0.3	0.3	0.6	0.6	0.6
	GB	8	1.0	2.1	4.0	0.1	0.6	1.2	0.1	1.5	3.3
	MV	2	9.0	10.0	11.0	1.1	1.2	1.4	12.3	12.3	12.4
	PD	3	3.0	5.0	9.0	0.3	0.8	1.2	1.0	4.8	10.4
	PP	2	1.0	1.5	2.0	0.8	0.8	0.8	0.8	1.3	1.7
	QP	1	2.0	2.0	2.0	0.0	0.0	0.0	0.1	0.1	0.1
2007	GB	2	1.0	2.5	4.0	0.1	0.4	0.6	0.1	1.3	2.6
	PD	6	1.0	2.3	6.0	0.2	0.5	0.8	0.2	1.4	5.0
	PP	1	3.0	3.0	3.0	0.4	0.4	0.4	1.1	1.1	1.1
2008	BR	4	1.0	3.0	6.0	0.0	0.3	0.5	0.0	1.2	3.1
	CP	2	1.0	2.0	3.0	0.1	0.1	0.1	0.1	0.3	0.4
	GB	7	1.0	1.9	4.0	0.1	0.7	1.6	0.1	1.2	3.4
	NP	1	2.0	2.0	2.0	0.1	0.1	0.1	0.2	0.2	0.2
	PD	9	1.0	2.8	6.0	0.0	0.4	1.1	0.0	1.5	4.6
	SR	5	1.0	2.2	4.0	0.1	0.6	0.9	0.1	1.5	3.4
2009	BR	6	1.0	4.2	9.0	0.1	0.3	0.6	0.1	1.8	4.8
	CP	1	2.0	2.0	2.0	0.2	0.2	0.2	0.4	0.4	0.4
	GB	10	1.0	1.4	2.0	0.1	0.7	1.8	0.1	1.0	3.2
	MH	1	2.0	2.0	2.0	0.1	0.1	0.1	0.3	0.3	0.3
	MV	3	1.0	3.0	4.0	0.2	0.3	0.3	0.2	0.8	1.3
	NP	3	1.0	4.3	6.0	0.2	0.5	0.6	0.2	2.6	3.7
	PD	3	2.0	3.7	6.0	0.5	0.6	0.6	1.2	2.2	3.8
	PP	1	1.0	1.0	1.0	0.2	0.2	0.2	0.2	0.2	0.2

	SR	8	1.0	2.8	7.0	0.0	0.6	1.6	0.0	1.9	7.5
2010	BR	2	2.0	2.5	3.0	0.1	0.2	0.2	0.4	0.4	0.5
	GB	2	1.0	2.5	4.0	0.4	0.5	0.6	0.4	1.5	2.6
	MV	1	1.0	1.0	1.0	0.1	0.1	0.1	0.1	0.1	0.1
	PD	1	2.0	2.0	2.0	0.7	0.7	0.7	1.4	1.4	1.4
	SR	3	1.0	2.7	5.0	0.3	0.8	1.1	0.3	2.6	5.5
2011	BR	1	1.0	1.0	1.0	0.3	0.3	0.3	0.3	0.3	0.3
	GB	4	1.0	2.3	5.0	0.0	0.5	0.8	0.0	1.4	4.1
	MV	1	2.0	2.0	2.0	0.1	0.1	0.1	0.1	0.1	0.1
	NP	1	1.0	1.0	1.0	0.1	0.1	0.1	0.1	0.1	0.1
	PD	5	1.0	2.0	3.0	0.1	0.5	1.0	0.1	1.3	3.1
	SR	6	1.0	1.8	3.0	0.2	0.4	0.8	0.3	0.8	2.5
2012	BR	1	2.0	2.0	2.0	0.2	0.2	0.2	0.4	0.4	0.4
	GB	1	2.0	2.0	2.0	0.1	0.1	0.1	0.3	0.3	0.3
	MH	1	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
	PD	6	1.0	3.3	7.0	0.2	0.6	1.1	0.2	2.5	7.5
	SR	3	1.0	1.3	2.0	0.2	0.4	0.8	0.2	0.7	1.6
2013	BR	4	1.0	3.3	7.0	0.0	0.3	0.7	0.0	1.5	5.0
	CP	2	3.0	3.5	4.0	0.4	0.5	0.6	1.2	1.8	2.5
	GB	5	1.0	1.8	3.0	0.0	0.5	0.9	0.0	1.0	1.9
	MH	3	2.0	3.3	5.0	0.2	0.3	0.5	0.5	1.0	1.3
	MV	1	1.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
	NP	3	1.0	1.7	3.0	0.0	0.2	0.3	0.0	0.4	0.9
	PD	4	1.0	2.0	4.0	0.1	0.4	0.6	0.1	0.8	2.0
	PP	4	1.0	3.3	7.0	0.0	0.3	0.7	0.0	1.5	5.0
	SR	4	1.0	3.3	7.0	0.0	0.3	0.7	0.0	1.5	5.0
2014	GB	2	1.0	1.0	1.0	0.1	0.3	0.5	0.1	0.3	0.5
	PD	1	1.0	1.0	1.0	0.2	0.2	0.2	0.2	0.2	0.2
	SR	1	1.0	1.0	1.0	0.4	0.4	0.4	0.4	0.4	0.4
2015	GB	1	1.0	1.0	1.0	0.1	0.1	0.1	0.1	0.1	0.1
	PD	6	1.0	1.3	2.0	0.0	0.4	0.5	0.0	0.5	1.1

Table D2. MWT statistics for hypoxic events (threshold = 5 mg/L, trigger duration = 1 d). Note: CP, GB were added in 2003; MV, PD, PP were added in 2004; MH, QP, TW were added in 2005; SR added in 2008.

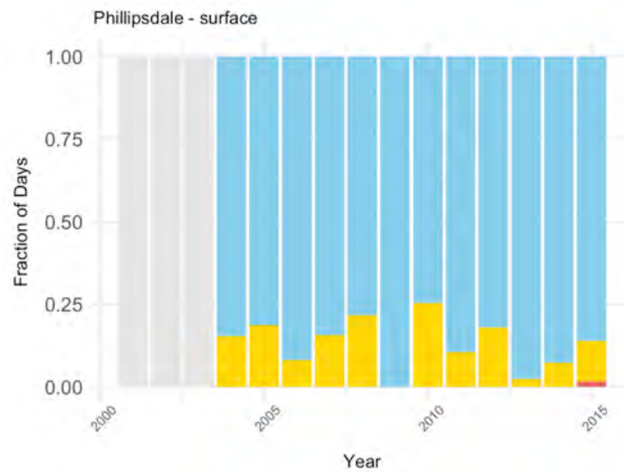
		No. of	Duration [day]			Event-mean deficit [mg O_2/L]			Deficit-duration [mg O_2/L day]		
Year	**Site**	**Events**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
2001	BR	6	1.0	16.3	45.0	0.0	1.0	2.1	0.0	28.7	95.9
	NP	7	1.0	6.0	13.0	0.0	0.7	2.1	0.0	6.6	27.2
2002	BR	2	1.0	7.5	14.0	0.1	0.3	0.5	0.1	3.8	7.5
	NP	5	2.0	9.8	17.0	0.1	0.9	1.7	0.2	11.9	28.4
2003	BR	5	1.0	4.6	11.0	0.1	0.3	0.6	0.2	1.8	6.4
	CP	2	1.0	1.5	2.0	0.1	0.2	0.3	0.1	0.4	0.6
	GB	10	1.0	4.6	21.0	0.2	1.2	2.8	0.2	8.6	59.6
	NP	4	1.0	2.0	5.0	0.0	0.3	0.6	0.0	0.7	2.0
2004	BR	10	1.0	2.8	12.0	0.0	0.3	1.1	0.0	1.8	12.8
	GB	14	1.0	5.7	41.0	0.1	1.0	3.1	0.1	7.6	71.5
	MV	7	1.0	2.1	4.0	0.2	0.4	0.6	0.2	0.9	2.2
	NP	14	1.0	2.3	5.0	0.0	0.6	1.3	0.0	1.6	6.4
	PP	9	1.0	2.2	4.0	0.1	0.4	0.9	0.1	1.2	3.6
2005	BR	12	1.0	6.2	22.0	0.1	0.6	1.3	0.2	5.5	29.5
	CP	6	1.0	9.0	25.0	0.0	0.6	1.2	0.0	8.2	29.8
	GB	13	1.0	6.0	32.0	0.1	1.2	2.2	0.1	10.3	62.2
	MH	4	1.0	2.3	6.0	0.1	0.3	0.7	0.1	1.2	4.2
	MV	4	2.0	5.5	12.0	0.2	0.5	0.9	0.4	4.1	11.1
	NP	8	1.0	7.6	20.0	0.1	0.9	1.7	0.1	9.5	33.4
	PD	5	2.0	23.6	42.0	0.3	1.4	2.0	0.7	39.8	72.4
	PP	6	1.0	4.8	15.0	0.0	0.4	0.9	0.0	3.4	13.9
	TW	2	2.0	2.5	3.0	0.2	0.2	0.3	0.4	0.6	0.8
2006	BR	4	3.0	19.5	36.0	0.1	1.3	2.1	0.3	33.2	74.6
	CP	4	1.0	17.3	54.0	0.2	0.7	1.6	0.2	23.8	88.3
	GB	14	2.0	6.4	20.0	0.5	1.4	3.0	1.0	11.5	59.5
	MH	4	2.0	6.3	11.0	0.2	0.6	0.9	0.4	4.2	7.6
	MV	5	3.0	12.6	43.0	0.2	1.2	3.1	0.9	29.8	132.2
	NP	3	1.0	4.3	11.0	0.1	0.4	0.8	0.1	3.2	9.3
	PD	6	1.0	4.3	10.0	0.1	0.7	1.4	0.1	4.8	12.7
	PP	7	1.0	9.0	22.0	0.3	0.9	1.7	0.3	11.2	36.8
	QP	3	3.0	16.3	42.0	0.3	0.6	1.2	1.2	18.1	51.9
	TW	2	3.0	7.5	12.0	0.3	0.6	1.0	0.8	6.1	11.5
2007	BR	9	1.0	4.4	11.0	0.0	0.5	1.2	0.0	3.3	13.1
	CP	10	1.0	7.7	54.0	0.0	0.3	1.0	0.0	6.3	54.7
	GB	17	1.0	4.1	31.0	0.1	0.5	2.0	0.1	4.9	61.9
	MH	10	1.0	3.8	8.0	0.1	0.5	0.9	0.1	2.4	7.4
	MV	11	1.0	3.3	12.0	0.0	0.4	1.5	0.0	2.5	17.4
	NP	7	1.0	6.6	27.0	0.0	0.4	1.1	0.0	4.0	20.1
	PD	10	1.0	11.3	28.0	0.3	1.1	2.3	0.4	17.8	58.6
	PP	16	1.0	4.8	34.0	0.1	0.5	1.4	0.1	4.6	47.7
	QP	5	1.0	2.2	6.0	0.0	0.2	0.5	0.0	0.7	2.9
2008	BR	4	1.0	22.3	83.0	0.3	0.7	1.8	0.3	38.9	153.3

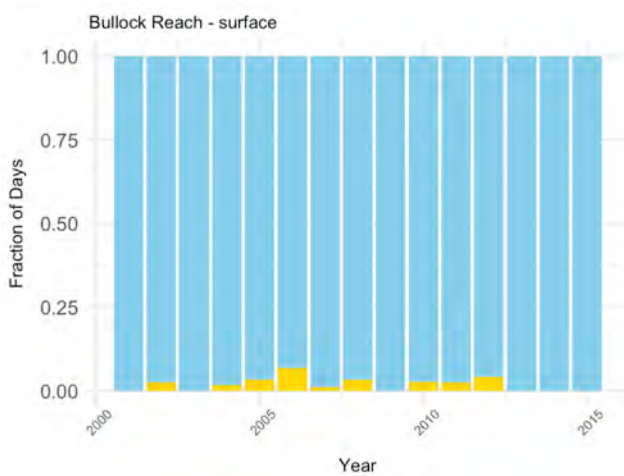
	CP	6	1.0	16.7	77.0	0.2	0.7	1.5	0.2	22.1	113.2
	GB	18	1.0	4.1	23.0	0.2	1.0	2.8	0.2	6.7	49.8
	MH	16	1.0	2.8	11.0	0.0	0.5	1.6	0.0	2.1	13.7
	MV	11	2.0	5.4	10.0	0.2	0.8	1.9	0.5	5.3	16.9
	NP	8	1.0	9.0	22.0	0.1	0.8	1.8	0.1	9.2	24.7
	PD	8	2.0	14.6	52.0	0.3	1.4	2.5	0.7	28.5	130.9
	PP	13	1.0	5.4	14.0	0.0	1.0	1.7	0.0	6.9	24.4
	QP	7	1.0	5.3	13.0	0.1	0.5	1.2	0.1	3.9	12.4
	SR	11	1.0	5.8	36.0	0.3	1.1	2.2	0.3	9.3	70.5
	TW	4	1.0	2.8	6.0	0.2	0.3	0.4	0.2	0.9	2.4
2009	BR	4	2.0	22.5	74.0	0.2	1.0	2.5	0.6	49.1	186.9
	CP	3	8.0	26.3	47.0	0.4	1.2	2.0	2.8	41.6	96.3
	GB	12	1.0	6.2	15.0	0.1	1.2	2.5	0.1	10.2	24.2
	MH	4	6.0	12.8	23.0	0.5	1.0	1.7	3.1	15.4	38.6
	MV	5	1.0	4.6	10.0	0.0	0.5	0.9	0.0	3.2	9.0
	NP	4	2.0	12.0	37.0	0.4	1.2	2.6	1.5	25.6	94.5
	PD	7	1.0	10.3	19.0	0.2	1.5	2.3	0.2	17.9	38.4
	PP	5	2.0	11.8	44.0	0.7	0.9	1.2	1.5	12.2	47.2
	QP	3	1.0	3.0	6.0	0.1	0.2	0.5	0.1	1.1	2.7
	SR	4	1.0	11.5	42.0	0.1	0.9	2.7	0.2	28.6	113.5
	TW	2	4.0	4.0	4.0	0.2	0.4	0.6	0.9	1.5	2.2
2010	BR	7	1.0	11.4	49.0	0.2	0.8	1.8	0.3	17.2	86.7
	CP	4	1.0	14.0	52.0	0.0	0.5	1.3	0.0	17.4	68.4
	GB	5	1.0	4.8	11.0	0.0	0.8	1.5	0.1	5.8	16.5
	MH	12	1.0	3.3	10.0	0.0	0.4	1.0	0.0	2.2	7.6
	MV	6	2.0	7.3	20.0	0.1	0.9	1.4	0.3	9.1	28.4
	NP	8	1.0	4.4	15.0	0.1	0.7	1.3	0.1	4.3	14.7
	PD	12	1.0	3.9	14.0	0.1	0.7	1.8	0.1	4.3	24.7
	PP	8	1.0	4.1	11.0	0.1	0.4	0.7	0.1	2.2	7.0
	QP	10	1.0	3.7	12.0	0.0	0.4	1.2	0.0	2.6	14.8
	SR	6	1.0	9.5	38.0	0.0	0.8	1.9	0.0	14.2	66.8
2011	BR	5	2.0	25.2	70.0	0.2	0.9	1.7	0.3	37.2	119.6
	CP	6	2.0	11.3	18.0	0.2	0.7	1.3	0.4	11.3	23.4
	GB	15	1.0	6.5	30.0	0.2	1.2	2.2	0.2	9.9	64.7
	MH	12	1.0	7.2	20.0	0.2	0.9	1.7	0.2	6.9	24.5
	MV	12	1.0	4.2	11.0	0.0	0.5	1.6	0.0	3.5	16.4
	NP	13	1.0	6.5	18.0	0.1	0.6	1.2	0.1	5.1	18.4
	PD	12	2.0	7.7	22.0	0.5	1.3	2.9	1.6	12.1	50.9
	PP	8	1.0	3.3	7.0	0.0	0.5	0.9	0.1	2.1	6.0
	QP	10	1.0	7.2	26.0	0.0	0.6	1.1	0.0	5.8	25.9
	SR	17	1.0	6.1	20.0	0.2	1.2	2.6	0.2	9.9	37.7
2012	BR	7	1.0	12.6	41.0	0.0	0.6	1.7	0.1	15.9	71.3
	CP	7	1.0	12.0	39.0	0.0	0.5	1.5	0.0	14.0	60.3
	GB	19	1.0	4.1	15.0	0.1	0.7	2.0	0.1	4.4	24.7
	MH	13	1.0	4.8	18.0	0.1	0.5	1.5	0.1	4.1	20.7
	MV	6	1.0	3.5	7.0	0.1	0.4	0.7	0.2	1.8	4.9
	NP	13	1.0	4.0	15.0	0.0	0.4	1.0	0.0	2.6	12.8

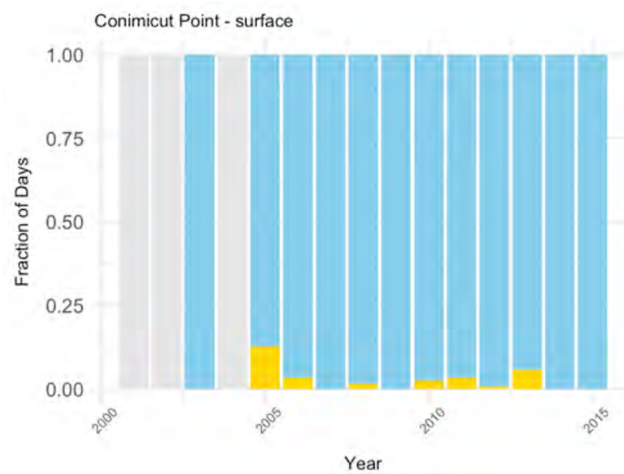
	PD	11	1.0	11.0	39.0	0.1	1.2	3.0	0.1	17.7	95.0
	PP	11	1.0	5.1	14.0	0.0	0.6	1.4	0.0	4.6	15.4
	QP	5	2.0	5.0	12.0	0.3	0.5	0.6	0.6	2.6	7.0
	SR	16	1.0	3.3	14.0	0.0	0.6	1.8	0.0	3.3	16.9
2013	BR	3	5.0	33.7	58.0	0.3	1.2	1.9	1.4	55.1	110.2
	CP	3	2.0	6.0	10.0	0.1	0.5	0.8	0.2	4.2	8.3
	GB	9	1.0	7.4	17.0	0.4	1.5	2.7	0.7	13.2	37.7
	MH	10	1.0	8.3	30.0	0.0	1.0	2.0	0.0	12.4	61.4
	MV	6	1.0	8.0	25.0	0.0	0.8	2.3	0.0	12.4	57.8
	NP	6	1.0	9.7	28.0	0.2	0.9	2.4	0.2	14.9	67.6
	PD	11	1.0	7.2	37.0	0.0	0.8	2.3	0.0	11.3	86.2
	PP	3	5.0	33.7	58.0	0.3	1.2	1.9	1.4	55.1	110.2
	QP	7	1.0	5.3	23.0	0.1	0.4	1.2	0.1	4.7	27.0
	SR	3	5.0	33.7	58.0	0.3	1.2	1.9	1.4	55.1	110.2
	TW	8	1.0	2.6	6.0	0.0	0.2	0.3	0.0	0.5	1.3
2014	BR	9	1.0	7.6	16.0	0.2	0.6	1.1	0.3	6.1	16.3
	CP	7	1.0	8.0	25.0	0.1	0.4	0.8	0.1	4.8	19.4
	GB	14	1.0	4.3	13.0	0.1	1.1	1.8	0.1	5.3	22.4
	MH	12	1.0	4.8	18.0	0.1	0.5	1.1	0.1	3.5	13.5
	MV	4	1.0	4.0	6.0	0.2	0.5	1.0	0.2	2.3	5.9
	NP	7	1.0	3.0	7.0	0.1	0.4	1.1	0.1	1.7	6.8
	PD	13	1.0	5.8	18.0	0.1	0.8	1.6	0.1	6.5	20.1
	PP	8	1.0	4.5	16.0	0.0	0.4	1.0	0.0	2.9	16.5
	QP	2	2.0	12.5	23.0	0.4	0.8	1.1	0.9	13.6	26.4
	SR	8	1.0	5.3	16.0	0.2	1.0	2.3	0.2	6.7	26.2
2015	BR	3	2.0	20.3	51.0	0.3	0.5	1.0	0.7	17.9	51.0
	CP	3	5.0	20.7	51.0	0.6	0.7	0.9	3.2	17.9	46.5
	GB	9	1.0	7.2	32.0	0.1	0.7	1.5	0.1	8.4	47.7
	MH	9	1.0	3.2	13.0	0.1	0.4	1.0	0.1	2.2	12.8
	MV	4	1.0	4.5	12.0	0.1	0.6	1.1	0.2	3.9	13.6
	NP	4	1.0	8.5	28.0	0.0	0.4	1.1	0.0	3.2	8.2
	PD	10	1.0	9.3	33.0	0.1	1.0	2.1	0.1	15.6	61.5
	PP	10	1.0	3.4	12.0	0.1	0.5	1.2	0.2	2.3	11.8
	QP	2	2.0	4.5	7.0	0.3	0.4	0.6	0.7	2.3	3.9

APPENDIX E. DO data from surface sondes as seasonal fraction of days in each DO status category. Graphs are arranged for sites starting in the north at Phillipsdale and moving south down the West Passage, followed by Greenwich Bay and Mt. Hope Bay.

Figure E1-A. Seasonal fraction of days with DO < 2 mg/L (Severely Hypoxic to Anoxic), 2 mg/L ≤ DO < 5 mg/L (Hypoxic), and DO ≥ 5 mg/L (Oxic). Data are from surface sondes at each site. Graphs are arranged N to S.







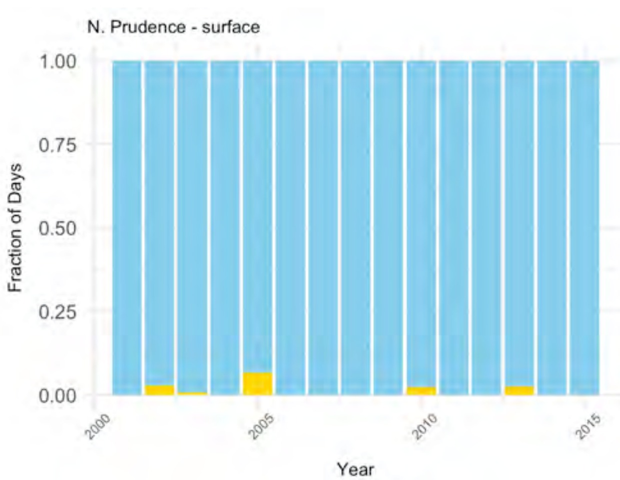
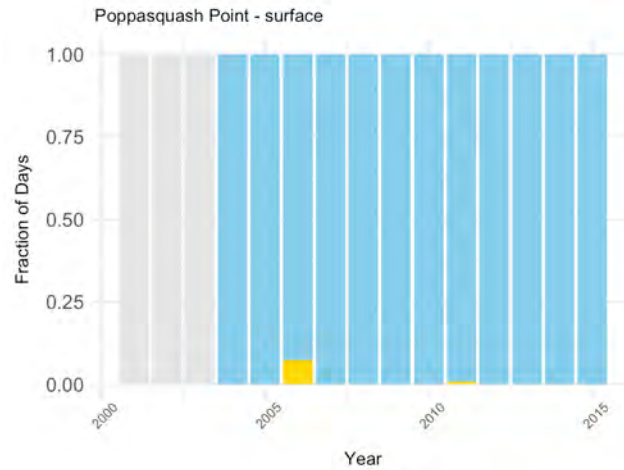
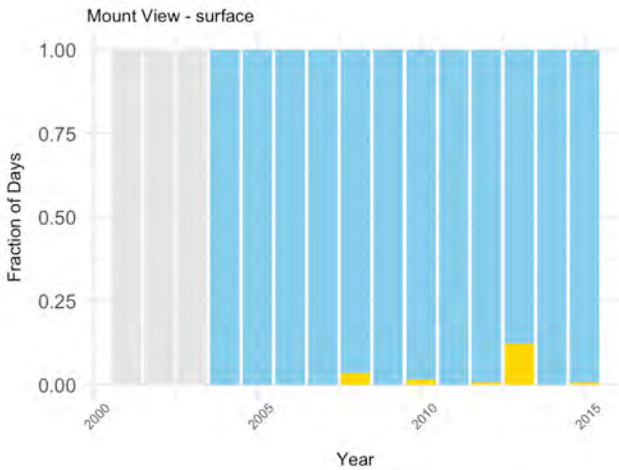
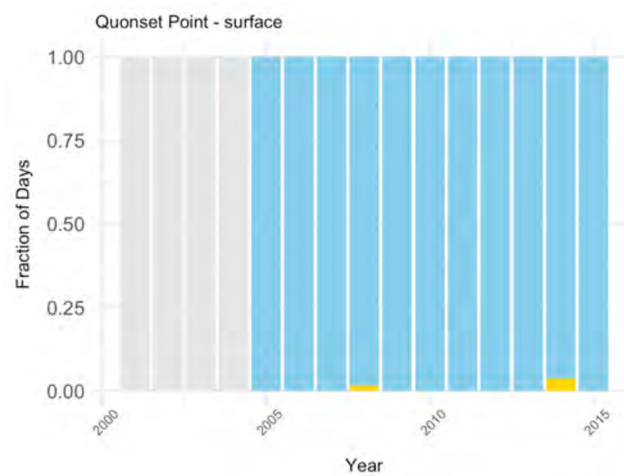
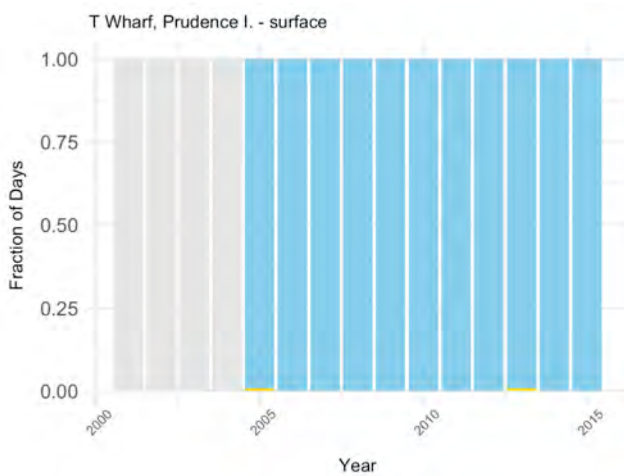


Figure E1-A *continued*. Seasonal fraction of days with DO < 2 mg/L (Severely Hypoxic to Anoxic), 2 mg/L ≤ DO < 5 mg/L (Hypoxic), and DO ≥ 5 mg/L (Oxic). Data are from surface sondes at each site. Graphs are arranged N to S; continued from previous page.









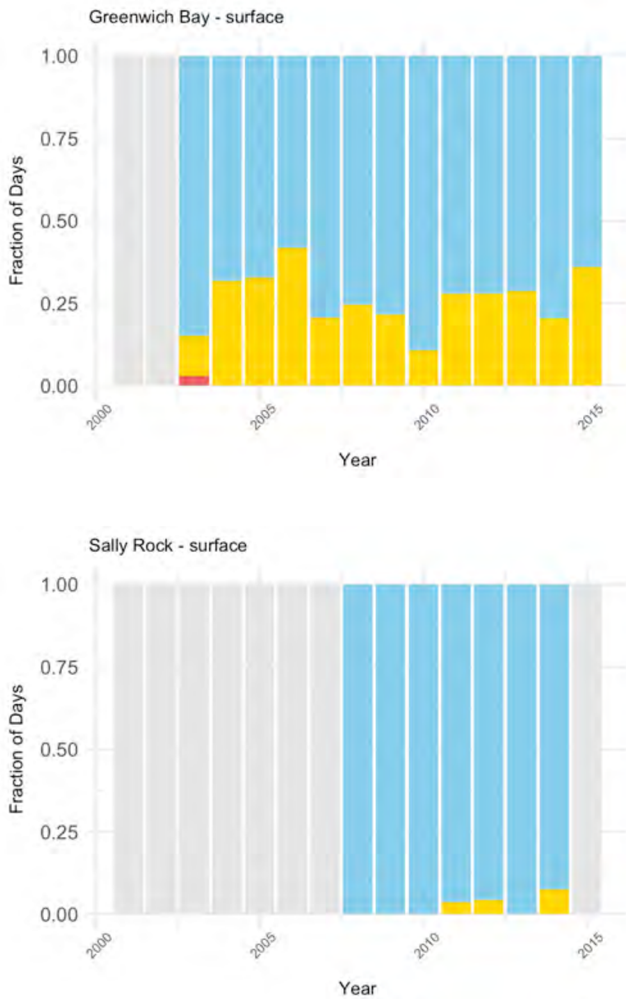


Figure E1-B. Greenwich Bay and Sally Rock surface sondes. Seasonal fraction of days with DO < 2 mg/L (Severely Hypoxic to Anoxic), 2 mg/L ≤ DO < 5 mg/L (Hypoxic), and DO ≥ 5 mg/L (Oxic).

Figure E1-C. Mt. Hope Bay surface sonde. Seasonal fraction of days with DO < 2 mg/L (Severely Hypoxic to Anoxic), 2 mg/L ≤ DO < 5 mg/L (Hypoxic), and DO ≥ 5 mg/L (Oxic).