

Evidence of persistent, recurring summertime hypoxia in Green Bay, Lake Michigan

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Abstract:

Six years (2009-2015) of temperature and dissolved oxygen profile data show hypoxic conditions are common in the bottom waters of southern Green Bay, Lake Michigan during the summer. Depleted oxygen concentrations ($< 5 \text{ mg L}^{-1}$) affect nearly 70% of the 38 stations sampled representing an area of $\sim 500\text{-}600 \text{ km}^2$. Stratification typically lasts 2+ months, from late June to early September, and some stations exhibit bottom water hypoxia ($< 2 \text{ mg L}^{-1}$) at a frequency of nearly 25% when sampled during this period. A monitoring program initiated in 1986 by the Green Bay Metropolitan Sewerage District has provided a 23 year, recreational season record (May-September) of continuous (15 minute interval) *in situ* bottom water oxygen and temperature measurements at the Entrance Light station of the Green Bay navigational channel. The duration of the hypoxic season ranges from 2 weeks to over 3 months at this shallow 7 meter offshore site. This variability likely results from a combination of thermal stratification, oxygen consumption in deeper waters of the bay, and physical forcing mechanisms that drive cool, oxygen depleted, bottom waters on a southerly trajectory across this sensor. These data suggest the duration of hypoxic conditions may have increased during the stratified season in recent years. Hypoxia in the bay would also appear to be sensitive to relatively small changes in these forces, particularly changes in organic carbon loading and the duration of stratification.

Key words: Green Bay, Lake Michigan, hypoxia, dissolved oxygen, historical records, dead zones

Background

Worldwide, the number of marine hypoxic zones has approximately doubled each decade since the 1960s, fueled largely by cultural eutrophication, and numbering over 400 today (Altieri and Gedan, 2015; Committee on Environment and Natural Resources, 2010; Diaz and Rosenberg, 2008). Freshwater systems appear to have had an earlier history of developing hypoxia beginning near the turn of the 20th century that is also linked to increased nutrient emissions but this history is limited to systems in which long term monitoring or paleolimnological records are available (Jenny et al. 2014, 2016). In the Great Lakes, the central basin of Lake Erie represents the best known and most intensively studied example of large scale hypoxia going back decades (Charlton, 1980; Rosa and Burns, 1987; Scavia et al., 2014), yet other regions of the Great Lakes are likely susceptible to conditions under which dissolved oxygen concentrations fall below the water quality standard of 5 mg L⁻¹ or even to the level generally recognized as defining hypoxia of < 2 mg L⁻¹ (Biddanda et al., 2018). This susceptibility is exacerbated by warming trends and by increased organic matter loading in the form of nutrient runoff fueled eutrophication (Rabalais et al., 2009; Rigosi et al., 2014). Hypoxia has probably been a feature of the Green Bay system (Figure 1) since the mid to early part of the last century (Kennedy, 1982, 1989), but the extent, duration and frequency of hypoxic “dead zones” has only recently received significant attention.

Oxygen depletion is not only a water quality standard issue and a recognized Beneficial Use Impairment for the bay, but the occurrence of hypoxia is a broad scale indicator of ecosystem health. Hypoxia integrates a number of key environmental processes and management challenges and co-occurs with a number of environmental stressors (Committee on Environment and Natural Resources, 2010): nutrient loading from point and non-point sources;

projected increases in the intensity of extreme precipitation and runoff events which in this system control up to 50-80% of the total load on an annual basis; hyper-eutrophication and excessive algal production; climate warming and extended stratification; increased retention of labile, algal-derived organic matter; and a severely limited benthos in terms of both numbers of organisms and their diversity. Arguably, two of the best indicators for Green Bay that sustained, permanent restoration has occurred will be an improvement in summertime hypoxia and an increase in abundance and diversity of the benthic fauna (Kaster et al., this issue).

Some of the earliest reports of hypoxia in the waters of Green Bay date from observations in the winters of 1939, 1956 and 1966 (Schraufnagel et al., 1968; WSCWP, 1939). Observations taken through the ice in what is now designated an Area of Concern (AOC) at the southern end of the bay (Figure 1), revealed extensive oxygen depletion. The major culprit at that time was assumed to be industrial waste water discharge loadings, primarily as waste sulphite liquor from paper mills in the Fox River, which resulted in river water that was often devoid of oxygen and which propagated in the river plume outward into the bay. In the late 1930's oxygen sensitive benthic species like the mayfly *Hexagenia limbata* were relatively abundant; however, by 1956 and 1969, benthic fauna surveys throughout the lower bay found *Hexagenia* to be completely absent (Balch et al., 1956; Howmiller, 1971; Howmiller and Beeton, 1971). Their disappearance was assumed to result from consistently low oxygen concentrations during the winter, which occasionally forced commercial fishermen to abandon their nets (Schraufnagel et al., 1968).

Water quality in the Fox River improved dramatically in the 1970's following implementation of the Clean Water Act's waste-water discharge limits (Harris et al., this issue). Winter surveys conducted in 2009 and 2010, as part of a cisco spawning habitat assessment,

showed bottom water oxygen concentrations to be consistently near saturation throughout the bay (Madenjian et al, 2011). A revisit of a few nearshore stations by our lab in 2014 in the waters off Dyckesville (eastern shore) and in 2015 inside Long Tail Point (western shore) confirmed dissolved oxygen at or above saturation under the ice (Klump and Kaster, unpubl). Improvements in water quality in the Fox River have apparently ameliorated depressed oxygen conditions of the lower bay in the winter. In summer, the shallow nature of these waters in the AOC (< 3 meters) generally assures adequate mixing and reaeration. This is not the case, however, for deeper regions of the bay where seasonal thermal stratification isolates bottom waters for extended periods of time (Grunert, 2013; Grunert et al., this issue).

Although infrequently examined, late summer conditions in the bottom waters of the bay at large were historically observed to exhibit highly depleted dissolved oxygen concentrations. Middle Green Bay, defined as the area from the entrance light at kilometer 16 (as measured from the mouth of the Fox River) to kilometer 56 off Sturgeon Bay, was generally seen as outside the influence of the Fox River plume, but cool (12.7° C), oxygen depleted (< 2.5 mg L⁻¹) waters were observed at the 24 and 40 kilometer stations along this transect (Schraufnagel et al., 1968). Several years later during the summer of 1980 under stratified conditions, Kennedy (1982) and Conley (1983) reported nearly anoxic waters in the lower Fox River and, by August, depleted bottom water oxygen levels as far north as Sturgeon Bay. More recently, during the summer of 2005, from June through September, Valenta (2013) reported dissolved oxygen levels in the bottom meter of the water column in lower Green Bay as being below 2 mg L⁻¹ for greater than 25% of the time. In an incident reported for August 5th of that summer, persistent winds apparently forced cool hypoxic bottom water into southern Green Bay's eastern shore reportedly triggering the beaching and massive fish kill of tens of thousands of round gobies (Qualls et al.,

2013). The net effect of the lateral advection of the hypoxic bottom waters was to strand massive numbers of fish when the gobies (which have limited buoyancy control or vertical mobility) swam ahead of the front until it hit the shoreline. Despite occasional reports of oxygen depletion in the bay going back ~80 years, however, no systematic mapping of the extent and duration of hypoxia has been attempted in Green Bay until recently.

Study Area

Morphologically, Green Bay is a large, semi-enclosed gulf in northern Lake Michigan hydrographically dominated by riverine inflows from the Fox River at the southern end and water mass exchange with Lake Michigan at the northern end (Figure 1). The bay is approximately 190 km in length and 37 km in width with a water surface area of 4,210 km², and a volume of approximately 67 km³. The bay has a distinct longitudinal depth gradient from the shallow southern end (mean depth = 2 m) to depths of 30-50 m in the northern reaches near Lake Michigan. The bay represents 7.4% of the total area of Lake Michigan and 1.4% of the total volume of Lake Michigan (Mortimer, 1978). The Green Bay watershed (~40,500 km²) comprises one-third of the land draining to Lake Michigan and is the third largest in the Great Lakes. Eleven major rivers and streams drain into Green Bay, with the largest, by far, being the Fox River (Bertrand et al., 1976). Modlin and Beeton (1970) estimated that the inflow and entrainment of Lake Michigan water into the northern bay was 128 times the Fox River inflow, a process that results in an easily detectable mixing gradient and lowers the hydraulic residence time for the bay as a whole to approximately 6 months, with dilution and mixing increasing from south to north (Bravo et al., 2017).

The Fox-Wolf River watershed makes up ~ 40% (16,600 km²) of the basin that drains to

the bay via the Fox River at its mouth in the City of Green Bay. The Fox has long been the largest single source of phosphorus to Lake Michigan, representing 30% of the total load (Dolan and Chapra, 2012). The lower bay also has a long history of excessive algal production, driving a persistent trophic gradient from hypereutrophic conditions in the lower bay near the mouth of the Fox River to mesotrophic to oligotrophic conditions at its connection with Lake Michigan ~ 150 km to the northeast (Lin et al., 2015; Sager et al., 1984; Sager and Richman, 1991; Yurista et al., 2015). The region of interest here is the area south of Chambers Island, a surface area of approximately $1.7 \times 10^9 \text{ m}^2$ (Auer and Canale, 1986; Maccoux et al., 2013) representing ~40% of the total area of the bay and the region within which this gradient is most strongly expressed.

Despite being a freshwater system, Green Bay has many estuarine-like characteristics, including water mass exchange and the mixing between riverine inflow and the open lake (Bravo et al., 2017; LaBuhn, 2016). Settling rates for particulates are high and depths relatively shallow, leading to the rapid delivery of fresh algal debris to the bottom, likely within a matter of days. With its unique morphology and restricted circulation, the bay functions as a very efficient nutrient and particle trap, sequestering 70-90% of the total phosphorus inputs within the bay in rapidly accumulating, organic rich sediments which reach an organic carbon content in excess of 10% by weight (Figure 2, Klump et al., 1997, 2009). These sediments quickly become anaerobic, within mm of the sediment-water interface (Klump et al., 2009), and sediment oxygen demand, in conjunction with stratification and hypolimnetic respiration, are the major causes of hypolimnetic oxygen depletion in the summer (Klump and Fermanich, 2017).

Methods

Water sampling and dissolved oxygen profiles were collected at two sets of stations totaling approximately 50 locations within the lower bay south of Chambers Island (Figure 1).

The first set of stations has been routinely occupied by the Green Bay Metropolitan Sewerage District (GBMSD), now NEW Water, during the recreational navigation season since the late 1980's, generally April/May to September/October. These stations focus on the lower Fox River, the Remedial Action Plan AOC (bounded by Long Tail Point and Point Sable to the north and the shoreline to the south) and the area just north of the navigational channel in southern Green Bay. The second set of stations (designated by the prefix GB), was originally based on the sampling grid of Cahill (1981) and was expanded to a 5 x 5 km grid by researchers at the University of Wisconsin-Milwaukee (UWM) in the mid 1980's, largely for sediment biogeochemistry studies. This grid was also adopted for the EPA Mass Balance study in 1988-90 (USEPA, 1989). Some 120 stations throughout the bay exist on this grid, with approximately 40 within the lower bay, south of Chambers Island where oxygen depletion is commonly observed. In the current hypoxia study, typically 15-25 of these UWM stations in the lower bay were occupied on any one cruise during the stratified season (July-mid September). Since 2012, the Great Lakes Observing System (glos.us) has maintained a buoy (NOAA 45014) in southern Green Bay during summer months that provides near real time surface water quality data and basic meteorological data (wind speed and direction, air temperature, solar radiation, relative humidity) (LaBuhn and Klump, 2016).

Beginning in September of 2009, and continuing during the summer months of 2010-2015, 25 bottom water surveys were conducted aboard the *R/V Neeskay* at subsets of the 38 stations shown in Figure 1 on an approximately monthly basis from June through September (Electronic Supplementary Material (ESM) Table S1). Vertical profiles of oxygen, temperature and specific conductivity were collected using standard YSI 6600 sondes outfitted with either the membrane electrode or optical dissolved oxygen sensors and optical turbidity sensors. Typically

two sondes were slowly lowered in tandem simultaneously at a rate, usually on the order of ~2-3 cm per sec, to allow the sensors to respond to the steep oxygen and temperature gradients observed in the bay. Optodes are particularly sensitive to rapid temperature changes and profiling across the thermocline occasionally required pausing to allow them to equilibrate. Oxygen sensors were calibrated frequently to 100% saturation in air correcting for ambient pressure following manufacturer's protocol, and bottom water readings generally agreed within < 0.3 mg L⁻¹. Only downcasts were used for profiling, and data were recorded continuously every 2 seconds. The bottom was determined by the noticeable spike in the turbidity sensor. Typically, profiles were collected over a period of 2-3 days, depending upon weather conditions and the number of stations occupied. GBMSD stations were sampled approximately every two weeks during the summer at stations which are focused in the extreme southern end of the bay. Profiles were also conducted using a YSI 6600 sonde. For graphical display and estimation of the areal extent of hypoxia, bottom water dissolved oxygen concentrations were contoured using Surfer™ software's default point kriging method. Data from both the GBMSD monitoring program and the UWM monitoring program were combined to produce these maps and the complete set of water column profiles are available through an online database (<http://uwm.edu/glos/green-bay-sonde-profiles/>).

Long-term continuous monitoring data collected by GBMSD in lower Green Bay beginning in 1986 used sondes deployed on a mooring near the Green Bay navigational channel Entrance Light (Lat: 44 39.137N Long: 87 55.473W) located 13 kilometers north of the mouth of the Fox River in lower Green Bay (Figure 1). GBMSD's monitor is a three-parameter water-quality monitoring system using YSI 6600 sondes, recording temperature, specific conductance, and dissolved oxygen concentrations at 15 minute intervals. Dissolved oxygen sensors (both

membrane and optical) were calibrated using 100% water-saturated air and current barometric pressure readings. All sensor calibrations followed the manufacturer's protocols for YSI 6 Series sondes and sensors. Both surface and bottom water sondes (one meter below water surface and one meter above the bottom, respectively) were typically maintained from June through September. Sondes were swapped out approximately every month with newly calibrated units to avoid data drift due to biofouling and to maintain sufficient battery power. A vertical profile, with an additional calibrated sonde, was taken when monitors were deployed for *in situ* calibration verification. Oxygen and temperature data were analyzed in each of the years for which the data were available from 1986 through 2016. In most years, the monitor was deployed in early June. In 1987, the monitor was not deployed until mid-July. From 1996 to 2001, this monitoring program was suspended. The program was reinitiated in 2002 and has continued since then. In 2006, the monitoring mooring was lost due to a large storm event. The mooring was typically retrieved for the season by mid-September. Only the data from the bottom sonde are reported here, but the differences between the surface and bottom water sonde temperature data are useful in determining periods of thermal stratification. A primary objective of this monitoring effort was to provide a continuous, temporal record of any changes in temperature and dissolved oxygen that may be associated with intrusions moving into lower Green Bay from the mid-bay. The data is available online at <http://fwwa.adc4gis.com> via the *database* search tab.

Results and Discussion

Thermal stratification in Green Bay is a consequence of both direct atmospheric forcing, i.e. low winds, high air temperatures, and increased solar radiation, as well as from indirect

atmospheric forcing that drives circulation patterns resulting in the southerly incursion of cooler bottom waters over these highly reducing organic rich sediments (Grunert et al., this issue; Hamidi et al., 2015). This two layer circulation regime can re-stratify a well-mixed water column within hours, and can set up stable, stratified water column conditions that persist for days to weeks, a time sufficient for sediment oxygen demand and hypolimnetic respiration rates to completely deplete hypolimnetic oxygen (Klump and Fermanich, 2017; LaBuhn, 2016; Valenta, 2013). Hence the morphometry, circulation patterns, and the thermal input-output balance of the bay interact to produce conditions that lead to variations in the degree, extent, and duration of hypoxia from day to day and from year to year (Bravo et al., 2017; Grunert et al., this issue). Modeling hypoxia, therefore, is somewhat more complex than in a system which is driven largely, or solely, by seasonal thermal fluctuations (Hamidi et al., 2015; Waples and Klump, 2002). An understanding of both the general circulation and the onset and duration of stratification in the bay are essential for determining the potential for hypoxic conditions to improve or worsen, particularly in the face of climate change projections of warmer conditions, less ice cover, and an earlier onset of summer (WICCI, 2011).

Oxygen depletion is dependent on the volume of the hypolimnion and the magnitude of oxygen sinks. Hypolimnetic thickness varies largely as a function of water depth, since wind induced turbulence imposes a mixed layer on the order of 10 meters throughout the bay, and waters >15 m depth typically remain seasonally stratified. Intermittent and even prolonged stratification (on the order of days), however, can occur in relatively shallow waters (7-10 meters), as a consequence of cool, denser bottom water incursions (Bravo et al., 2017; Grunert et al., this issue; Hamidi et al., 2015; Kennedy, 1989). Figure 3 shows a set of profiles for the July 24-26, 2012 cruise sampled during the presence of a fairly extensive hypoxic zone. Of note is

the progressively greater oxygen depletion as waters become shallower. In these shallower reaches of the bay, sediment oxygen demand and a reduction in the volume of the of the overlying hypolimnion combine to drive oxygen concentrations to nearly zero and create a zone where hypoxia is most prevalent (Gardiner et al., 1984; Klump and Fermanich, 2017; LaBuhn, 2016). Bottom water oxygen concentrations for all of the *R/V Neeskay* cruises from 2009-2015 is summarized in ESM Table S1.

Compiled profile data provide sufficient areal coverage of the lower bay to comprehensively map hypoxia in the bay for the first time since the 1980 study, and provide the first multi-year sequence showing the occurrence of “dead zones” within the bay (Figure 4). The areal extent of hypoxia varies, but some stations in the southern bay experience bottom water dissolved oxygen concentrations $< 2 \text{ mg L}^{-1}$ nearly 25% of the time during summer months, and are below the water quality standard of 5 mg L^{-1} for over 60% of the time between the onset of stratification and fall mixing (Figure 5). Stations with higher frequencies of water quality impairments during the height of the dead zone season (July and August) tend to group around station GB 9, typically including GB stations 5, 6, 8, 9, 10, 12, 13 and 17. This region, probably not coincidentally, is adjacent to the area reported for the 2005 fish kill (Qualls et al., 2013). Observed hypoxic zones are reflected in recent benthic surveys showing low abundance and diversity throughout nearly all of southern Green Bay, with low dissolved oxygen tolerant chironomids the predominant species and importantly the continued absence of *Hexagenia* (Edsall et al., 2005; Kaster et al., this issue).

While the “footprint” of hypoxia tends to center around the southeastern portion of the mid bay (between Sturgeon Bay and the AOC), it can also oscillate and shift both westward and northward. The extent of hypoxia also varies widely year to year, although with the caveat that

timing of sampling may influence this picture depending upon the preceding wind conditions and their effect on stratification and mixing (Grunert et al., this issue). The area of hypoxic bottom water generally peaks in early to late August, and in 2012 reached nearly 100 km², in contrast to 2014 and 2015 when the extent of hypoxia was only one-tenth of this level (Figure 6). By the end of the stratified period in early to mid-September, bottom waters below 5 mg L⁻¹ become more wide-spread and can extend into the northern portions of the bay stretching across nearly 400-500 km² of the area between Sturgeon Bay and the AOC. The duration of lowered oxygen concentrations in these deeper waters is relatively short, developing only after prolonged stratification at the end of the summer, and lasting only until the water column remixes, typically in mid to late September.

Little is known about the impact of hypoxia on the biotic community in this system. Fish, other than strictly demersal species, like gobies, have the ability to avoid hypoxic waters, but may suffer from a loss of benthic secondary production (Roberts et al., 2009) and physiological stress (Farrell and Richards, 2009). Benthic macrofauna diversity and abundance is very low – a condition that has persisted since the 1950's (Harris, 1998; Kaster et al., this issue; Qualls et al., 2013). Loss of the mayfly population, once abundant in Green Bay, for example, may also have depressed fisheries production via loss of a major benthic deposit feeder. Hypoxia has eliminated much of the acceptable benthic habitat occupied by nymphal mayflies over their 2 year life cycle (Kaster, unpub. data). Laboratory studies have shown that *Hexagenia* are capable of living in Green Bay sediments (Groff, 2016), but restoration of the benthos and repopulation will be hampered by recurring hypoxia. Interestingly, dreissenid mussels, while present in Green Bay, also appear to be limited by dissolved oxygen. Nowhere in the most frequent “dead zone” regions are dreissenid mussels found, although mooring lines and hardware

above the thermocline typically colonize with young of the year mussels by late summer. Biofouling of bottom water sensors in this region is virtually nonexistent. The absence of dreissenids may be due to the combined influences of hypoxia and the prevalence of highly fluid, anoxic muds throughout most of this region, making the survival of settling veligers problematic.

While the data shown in Figure 4 remains the only comprehensive set of areal data and is limited to 2009 to 2015, the GBMSD bottom water dissolved oxygen sensor at the Entrance Light station has been deployed more or less continuously during summer months from 1986-1995 and 2002-present (2016). This station is relatively shallow (7 meters); but, because winds often force cool hypoxic, hypolimnetic intrusions into the extreme southern bay (Kennedy, 1989), this station has a record that is useful in tracking the duration and frequency of hypoxia over this 24 year time period (Figure 7). The annual length of the hypoxic season may be estimated by the time between the first occurrence of hypoxia in early summer (generally late June to early July) and the last occurrence at fall overturn (usually early to mid-September) (Figure 8a). Over the period of record the average annual hypoxic “season” has been ~53 days. 2005 saw the longest season at 99 days and 2008 the shortest at 14 days. Perhaps not coincidentally, August, 2005 had the only documented fish kill episode reported by the Wisconsin Department of Natural Resources (WDNR) for Green Bay. Such interannual variability is not unexpected in a system which is poised around the physical conditions that trigger the onset and duration of hypoxia. In Lake Erie, for example, a much larger system, interannual variability in the spatial and temporal extent of Central Basin hypoxia is considerable, and strongly dependent upon hypolimnetic thickness, a function of external forcing particularly interannual and shorter term variability in the wind and heat flux (Bouffard et al., 2013). In a system somewhat more analogous to Green Bay in morphology and estuarine

circulation, the volume of hypoxia in Chesapeake bay can vary by 2.5 fold depending upon the direction of the mean summertime wind field (Scully, 2010), similar to the impact that prevailing summer wind fields have on the strength of the thermocline in Green Bay (Waples and Klump, 2002).

It is also important to note that the temporal extent or “season” of hypoxia does not correspond to its duration, since hypoxic conditions can be intermittent. Figure 8b shows the annual cumulative duration for bottom water oxygen concentrations in 1 mg L⁻¹ increments below 5 mg L⁻¹ for the period of June-September (~ 120 days). This corresponds to the period covering observed hypoxia. Although trends are somewhat problematic to identify with certainty, the length of time that this station is below the 5 mg L⁻¹ standard has been longer in recent years, in excess of 40-50 days, and the existence of dead zone conditions up to nearly a month. In the 1980’s and 90’s bottom water at Entrance Light fell below 5 mg L⁻¹ ~ 13% of the time and below 2 mg L⁻¹ ~ 3% of the time from June through September. Since 2007 those values have increased to 23% and 9%, respectively, suggesting that, on average, both duration and frequency of intrusions of oxygen depleted bottom waters may have increased. Hypoxia outside the months of July through September is relatively rare, and in only 5 years (1988, 1991, 1992, 2005 and 2008) did concentrations drop below 2 mg L⁻¹ in June, with two of the most prolonged hypoxia events occurring in 1992 (10 days) and 2005 (6 days). The other three years only experienced hypoxia at the EL station for less than 3 days. Lower oxygen concentrations typically fall with cooler bottom water temperatures, but the relationship is weak. In 2014 and 2015, cooler overall climatic conditions and weak stratification appear to have resulted in reduced oxygen depletion; but, overall, average hypolimnetic oxygen concentrations may have dropped by as much as 1 mg L⁻¹ since the 1980’s (Figure 9). The length of the depleted oxygen

period (i.e. when oxygen has fallen below 5 mg L^{-1}) has not changed significantly from ~ 74 days, but the DO appears to have decreased from $3.23 \pm 0.72 \text{ mg L}^{-1}$ to $2.66 \pm 0.79 \text{ mg L}^{-1}$ in the last decade. This could be the result of increasing hypoxia (i.e. oxygen demand) *per se* and/or due to variations in circulation patterns that force cool hypoxic bottom water further south onto this sensor mooring, a process that is highly dependent on the prevailing wind field (Grunert et al., this issue; Waples and Klump, 2002).

The volume of the hypolimnion in southern Green Bay is on the order of 10^{10} m^3 . If the concentration of oxygen has dropped by $0.6\text{-}1.0 \text{ mg L}^{-1}$ ($\sim 20\text{-}30 \text{ } \mu\text{mol L}^{-1}$) over the last $\sim 15\text{-}30$ years (depending upon the time frame for the regression used in Figure 9) this is equivalent to about a 1-2% annual increase in the Apparent Oxygen Utilization (AOU). AOU is defined as the difference between observed oxygen concentrations in the hypolimnion and the concentration at saturation in equilibrium with the atmosphere at ambient temperatures, and has been estimated for the bay by LaBuhn (2016) to reach, on average, $\sim 600 \text{ mmol m}^{-2}$. This increase in oxygen utilization, if real, could arise in a variety of ways, but most simply from either an increase in the input of respirable carbon and/or from an increase in the length of time the bay is stratified. In the former case, this can be calculated using the organic C: O_2 Redfield stoichiometry of 106:138 and the net annual carbon primary production in the bay of $\sim 7.2 \times 10^9 \text{ mol y}^{-1}$ estimated by Klump et al. (2009). If, for example, oxygen consumption has increased by $25 \text{ } \mu\text{mol L}^{-1}$ this translates to respiration of an additional 2×10^8 moles of carbon. This increase in respiration would only require a $\sim 2\%$ increase in carbon primary production even assuming a 20% burial rate, a value which would be virtually impossible to detect directly. Alternatively, respiration rates within the hypolimnion and from benthic respiration of labile carbon are estimated to be $\sim 26 \text{ mmol m}^{-2} \text{ d}^{-1}$ for the areal average for the bay as a whole (LaBuhn, 2016). Assuming a

hypolimnetic area of $1.2 \times 10^9 \text{ m}^2$, total respiration in the bay is $\sim 3 \times 10^7 \text{ mol d}^{-1}$. At this rate, the observed drop in oxygen could be generated in roughly 7 days. An increase in the length of the stratified period of a week would perhaps be less difficult to determine given sufficient long term records such as those being generated by the GLOS buoys (www.glos.us). The conclusion, however, is that hypoxia, especially at the thresholds of extent and duration, will also be relatively sensitive to changes in primary production and consequently nutrient loading, similar, in many ways, to the Central Basin of Lake Erie (Bocaniov et al., 2016; Rucinski et al., 2010).

Freshwater hydrologic systems are sensitive to climate, and the impact of warming trends over the last 50 years have been fairly pronounced in many lakes (Adrian et al., 2009; Dokulil, 2017, and references therein). Regional climate warming models for the upper Midwest project a lengthening of the “growing season” by 4-6 weeks (WICCI, 2011). Assuming all other things being equal and actual stratification extends 4 weeks longer, the impact on hypoxia could be significant. Using estimates based upon sediment oxygen demand measurements and observed hypolimnetic thickness for individual stations, a simple extrapolation of bottom water dissolved oxygen concentrations from typical summer conditions implies that prolonging stratification has the potential to drive peak seasonal hypoxia in the bay to a significantly greater areal footprint, perhaps in excess of double that observed in the past. This leads to the caveat, as voiced for Lake Erie, that the effectiveness of BMPs implemented in the watershed for improving water quality and hypoxia may be diminished under a warmer, wetter climate (Bosch et al., 2014).

Green Bay is similar to Lake Erie in that it has been severely impacted by excessive phosphorus loadings largely from anthropogenic sources, leading to excessive algal growth. Nutrient loading while variable, has not seen a significant trend and has remained relatively unchanged for the last 20 years, particularly from non-point sources (Dolan and Chapra, 2012;

Robertson, pers. comm.). Correlations between hypoxia metrics and phosphorus loading do not show a significant relationship on an annual basis. This is not surprising perhaps, because the physical dynamics play a dominant role and the Entrance Light sensor is not ideally placed to track hypoxia in the bay as a whole. However, these data are extremely useful as an indicator of the state of the system and changes that may have occurred over the last 30 years.

In Green Bay, deposition of organic matter is mainly confined to the mid-bay region south of Chambers Island where sediment accumulation rates reach up to 1 cm per year (Figure 2) (Klump et al., 2009). It has also been estimated that 70-90% of the phosphorus load to Green Bay is retained in the bottom sediments of the bay (Klump et al., 1997). It has long been recognized that anoxia in hypolimnia can trigger the release of sedimentary phosphorus to the overlying waters (Hupfer and Lewandowski, 2008; Mortimer, 1941; Nurnberg et al., 2013). The most common observation shows a marked increase in the phosphorus content in the lower hypolimnion, especially during the latter phase of thermal stratification (Lin et al., 2015; Zorn et al., this issue). Recent evidence from *in situ* soluble reactive phosphate sensors sampling at hourly intervals do show episodes of increased dissolved phosphate during periods of decreasing dissolved oxygen with a fairly consistent stoichiometry that implies biogeochemical control (Zorn et al., this issue).

Conclusion

One of the important implications of this data set are that hypoxia may have worsened in Green Bay over the last decade. Such extrapolations should be viewed with caution since the physics of the bay, particularly wind forcing, play a major role in both the depth and stability of the thermocline and bottom water reaeration, and the primary oxygen sensor for the long term data set is not ideally located to represent bay-wide trends. The conclusion, however, would appear

to be that the bay is poised to respond to changes in hypoxia from relatively small changes in forcing functions, such as carbon production and thermal stratification. In some ways this is also good news in that reductions in nutrient and carbon loading in response to proposed future management efforts on the landscape should translate relatively directly to improvements in water quality and reductions in oxygen depletion.

Models of watershed loading, biogeochemical cycles, and hydrodynamics are being coupled to downscaled regional climate scenarios to assess both current and future conditions in the bay and the efficacy of available strategies to mitigate hypoxia (Bravo et al., 2015, 2017; Klump and Fermanich, 2017). The investment in water quality improvements within the Green Bay system is approaching in excess of \$1B, largely in the form of PCB clean up and remediation (Harris et al., this issue). Future investments in nutrient abatement programs will likely run to the hundreds of millions of dollars in the Green Bay system, as well as in other highly developed Great Lakes watersheds – Western Lake Erie, Saginaw Bay, etc. Restoration of water quality, however, will require a significant and sustained effort to reduce nutrient and sediment loadings, the cooperation and buy-in of the large human populations within the Great Lakes watersheds, and resource agencies armed with science-based predictive tools that will allow effective, adaptive management essential for restoration of these ecosystems in the face of an uncertain future.

Long term projections are for a wetter and warmer climate with shorter winters, reduced ice cover, increased runoff, increased frequency of heavy precipitation events, and an extended stratified period (WICCI, 2011). These trends may well exacerbate hypoxia and confound management efforts to reduce nutrient inflow and improve water quality. Ultimately, the test of success of these management efforts will lie within the bay itself – elimination of hypoxia and

restoration of a healthy benthos. To see this will require measurements over a period of years (see e.g. Hagy et al., 2004). Creating an expanded observing system to continuously monitor the annual extent and duration of summertime hypoxia in that portion of southern Green Bay within which hypoxia occurs seems warranted and would leverage other long standing and ongoing water quality monitoring programs and initiatives, including monitoring by NEW Water (GBMSD), the USGS, the GLOS (NOAA 45014), the WDNR and others, and would provide verification of models being generated for the forecasting of future hypoxic conditions. The data from such a network could also provide a frequent “dead zone” update and inform management agencies and users of changing conditions over monthly to yearly time scales.

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Figure captions:

1. Sampling stations in Green Bay used in the current study (numbered). EL designates the Entrance Light station maintained by the Green Bay Metropolitan Sewerage District (GBMSD). Stations routinely sampled by GBMSD are designated by a +. The Area of Concern (AOC) is approximately the area of the bay south of a line drawn between Pt. Sable on the east and Long Tail Pt. on the west.
2. Map of surface sediment % organic C content (left panel) and the deposition of organic carbon ($\text{mol m}^{-2} \text{y}^{-1}$) as determined by mass sediment accumulation rates (right panel) (data from Klump et al. 2009)
3. Vertical profiles of dissolved oxygen, temperature and specific conductivity for a set of stations (see figure 1) along the major longitudinal axis of the bay for July 2012.
4. Areal distribution of bottom water dissolved oxygen concentrations measured during approximately monthly cruises from September of 2009 until August of 2015.
5. Frequency of observation of depleted bottom water dissolved oxygen concentrations measured in July and August as a function of station location (refer to figure 1).
6. Areal extent of oxygen depletion estimated from the plots given in figure 4 for the period 2009-2015.
7. Dissolved oxygen concentrations measured at 1 meter off the bottom at the Entrance Light (EL) monitoring station for all years of deployment 1986-2016.
8. Duration of hypoxia in Green Bay as measured in the bottom water at the Entrance Light station: a) Annual length of hypoxic period shown as spanning from the day (Julian) of the first observation to the day of the last observation for dissolved oxygen concentrations below 2 mg L^{-1} and, b) the annual duration, in days, of dissolved concentrations below 5 mg L^{-1} in 1

mg L⁻¹ increments (open symbols with + indicate < 2 mg L⁻¹). Solid line represents average number of days with bottom water dissolved oxygen concentration <2 mg L⁻¹ for two time periods.

9. The annual average dissolved oxygen concentration measured at the Entrance Light bottom sensor for all periods during which the concentrations fell below 5 mg L⁻¹.

Electronic Supplementary Material

Table S1. Cruise dates, stations profiled, and bottom water dissolved oxygen concentrations measured during the course of this study, 2009-2015.

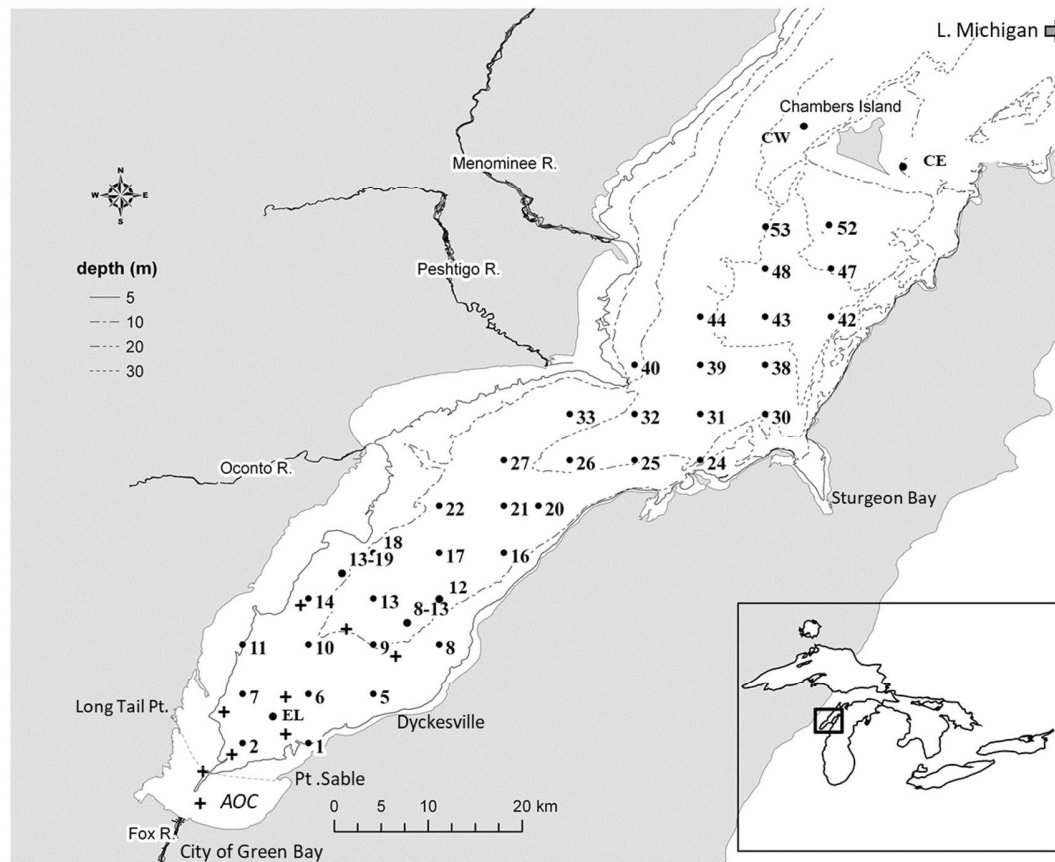
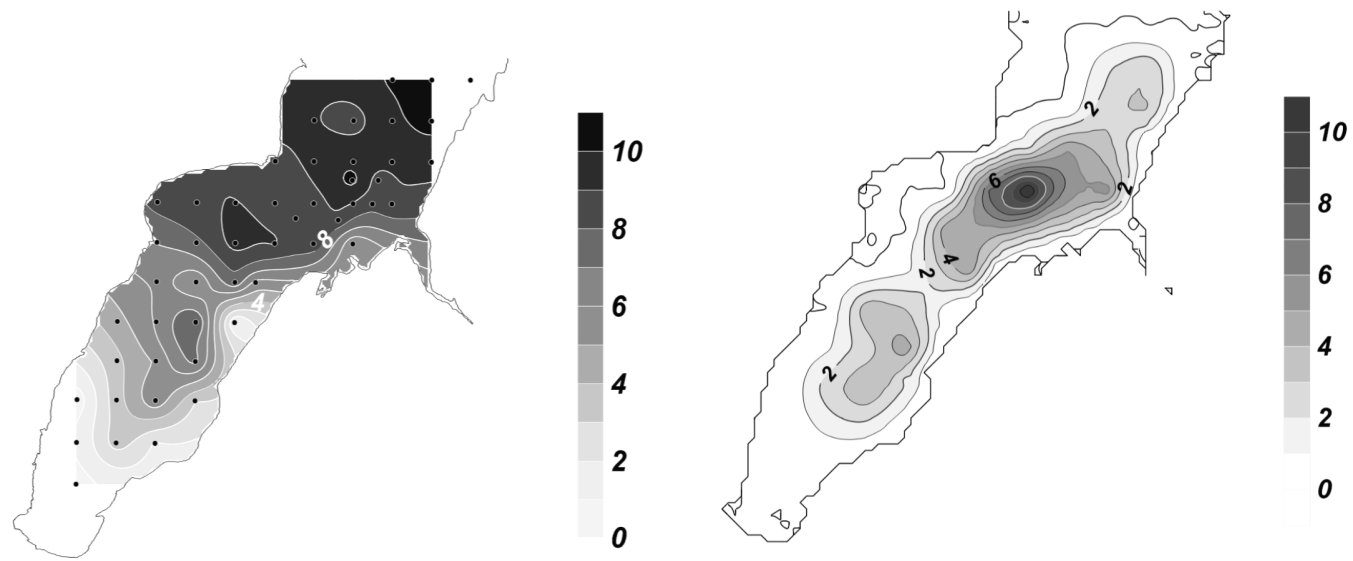


Fig. 1

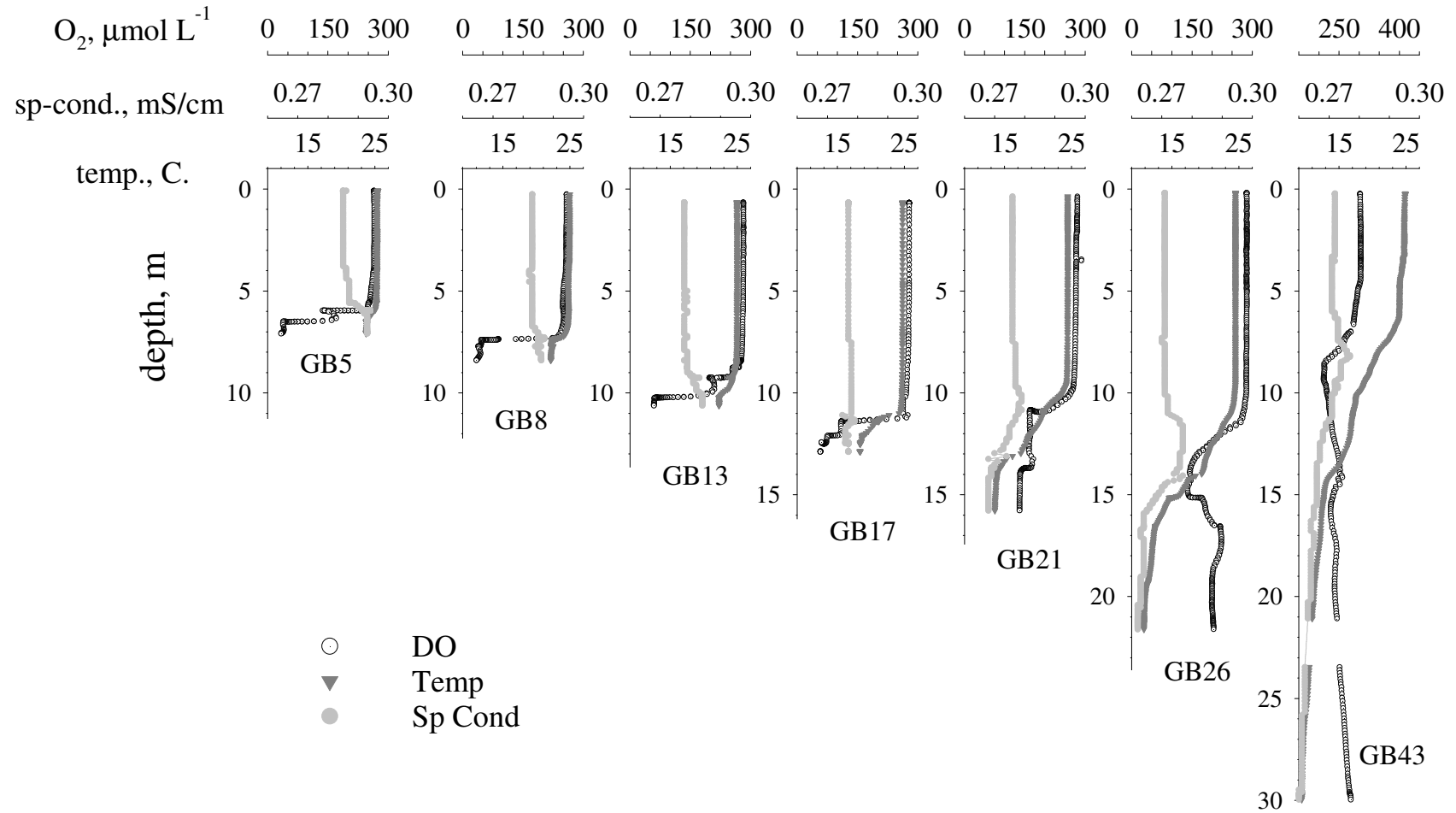


**Surface sediment
% organic carbon content**

**organic carbon deposition
moles $m^{-2} y^{-1}$**

Fig. 2

Fig. 3



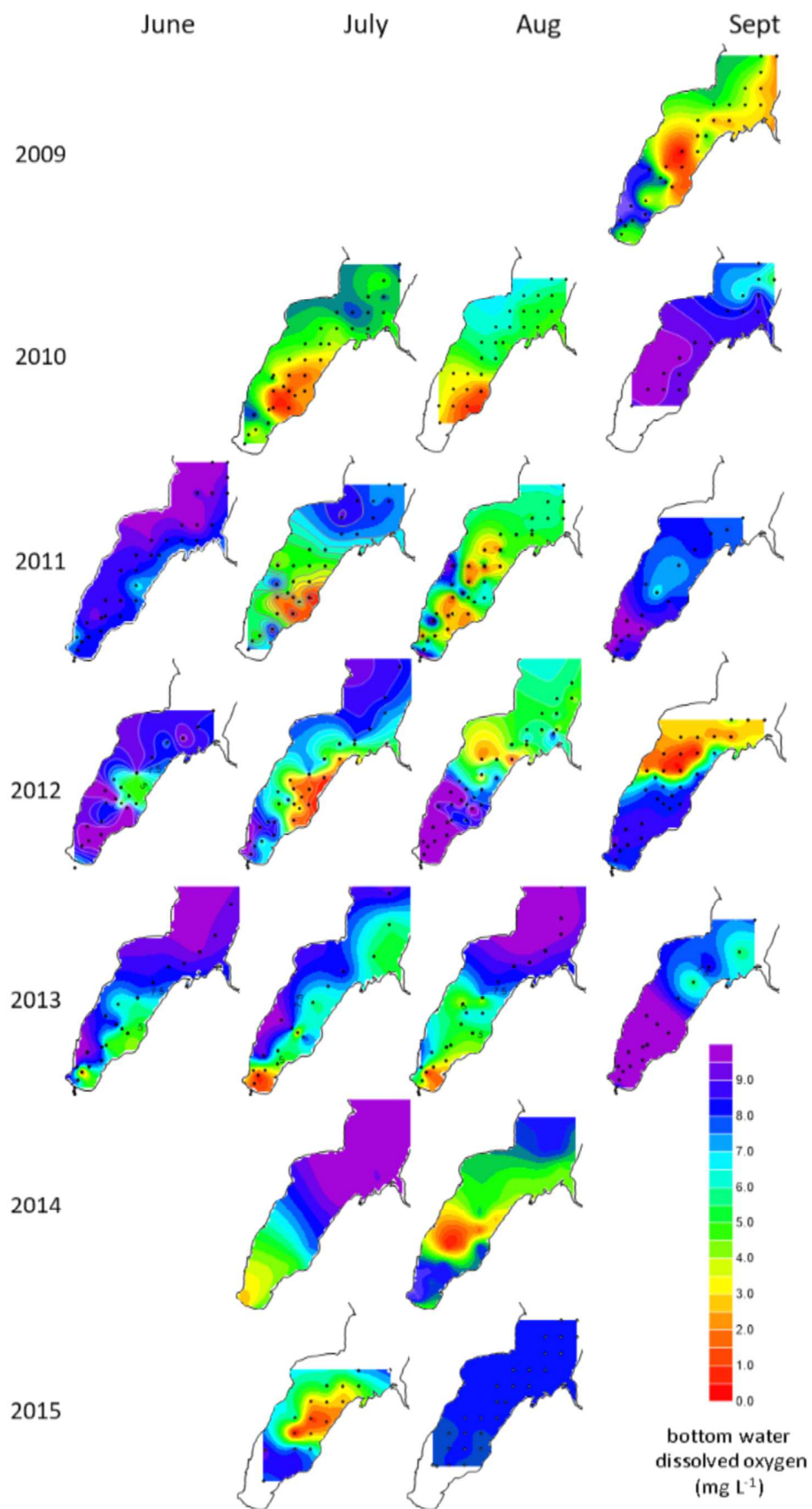


Fig. 4

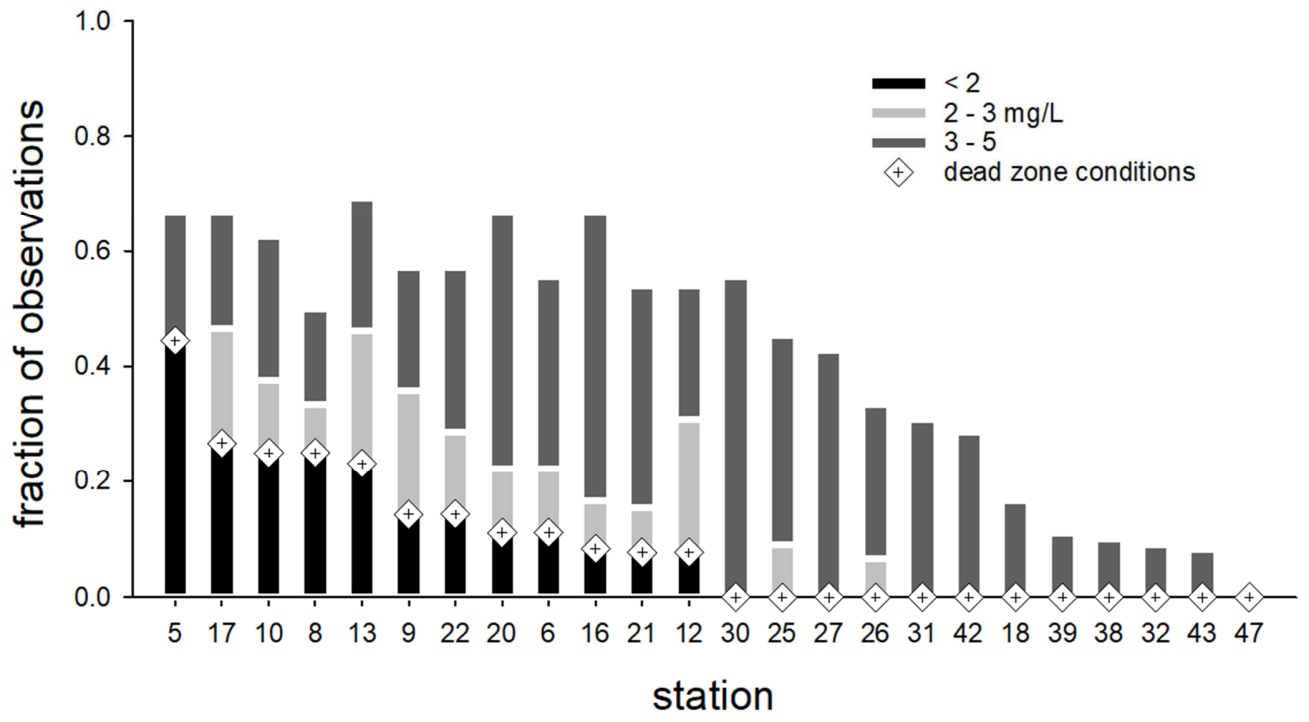


Fig. 5

Figure 6

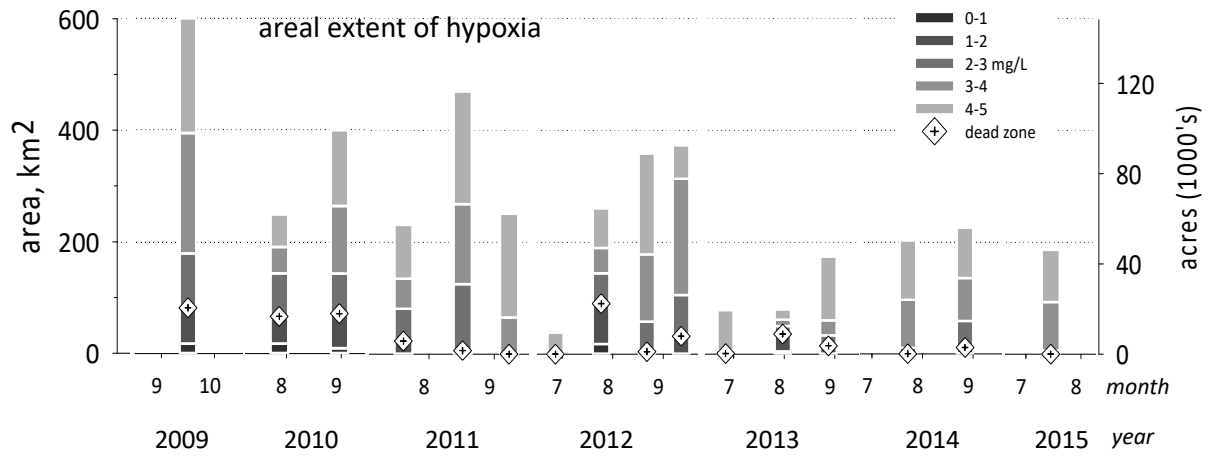


Figure 7

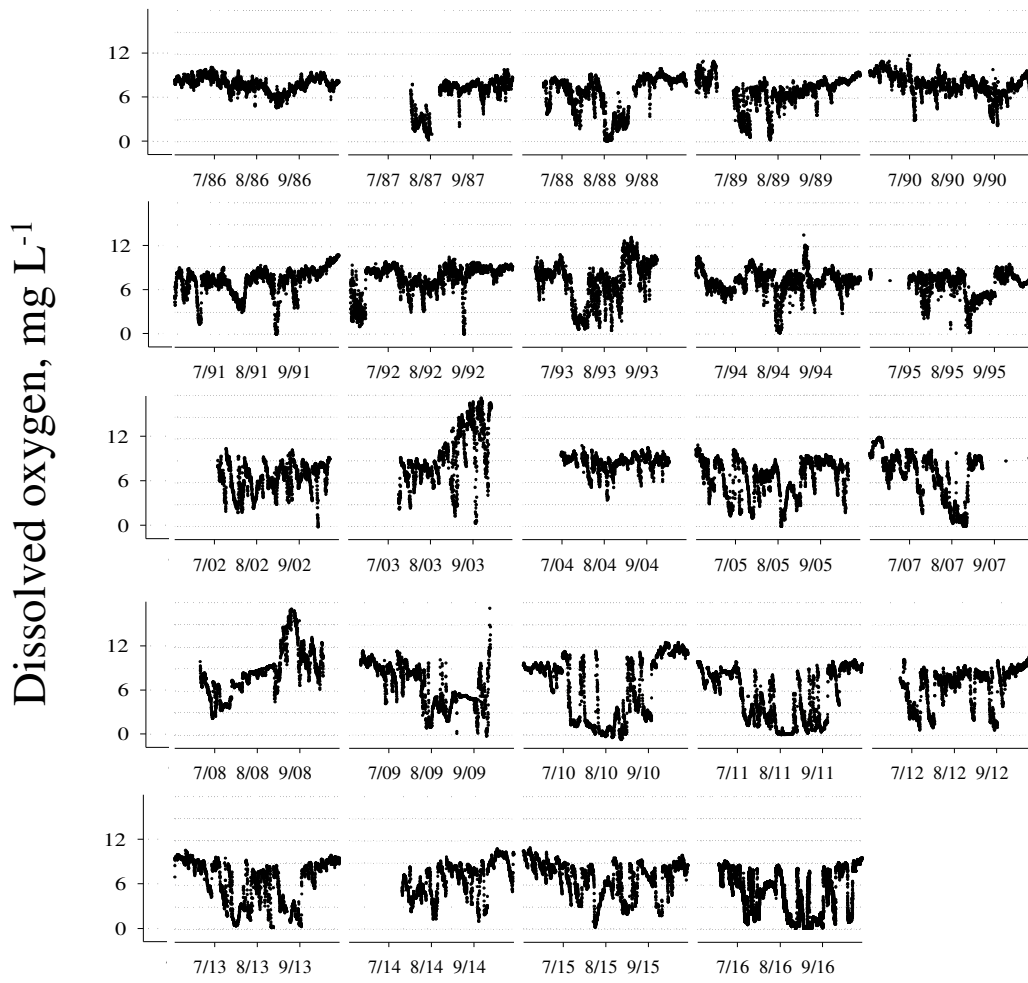
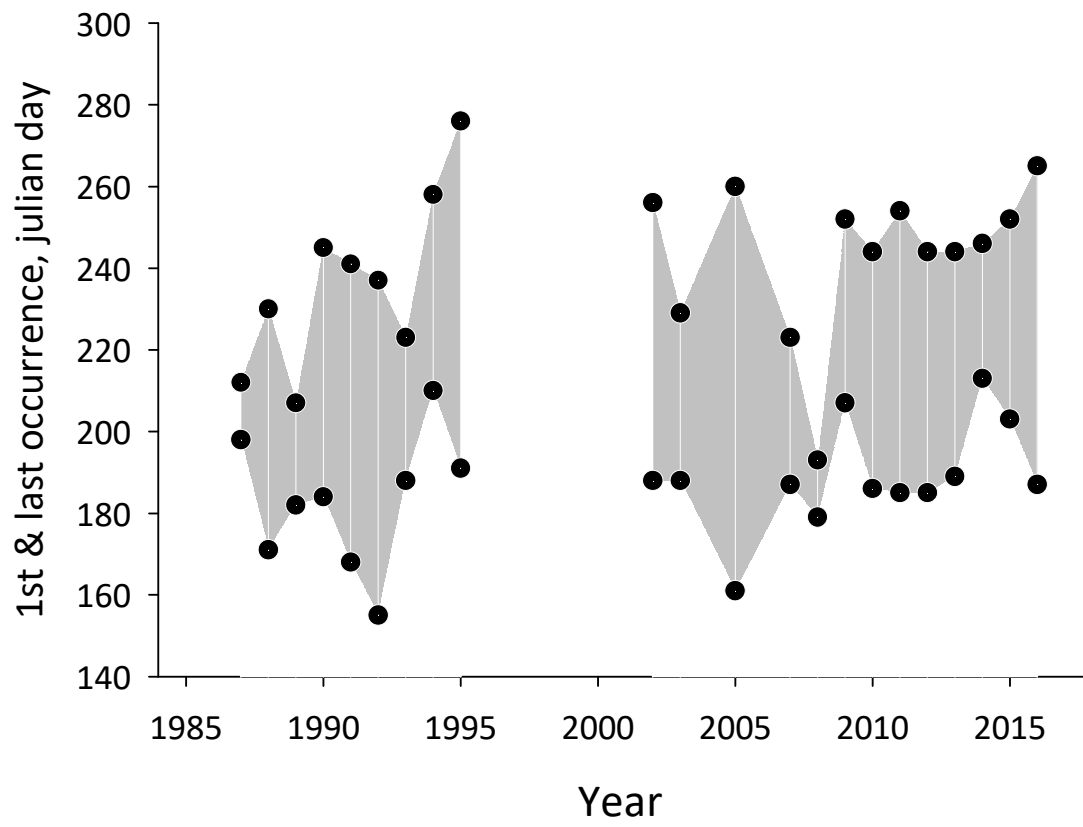


Fig. 8a.



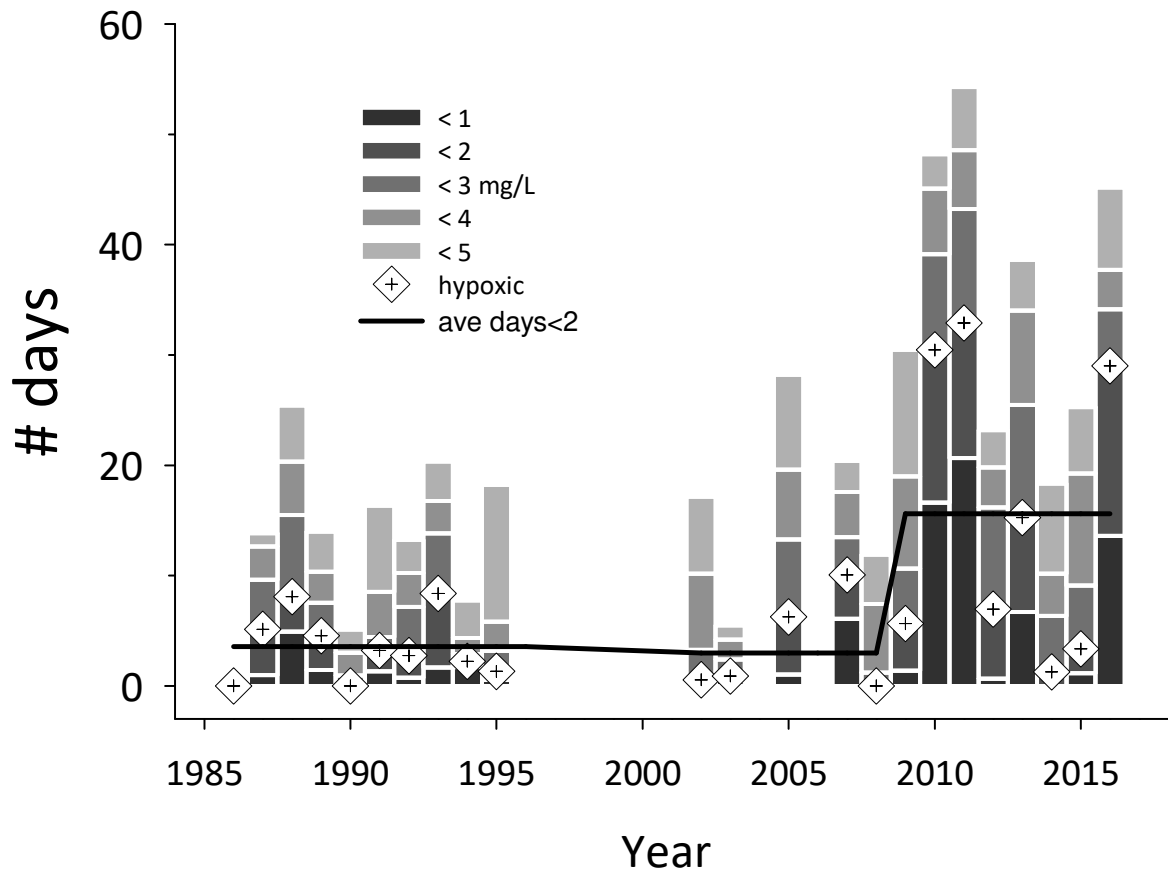


Fig. 8b.

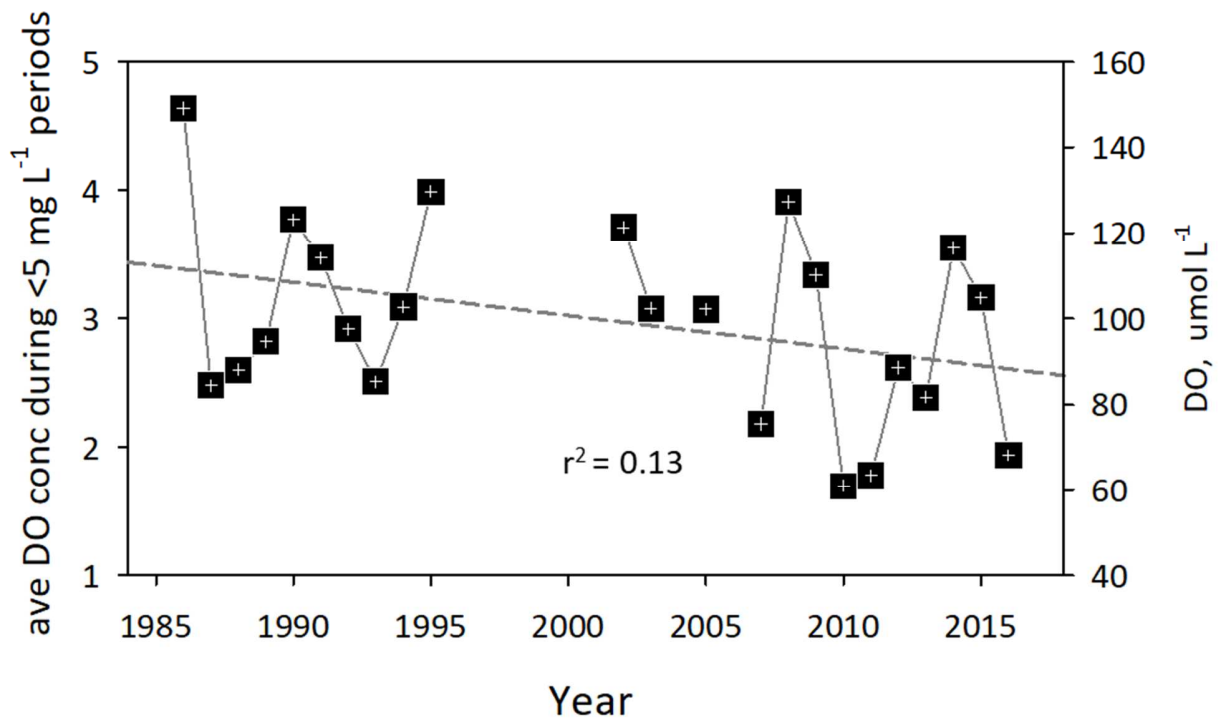
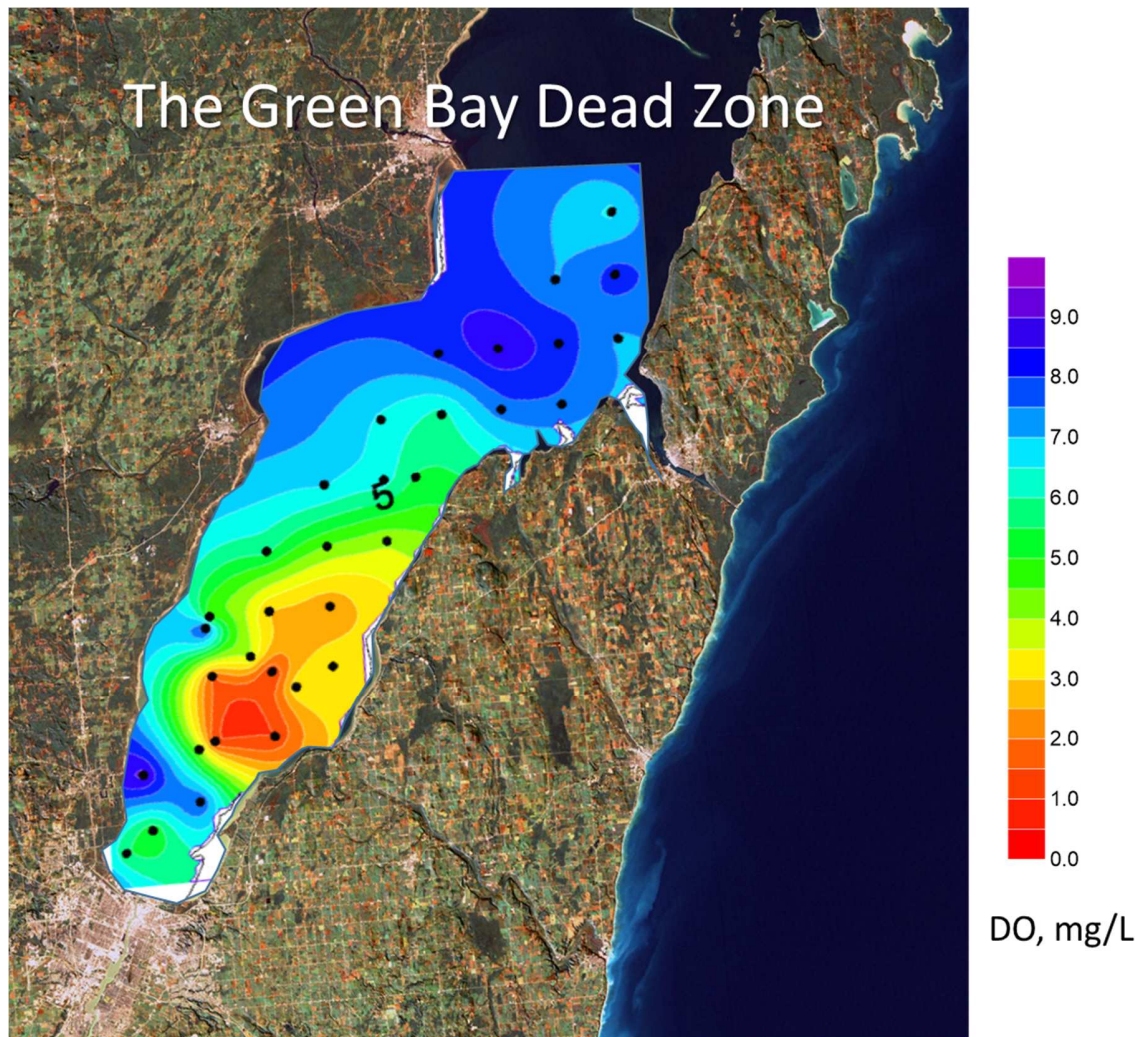


Fig. 9



Graphical Abstract: Summertime hypoxia (depleted dissolved oxygen in bottom waters) has become a frequent occurrence in Green Bay, Lake Michigan (data shown for July 2010).