Factors affecting low summer dissolved oxygen concentrations in Mississippi Delta bayous

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Streams in watersheds supporting intensive row-crop agriculture are vulnerable to ecological degradation due to non-point source discharge of pollutants such as nutrients. Low gradient streams such as bayous are especially susceptible due to increased water residence time, and often result in poor water quality and chronic low dissolved oxygen (DO) concentrations (hypoxia). The goal of the current study was to assess physical, chemical, and biological components affecting low DO during summer of 2011 in three Mississippi Delta bayous. Three sites were selected within each bayou: upstream channel, lake or open water in the water body mid-section, and downstream channel. Dissolved oxygen was monitored at 40 cm depth every 15 minutes for 6-7 days on alternate weeks. Stream surface water samples collected biweekly were analyzed for nutrient and chlorophyll a concentrations. Minimum daily DO levels were frequently below the State instantaneous minimum DO standard of 4 mg/L. Diel DO fluctuation (the difference between daily maximum and minimum DO concentrations) reflected large 24-h DO ranges (=10 mg/L) across all three bayous. Pearson product moment correlations showed minimum DO concentrations to be negatively correlated with total phosphorus (TP) concentrations across all habitats. Total nitrogen (TN) concentrations and dissolved organic carbon (DOC) concentrations were negatively correlated with minimum DO concentrations only in lake habitats. Diel DO fluctuation was positively correlated with water column chlorophyll a concentrations across all habitats. Upstream diel DO fluctuation was also positively correlated with water depth and TP concentrations while downstream diel DO fluctuation was positively correlated with TP but not water depth. Low summer DO concentrations and changes in diel DO fluctuations were affected by both nitrogen and phosphorus driving summer algal blooms (eutrophic to hypereutrophic conditions) in Mississippi Delta bayous. Organic carbon inputs may exacerbate DO minimums in these nutrient-rich systems. As a result, nutrient reduction in all habitats in conjunction with increased water depth in upstream habitats is necessary to improve summer DO concentrations in Mississippi Delta bayous.

INTRODUCTION

The availability of dissolved oxygen (DO) in lakes and streams is critical for most aquatic life (Paerl et al. 1998; Garvey et al. 2007; Justus et al. 2012). Hypoxia (low DO) is defined as concentrations that are below either 2 mg/L or 30% saturation (Shields and Knight 2012). Factors such as flow rate and nutrient enrichment resulting from agricultural runoff can have significant impacts on downstream water quality, including DO (Rohm et al. 2002).

Within the lower Mississippi River alluvial plain (i.e. the Delta), are extensive shallow (< 2 m), low velocity stream systems referred to as bayous. These systems exist in a landscape of low relief and modern intensive row-crop agriculture which includes the widespread use of nitrogen fertilizers. The Delta region receives approximately 130-150 cm precipitation annually, with about half occurring during the months of April-October (Sherman-Morris et al. 2012). Additionally, Delta farmers utilize groundwater for irrigation during extended dry periods from June-August, with substantial amounts of irrigation water returning to streams. For these reasons, Delta bayous can receive runoff pollutants from a variety of sources throughout much of the growing season and this, in turn, can affect stream hydrology, nutrient transport, and DO dynamics.

In Mississippi, state standards require that DO concentrations are to be maintained at a daily average of 5.0 mg/L or greater with an instantaneous minimum of 4.0 mg/L or greater at mid-depth in streams and shallow lakes approximately 2 m deep or less (MDEQ 2007). These standards are presumed to be protective of aquatic life and wildlife uses within these habitats and systems that are chronically below these thresholds are considered impaired.

The purpose of the present study was to examine hydrological (water depth), nutrient [nitrogen (N), phosphorus (P), carbon (C)], and biological (chlorophyll a) components that could affect DO concentrations in three Mississippi Delta study bayous located within an agricultural landscape.

MATERIALS AND METHODS

Three Delta bayous were studied: Cow Oak Bayou near Dundee in southern Tunica County, MS; Roundaway Lake Bayou in southern Coahoma County, MS; and Howden Lake Bayou near Alligator in eastern Bolivar County, MS (Fig. 1). Contributing watersheds ranged in size from 17.5-24.3 km^2, with low relief ranging from 17.3-22.6 m and watershed lengths ranging from 6.1-9.7 km (Table 1). All three bayous occur in intensively row-crop cultivated watersheds dominated by soybeans (*Glycine max*), corn (*Zea mays*), cotton (*Gossypium hirsutum*), and rice (*Oryza sativa*). In 2011, soybeans were the dominant row-crop in all three watersheds, followed by cotton in Cow Oak and Roundaway, and corn in Howden (Table 2).

Three sites within each bayou were designated for water quality and hydrological monitoring at locations within the upstream reach, lake reach, and downstream reach (Fig. 1). Mean summer 2011 water depth (±SD) at each site was as follows: Cow Oak, 0.70 (0.12) m upstream, 1.02 (0.06) m lake, 0.36 (0.02) m downstream; Roundaway, 0.20 (0.07) m upstream, 1.45 (0.21) m lake, 0.32 (0.12) m downstream; and Howden, 0.81 (0.03) m upstream, 1.03 (0.02) m lake, 0.61 (0.01) m downstream.

Surface water samples (10 cm below the water surface) were collected every two weeks beginning in January 2011. Samples were preserved on wet ice and transported to the USDA-ARS National Sedimentation Laboratory, Oxford, MS, for nutrient and chlorophyll analysis. *In-situ* DO was measured every 15 minutes at 40 cm depth (or 10 cm above the bayou stream bed when depth was <50 cm) during a one-week deployment period just prior to surface water sampling (one of every two weeks). Daily DO mean, minimum, and range (difference between maximum and minimum) concentrations were used. The current study focuses on summer 2011 water quality since summer is the season with the greatest frequency of hypoxia. Laboratory chemical analysis included soluble reactive phosphorus (SRP, filtered through a 45 µm cellulose nitrate filter and analyzed using the ascorbic acid method), total phosphorus (TP, persulfate digestion with ascorbic acid method), total nitrogen (TN, determined by the summation of NO_x-N and total Kjeldahl nitrogen), and total dissolved organic carbon (DOC, filtered through a 45 µm cellulose nitrate filter and analyzed using the high temperature combustion method) analyzed according to APHA (2005). TP and TN were analyzed using a Lachat Quik Chem 8500 Series 2 analyzer (Lachat Instrument, Loveland Colorado USA) while DOC was analyzed using a Teledyne Tekmar Apollo 9000 combustion TOC analyzer (Teledyne Tekmar, Mason, Ohio USA). Biological analysis included chlorophyll a (pigment extraction and spectrophotometric determination using the trichromatic method) as an indication of overall phytoplankton biomass (APHA 2005). Chlorophyll was analyzed using a Thermo Scientific Genesys 10s UV-Vis Spectrophotometer (Thermo Fisher Scientific, Inc., Waltham, Massachusetts USA). Detection limits were 0.02 mg/L for all nutrients and 0.1 µg/L for chlorophyll a.

Pearson Product Moment correlations generating corresponding correlation coefficients (*r*) were used to determine associations between summer 2011

DO parameters (daily mean, minimum , range) and either nutrients (TP, TN, DOC), chlorophyll a, or water depth within each bayou reach (upstream, lake, downstream) across all three bayous. Significant correlation coefficients were determined with an alpha level of 5% ($p \leq 0.05$).

RESULTS AND DISCUSSION

Dissolved oxygen concentrations within Cow Oak varied considerably across reaches throughout summer of 2011 (Table 3). In general, shallower upstream and downstream reaches had lower mean and minimum DO concentrations than the deeper lake reach. Dissolved oxygen range was greatest within the upstream and lake reaches and lowest in the downstream reach (Table 3). In comparison, Roundaway DO varied less across reaches yet still exhibited a similar trend of lower mean and minimum DO concentrations in shallower upstream and downstream reaches versus the deeper lake reach (Table 4). Dissolved oxygen ranges, in general, were also lower in channel reaches versus the lake reach. In contrast, Howden mean, minimum, and range of DO concentrations were generally greater in the upstream reach, lowest in the downstream reach, and intermediate in the lake reach (Table 5). Across all watersheds, a general summer seasonal trend in DO concentration was exhibited where DO was greatest in early summer and decreased thereafter until September. This indicated that DO deficit stress was greatest in August. Aquatic biota in Mississippi Delta bayous can be increasingly stressed by greater frequency and duration of hypoxic conditions, especially in August, when aquatic invertebrate and fish DO requirements may not be met. When such conditions become chronic, this can result in decreased animal diversity such as those occurring in the Big Sunflower River (Shields and Knight 2012) or in very shallow oxbow lakes (Dembkowski and Miranda 2012) in the lower Mississippi River alluvial plain.

Nutrient concentrations in the Mississippi Delta study bayous ranged from 1.5 to 2.5 fold across different bayous and among different reaches (Table 6). Cow Oak had consistently higher mean TP concentrations across all reaches compared with Roundaway (intermediate) and Howden (lowest). Roundaway had the highest TN concentrations while Cow Oak was intermediate and Howden showed the lowest TN. Mean DOC concentrations were, again, typically greater in Roundaway and lowest in Howden with Cow Oak intermediate. In general, shallower upstream reaches exhibited greater nutrient concentrations than lake reaches and downstream reaches were comparable to, or lower than, the lake reach. Concentrations of TP and TN observed in our study bayous were much greater than those measured in least impaired oxbow lakes in the lower Mississippi River alluvial plain of Arkansas (Justus 2010), but comparable with other shallow water bodies located within agricultural watersheds of the Mississippi Delta in Mississippi (Cullum et al. 2006; Shields et al. 2009; Lizotte et al. 2012; Shields et al. 2013). Mean measured DOC in the study bayous ranged from 7.3 mg/L to 11.5 mg/L with Roundaway usually having higher concentrations than either Cow Oak or Howden. DOC also typically decreased linearly from upstream to downstream within each watershed. Study bayou DOC concentrations were comparable to DOC concentrations occurring in eutrophic streams in the region that ranged from 5 mg/L to 22 mg/L (Bryson et al 2007).

Chlorophyll a concentrations (an estimate of phytoplankton biomass [Reynolds 2006; Bellinger and Sigee 2010]) varied substantially within reaches and among watersheds ranging from 14.8 µg/L to 107 µg/L (Table 6). Within Cow Oak, mean chlorophyll a concentrations were greater in upstream and lake reaches and lowest in the downstream reach. Chlorophyll a in Roundaway was greater in the lake and downstream reach but lowest in the upstream reach. In contrast, Howden had decreasing mean chlorophyll a going from upstream to lake to downstream reaches (Table 6). Observed ranges of chlorophyll a concentrations measured in the study bayous were typical of a variety of Mississippi Delta water bodies. Chlorophyll a concentrations within the Big Sunflower River were typically less than 30 µg/L (Shields and Knight 2012) while chlorophyll a in other Mississippi Delta rivers, streams and backwaters ranged from 18.3 μg/L to 116 μg/L (Bryson et al. 2007; Lizotte et al. 2012; Shields et al. 2013). Oxbow and floodplain lakes of the lower Mississippi alluvial plain had measured chlorophyll a concentrations ranging from 2.13 μg/L to 964 μg/L with most concentrations ranging from 30-100 μg/L (Justus 2010; Dembkowski and Miranda 2012; Knight et al. In Press).

During summer 2011, daily minimums and ranges of DO concentrations fluctuated in association with various nutrient concentrations across all bayou reaches (Table 7). Daily dissolved oxygen minimum concentrations were significantly negatively correlated with both TP and TN across all reaches, whereas DO minimums were negatively correlated with DOC only within the lake reach. These results are indicative of increasing nutrient concentrations leading to depressed daily DO minimum concentrations. In contrast, daily DO ranges were positively correlated with TP across all reaches but only positively correlated with TN in shallower upstream and downstream channel reaches and indicate TP and, to a lesser extent, TN lead to increased daily DO ranges. Daily DO ranges were also positively correlated with chlorophyll a concentrations across all reaches while daily DO minimums were negatively correlated only in the lake reach, suggesting phytoplankton in the bayous drives diel DO ranges but does not primarily determine the daily DO minimums. In conjunction with nutrients and phytoplankton, daily DO ranges were additionally positively correlated with water depth in upstream and lake reaches suggesting hydrological, chemical and biological components in bayous in combination affect observed daily DO concentrations.

The Mississippi Delta is well known for its high row crop productivity with intensive agriculture producing significant agricultural runoff that affects water quality of rivers and streams in the region (Rohm et al. 2002; Bryson et al. 2007; Hicks and Stocks et al. 2010). Excessive TP and TN concentrations leading to eutrophication in rivers and streams of the region are considered to be the primary cause of DO depletion in low-flow lotic waters (Rohm et al. 2002) and this was supported by the results of our study. In addition to eutrophication, the effects of hydrology on DO were shown to be another important factor. Lizotte et al. (2012) indicated that water depth significantly influences water quality such as TP and TN concentrations as well as diel DO ranges whereby increased water depth decreased these water quality parameters. Understanding such complex responses of DO concentrations to hydrological, biological and chemical processes in Mississippi Delta bayous is critical for habitat restoration (Shields et al. 2012; Shields et al. 2013).

Results of this study also have significant implications for determining appropriate nutrient criteria for Mississippi Delta rivers and streams. By showing clear linkages between TP and TN concentrations, water depth, and daily DO minima and ranges, state and federal agencies can produce more scientifically sound criteria for water management, nutrients, and DO concentrations necessary for attaining and maintaining aquatic life use of a Mississippi Delta water body.

Concurrent and future research efforts planned to coincide with the collection and assessment of the water quality data presented in this study include examination of: a) the effects of suspended sediment, turbidity, and light limitation on DO dynamics; b) fish and invertebrate community composition; c) phytoplankton and benthic algal community structure and function; and d) organic matter processing.

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Table 1. Watershed characteristics of the three Mississippi Delta study bayou watersheds.

	Delta Bayou Watershed		
Parameter	Cow Oak	Roundaway	Howden
Watershed perimeter, km	33.2	38.0	37.0
Watershed area, km^2	24.3	17.5	17.9
Maximum elevation, m	192.0	161.3	160.9
Minimum elevation, m	169.4	144.0	142.0
Relief, m	22.6	17.3	19.0
Watershed length, km	7.1	6.1	9.7

Table 2. Watershed row-crop land-use of the three Mississippi Delta study bayou watersheds in 2011.

	Delta Bayou Watershed		
Land-use (%)	Cow Oak	Roundaway	Howden
Soybeans	64	36	57
Cotton	11	20	0
Corn	1	8	27
Rice	9	19	3
Riparian/Trees	6	12	10
Fish Pond	1	2	0
Other	8	3	3

Table 3. Mean, maximum, minimum, and range of dissolved oxygen concentrations measured for one week at 15-min intervals and 40 cm depth (or 10 cm above the bayou stream bed when depth was <50 cm) in upstream, lake, and downstream reaches of Cow Oak Bayou watershed during summer 2011.

		Dissolved oxygen (mg/L)			
Location	**Date**	**Mean**	**Maximum**	**Minimum**	**Range**
Upstream	6/27/2011	6.78	13.60	0.63	12.97
	7/11/2011	6.58	16.70	0.01	16.69
	7/25/2011	7.64	14.78	0.00	14.78
	8/8/2011	ND[a]	ND	ND	ND
	8/22/2011	ND	ND	ND	ND
	9/6/2011	3.57	6.48	0.46	6.02
	9/19/2011	2.74	4.42	0.61	3.81
Lake	6/27/2011	9.65	14.08	5.02	9.06
	7/11/2011	5.29	10.45	0.57	9.88
	7/25/2011	8.90	15.96	1.45	14.51
	8/8/2011	6.98	13.00	1.81	11.19
	8/22/2011	4.71	9.58	1.61	7.97
	9/6/2011	5.25	6.17	3.38	2.79
	9/19/2011	6.98	9.96	4.84	5.12
Downstream	6/27/2011	2.74	7.09	0.81	6.28
	7/11/2011	2.67	6.55	0.00	6.55
	7/25/2011	ND	ND	ND	ND
	8/8/2011	4.26	8.98	1.06	7.92
	8/22/2011	3.04	5.46	0.53	4.93
	9/6/2011	3.15	5.06	1.72	3.34
	9/19/2011	2.40	3.96	1.39	2.57

[a]ND = no data available for this date

Table 4. Mean, maximum, minimum, and range of dissolved oxygen concentrations measured for one week at 15-min intervals and 40 cm depth (or 10 cm above the bayou stream bed when depth was <50 cm) in upstream, lake, and downstream reaches of Roundaway Lake Bayou watershed during summer 2011.

		Dissolved oxygen (mg/L)			
Location	**Date**	**Mean**	**Maximum**	**Minimum**	**Range**
Upstream	6/27/2011	2.63	5.12	0.62	4.50
	7/11/2011	2.82	5.00	0.26	4.74
	7/25/2011	0.90	2.44	0.03	2.41
	8/8/2011	5.53	7.32	1.49	5.83
	8/22/2011	4.41	4.94	3.26	1.68
	9/6/2011	5.19	5.71	4.88	0.83
	9/19/2011	6.40	6.94	5.49	1.45
Lake	6/27/2011	5.48	8.73	1.20	7.53
	7/11/2011	4.22	7.13	0.06	7.07
	7/25/2011	10.22	15.71	5.69	10.02
	8/8/2011	7.34	12.66	3.42	9.24
	8/22/2011	5.65	9.32	2.61	6.71
	9/6/2011	6.01	6.90	5.08	1.82
	9/19/2011	5.98	8.21	3.64	4.57
Downstream	6/27/2011	3.41	8.56	0.00	8.56
	7/11/2011	ND[a]	ND	ND	ND
	7/25/2011	ND	ND	ND	ND
	8/8/2011	7.29	8.24	0.81	7.43
	8/22/2011	ND	ND	ND	ND
	9/6/2011	3.09	5.22	0.24	4.98
	9/19/2011	4.44	6.29	2.83	3.46

[a]ND = no data available for this date

Table 5. Mean, maximum, minimum, and range of dissolved oxygen concentrations measured for one week at 15-min intervals and 40 cm depth (or 10 cm above the bayou stream bed when depth was <50 cm) in upstream, lake, and downstream reaches of Howden Lake Bayou watershed during summer 2011.

		Dissolved oxygen (mg/L)			
Location	**Date**	**Mean**	**Maximum**	**Minimum**	**Range**
Upstream	6/27/2011	11.48	16.67	6.07	10.60
	7/11/2011	7.46	12.42	3.23	9.19
	7/25/2011	8.55	12.23	4.72	7.51
	8/8/2011	4.30	8.28	1.16	7.12
	8/22/2011	8.26	13.48	3.78	9.70
	9/6/2011	1.32	3.75	0.05	3.70
	9/19/2011	6.00	8.62	3.58	5.04
Lake	6/27/2011	7.33	9.89	3.76	6.13
	7/11/2011	6.64	9.22	4.10	5.12
	7/25/2011	6.38	11.64	2.59	9.05
	8/8/2011	ND[a]	ND	ND	ND
	8/22/2011	7.30	10.40	4.42	5.98
	9/6/2011	4.29	5.83	2.97	2.86
	9/19/2011	4.19	6.55	2.36	4.19
Downstream	6/27/2011	ND	ND	ND	ND
	7/11/2011	4.18	6.47	2.37	4.10
	7/25/2011	2.90	5.89	0.85	5.04
	8/8/2011	2.97	5.42	0.82	4.60
	8/22/2011	2.50	5.97	0.48	5.49
	9/6/2011	4.04	5.45	2.86	2.59
	9/19/2011	4.76	6.93	3.44	3.49

[a]ND = no data available for this date

Table 6. Mean (Standard Deviation) summer 2011 total phosphorus (TP), total nitrogen (TN), total dissolved organic carbon (DOC), and chlorophyll a concentrations in the three Mississippi Delta study bayou watersheds.

		Delta Bayou Watershed		
Location	Nutrient	Cow Oak	Roundaway	Howden
Upstream	TP (µg/L)	319 (173)	132 (20)	142 (26)
	TN (mg/L)	2.9 (1.5)	2.2 (1.2)	1.7 (0.5)
	DOC (mg/L)	11.5 (3.0)	11.1 (5.7)	8.5 (2.6)
	Chlorophyll a (µg/L)	107.0 (69.6)	14.8 (8.9)	43.6 (32.2)
Lake	TP (µg/L)	300 (78)	227 (148)	116 (29)
	TN (mg/L)	2.0 (0.6)	2.2 (1.0)	1.2 (0.1)
	DOC (mg/L)	7.9 (2.5)	10.4 (3.6)	7.2 (2.6)
	Chlorophyll a (µg/L)	106.1 (101.0)	76.0 (63.3)	26.6 (11.2)
Downstream	TP (µg/L)	262 (74)	210 (119)	118 (25)
	TN (mg/L)	1.5 (0.5)	2.6 (1.4)	1.1 (0.2)
	DOC (mg/L)	7.8 (2.7)	10.0 (5.1)	7.3 (2.7)
	Chlorophyll a (µg/L)	39.9 (16.9)	43.7 (24.1)	18.4 (6.3)

Table 7. Pearson Product Moment correlation coefficients (r) and sample sizes (n) between summer 2011 dissolved oxygen (mean, minimum, range) concentrations and nutrients, chlorophyll a, or water depth in the three Mississippi Delta study bayou watersheds. The asterisk (*) denotes statistically significant r values, $p < 0.05$.

			Dissolved Oxygen (mg/L)		
Location	Parameter	(n)	Mean	Minimum	Range
Upstream	TP (µg/L)	21	0.117	-0.770*a	0.661*b
	TN (mg/L)	21	-0.044	-0.583*b	0.473*
	DOC (mg/L)	21	-0.172	-0.328a,b	0.071
	Chlorophyll a (µg/L)	21	0.219	-0.524*b	0.656*
	Water depth (m)	17	0.256	-0.328	0.833*a
Lake	TP (µg/L)	20	0.023	-0.627*a	0.489*a,b
	TN (mg/L)	20	0.119a,b	-0.670*a	0.412a,b
	DOC (mg/L)	20	-0.414a,b	-0.750*a	0.054a,b
	Chlorophyll a (µg/L)	20	0.317	-0.515*a,b	0.659*
	Water depth (m)	13	-0.206	0.353a	0.567*a
Downstream	TP (µg/L)	16	-0.084a	-0.730*a	0.784*
	TN (mg/L)	16	0.539*	-0.563*a,b	0.653*b
	DOC (mg/L)	16	0.360	-0.296a	0.196
	Chlorophyll a (µg/L)	16	0.133a,b	-0.434a,b	0.742*
	Water depth (m)	14	0.090	0.453a,b	-0.359a,b

[a] Log_{10} dissolved oxygen

[b] Log_{10} nutrient, chlorophyll a, or water depth

Figure 1. Map of the three study bayous in the Mississippi Delta showing the locations of upstrea, lake, and downstream sampling sites.