Diffusive Nutrient Fluxes and Sediment Oxygen Demand in Petenwell and Castle Rock Lakes, Wisconsin River System

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OBJECTIVES

The objectives of this research were to estimate 1) rates of nitrogen and phosphorus flux from sediment under controlled laboratory redox (Eh; aerobic or anaerobic conditions) and pH conditions and 2) sediment oxygen demand for intact sediment cores collected at various stations in Petenwell and Castle Rock Lakes.

APPROACH

Laboratory-derived rates of phosphorus and nitrogen release from sediment

Phosphorus. The goals of this task were to measure rates of phosphorus (P) release from sediments as a function of oxidation-reduction condition (i.e., redox; aerobic or anaerobic conditions) and pH in order to evaluate the importance of this source relative to other P inputs to the lake. Elevated pH (i.e., > 8) near the sediment-water interface may enhance or exacerbate the rate of P release from aerobic sediment due to ligand exchanges. Typically under aerobic conditions, phosphate (PO_4^{3-}) is adsorbed to ferric oxyhydroxides (Fe(OOH)) in the oxidized microzone of surface sediment and unavailable for mass transport to the overlying water column. As pH increases to greater than ~ 9.0, binding of PO_4^{3-} diminishes and competition for binding sites by OH^- can result in the release of PO_4^{3-} and diffusion into the overlying water column for uptake by algae. Photosynthetic activities by phytoplankton can increase pH substantially (i.e., > 9) without changing alkalinity appreciably, and indirectly promote desorption of P via ligand exchange processes between PO_4^{3-} and OH^-.

Experimental procedures followed those in James (2010). Undisturbed replicate (3 per treatment) sediment cores were collected at various sampling stations (Fig. 1; Table 1) in August, 2013, for determination of rates of P release from sediment. A gravity sediment coring device (Aquatic Research Instruments, Hope ID) equipped with an acrylic core liner (6.5-cm ID and 50-cm length) was used to collect sediment. The core liners, containing both sediment and overlying water, were immediately sealed using rubber

stoppers and stored in a covered container until analysis. Additional lake water was collected for incubation with the collected sediment.

In the laboratory, sediment cores were carefully drained of overlying water and the upper 10 cm layer was transferred intact to a smaller acrylic core liner (6.5-cm dia and 20-cm ht) using a core remover tool. Water collected from the lake was filtered through a glass fiber filter (Gelman A-E); 300 mL was then siphoned onto the sediment contained in the small acrylic core liner without causing sediment resuspension. Sediment incubation systems, therefore, consisted of the upper 10-cm of sediment and filtered overlying water contained in acrylic core liners that were sealed with rubber stoppers. The sediment incubation systems were placed in a darkened environmental chamber and incubated at a constant temperature. The incubation temperature was maintained at 20 ^{o}C to simulate average summer temperatures. The oxidation-reduction environment in each system was controlled by gently bubbling either air (aerobic) or nitrogen (anaerobic) through an air stone placed just above the sediment surface. Bubbling action ensured complete mixing of the water column but did not disrupt the sediment. Anoxic conditions were verified using a dissolved oxygen electrode. The pH of aerobic sediment systems was adjusted by bubbling with air (pH ~ 8.3) or CO_2-free air (pH ~ 9.0).

Water samples for soluble reactive phosphorus (SRP) were collected at one to three day intervals over the entire incubation period. Samples (10 mL) were collected from the center of each sediment incubation system using a syringe and immediately filtered through a 0.45 μm membrane syringe filter. The water volume removed from each system during sampling was replaced by addition of filtered lake water preadjusted to the proper oxidation-reduction condition. These volumes were accurately measured for determination of dilution effects. SRP was measured colorimetrically using the ascorbic acid method (APHA 2005). Rates of SRP release from the sediment (mg/m^2 d) were calculated as the linear change in concentration in the overlying water divided by time and the area of the incubation core liner. Regression analysis was used to estimate rates over the linear portion of the data.

Nitrogen. To a subset (2 replicates) of the same sediment incubation systems (Fig. 1; Table 1), an additional 10 mL was filtered through a 0.45 μm syringe filter for determination of ammonium-N (NH_x-N) and nitrate-nitrite-N (NO_x-N). Samples were collected twice a day over the first three days of incubation, then daily thereafter. Filtered samples were preserved with sulfuric acid and shipped to the University of Wisconsin – Stevens Point, Water and Environmental Analysis Laboratory for analysis. Rates of N flux were calculated as described above for P.

Sediment oxygen demand

Two sediment cores collected at stations listed in Table 1 were used to determine sediment oxygen demand (SOD) using a modification of methods described in Plumb (1981). In the laboratory, the upper 2 cm of the sediment core was transferred intact to a small aluminum dish and placed on a trivet inside a 1 liter glass beaker (10 cm diameter by 20 cm height). The trivet positioned the sediment core 3 cm above a micro-magnetic stir bar that was located in the bottom of the beaker to provide circulation during SOD experiments. Very small magnetic stir bars (10 mm length by 3 mm diameter) were used to create gentle circulation in each system. The beaker containing a sediment dish, trivet, and magnetic stir bar was slowly filled with ~0.75 L of filtered (Gelman A/E glass fiber; nominal pore size = 2 μm) lake water that had been pre-equilibrated with atmospheric oxygen. The SOD systems were placed on a magnetic stir motor an environmental chamber. Temperature was maintained at a constant 20 ^{o}C throughout the incubation period.

A YSI Model 6600 data sonde, fitted with a temperature and dissolved oxygen probe, was inserted into the beaker so that no airspace was left in the system and secured in the environmental chamber with a stand and clamp. The dissolved oxygen probe was positioned 5 cm above the sediment interface for SOD determinations. Prior to the experiment, dissolved oxygen probes were precalibrated against known Winkler titrations. Temperature and dissolved oxygen were monitored at 10 minute intervals in

the sediment system for a period of greater than 3000 minutes (i.e., 2.0 days). Data sonde dissolved oxygen calibration was checked after each experiment.

The rate of dissolved oxygen depletion was calculated as the change in dissolved oxygen mass over the linear range of depletion (i.e., the first 1000 or 3000 min), divided by time and the area of the sediment dish (mg/m^2 d). A control system that did not contain sediment was also monitored in order to account for any dissolved oxygen demand in the water column. SOD was calculated as the rate of dissolved oxygen depletion in the sediment system minus the rate of dissolved oxygen depletion in the control system.

RESULTS AND INTERPRETATION

Phosphorus flux rates

Under anaerobic conditions, phosphorus mass and concentration increased rapidly in the overlying water column over the first several days for all incubations (Fig. 2 and 3). Rates of P increase began to level off after ~ day 5 as a function of diminishing diffusional concentration gradients at the sediment-water interface. The mean P concentration in the overlying water column approached or exceeded 1 mg/L for PL-2, PL-4, CRL-1, and CRL-2 sediment systems toward the end of the incubation period (Table 2). Although lower in CRL-4 systems, the mean concentration nevertheless exceeded 0.50 mg/L by the end of the incubation period.

Rates of P release from sediment under anaerobic conditions were relatively high over all stations in both lakes, ranging between a mean 8.4 and 23.4 mg/m^2 d (Table 2; Fig. 4). Although there was an apparent trend of decreasing anaerobic P rates with distance from Petenwell headwaters to Castle Rock headwaters, means were not significant ($P>0.05$; ANOVA; SAS 1994). In general, sediment located in the Yellow River arm of Castle Rock Lake exhibited the lowest rates of P release under anaerobic conditions, while mean

rates at main stem stations were higher and similar with a grand mean of 18.3 mg/m^2 d (± 1.6 SE).

P mass and concentration increases in the overlying water column were generally much lower under aerobic conditions (Fig. 5 and 6). Two incubation systems exhibited anomalous spikes in P concentration that were not considered in rate calculation (i.e., PL 4-Thalweg, PL 4-Side). Causes for these patterns are not precisely known but may be related to local sediment resuspension by burrowing invertebrates in these particular systems. For all other incubation systems, P mass and concentrations in the overlying water column were usually very low and constant over the first 5 to 10 days and then increased thereafter. P concentration in the overlying water column at the end of incubation ranged between 0.05 and 0.06 mg/L for Petenwell Lake aerobic systems and between 0.03 and 0.04 mg/L for Castle Rock Lake incubation systems (Table 2).

Mean aerobic P release rates ranged between 0.1 and 0.4 mg/m^2 d. Although much lower than rates under anaerobic conditions, aerobic sediments still represented a potential P source to the overlying water column. Clear longitudinal trends in the mean aerobic P release rate were not evident (Fig. 7). Overall, mean aerobic P release rates were higher in Petenwell versus Castle Rock Lake.

While elevating pH in the overlying water column of aerobic systems was associated with the buildup of higher P concentrations (Fig. 8 and 9) and greater rates of P release, versus those under nominal pH conditions (Table 2), there were no significant differences in the mean rate as a function of pH due to high variability ($P>0.05$; T-Test comparison of means; SAS 1994; Fig. 10). Indeed, the grand mean aerobic P release rate over all stations was nearly double at 0.30 mg/m^2 d at slightly higher pH versus the grand mean rate of 0.17 mg/m^2 d at nominal pH. The mean P concentration in the overlying water column was also generally higher for aerobic systems incubated at a higher pH (Table 2).

Nitrogen flux rates

Under anaerobic conditions, ammonium mass and concentration increased in the overlying water column over time (Fig. 11 and 12). This pattern could be attributed to diffusive efflux (i.e., mass transfer of NH_x-N from the sediment to the overlying water column) due to organic N mineralization because anaerobic conditions inhibited bacterial nitrification (i.e., conversion of ammonium to nitrate). Nitrification is an aerobic metabolic process that occurs in the oxygenated microzone at the sediment-water interface. Diffusive NH_x-N efflux from the sediment under anaerobic conditions ranged between 11 and 63 mg/m^2 d and was greatest for sediment collected at PL-4 thalweg (Table 3; Fig. 13 and 14). These fluxes were similar to those reported in James et al. (2008) and James (2010) for backwater sediments of the Upper Mississippi River.

Under aerobic conditions, some diffusive NH_x-N efflux occurred over the first 1 to 2 days for most incubation systems (Fig. 15 and 16), resulting in positive rates (Table 3). These aerobic effluxes were usually lower than anaerobic effluxes (Fig. 13 and 14). The difference can be attributed to bacterial nitrification of ammonium under aerobic conditions. However, subsequent influx of NH_x-N back to the sediment occurred toward the end of the incubation period, which was unusual. Diffusive NH_x-N influx would suggest that porewater NH_x-N concentrations were very low within the oxidized sediment microzone relative to the overlying water and would also suggest that bacterial nitrification was occurring toward the end of the incubation period. For most incubations, diffusive NH_x-N influx coincided with NO_x-N efflux (see below), and mean rates were very similar (Table 3). This pattern and similarity between rates further suggested bacterial nitrification of ammonium to nitrate.

Nitrate concentrations were initially undetectable in the overlying water column at the beginning of sediment incubation. Thus, rates of NO_x-N influx into the sediment under anoxic conditions were essentially zero (not shown) because bacterial denitrification (conversion of nitrate-nitrite to N_2) is an anaerobic process and NO_x-N was not available for metabolism. A similar pattern occurred (i.e., undetectable NO_x-N for metabolic

processing), at least during the first two days of incubation, for sediment cores incubated under aerobic conditions (Fig. 17 and 18). However, NO_x-N efflux was observed by day 3 for most sediment systems. In nearly all cases, aerobic NH_x-N influx rates were similar to aerobic NO_x-N efflux rates (Fig. 19 and 20). This pattern was attributed to bacterial nitrification; thus, NH_x-N diffused into the oxized microzone, was subsequently converted to NO_x-N via bacterial nitrification, and then diffused out of the oxidized microzone and into the overlying water column.

Patterns of NH_x-N and NO_x-N flux between the sediment and overlying water column were unusual compared to other recent studies of sediment N dynamics for backwater sediments of the upper Mississippi River (James et al. 2008; James 2010). In those studies, net NH_x-N efflux occurred as a result of organic N mineralization while net NO_x-N influx (i.e., mass transfer from the overlying water column to the sediment) occurred as a result of bacterial nitrification (i.e., conversion of ammonium to nitrate) and denitrification (i.e., conversion of nitrate to N_2). Denitrification was driven by high NO_x-N concentrations in the overlying water column.

For Petenwell and Castle Rock Lake sediments, NO_x-N concentrations in the overlying water column were undetectable suggesting that NO_x-N sources for denitrification were probably derived from organic N mineralization to NH_x-N in the sediment and conversion to NO_x-N via bacterial nitrification (i.e., coupled nitrification-denitrification). Denitrification is most likely occurring in Petenwell and Castle Rock Lake sediments but rates could be quantified via the present experimental approach because NO_x-N concentrations in the overlying water column were undetectable. N-15 tracer studies (Rysgaard et al. 1993) or experimental NO_x-N additions to the overlying water column of incubation systems would be needed to quantify denitrification. The fact that NO_x-N is undetectable in the water column of Petenwell and Castle Rock Lakes despite the agricultural and industrial nature of the watershed lends suggests that denitrification is occurring in the system and this metabolic process is probably limited by NO_x-N availability. Richardson et al. (2008) similarly reported that low NO_x-N

availability was likely limiting denitrification processes in many regions of Pool 8 of the Upper Mississippi River.

Sediment oxygen demand

Dissolved oxygen depletion in the SOD incubation systems exhibited a slight biphasic pattern; it was faster over the first ~1,000 min and declined at a lower rate thereafter (Figure 21). The SOD was greatest for Petenwell Lake sediments; averaging ~ 1.7 g/m^2 d over the first 1,000 min and ~ 1.2 g/m^2 d over the first 3,000 min of incubation (Table 4). SOD was consistent over all sediment stations in Castle Rock Lake, averaging ~1.4 g/m^2 d over the first 1,000 min and ~0.9 g/m^2 d over the first 3,000 min of incubation. The SOD estimate was lower when declines in dissolved oxygen over a 3,000 min period were considered due to the slight biphasic pattern of depletion (Fig. 22). However, this latter estimate incorporated the overall dissolved oxygen depletion patterns and is probably more representative of in situ rates. Hypolimnetic dissolved oxygen demand in lakes typically range between 0.06 and 2 g DO/m^2 d (Chapra 1997). Thus, SOD for Petenwell and Castle Rock Lakes fell well with the ranges reported by others.

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Table 1. Reservoir, station sediment sampling locations, and numbers of sediment cores collected for determination of rates of phosphorus (P) and nitrogen (N) species flux under aerobic or anaerobic conditions and sediment oxygen demand (SOD). With the exception of PL 4-side, all stations were located in the main channel (i.e., thalweg). PL 4-side was positioned off thalweg to capture sediment fluxes as a function of shallower sediment. N0x = nitrate-nitrite-N and NHx = ammonium-N.

Reservoir	Station location	Lat	Long	Depth	P Flux			N Flux		SOD
				(ft)	Aerobic Nominal pH	Aerobic Elevated pH	Anaerobic	Aerobic N0x & NHx	Anaerobic N0x & NHx	
Petenwell	PL 2-In thalweg	44.12535	-89.98972	~30	3		3	2	2	2
Petenwell	PL 4-In thalweg	44.19125	-89.91356	~10	3	3	3	2	2	2
Petenwell	PL 4-Off thalweg (side)			~5	3	3				
Castle Rock	CRL 1-In thalweg	43.87881	-89.96245	~20	3	3	3	2	2	2
Castle Rock	CRL 2-In thalweg	43.91861	-89.95735	~16	3	3	3	2	2	2
Castle Rock	CRL 4-In thalweg	43.91624	-90.01610	~13	3	3	3	2	2	2

Table 2. Mean (1 standard error in parentheses; n = 3) rates of phosphorus (P) release under aerobic and anaerobic conditions and mean P concentration (n = 3) in the overlying water column near the end of the incubation period for intact sediment cores collected at various stations in Petenwell and Castle Rock Reservoirs.

Reservoir	Station	Diffusive P flux					
		Aerobic				Anaerobic	
		Nominal pH		Elevated pH			
		(mg/m^2 d)	(mg/L)	(mg/m^2 d)	(mg/L)	(mg/m^2 d)	(mg/L)
Petenwell	2-In thalweg	0.37 (0.05)	0.064 (0.017)			15.7 (2.2)	0.992 (0.168)
Petenwell	4-In thalweg	0.19 (0.03)	0.046 (0.004)	0.32 (0.08)	0.083 (0.024)	23.4 (0.4)	1.383 (0.165)
Petenwell	4-Off thalweg (side)	0.15 (0.14)	0.059 (0.012)	0.55 (0.11)	0.112 (0.005)		
Castle Rock	1-In thalweg	0.05 (0.01)	0.032 (0.008)			20.2 (3.9)	1.517 (0.165)
Castle Rock	2-In thalweg	0.15 (0.05)	0.041 (0.003)	0.24 (0.04)	0.074 (0.008)	14.0 (3.2)	1.026 (0.177)
Castle Rock	4-In thalweg	0.11 (0.02)	0.026 (0.003)	0.10 (0.03)	0.027 (0.006)	8.4 (2.9)	0.556 (0.204)

Table 3. Mean (1 standard error in parentheses; n = 2) rates of ammonium-nitrogen (NHx) and nitrate-nitrite nitrogen (N0x) flux under aerobic and anaerobic conditions and mean concentration (n = 2) in the overlying water column near the end of the incubation period for intact sediment cores collected at various stations in Petenwell and Castle Rock Reservoirs.

Reservoir	Station	Diffusive NHx flux					Diffusive N0x flux			
		Aerobic			Anaerobic		Aerobic		Anaerobic	
		+ rate (mg/m^2 d)	- rate (mg/m^2 d)	(mg/L)	(mg/m^2 d)	(mg/L)	(mg/m^2 d)	(mg/L)	(mg/m^2 d)	(mg/L)
Petenwell	2-In thalweg	18.2 (2.3)	-26.2 (1.0)	1.08 (0.03)	21.9 (3.3)	1.60 (0.05)	19.7 (2.2)	0.55 (0.5)	ND	ND
Petenwell	4-In thalweg	48.1 (3.6)	ND	2.24 (0.05)	63.3 (9.8)	3.29 (0.26)	13.1 (2.2)	0.35 (0.05)	ND	ND
Castle Rock	1-In thalweg	ND	-15.0 (1.3)	0.54 (0.06)	39.5 (8.1)	1.22 (0.23)	14.5 (1.7)	0.30 (0.10)	ND	ND
Castle Rock	2-In thalweg	30.0 (3.1)	-21.7 (2.3)	1.23 (0.04)	26.4 (5.8)	2.19 (0.08)	24.5 (3.0)	0.70 (<0.10)	ND	ND
Castle Rock	4-In thalweg	8.0 (1.7)	-21.1 (0.3)	0.75 (0.01)	11.4 (0.2)	0.72 (0.01)	20.9 (<0.1)	0.50 (<0.10)	ND	ND

Table 4. Mean (1 standard error in parentheses; n = 2 to 3) rates of sediment oxygen demand (SOD) for the upper 2-cm intact sediment section. SOD for each reservoir station is corrected for the control (i.e., no sediment) oxygen demand (also shown below). SOD is calculated over 1,000 min and 3,000 min of incubation.

Reservoir	Station	SOD (1,000 min)		SOD (3,000 min)	
		(g/m^2 d)	(STDERR)	(g/m^2 d)	(STDERR)
Control		0.13		0.12	
Petenwell	2-In thalweg	1.77	< 0.01	1.22	0.10
Petenwell	4-In thalweg	1.60	0.04	1.19	0.03
Castle Rock	1-In thalweg	1.36	0.04	0.99	0.13
Castle Rock	2-In thalweg	1.33	0.05	0.88	0.10
Castle Rock	4-In thalweg	1.39	0.18	0.96	0.12

Figure 1. Sediment sampling station locations.

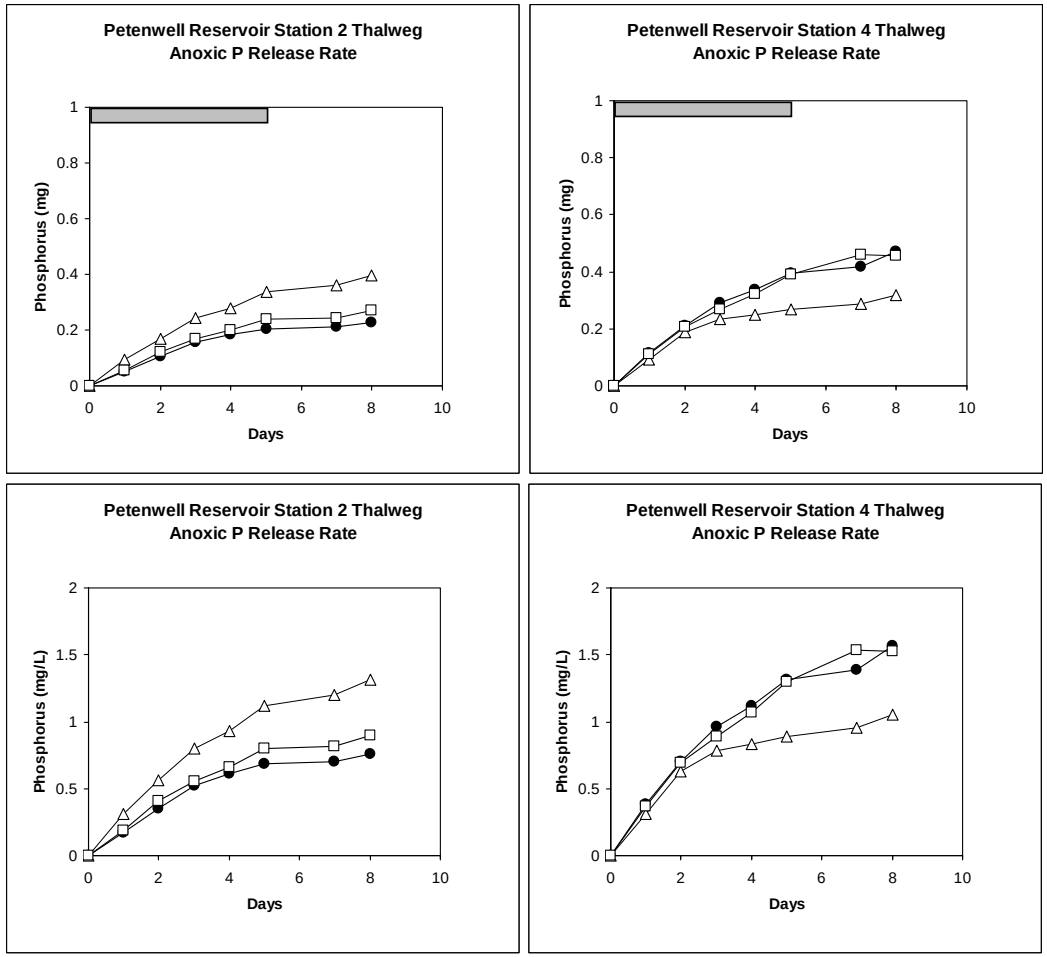

Figure 2. Variations in soluble phosphorus (P) mass (upper panels) and concentration (lower panels) versus time for Petenwell Lake sediment core systems incubated under anaerobic (anoxic) conditions. Grey horizontal bar denotes the approximate time period used for estimating rates of P release.

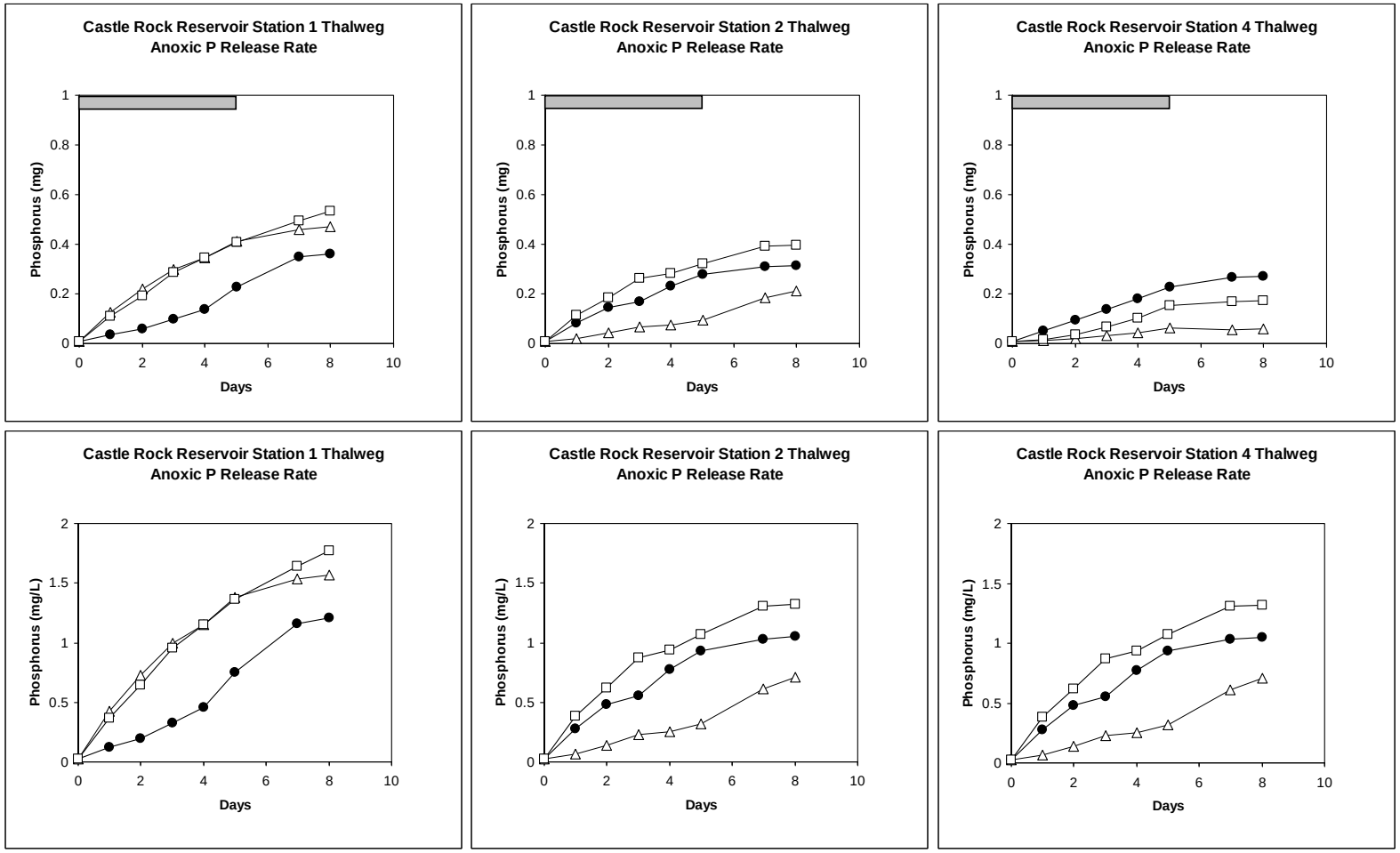

Figure 3. Variations in soluble phosphorus (P) mass (upper panels) and concentration (lower panels) versus time for Castle Rock Lake sediment core systems incubated under anaerobic (anoxic) conditions. Grey horizontal bar denotes the approximate time period used for estimating rates of P release.

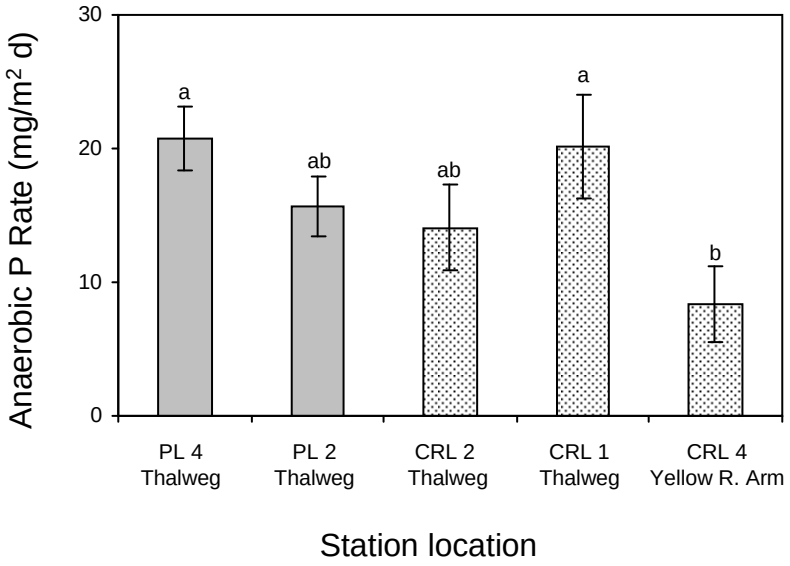

Figure 4. Mean (n=3) rates of phosphorus (P) release under anaerobic conditons for sediment cores collected in Petenwell (PL) and Castle Rock (CRL) lakes. Vertical brackets represent 1 standard error of the mean. Different letters above column means indicate significant differences (P<0.05) based on ANOVA (SAS 1994). Data were log transformed to stabilize the variance.

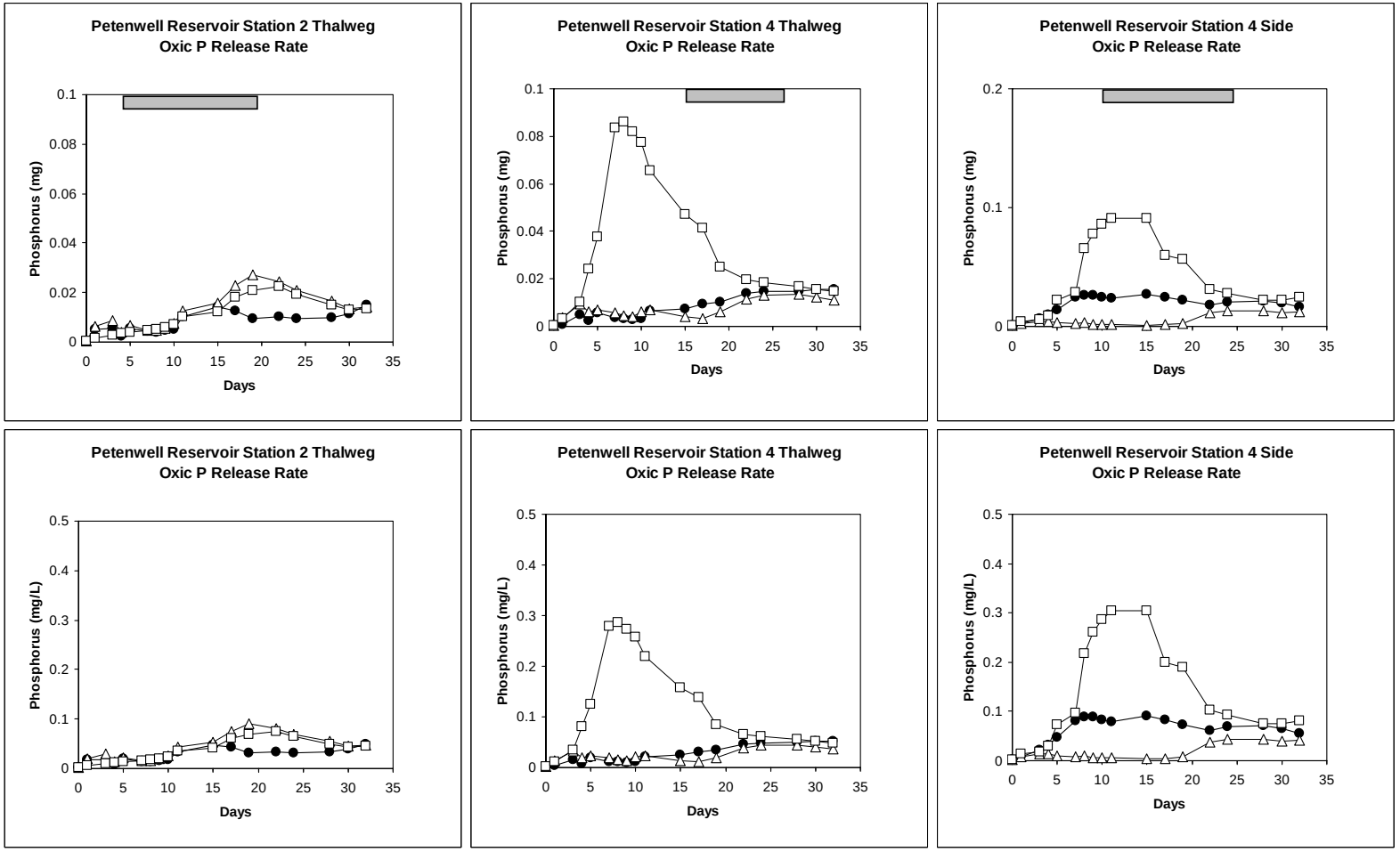

Figure 5. Variations in soluble phosphorus (P) mass (upper panels) and concentration (lower panels) versus time for Petenwell Lake sediment core systems incubated under aerobic (oxic) conditions. Grey horizontal bar denotes the approximate time period used for estimating rates of P release.

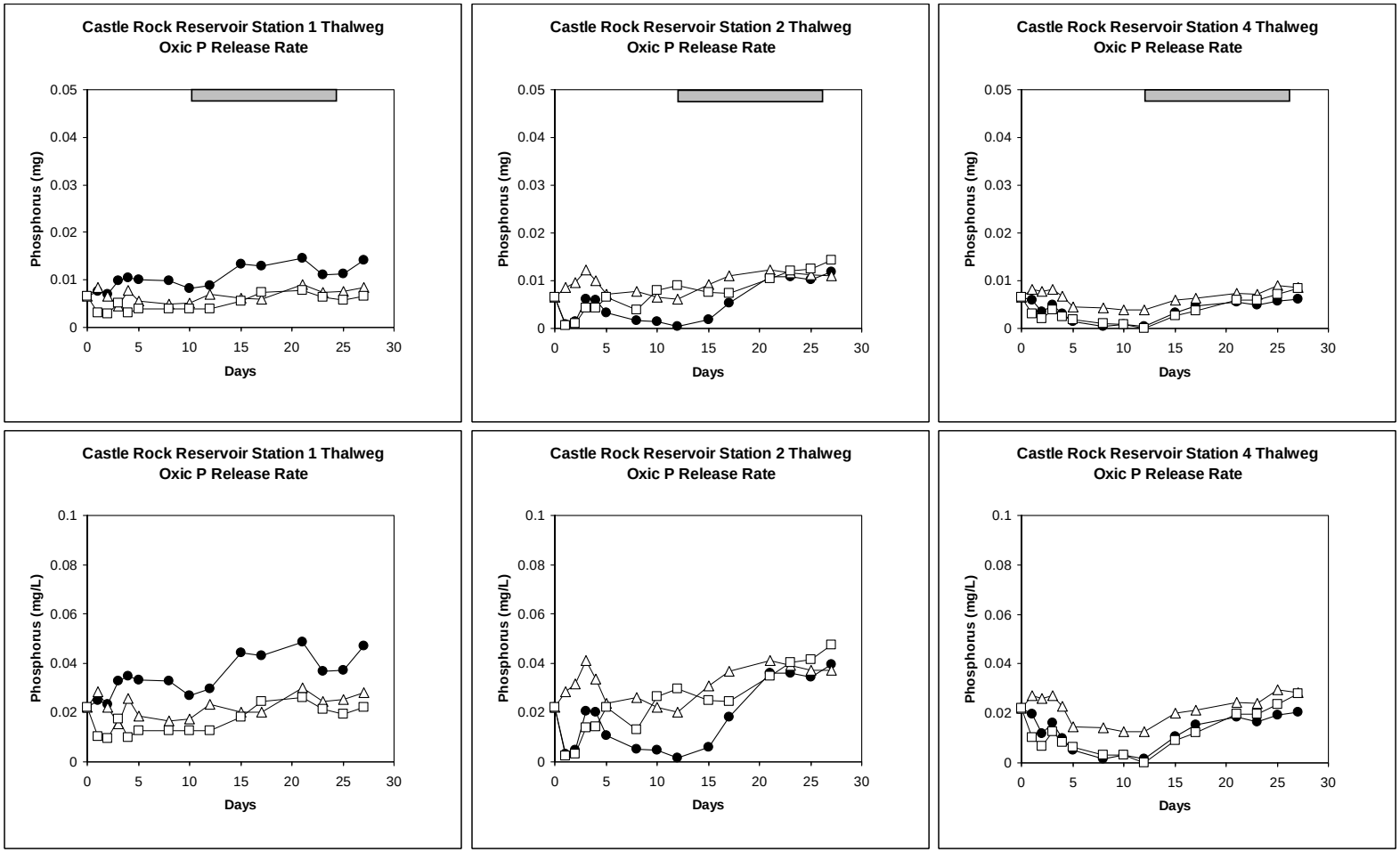

Figure 6. Variations in soluble phosphorus (P) mass (upper panels) and concentration (lower panels) versus time for Castle Rock Lake sediment core systems incubated under aerobic (oxic) conditions. Grey horizontal bar denotes the approximate time period used for estimating rates of P release.

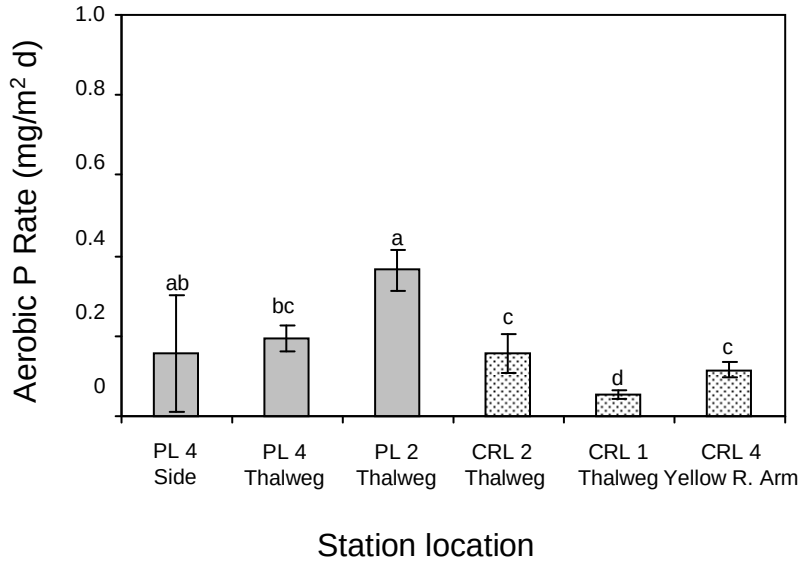

Figure 7. Mean (n=3) rates of phosphorus (P) release under aerobic conditons for sediment cores collected in Petenwell (PL) and Castle Rock (CRL) lakes. Vertical brackets represent 1 standard error of the mean. Different letters above column means indicate significant differences (P<0.05) based on ANOVA (SAS 1994). Data were log transformed to stabilize the variance.

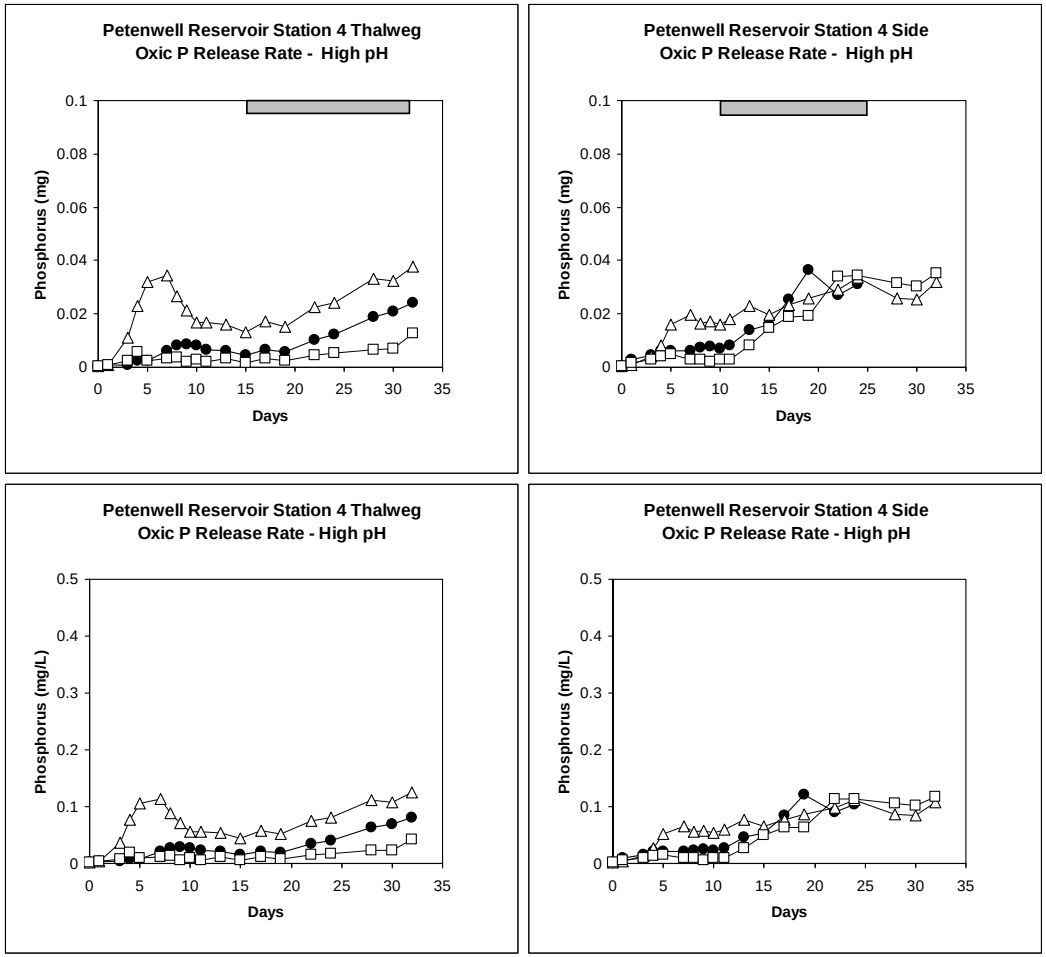

Figure 8. Variations in soluble phosphorus (P) mass (upper panels) and concentration (lower panels) versus time for Petenwell Lake sediment core systems incubated under aerobic (oxic) conditions and at a nominal or slightly higher pH. Grey horizontal bar denotes the approximate time period used for estimating rates of P release.

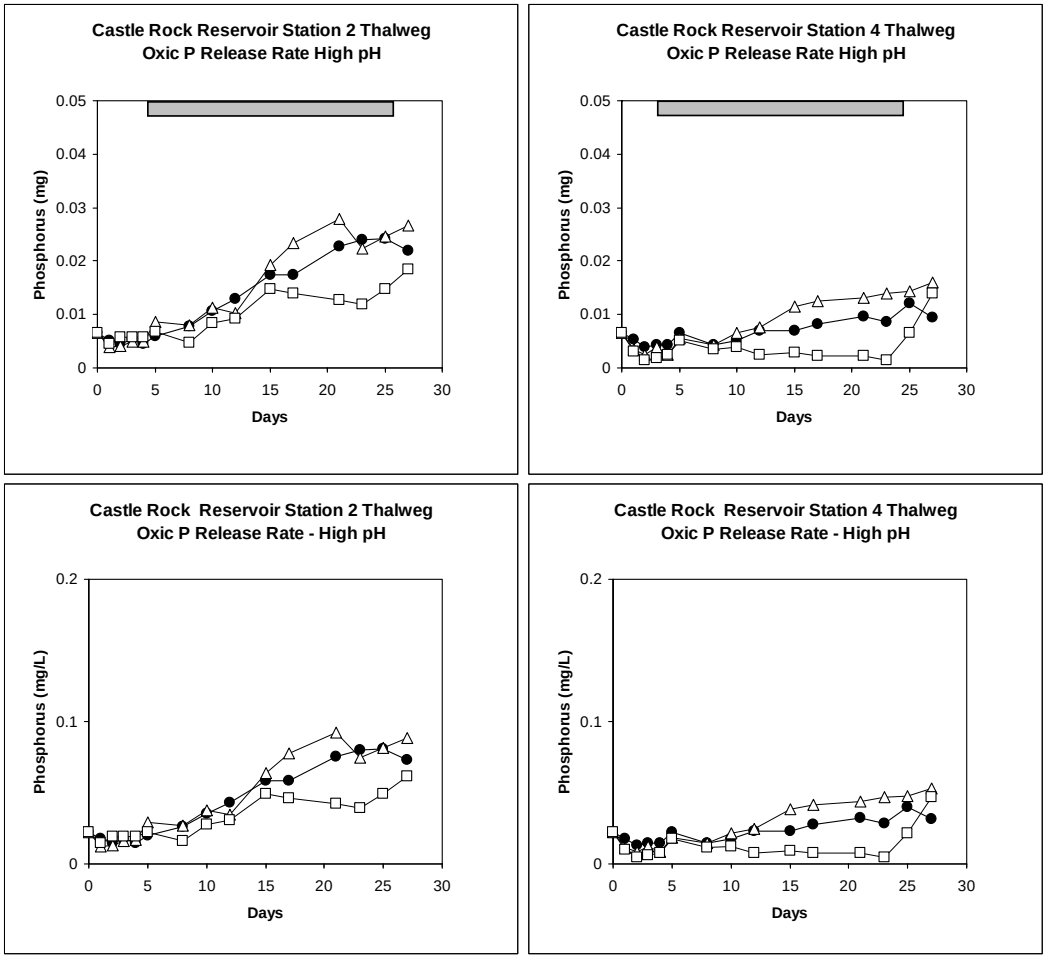

Figure 9. Variations in soluble phosphorus (P) mass (upper panels) and concentration (lower panels) versus time for Castle Rock Lake sediment core systems incubated under aerobic (oxic) conditions . Grey horizontal bar denotes the approximate time period used for estimating rates of P release.

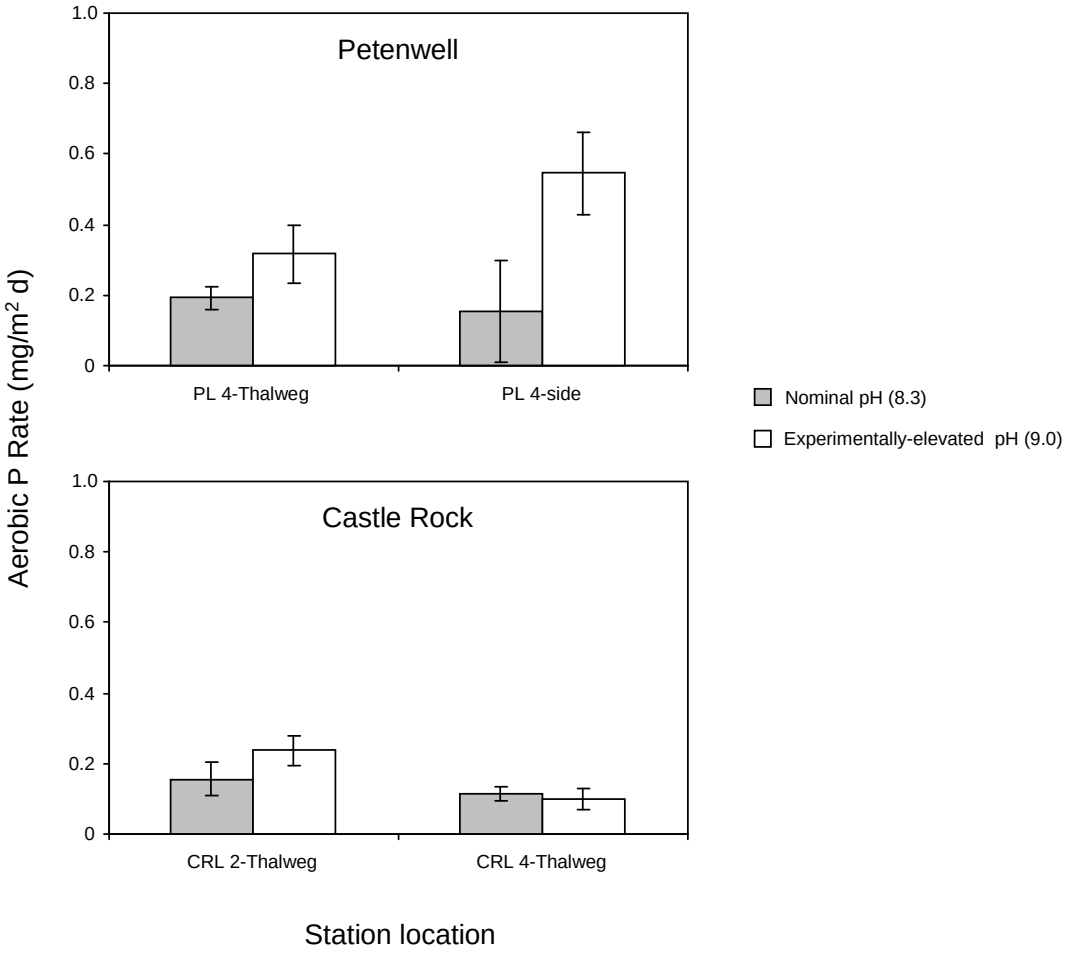

Figure 10. Mean (n=3) rates of phosphorus (P) release under aerobic conditons and at a nominal or slightly higher pH for sediment cores collected in Petenwell (PL) and Castle Rock (CRL) lakes. Vertical brackets represent 1 standard error of the mean. No significant differences ($P<0.05$) were found between treatments based on ANOVA (SAS 1994). Data were log transformed to stabilize the variance.

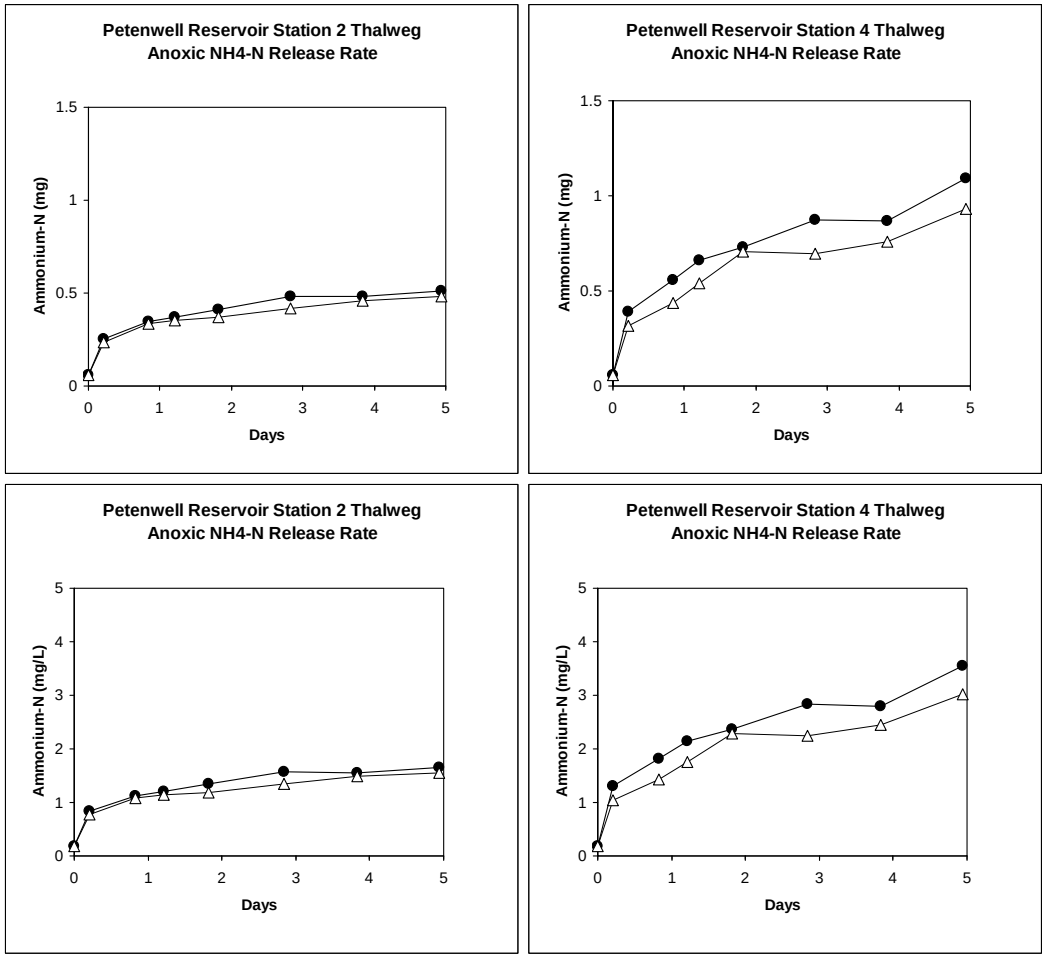

Figure 11. Variations in ammonium-N (NH_x-N) mass (upper panels) and concentration (lower panels) versus time for Petenwell Lake sediment core systems incubated under anaerobic (anoxic) conditions.

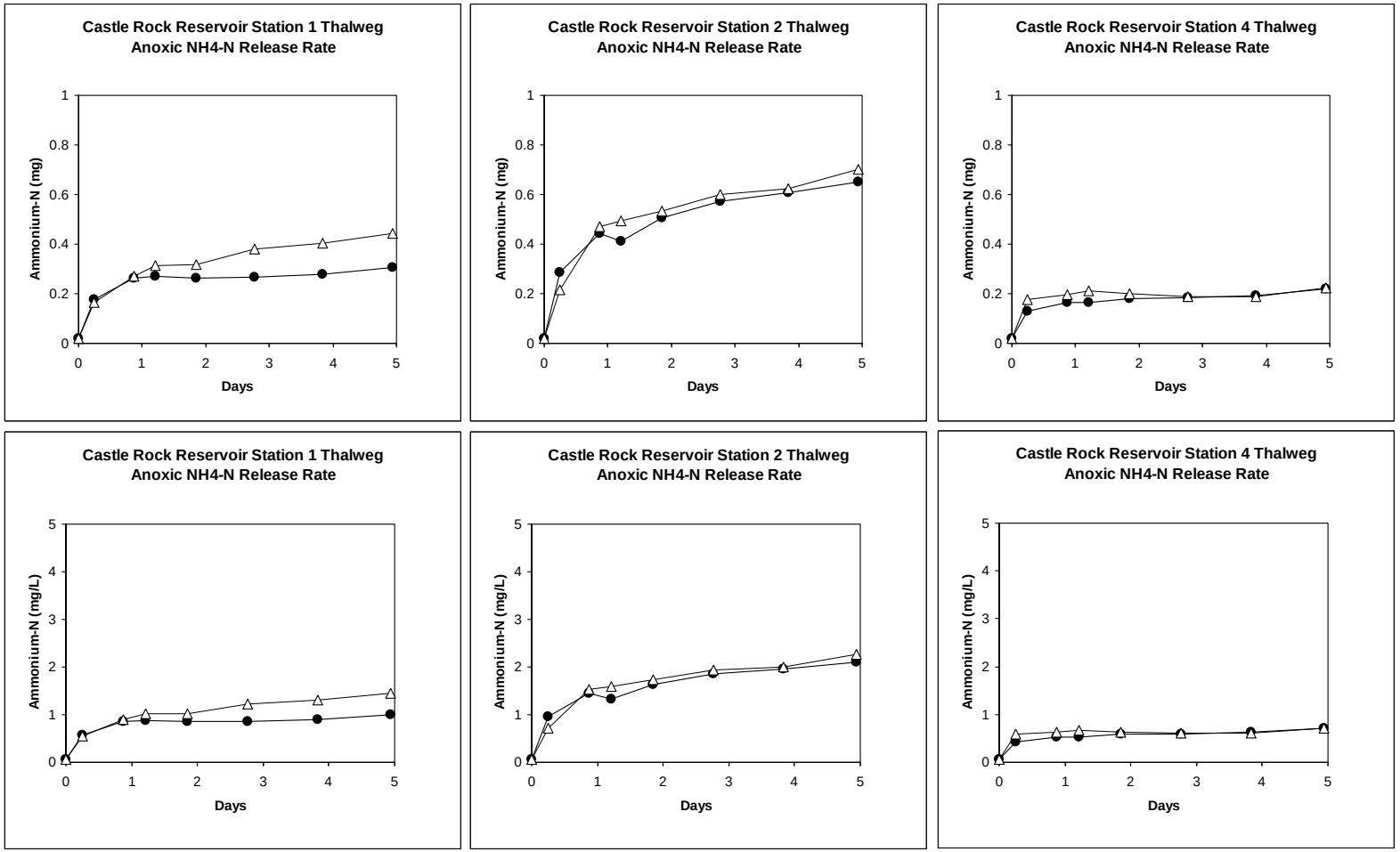

Figure 12. Variations in ammonium-N (NH_x-N) mass (upper panels) and concentration (lower panels) versus time for Castle Rock Lake sediment core systems incubated under anaerobic (anoxic) conditions.

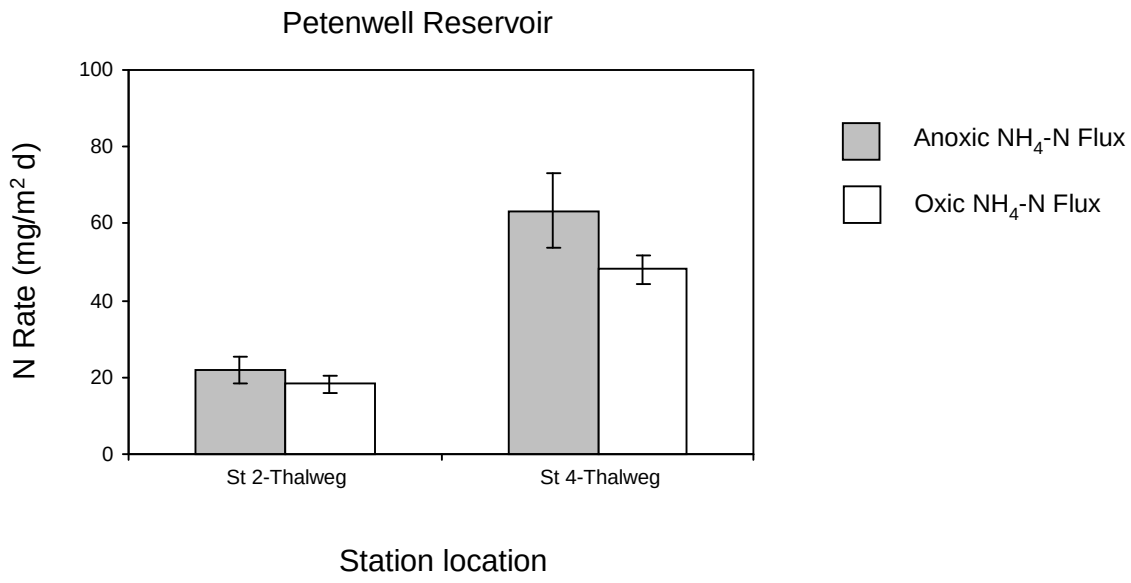

Figure 13. Mean (n=3) rates of ammonium-N (NH_x-N) release under aerobic (oxic) and anaerobic (anoxic) conditions for sediment cores collected in Petenwell lake (PL). Vertical brackets represent 1 standard error of the mean.

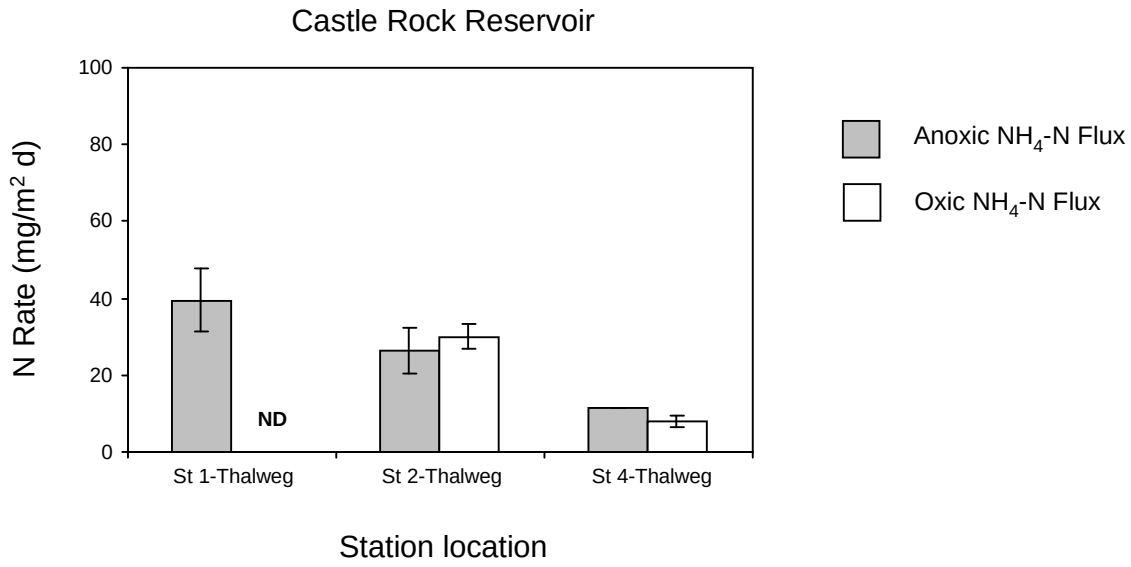

Figure 14. Mean (n=3) rates of ammonium-N (NH_x-N) release under aerobic (oxic) and anaerobic (anoxic) conditions for sediment cores collected in Castle Rock Lake (CRL). Vertical brackets represent 1 standard error of the mean.

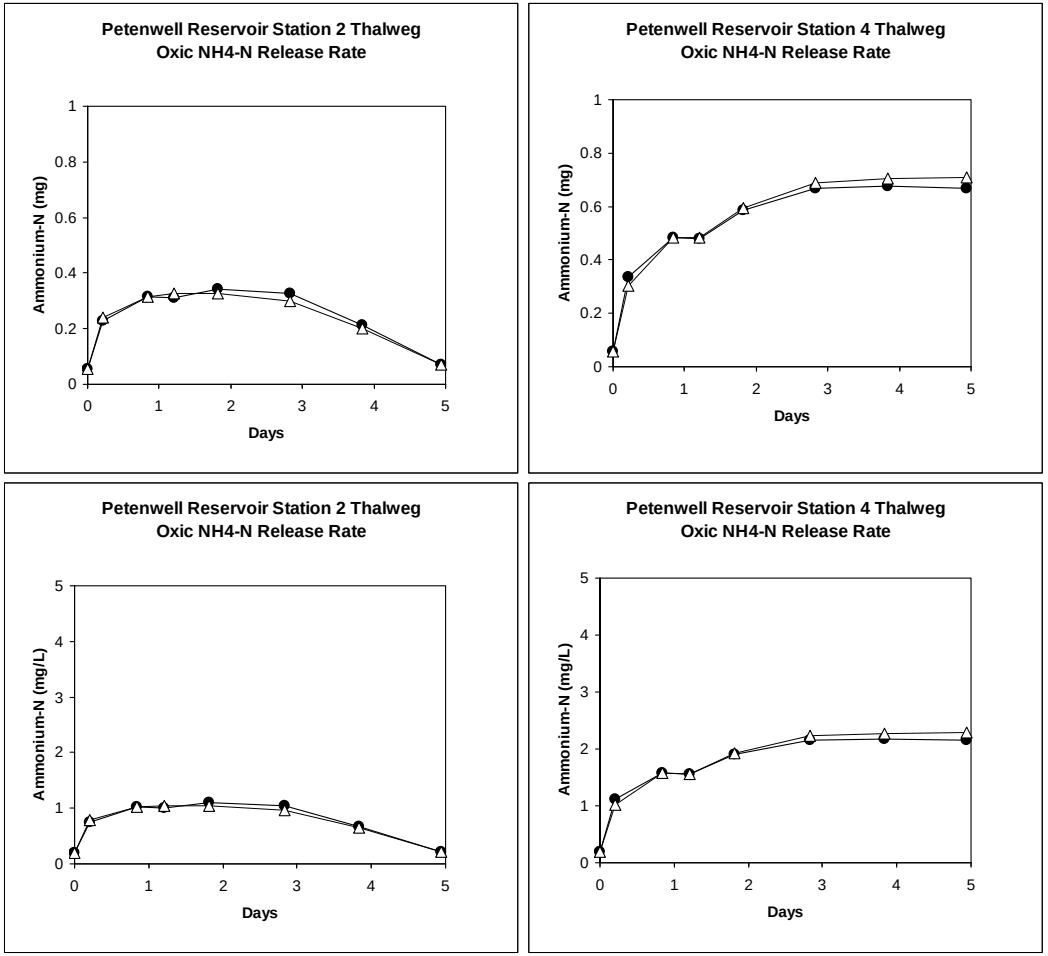

Figure 15. Variations in ammonium-N (NH_x-N) mass (upper panels) and concentration (lower panels) versus time for Petenwell Lake sediment core systems incubated under aerobic (oxic) conditions.

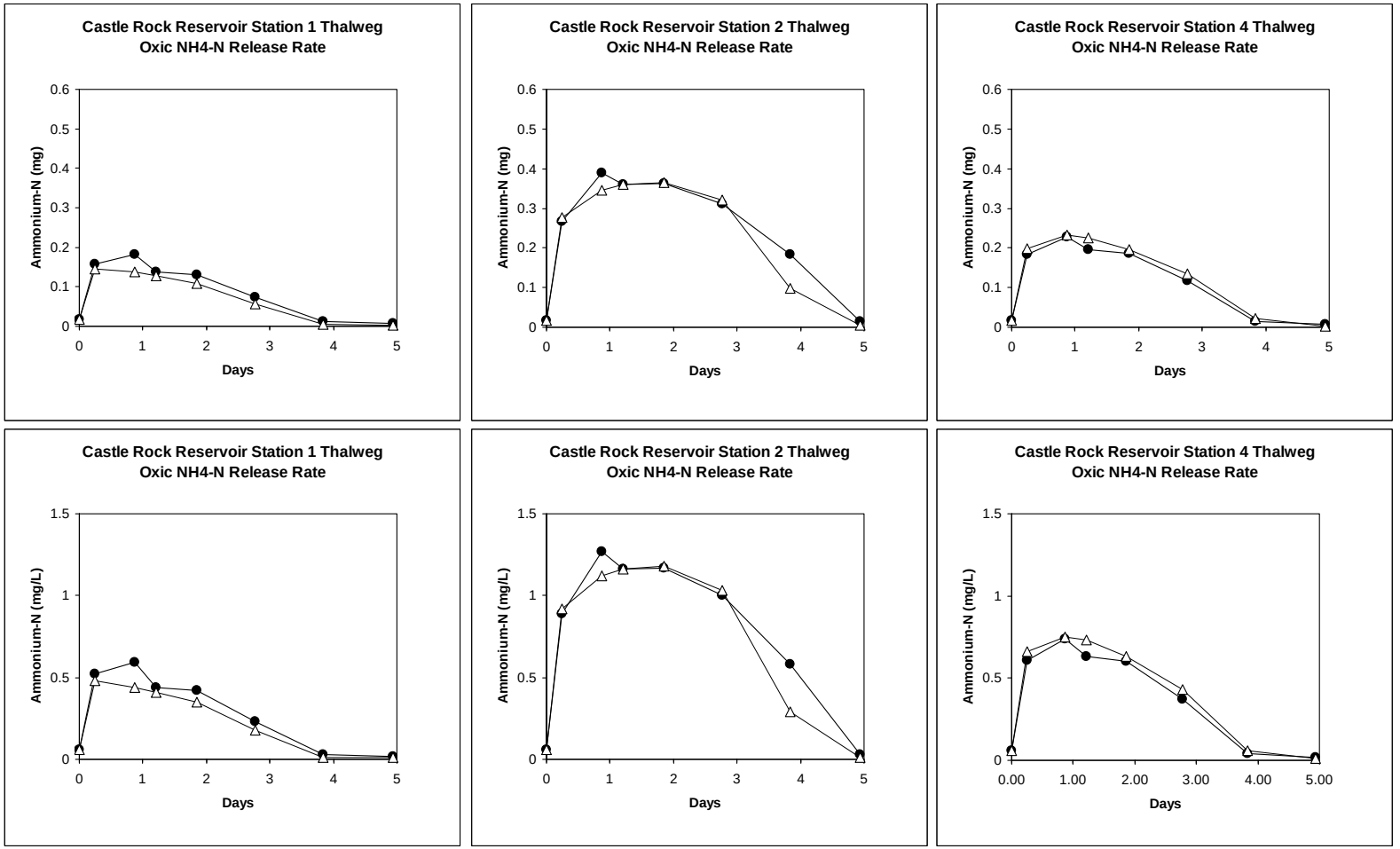

Figure 16. Variations in ammonium-N (NH_x-N) mass (upper panels) and concentration (lower panels) versus time for Castle Rock Lake sediment core systems incubated under aerobic (oxic) conditions.

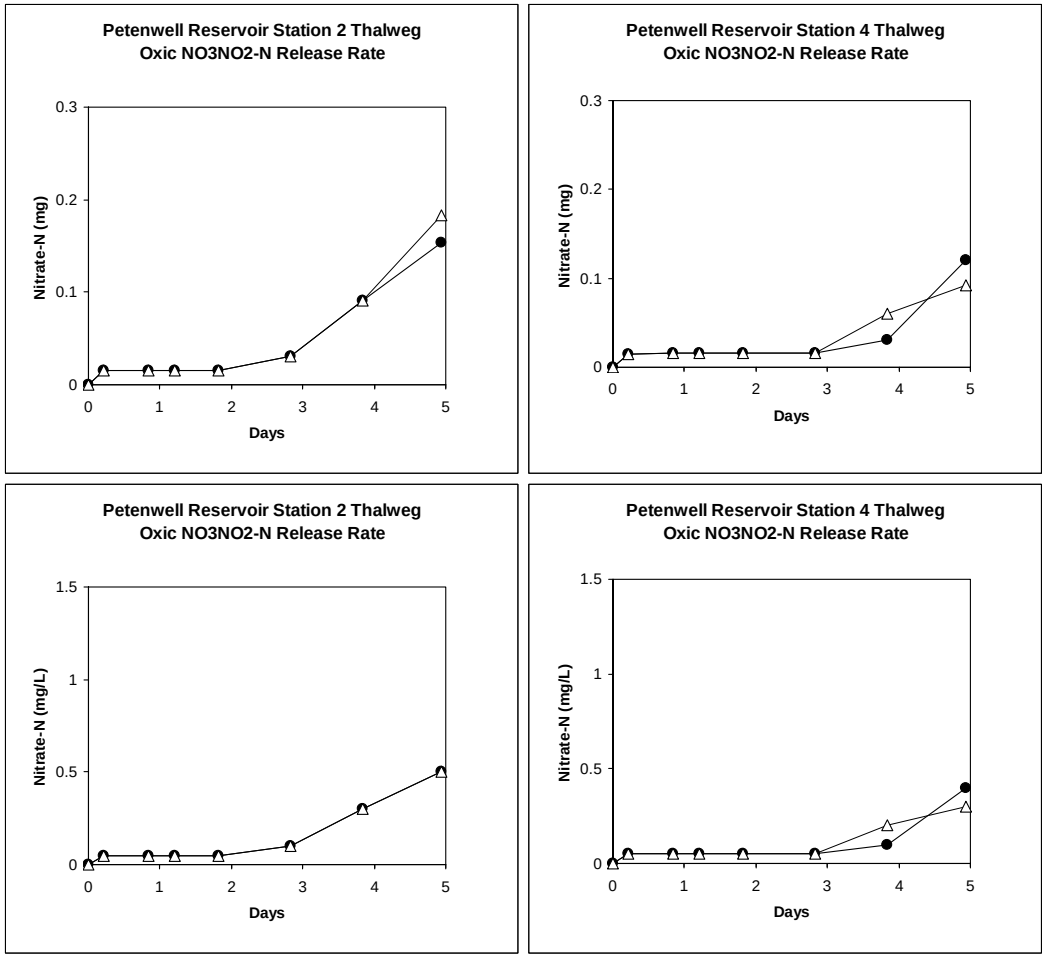

Figure 17. Variations in nitrate-nitrite-N (NO_x-N) mass (upper panels) and concentration (lower panels) versus time for Petenwell Lake sediment core systems incubated under aerobic (oxic) conditions.

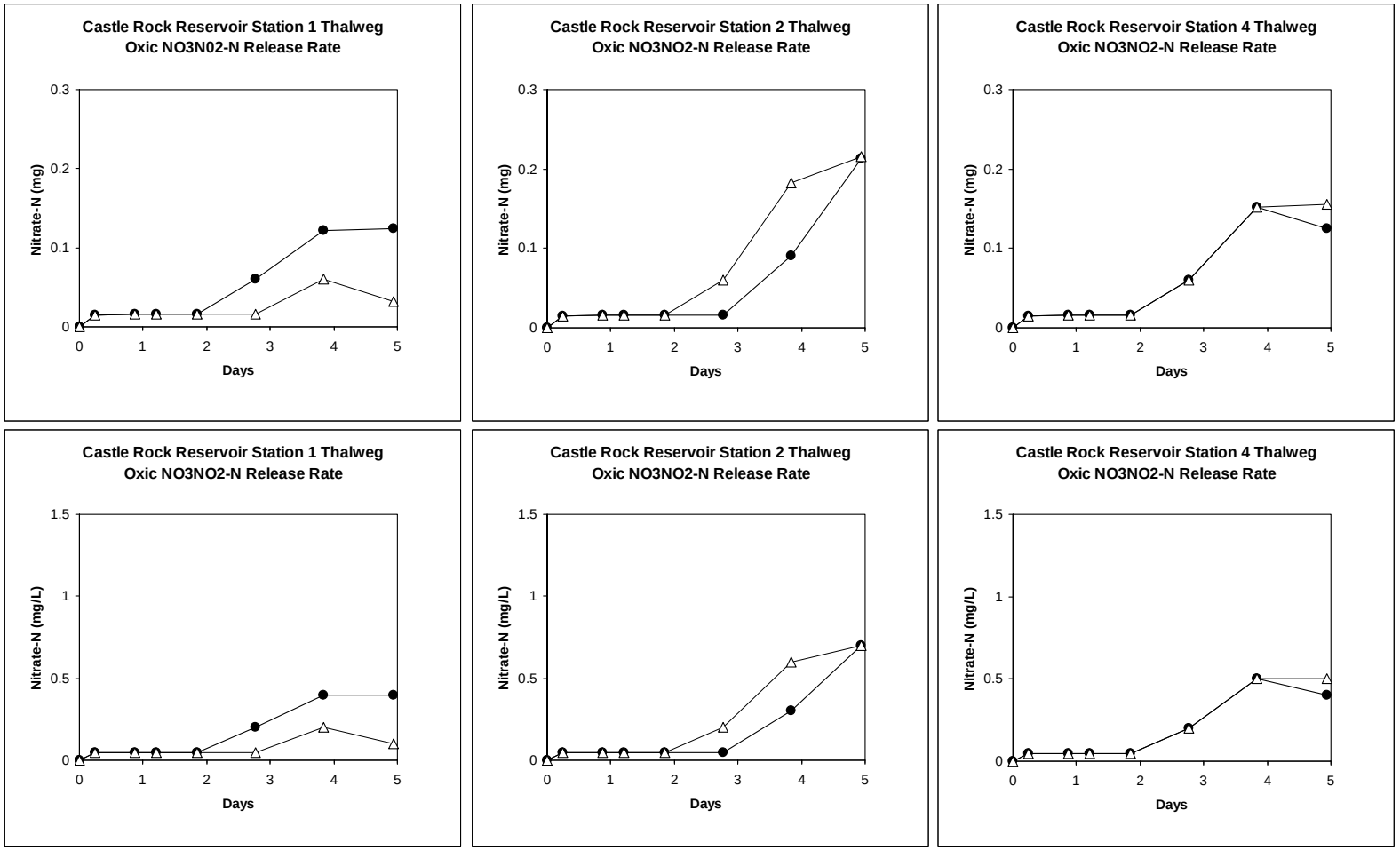

Figure 18. Variations in nitrate-nitrite-N (NO_x-N) mass (upper panels) and concentration (lower panels) versus time for Castle Rock Lake sediment core systems incubated under aerobic (oxic) conditions.

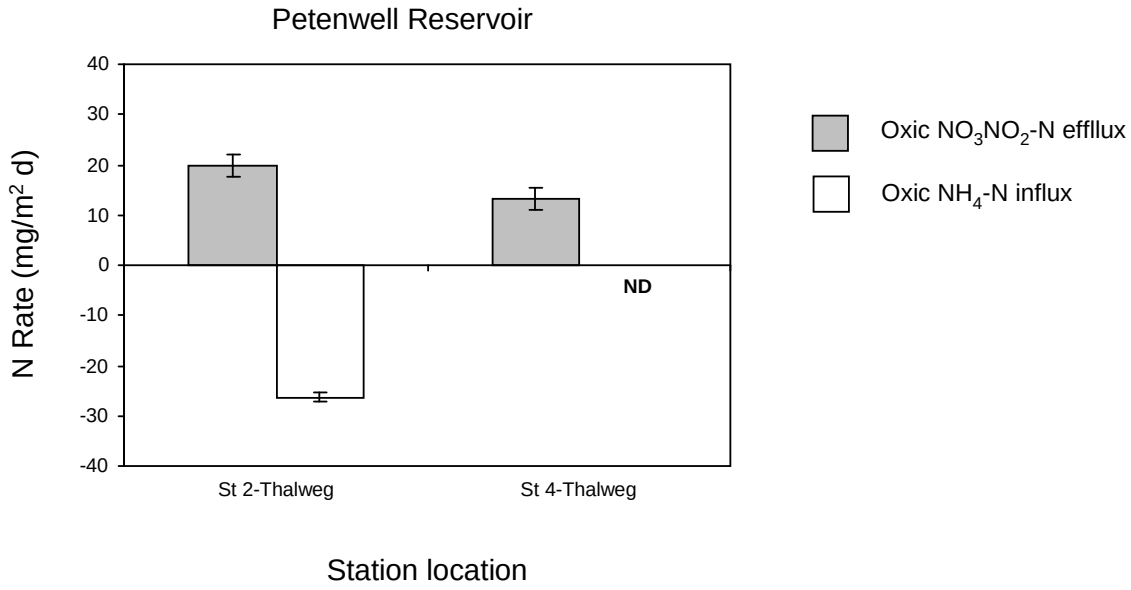

Figure 19. Mean (n=3) rates of ammonium-N (NH_x-N) influx (i.e., mass transfer into sediment) and nitrate-nitrite-N (NO_x-N) efflux (i.e., mass transfer out of sediment) under aerobic (oxic) conditions for sediment cores collected in Petenwell Lake (PL). Vertical brackets represent 1 standard error of the mean.

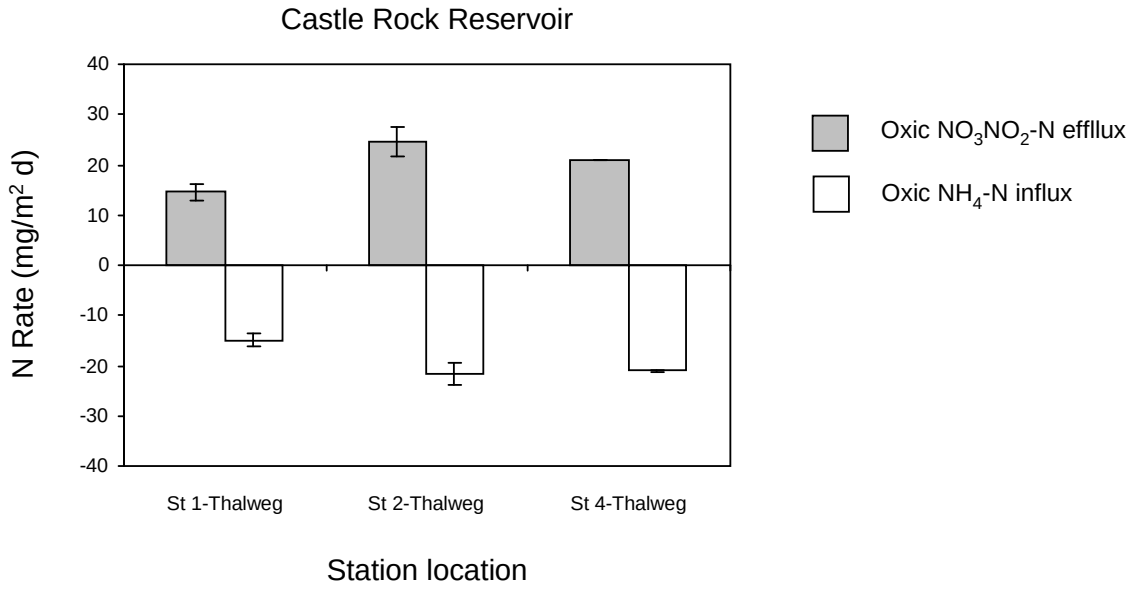

Figure 20. Mean (n=3) rates of ammonium-N (NH_x-N) influx (i.e., mass transfer into sediment) and nitrate-nitrite-N (NO_x-N) efflux (i.e., mass transfer out of sediment) under aerobic (oxic) conditions for sediment cores collected in Castle Rock Lake (CRL). Vertical brackets represent 1 standard error of the mean.

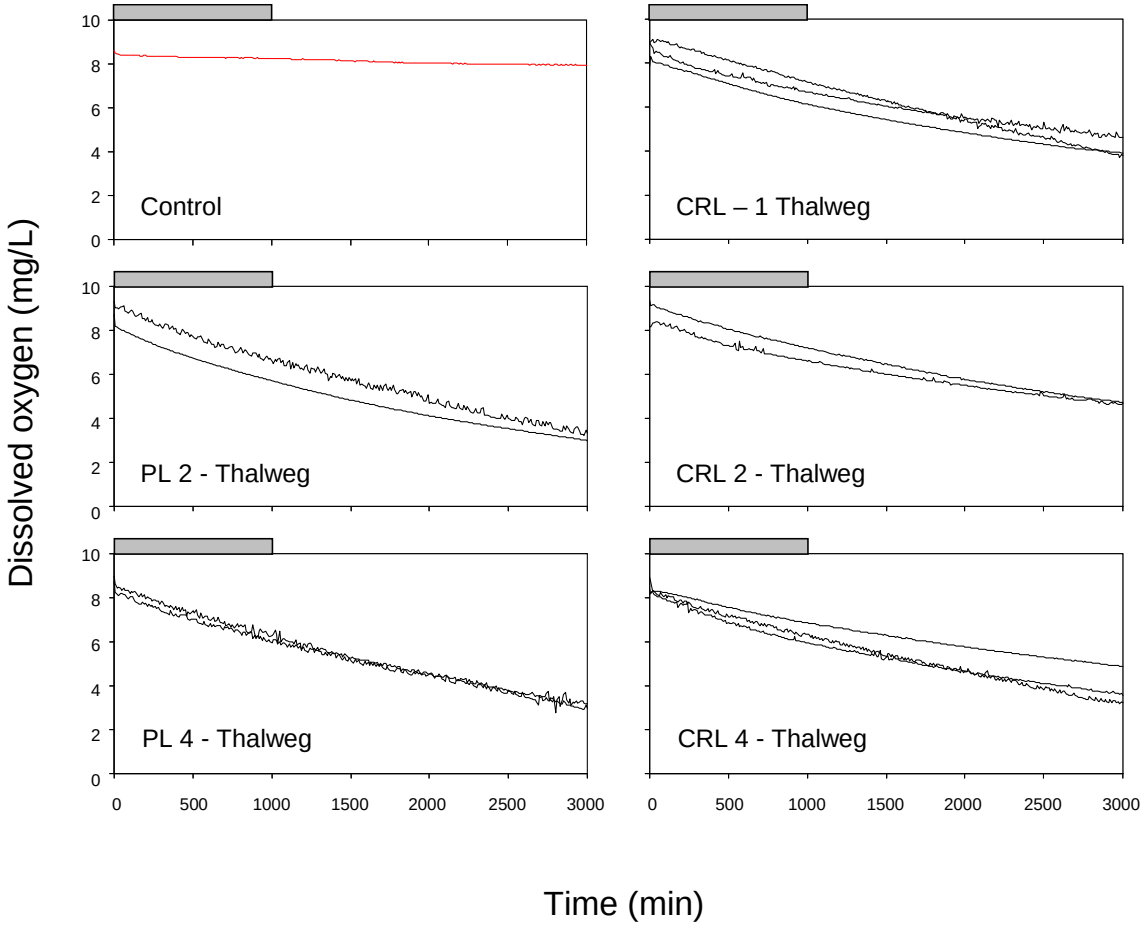

Figure 21. Depletion of dissolved oxygen versus time in control (i.e., water-only system without sediment) and petenwell (PL) of Castle Rock (CRL) sediment systems.

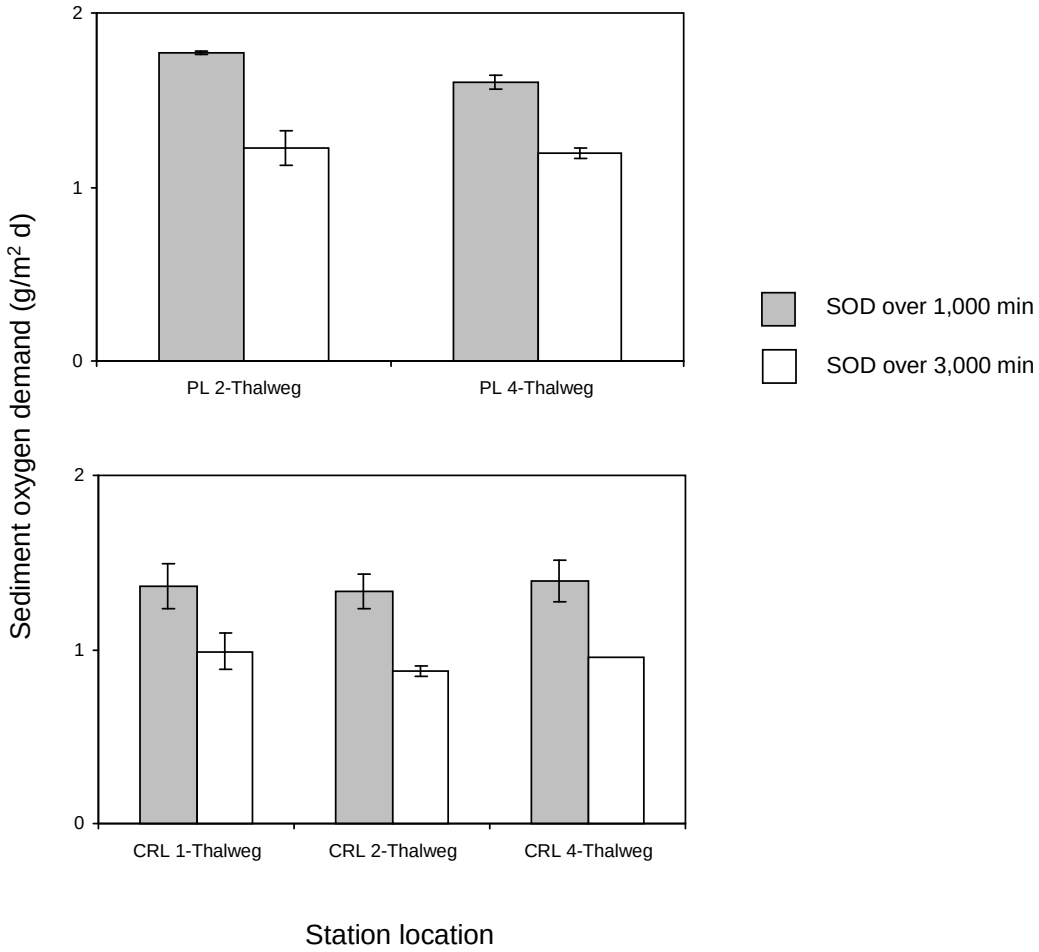

Figure 22. Mean (n=3) sediment oxygen demand estimated over the first 1,000 min and 3,00 min of incubation for sediment cores collected in Petenwell lake (PL) and Castle Rock Lake (CRL). Vertical brackets represent 1 standard error of the mean.