Use of Aluminum Sulfate to Reduce High pH in Fingerling Striped Bass Production Ponds Fertilized with Nitrogen and Phosphorus to Control *Prymnesium Parvum*

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Management Data Series
No. 274
2012

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ACKNOWLEDGEMENTS

We thank the Dundee state fish hatchery staff for help with data collection. Technical support was provided by the Texas Parks and Wildlife Department Environmental Contaminants Laboratory. This study was funded in part by Federal Aid in Sport Fish Restoration Grant F-95-D to the Texas Parks and Wildlife Department.

ABSTRACT

Previous studies revealed that addition of inorganic nitrogen (N) and phosphorus (P) at a rate of 300 µg N/L plus 30 µg P/L is effective in controlling *Prymnesium parvum* cell density and ichthyotoxicity. A major obstacle to utilizing this technique effectively in striped bass *Morone saxatilis* culture ponds has been elevated pH levels that are toxic to striped bass fry and fingerlings. We evaluated aluminum sulfate (alum) for efficacy in lowering pH in ponds fertilized (300 µg N/L plus 30 µg P/L thrice weekly) for *P. parvum* control. Further, the effects of alum on dissolved P and N concentrations and on the efficacy of the fertilization regimen for *P. parvum* control were examined. Ten 0.1-ha plastic-lined ponds were used; all were subjected to the same fertilization regimen. Five ponds received alum applications (1 mg/L alum for 1 mg/L phenolphthalein alkalinity) when afternoon pH was 9.0 or greater. The remaining five ponds received no alum and served as controls. Striped bass fingerlings (22 mm total length) were produced in these ponds in 42 d. Alum reduced pH by 13 % in the morning and 8% in the afternoon compared to the controls but was unable to maintain afternoon pH <9. Alum reduced concentrations of total P, soluble reactive P, total Kleldahl N, nitrite + nitrate N, and total N but not ammonium N. The fertilization regimen was ineffective in controlling *P. parvum* probably because of N and P removal by alum. Striped bass production was poor in all ponds because of high pH. Future studies should investigate higher alum treatment rates (e.g., phenolphthalein alkalinity:alum = 1:1.5 or 1:2) along with a modification of the fertilization regimen such as the timing or frequency of fertilization.

INTRODUCTION

Prymnesium parvum causes large losses of fish in brackish aquaculture ponds when cell densities and ichthyotoxin concentrations are not eliminated or drastically reduced (Tal and Shelubsky 1952; Shilo and Shilo 1953; Guo et al. 1996). In 2001 and 2002, *P. parvum* was first identified as the cause of fish mortalities at the Texas Parks and Wildlife Department (TPWD) Dundee Fish Hatchery (DFH) and Possum Kingdom Fish Hatchery (PKFH), respectively. Since 2001, TPWD has investigated methods for controlling *P. parvum* cell densities and ichthyotoxicity (Dorzab and Barkoh 2005; Smith 2005a, b; Barkoh et al. 2003; 2004; 2008, 2011; Kurten et al. 2007, 2010, 2011). The current control strategies include the use of ammonium sulfate $\{(NH_4)_2SO_4\}$ or copper sulfate ($CuSO_4$) to reduce cell densities and potassium permanganate ($KMnO_4$) to mitigate ichthyotoxicity (Barkoh and Fries 2005; Barkoh et al. 2010). These strategies have been used relatively successfully at DFH and PKFH (Kurten et al. 2010); however, there are significant risks associated with these approaches when used in ponds for culturing sensitive fish such as striped bass *Morone saxatilis* fry and fingerlings.

Effective use of ammonium sulfate to lyse *P. parvum* cells requires current knowledge of cell densities, pond water conductivity, pH, temperature, and total ammonia concentration in order to determine if a treatment is warranted and to calculate the un-ionized ammonia (NH_3) application rate needed for control (Shilo and Shilo 1953; Barkoh et al. 2004, 2010). The ability to accurately anticipate future temperature and pH dynamics in ponds also is required because sensitive fish species can be vulnerable to elevated NH_3 (Bergerhouse 1993; Oppenborn and Goudie 1993; Ashe at al. 1996; Harcke and Daniels 1999; Barkoh et al. 2004) associated with increases in temperature and pH (Emerson et al. 1975). The range of NH_3 concentrations that effectively lyses *P. parvum* cells without also causing significant fish mortality is quite narrow (Barkoh et al. 2004, 2010) and can change rapidly when weather changes pond pH and water temperatures. In early spring, cool water temperatures and low pH can make target NH_3 concentrations that lyse *P. parvum* cells ($\geq$0.14 mg/L; Barkoh et al. 2003; 2010) difficult to achieve. With regards to copper sulfate, its use in striped bass fingerling rearing ponds is inappropriate because it also kills phytoplankton and can be toxic to zooplankton and aquatic insects (McKnight et al. 1983; Welch et al. 1990; Guo et al. 1996; Irwin 1997). These adverse effects of copper sulfate disrupt the pond food web that supports fingerling production. In addition, the use of ammonium sulfate or copper sulfate is labor-intensive and costly.

We have investigated fertilization of aquaculture ponds, as an alternate method to the current chemical applications, for *P. parvum* control since 2001 (Barkoh and Fries 2005). We have not determined whether the mechanism of *P. parvum* control is through reduction in allelopathy or through competitive exclusion by other algae, or a combination of both, but we have found that inorganic fertilization (300 µg N/L plus 30 µg P/L) is a viable method for eliminating *P. parvum* from ponds (Kurten et al. 2007). Incidentally, elevated pH and NH_3 were two issues that emerged with the development of the effective fertilization regimen for *P. parvum* control. We have resolved the high NH_3 problem by using nitrate (NO_3) instead of ammonium (NH_4) as the source of inorganic nitrogen (N; Kurten et al. 2010) but found cottonseed meal fertilization ineffective in reducing the high pH stimulated by our inorganic fertilization regimen (Kurten et al. 2011).

Alum (aluminum sulfate; $Al_2(SO_4)_3.14H_2O$) is acidic in water and can reduce total alkalinity and pH by neutralizing carbonate and bicarbonate compounds with a greater decline in pH when applied to water with low initial total alkalinity (Boyd 1979a; 1990; Wilkinson 2002). Alum treatments of 15-25 mg/L have been reported to lower pH by 0.4-1.5 units in 48 h (Boyd 1979a). Mandal and Boyd (1980) used alum to reduce pH by 0.3 and 0.8 in 8 and 16 d, respectively whereas Masuda and Boyd (1994) applied alum at 20 mg/L to lower pH by 0.8**.** A major concern with using alum in fertilized ponds, such as in this study, is that alum precipitates phosphorus as insoluble aluminum phosphate (Boyd 1979a; Masuda and Boyd 1994; Wilkinson 2002), making it unavailable for phytoplankton growth. We investigated the efficacy of alum in maintaining pH <9 in ponds subjected to our inorganic fertilization regimen (300 µg N/L:30 µg P/L three times weekly applications) for controlling *P. parvum* (Kurten 2007; 2010). We also examined the effect of alum on the fertilizer chemicals (P and N) and on the effectiveness of the inorganic fertilization regimen in controlling *P. parvum*.

MATERIALS AND METHODS

Pond filling, fertilization, and alum treatment

This study was conducted in ten 0.1-ha plastic-lined ponds at the DFH, Archer County, Texas from April 7 through May 31, 2008 during the normal period of phase 1 (35-45 mm) striped bass fingerling production. Ponds were filled two weeks (day -14) before fry stocking (day 0 was day of fish stocking) with water from Lake Diversion, the source of water to the hatchery, which has the following water quality characteristics (in mg/L): total suspended solids (TSS) 19; total dissolved solids (TDS) 2,923; Cl 1,031; SO_4 654; Ca 173; Mg 51; Na 550; K 14; and alkalinity 99. Ponds were randomly assigned to control and treatment groups; each comprised five replicate ponds. Control ponds received no alum treatments whereas treatment ponds received alum when afternoon pH was 9.0 or higher. Alum treatments were estimated from phenolphthalein alkalinity. Phenolphthalein alkalinities were determined on approximately 300-mL pond water samples by using the standard sulfuric acid titration procedure in Standard Methods (2320 B, APHA 1998; Boyd 1979b). Water samples were collected from ponds in white, opaque, 1-L polyethylene bottles from depths of 25-30 cm. Titrations were completed within 25 min after water sample collection. Alum treatments were applied at a 1:1 ratio (i.e., for every 1 mg/L phenolphthalein alkalinity, 1 mg/L alum was applied to the pond; Boyd 1990). Alum was applied by broadcasting onto the pond water surface on the windward side of the pond and allowing wind action to disperse it across the pond.

All ponds were subjected to the same inorganic and organic fertilization regimens. Inorganic fertilization consisted of three times weekly applications of 300 µg N/L plus 30 µg P/L beginning on day -14 and ending on day 39, three days until harvest of fingerlings. Potassium nitrate (KNO_3; N-P-K = 13.5-0-46.2) and phosphoric acid (H_3PO_4; 0-54-0) were the sources of inorganic N and P, respectively. Organic fertilization followed a standard TPWD regimen of three applications of cottonseed meal during the production season: 170.3 kg/ha during pond filling (day -10), 56.8 kg/ha on day 1, and 56.8 kg/ha on day 8.

Water quality

Morning and afternoon water temperatures, pH, and dissolved oxygen (DO) concentrations were measured twice daily (0700 and 1500 hours) using a YSI 650 MDS handheld meter fitted with a YSI 600 XL multiprobe sonde (Yellow Springs Instruments, Yellow Springs, Ohio). Water samples were taken twice a week for nutrient and chlorophyll-*a* analyses from 25-30 cm below the pond water surface using opaque, white (1 L) and brown (250 mL) polyethylene bottles, respectively. Water samples were packed on ice and shipped overnight to the TPWD Environmental Contaminants Laboratory in San Marcos, Texas for analysis. Total P (TP), orthophosphate-P (PO_4-P), total Kjeldahl N (TKN), nitrite plus nitrate-N (NO_{2+3}-N), ammonium-N (NH_4-N), and chlorophyll *a* were measured each Tuesday and Friday after pond filling. These analyses were performed using USEPA-approved methods (USEPA 1983) or standard methods (APHA 1998). Methods and detection limits were as follows: TP (USEPA 365.4; P = 22 µg P/L), PO_4-P (USEPA 365.3; P = 1.7 µg P/L), TKN (USEPA 351.2; N = 83 µg N/L), NO_{2+3}-N (USEPA 353.2; N = 7 µg N/L), NH_3-N (USEPA 350.1; N = 19 µg N/L) and chlorophyll *a* (APHA 10200H; 1.17 µg /L). Inorganic N was estimated as the sum of NO_{2+3}-N and NH_3-N, organic N by subtracting NH_3-N from TKN, and organic P by subtraction PO_4-P from TP (USEPA 1983; APHA et al. 1998).

Prymnesium parvum cell density and toxicity

Prymnesium parvum cell densities and ichthyotoxicity were monitored twice weekly using standard TPWD fish hatchery procedures (Southard and Fries 2005). Cell densities were estimated by examining 10-µL fresh unfixed water samples from ponds with a hemacytometer at 400X magnification. Ichthyotoxicity bioassays were performed each Wednesday, after pond filling, using fathead minnow *Pimephales promelas* fry as test animals at 28°C. Individual bioassays utilized water collected from each pond and four test animals each were exposed to 100 mL undiluted water, 100 mL undiluted water plus 2 mL cofactor, or water diluted by 1/5 with *P. parvum*-free water plus 2 mL cofactor. Four fish were also placed in undiluted *P. parvum*-free water for control. The cofactor solution consisted of 0.003 M 3,3'-iminobispropylamine and 0.02 M tris buffer (pH 9.0) and functioned to increase the toxicity of *P. parvum* ichthyotoxin, allowing the otherwise sublethal levels to be detectable. Mortalities of test animals were determined after 2 h, and toxicity in terms of ichthyotoxicity units (ITU) was determined as follows: mortality in undiluted water indicated a high level of toxicity (25 ITU); mortality in 1/5 water dilution plus cofactor, moderate toxicity (5 ITU); mortality in undiluted water plus cofactor, low toxicity (1 ITU); and zero mortality in all bioassays, no toxicity (0 ITU).

Fish production

Fourteen days after filing, ponds were stocked at approximately 500,000 fry/ha (500,010-503,870 fry/ha) with 4-d-old striped bass fry (6 mm total length) which were hatched at DFH. Fry were enumerated into 57-L vats (1 vat per pond) using a Jensorter fry counter. Fry were acclimated to pond water temperatures (19.45-19.67 °C) and pH (8.20-8.74) by using an air-lift pump system to exchange the water in each vat at a rate of 1 L/min for 1 h. Fry were stocked between 2000 and 2200 hours. After stocking, fry were reared for 42 d following TPWD striped bass culture guidelines (Lyon et al. 2006). At harvest, ponds were drained to allow the fish to collect in the harvest basins from where a sample of 100-200 fingerlings was collected for each pond. These fish were enumerated and weighed to calculate number of fish/kg and then 40 fish

in a subsample were individually measured for total lengths. All the fish from each pond were harvested and weighed. Total number of fingerlings from each pond was estimated from total weight and fish/kg data. Fish survival (percent return) was calculated for each pond.

Data analysis

Data were analyzed with PROC MIXED (SAS Institute Inc. 2002). Because data were collected repeatedly from each pond, we modeled the data assuming a repeated measures construct with ponds as subjects. We tested a variety of covariance constructs (none, variance component, compound symmetry, first order autoregressive, and spatial power structure) until we found the one that provided the best fit to the data for each response variable. The Akaike's Information Criterion and the Null Model Likelihood Ratio test were used to determine the model of best fit for the data (Littell et al. 2000). We tested the effects of treatment, sampling date, and the treatment × sampling date interaction on each variable. *Prymnesium parvum* cell density data were square root (X + 0.5)-transformed and chlorophyll-*a* and all nutrients data, except NH_3-N, were $\log_{10}(X + 1)$-transformed before analysis due to skewness and zeros in the data. For all analyses, differences were considered significant at *P*-values less than or equal to 0.05.

RESULTS

Alum treatment

Mean phenolphthalein alkalinity was 6.7 mg/L in alum ponds, and the quantity of alum required for treatments averaged 1,055 kg or 7.2 mg/L. The pH criterion ($pH \geq 9$) for alum treatment was triggered beginning on day -6, and alum treatments were applied at 2.5-d (1- to 5-d) intervals for 54 d.

Water quality

Mean morning or afternoon pH was significantly lower in alum ponds than in control ponds on most sampling days and over the course of the study (Figure 1; Table 1). Mean morning pH for alum ponds was 8.2 compared to 9.4 for control ponds (13% decline), and mean afternoon pH for alum ponds was 9.0 compared to 9.8 for control ponds (8% decline). Morning pH was below the threshold (pH 9) on all but one day whereas afternoon pH exceeded the threshold on most days. By day 10, when stocked fish were 14-d old, mean morning pH were 8.53 (range = 8.10-9.05) and 9.8 (range = 9.45-10.22) and mean afternoon pH were 9.19 (range 8.77-9.48) and 10.07 (range = 9.74-10.47) for alum and control ponds, respectively. Mean DO concentrations statistically differed between alum and control ponds (Table 1). Similarly, mean DO concentrations significantly differed between alum treatment and control over time, but the pattern was inconsistent: mean DO was higher in alum ponds on some days and lower on other days compared to control ponds (Figure 2). Concentrations of morning DO were lower and below 5 mg/L in control ponds on a few sampling days toward the end of the study. Pond water temperatures were reduced from a maximum of 22°C to a minimum of 16°C by a cold front shortly after pond filling (day -12). Subsequently, water temperatures rose gradually to approximately 19 °C on the day of fry stocking and to a maximum of 31°C on day 37 (Figure 3). The difference in morning or afternoon water temperature was not statistically significant between treatment and control ponds (Table 1).

Nutrients

Mean concentrations of all N compounds, except NH_3-N, were significantly lower in alum ponds than in control ponds and varied over time (Table 1; Figure 4). Starting on day 5, mean concentrations were significantly lower in alum than in control ponds on 6 of 10 sampling days for NO_{2+3}-N and 2 of 10 sampling days for TKN. Mean concentration of NH_3-N did not significantly differ between treatment and control ponds on any sampling day or over the course of the study. Mean concentrations of PO_4-P and TP were significantly lower in alum than in control ponds (Table 1): differences were significant on 7 of 10 sampling days for PO_4-P and 5 of 10 sampling days for TP (Figure 5).

Phytoplankton biomass, and P. parvum density and toxicity

Mean chlorophyll-*a* concentrations (surrogate measures of phytoplankton biomass) were not significantly different between treatment and control (Table 1; Figure 6). Chlorophyll-*a* concentrations remained low and steady from day -14 until day 30 when concentrations increased shapely and remained high through the end of the study (Figure 6). Overall mean *P. parvum* cell densities were 49.7 and 27.4 cells/mL for alum and control ponds, respectively but the difference was not statistically significant (Table 1). Cell densities peaked in both alum and control ponds by day -7 before declining to undetectable levels by day 7 in control ponds and day 15 in alum ponds (Figure 7). *Prymnesium parvum* ichthyotoxicity was never detected in either alum or control ponds.

Fingerling Production

All ponds were drained to harvest the fingerlings on day 42. Fingerling production was poor in both treatment and control ponds (Table 2). Alum ponds had an average survival of 4.1% compared to no survival in control ponds (Table 2).

DISCUSSION

At the rate used in this study, alum was ineffective in maintaining afternoon pH below 9. However, alum reduced dissolved inorganic N and P levels to the extent that it negatively affected the efficacy of the fertilization regimen for controlling *P. parvum*. The reductions in pH of alum ponds, 13 % in the morning and 8% in the afternoon from the control, were statistically significant but biologically inconsequential. Afternoon pH remained consistently near or higher than 9.0 which is considered unsuitable for successful production of phase-1 fingerling *Morone* spp. from fry (Anderson 1993; Barkoh 1996). Alum application rates of 15-25 mg/L, each applied once, decreased pH by 0.4-1.5 units, followed by gradual increases in pH to pretreatment levels in 30-60 d (Boyd 1979a; Mandal and Boyd 1980; Masuda and Boyd 1994). In this study, alum applications (mean rate = 7.2 mg/L) reduced pH by 0.8-1.2 units, followed by relatively rapid increases in pH to 9 or greater in about 2.5 d (range = 1 – 5 d). Fertilization of alum ponds with inorganic N and P fertilizers could have accelerated the return of pH to levels above 9. Alum treatments cause declines not only in alkalinity and pH but also declines in soluble P and N (Boyd 1979a; Boyd 1990; Masuda and Boyd 1994; Holz and Hoagland 1999; Rishel and Ebeling 2006). These nutrients are reduced through coagulation and precipitation with aluminum ions whereas alkalinity and pH are reduced when the hydrogen ions from alum react

with alkalinity ions to produce carbon dioxide (CO_2) and water (Boyd 1979a, 1990). Limited or reduced nutrient availability decreases phytoplankton growth and CO_2 uptake (Boyd 1979b; Hecky and Kilham 1988; Boyd 1997; Kurten et al. 1999). Under these conditions, it takes relatively more time for the reduced pH to return to pretreatment levels (Boyd 1990; Masuda and Boyd 1994). Conversely, our fertilization of alum ponds replaced some of the nutrients removed by alum, since the mean concentrations were lower than those of the control (Table 1), to support higher rates of CO_2 uptake by phytoplankton than otherwise. Consequently, pH increased quickly from the low levels achieved by alum applications.

Alum reduced concentrations of measured N (NO_{2+3}-N, TKN, and TN) and P (PO_4-P and TP) compounds except NH_3-N (Figure 4 and 5) which agrees with results of previous studies (Malhotra et al. 1964; Malecki-Brown et al. 2009). Thus, alum application negated the result of our fertilization strategy which was to provide adequate quantities of P and N to control *P. parvum*. Though *P. parvum* density did not statistically differ between alum and control ponds, probably because of the high variability in the data, the density in alum ponds was almost twice that in control ponds. Further, *P. parvum* was undetectable in control ponds approximately 8 d before becoming undetectable in alum ponds. Thus, *P. parvum* control was worse in alum ponds, indicating that the fertilization was ineffective in controlling the algae and suggests that the strategy used in the application of alum and fertilizers in this study is not appropriate for achieving success in the control of *P. parvum*. *Prymnesium parvum* ichthyotoxicity was never an issue during this study probably because of adequate availability of nutrients (P and N) and, consequently, lack of stress on these algae. Phosphorus- and N-deficiency conditions cause toxin production or release in *P. parvum* (Granéli and Johansson 2003).

Striped bass production was poor overall and worse in control ponds probably due to high pH ($\geq$9) levels during the course of the study. Barkoh (1996) achieved better fingerling striped bass production in ponds with mean pH $\leq$8.5. Further, avoiding pH>9 in the week striped bass fry (e.g., 4-d old) were stocked or pH>8.5 before striped bass were 14 d old resulted in successful fingerling striped bass production in ponds (Anderson 1993). These conditions were not achieved in this study and thus explain the observed poor fingerling striped bass production.

Our results support reports that alum can reduce pH of water (Mandal and Boyd 1980; Rishel and Ebeling 2006) and thus has promise as a tool for managing pH levels in fish culture ponds (Boyd 1990; Tucker and D'Abramo 2008). However, the concurrent use of alum to control pH of ponds receiving fertilization as a management strategy for the culture of sensitive fish needs a better strategic execution than was employed in the present study. We suggest future studies investigate higher alum treatment rates (e.g., phenolphthalein alkalinity:alum = 1:1.5 or 1:2) along with a modification of the current fertilization regimen. We theorize that a higher alum treatment rate would cause a larger reduction in pH since the extent of pH depression by alum is related to total alkalinity (Boyd 1979a). Because of the high alkalinity of the DFH water, increasing alum application rates beyond the phenolphthalein alkalinity demand may achieve lower pH levels. In addition, discontinuing inorganic fertilization (or reducing the application frequency) after *P. parvum* cells are eliminated or drastically reduced, for example, would minimize phytoplankton growth and CO_2 uptake. Such a strategy could lengthen the time for pH to return to pretreatment levels and thereby allow the fish to reach life stages that can tolerate the ambient pH levels.

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TABLE 1.—*P*-values for model effects of repeated measures analysis of variance and mean (SE) values of variables measured in ponds fertilized with 300 µg N/L and 30 µg P/L three times weekly (control) or 300 µg N/L and 30 µg P/L three times weekly plus alum treatments when afternoon pH was or exceeded 9.0 (alum) at the Dundee state fish hatchery in spring 2008. Values for organic and inorganic N and P were derived and not analyzed using analysis of variance. Differences were considered significant at $P \leq 0.05$.

Variables	Model effects			Treatment	
	Treatment	*Day*	*Day* x *Treatment*	Alum	Control
Morning temperature	0.7033	<0.0001	0.4290	20.0 (3.44)	20.0 (3.39)
Afternoon temperature	0.0965	<0.0001	<0.0001	22.5 (3.70)	22.7 (3.74)
Morning dissolved oxygen (mg/L)	<0.0001	<0.0001	<0.0001	8.5 (1.73)	8.0 (2.37)
Afternoon dissolved oxygen (mg/L)	0.0343	<0.0001	<0.0001	10.8 (1.52)	11.2 (2.07)
Morning pH	<0.0001	<0.0001	<0.0001	8.2 (0.57)	9.4 (0.79)
Afternoon pH	<0.0001	<0.0001	<0.0001	9.0 (0.46)	9.8 (0.81)
Chlorophyll *a* (µg/L)	0.7353	<0.0001	<0.0001	3.0 (2.53)	2.9 (2.07)
P. parvum density (cells/mL)	0.2474	<0.0001	0.0044	49.7 (141.80)	27.4 (90.9)
NO_{2+3}-N (mg/L)	0.0010	<0.0001	<0.0001	0.50 (0.33)	1.16 (0.78)
NH_3-N (mg/L)	0.4611	<0.0001	<0.0001	0.04 (0.01)	0.04 (0.01)
Total Kjeldahl N (mg/L)	<0.0001	<0.0001	<0.0001	2.5 (1.12)	3.00 (1.23)
Total N (mg/L)	<0.0001	<0.0001	<0.0001	3.0 (1.09)	4.16 (1.80)
Total P (mg/L)	<0.0001	<0.0001	<0.0001	0.11 (0.09)	0.24 (0.20)
PO_4-P (mg/L)	<0.0001	<0.0001	<0.0001	0.04 (0.02)	0.10 (0.5)
Inorganic N (mg/L)	-	-	-	0.53 (0.33)	1.20 (0.78)
Organic N (mg/L)	-	-	-	2.4 (1.13)	2.96 (1.23)
Organic P (mg/L)	-	-	-	0.08 (0.09)	0.14 (0.17)

TABLE 2.—Mean values of fish production variables for ponds fertilized with 300 µg N/L and 30 µg P/L three times weekly (control) or 300 µg N/L and 30 µg P/L three times weekly plus alum treatments when afternoon pH was or exceeded 9.0 (alum) at the Dundee state fish hatchery in spring 2008.

	Treatment	
Variable	Alum	Control
Number stocked	50,048	50,222
Number harvested	2,072	0
Survival (%)	4.1	0
Total length (mm)	22.3	0.0

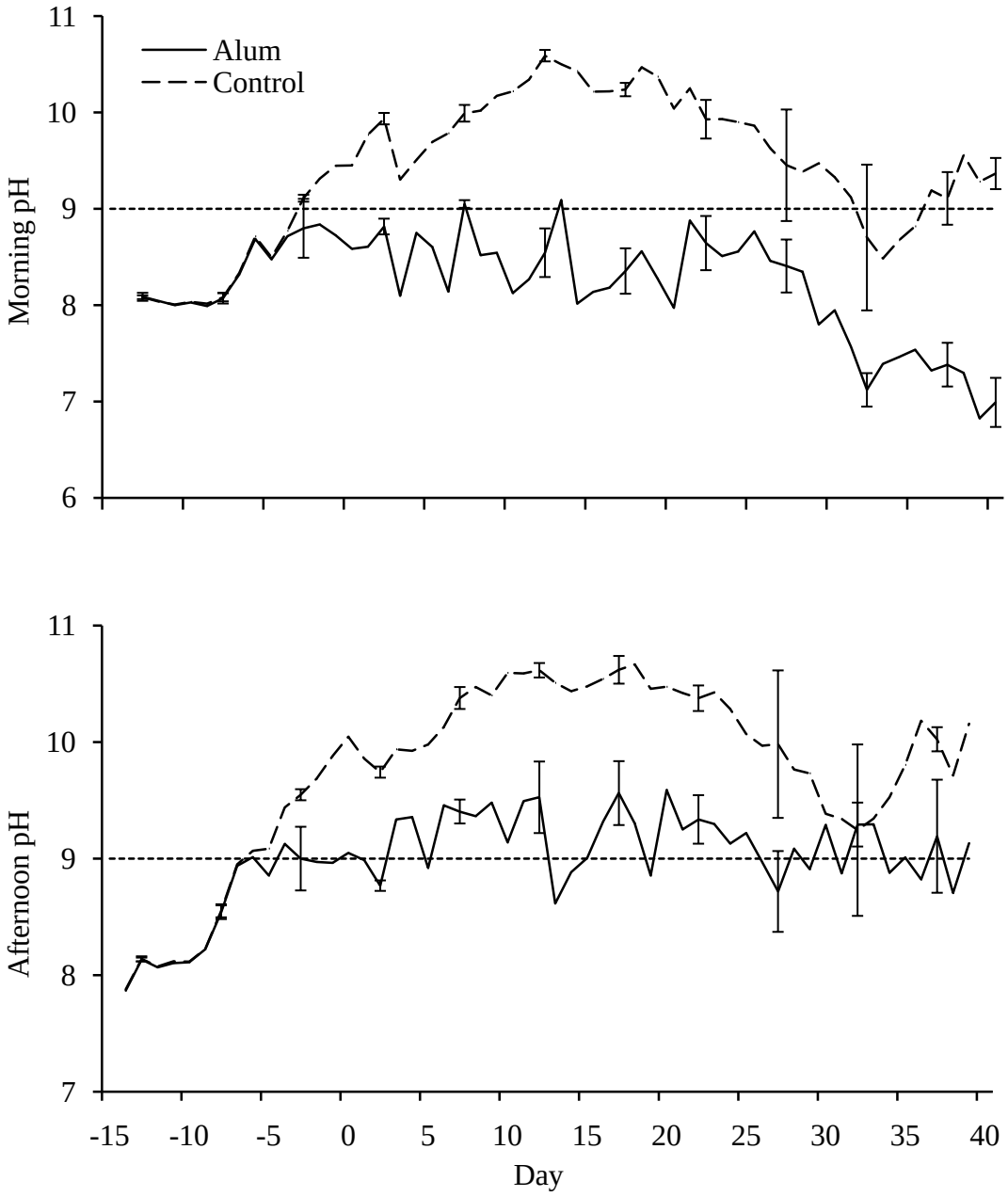

FIGURE 1.—Trends of mean morning and afternoon pH in ponds fertilized with 300 µg N/L and 30 µg P/L three times weekly (control) or 300 µg N/L and 30 µg P/L three times weekly plus alum treatments when pH was or exceeded 9.0 (alum) at the Dundee state fish hatchery in spring 2008. Vertical bars are standard errors; horizontal dotted line is the pH threshold (9.0) for managing pH in fingerling *Morone* spp. production ponds.

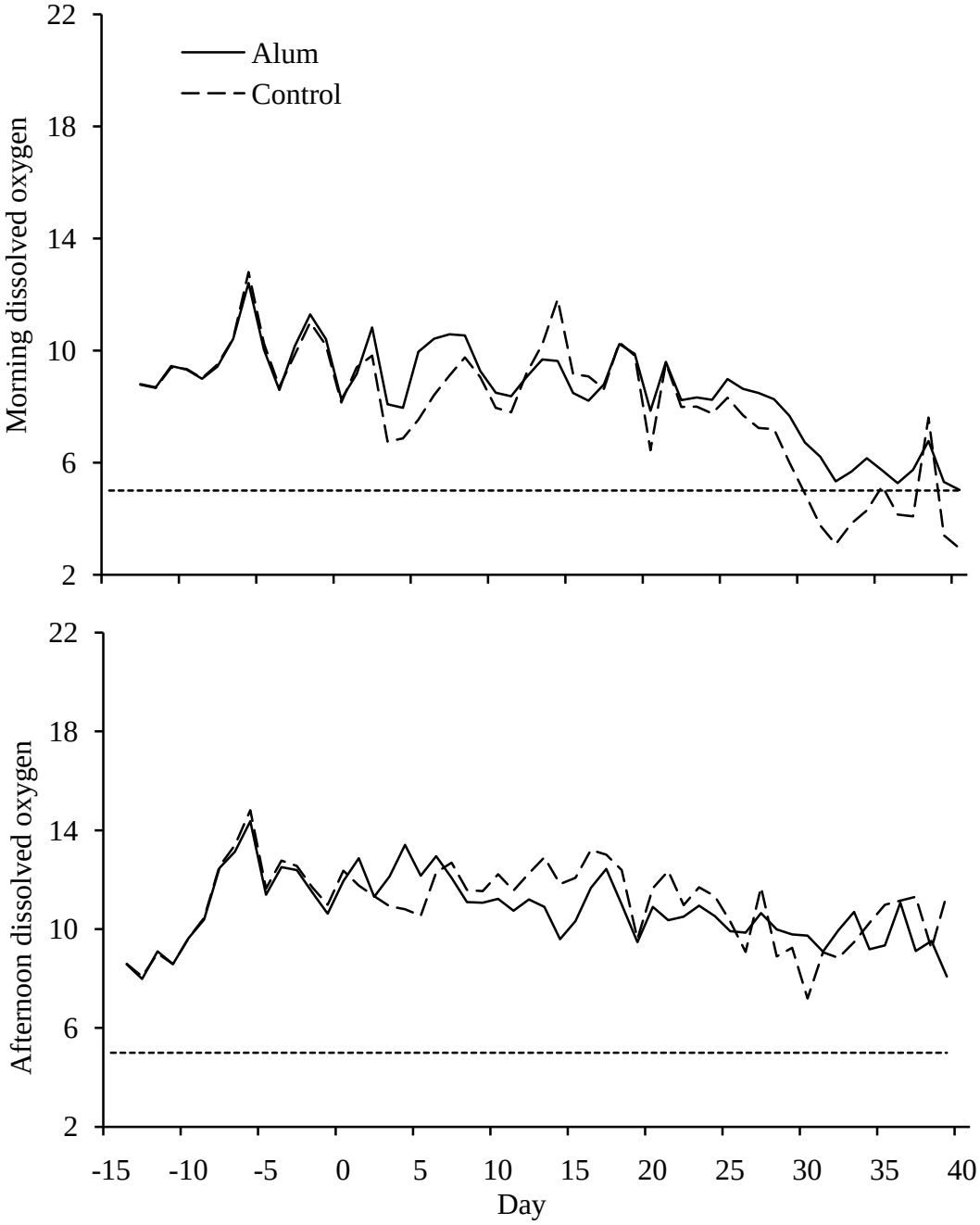

FIGURE 2.—Trends of mean morning and afternoon dissolved oxygen concentrations (mg/L) in ponds fertilized with 300 µg N/L and 30 µg P/L three times weekly (control) or 300 µg N/L and 30 µg P/L three times weekly plus alum treatments when pH was or exceeded 9.0 (alum) at the Dundee state fish hatchery in spring 2008. Horizontal dotted line is the minimum safe dissolved oxygen concentration (5 mg/L) for the production of *Morone* spp. fingerlings.

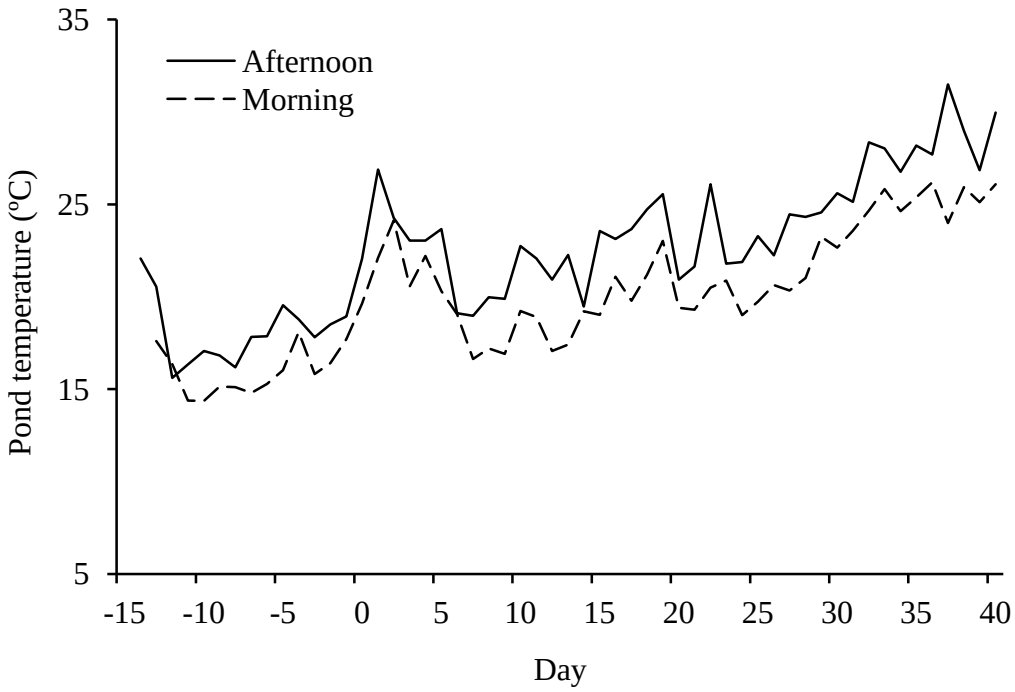

FIGURE 3.—Pooled mean morning and afternoon water temperatures in ponds fertilized with 300 µg N/L and 30 µg P/L three times weekly (control) or 300 µg N/L and 30 µg P/L three times weekly plus alum treatments when pH was or exceeded 9.0 (alum) at the Dundee state fish hatchery in spring 2008.

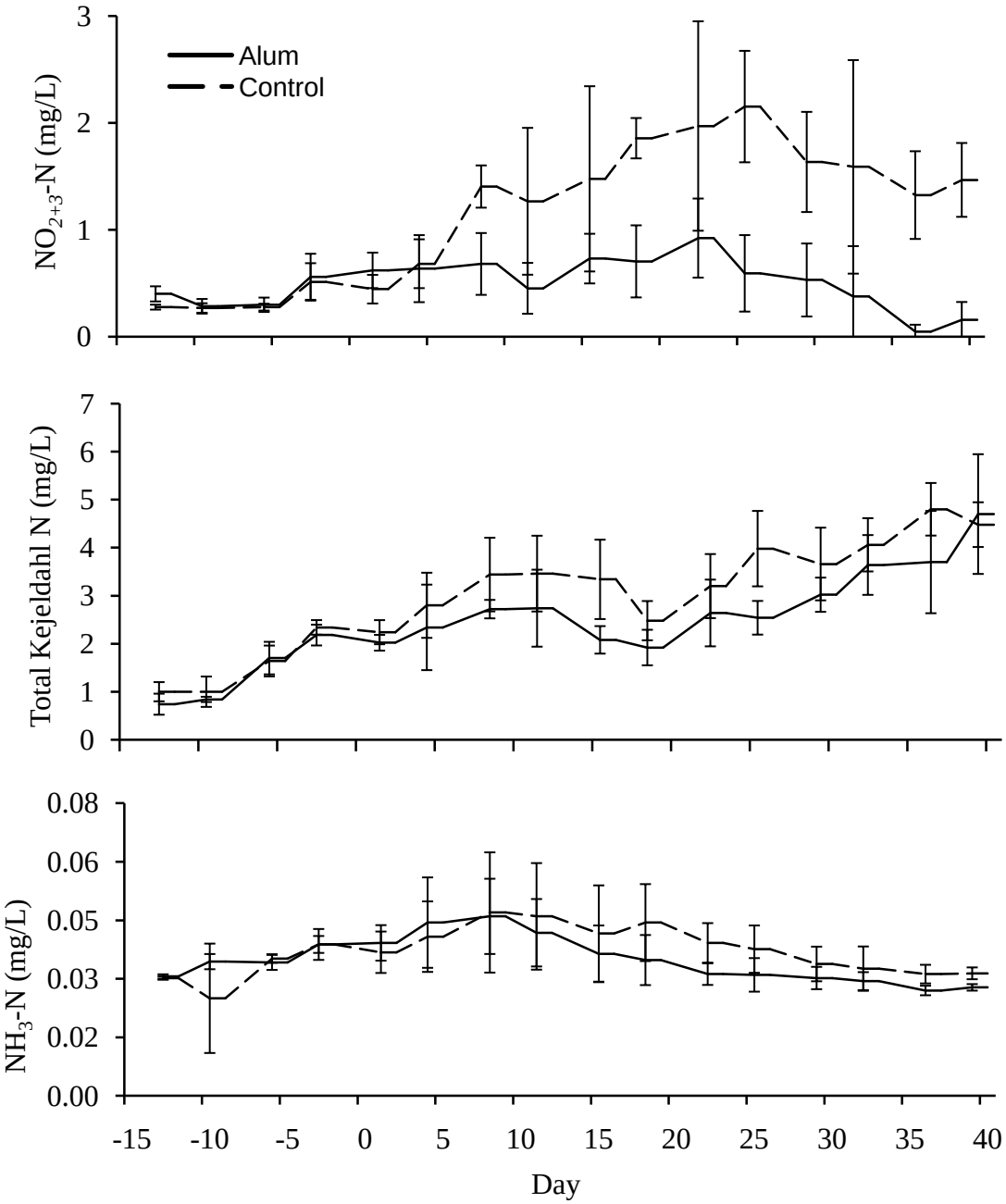

FIGURE 4.—Trends of mean nitrogen concentrations in ponds fertilized with 300 µg N/L and 30 µg P/L three times weekly (control) or 300 µg N/L and 30 µg P/L three times weekly plus alum treatments when pH was or exceeded 9.0 (alum) at the Dundee state fish hatchery in spring 2008. Vertical bars are standard errors.

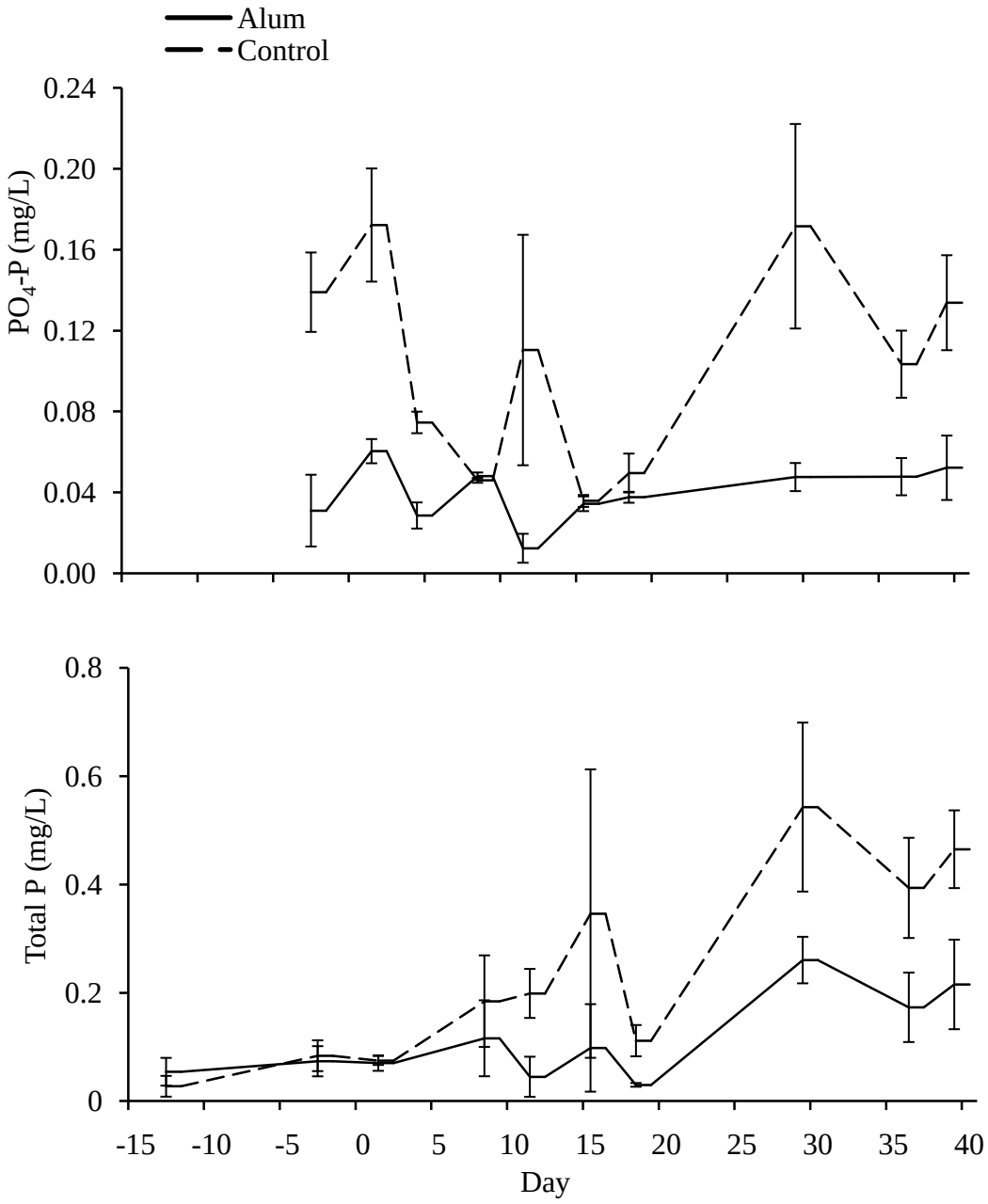

FIGURE 5.—Trends of mean phosphorus concentrations in ponds fertilized with 300 µg N/L and 30 µg P/L three times weekly (control) or 300 µg N/L and 30 µg P/L three times weekly plus alum treatments when pH was or exceeded 9.0 (alum) at the Dundee state fish hatchery in spring 2008. Vertical bars are standard errors.

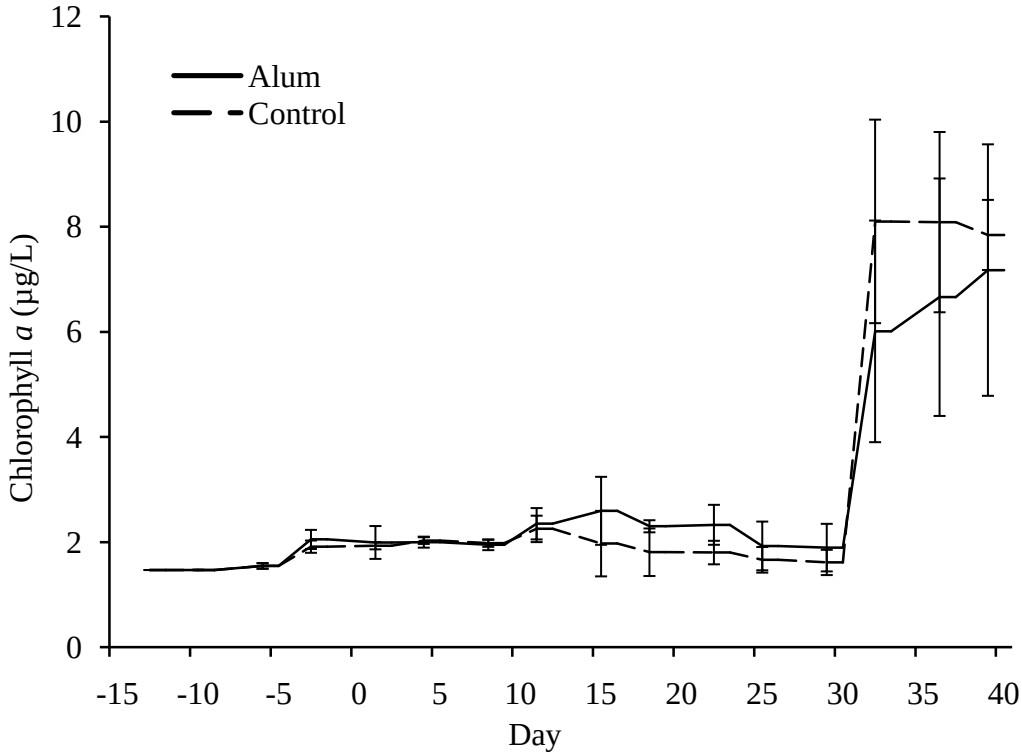

FIGURE 6.—Trends of mean chlorophyll-*a* levels in ponds fertilized with 300 µg N/L and 30 µg P/L three times weekly (control) or 300 µg N/L and 30 µg P/L three times weekly plus alum treatments when pH was or exceeded 9.0 (alum) at the Dundee state fish hatchery in spring 2008. Vertical bars are standard errors.

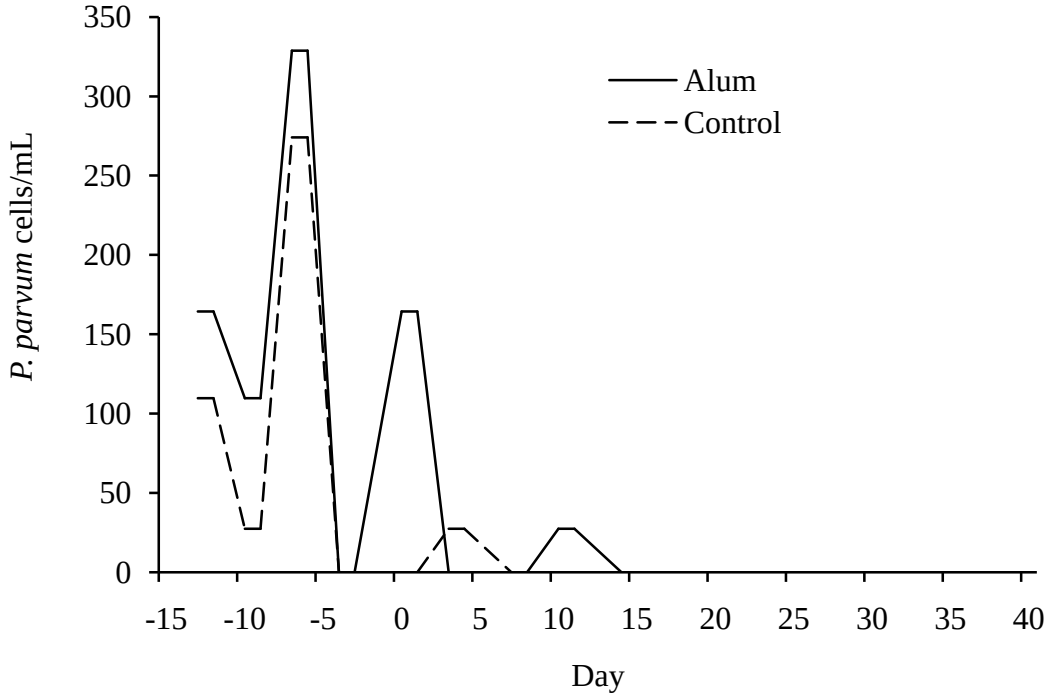

FIGURE 7.—*Prymnesium parvum* cell densities in ponds fertilized with 300 µg N/L and 30 µg P/L three times weekly (control) or 300 µg N/L and 30 µg P/L three times weekly plus alum treatments when pH was or exceeded 9.0 (alum) at the Dundee state fish hatchery in spring 2008.

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