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Managing phosphorus fertilizer to reduce algae, maintain water quality, and sustain yields in water-seeded rice

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ABSTRACT

In water-seeded rice systems, cyanobacteria (*Nostoc spongiaeforme*) hinder early-season crop growth by dislodging and reducing light to seedlings. Since algae are often phosphorus (P) limited, we investigated whether changing the timing of P fertilizer application could reduce algal growth without reducing crop yields or increasing mid-season water P concentrations to levels of concern for water quality. Water P and algae were monitored in 10 and 12 (respectively) side-by-side fields (16–60 ha in size) where P fertilizer was applied pre-plant or where P application was delayed until after rice plants had emerged above the surface of the floodwater (2–5 weeks after seeding). Early-season water P concentration and algal occurrence were higher ($P < 0.001$ and $P = 0.018$, respectively) when P fertilizer was applied pre-plant as opposed to delayed. In fields receiving a delayed P application, water P increased to as high as 1.68 mg L^{-1} immediately following application and subsequently declined by 0.054 mg L^{-1} day^{-1} ($P = 0.029$). A separate study evaluated the effect of P fertilizer timing on crop productivity and P uptake. Triple-super-phosphate was either not applied or was applied to the soil surface in the fall prior to the cropping season, immediately prior to planting, 35 days after seeding (DAS) and 49 DAS at a rate of 25 kg ha^{-1} P. P uptake and agronomic P use efficiency (APUE) were similar when P was applied at seeding or 35 DAS. However, relative to P application at seeding, yields were reduced by 6% and there was lower APUE when P was applied after harvesting the previous crop or at 49 DAS ($P < 0.05$). These results indicate that correctly timed, delayed fertilizer P applications can maximize rice yield while reducing early-season interference from algae. However, because delayed applications of P fertilizer also increased water P concentrations, drainage water must be managed carefully following application.

1. Introduction

Due to their nitrogen (N)-fixing capacity, cyanobacteria or blue-green algae have been studied as a potential source of N in flooded rice (*Oryza sativa*) systems where N is the primary limitation to crop growth (Whitton, 2000). Although their presence might benefit rice growth in such contexts, it has been shown that blue-green algae can hinder rice growth in high-yielding, fertilized, water-seeded rice systems (Spencer et al., 2006). In California rice systems, N and phosphorus (P) are typically applied pre-plant at 112–180 kg ha^{-1} and 20–30 kg ha^{-1}, respectively, and P is either applied directly to the soil surface or minimally incorporated (Hill et al., 2008). Following application, pre-germinated rice seeds are broadcast seeded into a standing flood via airplane (referred to as water-seeded rice). Depending on the temperature and depth of the floodwater, rice seedlings emerge above the surface of the water between two and three weeks after seeding.

In water-seeded rice, seedling emergence can be disrupted by the presence of algal mats that are predominantly composed of the filamentous cyanobacteria, *Nostoc spongiaeforme* (also known as "black algae" or "elephant hide algae") (Spencer et al., 2006). As the connected algal cells develop near the soil surface, oxygen accumulates beneath them and eventually lifts the mat to the surface of the water, uprooting young rice seedlings in the process. Subsequently, the mats are blown across fields, blocking light to young rice seedlings and accumulating on the leeward side of the field, which results in a diminished crop stand density (Spencer et al., 2006). Reducing the occurrence of algae by the application of either copper sulfate or herbicide mixes has been minimally effective (Spencer et al., 2006, 2009). Therefore, alternative means of algal control are needed.

Cyanobacteria have been broadly described as P-limited due to their N_2-fixing capacity (Whitton, 2000). Although this characterization may be an oversimplification in N-poor environments

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(Sterner, 2008), there is evidence that in rice systems algal growth is limited, in part, by water P concentrations (Spencer et al., 2006). A number of studies have shown that water P concentrations increase significantly early in the season due to pre-plant fertilizer applications (Jeon et al., 2004, 2007; Kang et al., 2006; Wang et al., 2001). If algae are P-limited, these higher P concentrations can promote algal growth at a time that is particularly detrimental to rice growth. Thus, shifting the application of P fertilizer to another time in the season might reduce interference from algae during stand establishment in water-seeded rice. However, the effects of delayed P applications on crop yields and subsequent water P concentrations are not known.

P concentrations in surface waters are a point of environmental concern nationally and globally (Carpenter et al., 1998). Currently there are no enforced water quality standards for P concentrations in California's surface waters; however, pertinent P threshold values do exist for this and other regions. The United States Environmental Protection Agency (EPA) sampled water bodies spanning California's Sacramento and San Joaquin Valleys between 1990 and 1998 ($n = 40$) and suggested that the 1st quartile value (0.08 mg P L^{-1}) should serve as an initial threshold (USEPA, 2001). The State of Florida has undertaken the subsequent steps in this EPA process and proposed P threshold values that range from 0.03 to 0.73 mg P L^{-1}, with the higher values in areas where land use is predominantly agricultural (USEPA, 2010). Meanwhile, the State of Wisconsin recently adopted a statewide threshold of 0.10 mg P L^{-1} for surface waters (WDNR, 2010), which is the same water quality target used by the Republic of Korea, where flooded rice is a major agricultural crop (Kang et al., 2006). Despite the lack of a specific water quality target in California, elucidating the effects of fertilizer P management on surface water quality is a necessary step in avoiding future problems.

In addition to water quality, the timing of P fertilizer applications affects rice yields. Fageria (2004) reported that 99% of P uptake occurs later than 35 days after seeding (DAS) and 80% occurs after panicle initiation in lowland rice, indicating that absolute crop demand for P is low early in the season. Nevertheless, early season deficiencies reduce plant vigor, tillering and yield potential (Dobermann and Fairhurst, 2000). Therefore, understanding how variously timed applications affect yield is important. In a drill-seeded Louisiana rice system, Patrick et al. (1974) found that, when P was applied two weeks after seeding, rice suffered no yield loss compared to pre-plant P applications, but yields were reduced when P was applied 28–42 DAS. In contrast, Slaton et al. (2002) reported no yield decline when P was applied 35–40 DAS in drill seeded rice, but a significant yield decline when P was applied 65–70 DAS.

The effect of P fertilizer timing on yield has not been studied in water-seeded rice systems. The majority of the rice grown in California is water seeded into heavy clay soils that are neutral-to-acidic in pH and contain a relatively large reducible iron fraction (Linquist et al., 2010), characteristics that favor a gradual increase in the bioavailability of P under the reducing conditions of an extended flood (Diamond, 1985; Patrick and Mahapatra, 1968). These physical characteristics, combined with the annual application of P fertilizers at or above the rate needed to replace P uptake from the previous crop, results in fewer than 10% of fields demonstrating a response to P fertilizer (Linquist and Ruark, 2011). This indicates that the risk of yield loss due to unconventional P fertilizer application timing is low for the majority of rice fields in the region.

We conducted two studies to determine the impact of P fertilizer application timing on algal growth, water quality and rice yields. The primary objective for the first study was to test whether delaying the application of P fertilizer until after the rice plants have emerged from the water will reduce early-season water P concentrations and algal abundance in rice fields. A second objective was to monitor water P concentrations after the delayed application of P fertilizer to flooded fields. The objective for the second study was to determine whether fall applied or delayed applications of P fertilizer would result in lower rice yields compared to conventional, pre-plant applications of P in P deficient fields.

2. Methods

2.1. P fertilizer timing, water P concentration and algal abundance

During the 2008 and 2009 growing seasons an experiment was carried out in six locations across three counties in the Sacramento Valley, CA, USA. At each location, in side-by-side fields, we evaluated two treatments: (1) fertilizer P applied before flooding (PRE) as is conventionally done and (2) a delayed fertilizer P application in which fertilizer P was applied between 16 and 32 days after seeding (DELAYED). Fields ranged in size from 16 to 60 ha, had comparable P fertilization history, and did not differ significantly in background soil P (see Section 3). Soluble P fertilizer was applied by the growers, and the amount applied varied among locations (19–28 kg P ha^{-1}) but was approximately the same within each location for each treatment (Table 1).

In five locations (water samples were not taken at location F) water was sampled from both PRE and DELAYED fields between when they were flooded and the delayed application of P fertilizer. After the delayed application of P fertilizer, water was only sampled from DELAYED fields (Table 1). Water was sampled every 1–4 days during the period before the delayed application of P and every 2–8 days after the delayed application. The difference in sampling frequency between locations and fields was caused by differences in water management and the timing of fertilizer application. At each sampling event a 1 L sample of water was collected from the water column approximately 3 m from the edge of the field. Samples were kept on ice until being filtered through a 2 mm sieve, a 0.45 μm glass filter and analyzed for soluble reactive phosphorus (PO_4-P, heretofore and henceforth referred to as water P) using the ascorbic acid molybdenum blue method modified from Murphy and Riley (1962) with a lower detectable limit of 0.01 mg L^{-1} P (APHA, 1999). Prior to the delayed application of P, a total of 40 and 43 measurements of water P were taken from the PRE and DELAYED fields, respectively. After the delayed application of P, 23 measurements of water P were taken from DELAYED fields (Table 1). When possible, inlet water was also sampled and analyzed using the same method as above. A total of 29 inlet samples were taken from the PRE fields; a total of 18 inlet samples were taken from the DELAYED fields prior to the delayed application of P fertilizer; and 20 inlet samples were taken from the DELAYED fields after the delayed application of P fertilizer.

In all six locations, the relative abundance of *N. spongiaeforme* was measured in PRE and DELAYED fields prior to the delayed application of P fertilizer, between 2 and 23 days after the initial flood was brought onto the field. Abundance was assessed based on the presence/absence of *N. spongiaeforme* in photographs taken at a consistent angle every 10 m around the perimeter of a field. A total of 2779 photographs were assessed for the presence/absence of *N. spongiaeforme*. Abundance is expressed as a percentage of photographs with *N. spongiaeforme* present out of the total number of photographs taken for each location-day combination. As with the water samples, differences in sampling timing between locations was due to differences in water management and the timing of the delayed fertilizer application. In two of the locations (A and F), algal abundance was assessed multiple times, with at least 10 days

Table 1
The rate and timing of P fertilizer and the number of water P (PO_4-P) and algal occurrence observations in rice fields receiving pre-plant (PRE) or delayed (DELAYED) applications of P fertilizer.

Location	PRE					DELAYED				
	P rate (kg P ha^{-1})	P timing	Water P observations (n)		Algae observations (n)	P rate (kg P ha^{-1})	P timing	Water P observations (n)		Algae observations (n)
			Before delayed P application	After delayed P application				Before delayed P application	After delayed P application	
A	22	Preplant	6	–	2	19	16 DAS[a]	6	4	2
B	19	Preplant	10	–	1	19	32 DAS	11	5	1
C	19	Preplant	8	–	1	19	26 DAS	9	4	1
D	19	Preplant	8	–	1	22	28 DAS	8	5	1
E	28	Preplant	8	–	1	30	28 DAS	9	5	1
F	20	Preplant	–	–	3	20	32 DAS	–	–	3

[a] DAS, days after seeding.

between assessments at the same location. There were a total of 9 paired observations of algal abundance (Table 1).

After a $\log_{10}$ transformation of the observed values to meet assumptions of normality and homogenous variance, the MIXED procedure in SAS 9.1.3 (SAS Institute, USA, 2002–2003) was used to analyze: (1) water P measurements taken prior to the delayed application of P fertilizer and (2) algal abundance. Time was normalized between locations such that time zero (T_0) was the location-specific first day of flooding. The effects of P management, time, and the interaction of P management and time were designated as fixed effects, and a random intercept was designated for the effect of location to account for the random variations in background soil P content, redox conditions, and intake water temperature and P content (Moser, 2004). Water P measurements taken after the delayed application of P fertilizer were analyzed using a different model in the MIXED procedure in SAS 9.1.3 (SAS Institute, USA, 2002–2003) after a $\log_{10}$ transformation of the observed values. Time was normalized between locations such that T_0 was the location-specific day of delayed P application. Changes in water P after the delayed application were modeled with time designated as a fixed effect and the effect of location designated as a random coefficient across time with an unstructured covariance structure to account for random variations in background P (as above) and random variations in slope (Moser, 2004). Model fit (R^2) was assessed by a simple linear regression of the predicted and observed values.

2.2. *P fertilizer timing and rice yield*

The effect of P fertilizer management on crop productivity was evaluated in two locations in Butte County, CA, USA. Unless a response to P fertilization has been confirmed, equivalent yields resulting from differing P fertilization strategies can produce misleading conclusions. Therefore, P deficient fields were chosen to ensure that potentially differential effects of alternatively timed applications of P fertilizer on rice growth would not be masked by the high levels of background P typically found in California systems (Linquist and Ruark, 2011). Fields were chosen where P deficiencies were likely based on soil test results showing Olsen P values (Olsen and Sommers, 1982) <6 mg P kg^{-1} soil (Linquist and Ruark, 2011). Both soils were Lofgren-Blavo Complex Vertisols with the following properties: 13–19% sand; 20–24% silt; 59–65% clay; 2.9–5.3 mg kg^{-1} P (Olsen); 0.6–1.0 mg kg^{-1} P (Bray); 1.9–2.5% total C; 22.5–34.7 g kg^{-1} total Fe; 1.1–2.9 mg kg^{-1} Al (KCl extractable); and pH 5–5.4 (saturated paste). In one location the straw from the previous crop had been incorporated via tillage the previous fall and the field was kept flooded during the winter rainy season. In the other location the straw from the previous crop was burned during the fall and the field was drained during the winter rainy season.

Between November 2008 and September 2009, the effects of five P fertilizer timing treatments were tested in a randomized complete block design with each treatment being replicated six times. The treatments were: (1) a control with no P applied (ZERO); and P applied (2) in the fall prior to the cropping season (FALL); (3) after spring tillage had been completed and prior to seeding, which is the conventional practice (PRE); (4) 35 days after seeding (35 DAS); and (5) 49 DAS, about ten days prior to panicle initiation (49 DAS). In all treatments where P was applied, it was applied at a rate of 25 kg P ha^{-1} in the form of triple-super-phosphate (TSP) to the soil surface. Plot size was at least 5 m × 2.5 m. For the FALL treatment, in November 2008 P fertilizer was broadcast over 1000 m^2 in a randomized section of each block. A 60 m buffer on either side of the FALL treatment plots was created to ensure that the fall applied TSP did not jeopardize the other treatments following tillage events.

Aboveground plant biomass was assessed at 21, 35, 60 DAS by cutting all plants in a 0.09 m^2 area at ground level, drying them to

Table 2
P-values for the effects of P management, time and their interaction on water P (PO_4-P) and algal occurrence during the period before the delayed application of P fertilizer in PRE and DELAYED fields as modeled using a mixed linear regression model.

	Water P (mg L^{-1})	Algae (%)
P management	<0.001	0.018
Time	0.392	0.113
Management × time	0.347	0.30
R^2	0.35	0.57

constant moisture at 60 °C, and weighing them. Yields and above ground biomass at harvest were determined based on a hand harvest of a 1 m^2 area in each treatment. P content in aboveground biomass was determined using the methods of Prokopy (1995). Plant responses to P fertilization were analyzed using a general linear model in the GLM procedure in SAS 9.1.3 (SAS Institute, USA, 2002–2003). Variance was modeled as a function of the effects of treatment, location, and block nested within location. For response variables that included a direct measurement of plant P content, a block-specific, pre-experiment soil Olsen-P value was included as a covariate. Mean separations were made using Tukey's Honestly Significant Difference test ($P < 0.05$).

3. Results

3.1. P fertilizer timing, water P concentration and algal abundance

Early-season water P concentrations were higher in PRE fields than DELAYED fields ($P < 0.001$, Table 2). Before the delayed application of P, the mean water P concentration in the PRE fields was 0.025 mg L^{-1} and the maximum concentration was 0.174 mg L^{-1} compared to a mean concentration of 0.013 mg L^{-1} and a maximum concentration of 0.032 mg L^{-1} in the DELAYED fields where no P had yet been applied (Table 3). This was in spite of a lower mean inlet concentration in the PRE fields (0.012 mg L^{-1} P) than the DELAYED fields (0.026 mg L^{-1} P) ($P = 0.007$, Table 3). Water P concentrations did not change with time during the period between flooding and the delayed application of P fertilizer, and the effects of P fertilizer management did not vary across the sampling period (Table 2). Of the 40 observations made in the PRE fields and the 43 observations made in the DELAYED fields before fertilizer application, 13 and 30 observations were below the detection limit, respectively. As a result, a large portion of the variability was unexplained by the model ($R^2 = 0.35$, Table 3).

In addition to having a higher concentration of water P, PRE fields had a higher occurrence of algae than DELAYED fields ($P = 0.018$, Table 2). On average, *N. spongiaeforme* was present in 33% of the photographs taken around the perimeter of the PRE fields and 13% of the photographs taken around the DELAYED fields (Table 3). The maximum, median and minimum algal abundance values observed in the PRE fields were all higher than DELAYED fields as well (Table 3). As with water P, algal abundance was not affected by time during the sampling period, and the effects of P management did not change during the sampling period (Table 2). The effects of P fertilizer timing on water P and algae were not confounded by significant differences in background soil P, with PRE fields averaging 11.4 ± 2.3 mg P kg^{-1} soil and DELAYED fields averaging 10.6 ± 2.1 mg P kg^{-1} soil (Olsen and Sommers, 1982) ($P = 0.83$).

The delayed application of P fertilizer to the flooded fields resulted in a spike in water P concentrations that declined rapidly (Fig. 1). In DELAYED fields, during the 8 days following the delayed application of P fertilizer, 7 of the 11 observations exceeded 0.174 mg L^{-1} P (Fig. 1), the maximum value in the PRE treatment (Table 3), with the maximum concentration reaching 1.68 mg L^{-1} (Table 3). Within two weeks, the values in all locations had fallen below 0.15 mg L^{-1} (Fig. 1). There was considerable variability between locations in both the initial concentrations and the rate of decline (Fig. 1). All but one of the values measured in location E was higher than 0.1 mg L^{-1} P, whereas in location D only a single value was above the 0.01 mg L^{-1} lower detection limit. The mixed model with random coefficients for location effectively accounted for this variability ($R^2 = 0.87$), and predicted that the water P concentration declined at a rate of −0.054 mg L^{-1} day^{-1} ($P = 0.029$) following the application of P fertilizer. Yet, because the modeled intercept (water P concentration at T_0) was not significant ($P = 0.349$), it is not possible to make a precise prediction about when P concentrations might have reached a specific concentration threshold.

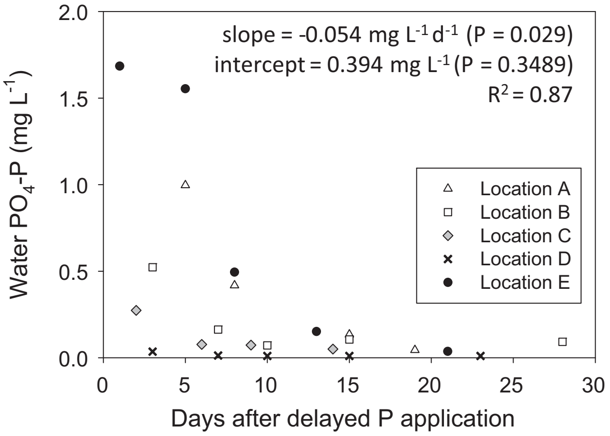

Fig. 1. Changes in water P (PO_4-P) concentration following the delayed application of P fertilizer. Slope and intercept estimates have been back transformed after being modeled by a mixed linear regression using $\log_{10}$ transformed values.

3.2. P fertilizer timing and rice yield

Data from the two locations were combined after a non-significant location by treatment interaction was confirmed. Yields in plots where P fertilizer was not applied averaged 10.9 t ha^{-1} and increased significantly in all treatments where P was applied up to 12.5 t ha^{-1} in the conventional (PRE) treatment (Table 4), confirming the deficiency predicted by the pre-season Olsen-P values below 6 mg P kg^{-1} soil (Linquist and Ruark, 2011). Deficiency was also confirmed by straw P concentrations in all treatments that fell below the 0.06% critical threshold for deficiency reported by Dobermann and Fairhurst (2000) (Table 4), as well as by visible symptoms of relative deficiency observed throughout the season in plants in the ZERO treatment as compared to those in treatments where fertilizer P was applied (smaller plants; reduced tillering; delayed flowering).

Although at 60 DAS rice plants in the 35 DAS and 49 DAS treatments had taken up significantly less P than plants the PRE treatment, they had also taken up more P than plants in the ZERO treatment (Table 4). Further, by harvest, rice in the 35 DAS and 49 DAS treatments had taken up an equivalent amount as those in the PRE treatment (Table 4). Phosphorus application 35 DAS did not significantly reduce yields or agronomic P use efficiency (APUE) compared to the conventional practice (Table 4); whereas, P applied 49 DAS resulted in a 6% yield loss and a 45% reduction in APUE as compared to the PRE treatment (Table 4). Meanwhile, plants in the FALL treatment took up less P than those in the PRE treatment early in the season (21 and 35 DAS) as well as overall, but took up an equivalent amount of P as the PRE treatment between tillering and panicle initiation (35 and 60 DAS) (Table 4). Yields in the FALL

Table 3
Water P (PO_4-P) concentrations and algal occurrence in rice fields receiving pre-plant (PRE) or delayed (DELAYED) applications of P fertilizer.

	PRE			DELAYED		
	Water P (mg L^{-1})		Algae (%)	Water P (mg L^{-1})		Algae (%)
	Before delayed P application	After delayed P application		Before delayed P application	After delayed P application	
Mean	0.025	–	33	0.013	0.305	13
Max	0.174	–	75	0.032	1.684	30
Median	0.016	–	39	0.010	0.092	8
Min	0.010	–	7	0.010	0.010	3
Inlet mean (*n*)	0.012 (29)	–	–	0.026 (18)	0.023 (20)	–

treatment were 6% lower than the PRE treatment and APUE was reduced by 46% (Table 4).

4. Discussion

The highly significant effect of P management on water P concentration ($P < 0.001$, Table 2) as well as the greater mean, maximum, and median values observed in the PRE fields relative to the DELAYED fields during the first sampling period (Table 3) clearly indicate that a pre-plant P fertilizer application resulted in higher relative water P concentrations early in the season. Since fields where a soluble P fertilizer has been added to the soil surface are being compared to fields where, at this point in time, none had been added, a relatively higher concentration of water P in the PRE fields is to be expected. However, the absolute concentrations reported here are less certain. As mentioned above, 52% of the observations taken before the delayed application of P fertilizer had P concentrations below the lower detection limit for the method used (APHA, 1999), and a large portion of the variability was unexplained by the model ($R^2 = 0.35$) as a result. Additionally, the values observed in this study are low relative to P concentrations reported by Chung et al. (2003) for a study conducted in South Korea with similar P fertilization rate. Chung et al. (2003) reported a range of 0.03–0.28 mg L^{-1} P in ponded water and an average concentration of 0.09 mg L^{-1} P in drainage water in rice fields that had received pre-plant applications of 21–24 kg ha^{-1} P. A possible explanation for the lower values in the present study is that the mean value of the inlet irrigation water was 0.012 mg L^{-1} P (Table 3) compared to the 0.10 mg L^{-1} P in Chung et al. (2003). Regardless, pre-plant applications of P clearly increased the relative early-season water P concentrations in this study.

Higher initial water P concentrations are supported by the concurrently higher occurrence of algae in PRE fields relative to DELAYED fields during the first few weeks after flooding ($P = 0.018$, Table 2). Water P concentrations in rice fields are variable due to abiotic factors such as flooding, soil type (Diamond, 1985) and the input of inorganic fertilizer (Kang et al., 2006) as well as biotic factors such as adaptations among algae for the rapid uptake of P in high P environments (Mateo et al., 2006; Portielje and Lijklema, 1994) and P release as algae die. In light of the multiple factors influencing the availability of P and the evidence that algae are P-limited in this environment (Spencer et al., 2006), the observable algal biomass after the initial flood can be seen as presenting an average, field-scale indication of P availability. Although the presence/absence approach used in this study is an imperfect representation of algal biomass, it is, nonetheless, a common, field-scale assessment method for algal biomass (USEPA, 2002; Flotemersch et al., 2006). Given the scale and extent of the fields, the presence/absence of algae in thousands of photographs provides a relative indication of algal biomass between the two management approaches. During the 2–23 days after the initial flood, the algae in the DELAYED treatment were P-limited relative to those in the PRE treatment with the average occurrence in the PRE fields more than doubling that in the DELAYED fields (Table 3). Given that cyanobacteria are often P-limited (Whitton, 2000) and have been shown to be P-limited in this system in particular (Spencer et al., 2006), the relative algal abundance in the PRE fields was expected, and it has immediate implications for rice growers trying to reduce interference from algae.

Specifically, growers may be able to reduce algal interference by shifting the application of P to some other point during the season or by eliminating it altogether until soil or plant tissue tests indicate the need for it. Although yield reductions were observed in the ZERO, FALL and 49 DAS treatments in two fields with P deficiency (Table 4), the fields where water P and algae were measured were not P deficient, and the vast majority of fields in this region do not demonstrate a yield response to P fertilization (Linquist and Ruark, 2011). Therefore, in most cases, the risk of yield loss due to eliminating or changing the timing of P fertilizer application would be small within a single season. Intra-season P management aside, over the long-term P should be managed such that inputs and outputs are balanced and soil P remains relatively constant over time (Linquist and Ruark, 2011).

If P applications are shifted to another part of the season, care needs to be taken to avoid creating a downstream water quality problem. P fertilizer that was applied post-plant resulted in spikes in water P concentration beyond the maximum concentrations seen in the PRE treatment and above various thresholds of concern for water quality (Fig. 1, Table 3). Eleven of the 23 observations made in the DELAYED treatment after the in-season application of

Table 4
Aboveground P uptake, P concentration in straw and grain at harvest, agronomic P use efficiency (APUE, kg grain increase per kg P applied), and grain yield for treatments that varied in the application timing of 25 kg ha^{-1} P. The timing of P fertilization was the previous fall (FALL), pre-plant (the conventional practice) (PRE), 35 days after seeding (35 DAS), 49 DAS, and a control where no fertilizer P was applied (ZERO). Means with different letters indicate significant differences ($P < 0.05$) as determined by the Tukey's HSD test.

P management	P uptake (kg ha^{-1})				P concentration (%)		APUE	Grain yield (kg ha^{-1})
	21 DAS	35 DAS	60 DAS	Harvest	Straw	Grain		
ZERO	0.12 b	0.48 c	5.01 d	24.14 c	0.037 c	0.182 b	–	10,933 c
FALL	0.13 b	1.21 b	11.51 ab	31.55 b	0.049 b	0.220 a	28.8 b	11,795 b
PRE	0.16 a	1.95 a	12.44 a	35.09 a	0.051 ab	0.230 a	53.1 a	12,526 a
35 DAS	–	–	9.95 bc	33.30 ab	0.050 ab	0.226 a	44.3 ab	12,260 ab
49 DAS	–	–	9.17 c	32.95 ab	0.055 a	0.226 a	29.2 b	11,810 b

P exceeded 0.10 mg L^{-1} P (Fig. 1), which is the threshold value for water P concentration in South Korea (Kang et al., 2006), the state of Wisconsin (WDNR, 2010), and is 0.02 mg L^{-1} P higher than the initial EPA recommendation value for California's Central Valley (USEPA, 2001). Yet, the range of values was comparable to those reported by Kang et al. (2006) and Jeon et al. (2007) based on studies conducted at the rice watershed scale in South Korea (Table 3). Therefore, although the P concentrations observed in these rice fields following delayed applications of P fertilizer were high relative to various water quality standards, they are not high when compared to other rice growing regions. Further, the concentrations declined −0.054 mg L^{-1} day^{-1} (Fig. 1), which agrees with the sharp declines in P concentrations following fertilization events reported by Jeon et al. (2004, 2007). The rapid decline in water P concentration is likely due to the sink created for the soluble, inorganic P through adsorption to soil particles (Ponnamperuma, 1972) as well as by uptake from both algae and the rice plants that had emerged from the floodwater and were beginning to tiller actively (Dobermann et al., 1998). Finally, although the concentration of P following the delayed application of P fertilizer was highly location-specific, within 2 weeks water P concentrations in all fields had returned to within the range of concentrations observed in the PRE fields (Fig. 1).

Of the seasonal P uptake by the rice plants, only 4% occurred between 0 and 35 DAS while 96% occurred between 35 DAS and harvest (Table 4). This agrees with previous results showing that 99% of P uptake occurs later than 35 DAS in flooded rice (Fageria, 2004), and may explain why the 35 DAS treatment did not suffer a yield penalty and had a comparable APUE relative to the PRE treatment (Table 4). However, 21% of the seasonal uptake occurred between tillering and panicle initiation (35 and 60 DAS) (Table 4), which is the morphological period when P uptake rates are highest (Dobermann et al., 1998). This may help to explain why rice in the 49 DAS treatment had 6% lower yields and a lower APUE than rice in the PRE treatment despite the fact that the overall uptake in the 49 DAS and PRE treatments was equivalent (Table 4). The P taken up in the 49 DAS treatment but not allocated to grain resulted in a higher straw P concentration than the PRE and 35 DAS treatments ($P < 0.10$) (Table 4), following a similar trend reported by Slaton et al. (2002). P deficiency is known to reduce the number of leaves, number of panicles, and grains per panicle in rice (Dobermann and Fairhurst, 2000). Although yield components were not accounted for here, the increased straw P content ($P < 0.10$) coupled with a decreased APUE ($P < 0.10$) in the 49 DAS treatment relative to the PRE and 35 DAS treatments (Table 4) indicate that a relative P deficiency occurred in plants that did not receive P fertilizer until 49 DAS, reducing their yield potential. Similar to this study, Slaton et al. (2002) reported no yield declines when P fertilizer application was delayed until 35–40 DAS, but yields did decrease when P applications were delayed until 65–70 DAS. Therefore, to avoid yield reductions due to P deficiency, growers implementing a mid-season application of P fertilizer should apply P as soon as the rice plants are large enough to withstand algal interference, sometime between 3 and 5 weeks after planting.

P fertilizer applied during the previous fall may also be a viable management alternative. Although plants in the FALL treatment suffered a 6% yield penalty compared to those in the PRE treatment, they also demonstrated an 8% yield response relative to the ZERO and took up an equivalent amount of P as the PRE treatment between tillering and panicle initiation (Table 4). This indicates that a portion of the fertilizer P applied in the fall was available to the rice plants during a critical developmental period. However, due to the large iron and clay fractions in these acid soils, some of the fall applied P is likely to have been immobilized during wetting and drying periods over the course of the winter and spring (Kuo and Mikkelsen, 1979), making it relatively less available overall than an equivalent amount applied immediately before planting. This is evident in the reduced total uptake at harvest in the FALL versus PRE treatment (Table 4). Nonetheless, the degree of soil P deficiency in the fields where the effects of P fertilizer timing were measured is rare in California rice systems (Linquist and Ruark, 2011). Therefore, fall applications of P may yet be a viable alternative to pre-plant applications in the majority of California rice fields, particularly if a higher rate of fertilization is applied. However, it should be noted that the effect of fall applied P on early season water phosphate concentrations and/or algal growth is not reported here. Finally, because the effects of P fertilizer timing on rice growth were measured on P deficient fields, it is important to emphasize that such effects would be less pronounced in the majority of California rice fields, which are generally not P deficient (Linquist and Ruark, 2011).

5. Conclusion

Withholding pre-plant applications of P fertilizer reduced early-season water P concentrations and the occurrence of floating algae in water-seeded rice fields. Therefore, eliminating, delaying or reducing the rate of P applications may be appropriate for growers trying to minimize seedling disruption due to floating algae. In addition, if timed correctly, delayed applications of P fertilizer did not reduce yields relative to conventional, pre-plant applications of P. However, because in-season applications of P also resulted in mid-season water P concentrations that might compromise surface water quality, outlet water must be managed carefully post-application.

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