



# Re-Evaluating Diagnostic Phosphorus Tests for Rice Systems Based on Soil Phosphorus Fractions and Field Level Budgets

Bruce Linquist\* and Matthew Ruark

## ABSTRACT

The efficient management of P fertilizer in rice (*Oryza sativa* L.) systems is essential in ensuring optimal yields while also avoiding problems related to over application. Identifying P deficient soils is critical to developing efficient P recommendations. The objectives of study were to determine the extent of P deficiencies in California rice systems, evaluate diagnostic P tests, and identify soil P fractions that contribute to crop P nutrition. On-farm P-omission experiments were conducted at 64 sites where we measured Y-leaf P concentration, P uptake, and grain yield. Soil samples were collected and analyzed for Olsen and Bray-P as well as being subjected to a sequential P fractionation scheme to determine  $\text{NaHCO}_3$ , NaOH, and HCl inorganic (Pi) and organic (Po) P. From grower interviews, an annual input/output P budget was constructed for each site that accounted for P fertilizer inputs and outputs (P removed at harvest) over the previous 5 yr. Olsen-P (critical value:  $6 \text{ mg kg}^{-1}$ ) and Y-leaf P tests (critical value: 0.2%) were reasonable at predicting P deficiencies across a wide range of soil types. The P budget, correlated with Olsen and Y-leaf P, was also helpful in determining if the grower applied P rates were adequate as the only P deficient sites had a P budget of  $0.5 \text{ kg P ha}^{-1} \text{ yr}^{-1}$  or less. Sodium bicarbonate inorganic P ( $\text{NaHCO}_3$ -Pi), NaOH-, and HCl-Pi and -Po fractions were all correlated with Y-leaf P concentrations. The only Po fraction correlated with Y-leaf P and the P budget was HCl-Po. The primary sinks for excess applied P fertilizer were the  $\text{NaHCO}_3$ -Pi and NaOH-Pi fractions.

PHOSPHORUS, A NONRENEWABLE RESOURCE, is an essential plant nutrient; however, it is also a leading water quality impairment (Sharpley et al., 2003). Furthermore, excess P can lead to excessive algae growth in wet-seeded rice systems (Spencer et al., 2006). Efficient P fertilizer management is necessary for maintaining the sustainability of these systems—both economically and environmentally. Accurately identifying P deficient soils is a critical first step in developing efficient P management strategies.

Soil and plant tissue tests are often used as a basis for determining the need for fertilizer applications. Currently used soil P tests for rice production are limited in their ability to predict a response to P. This is highlighted by the fact that in the U.S. soil tests to estimate P availability in rice systems vary by region and critical values for each test remains uncertain (Norman et al., 2003). Olsen-P (sodium bicarbonate extraction) is the most commonly used test for rice soils in California but Bray-1 P (ammonium fluoride and hydrochloric acid extraction) is occasionally used. An Olsen-P value of  $6 \text{ mg kg}^{-1}$  or less is considered deficient; however this is based on laboratory and greenhouse experiments (Williams, 2010; RRB, 1980) and has not been field validated. In contrast, Dobermann and Fairhurst (2000) report that the critical Olsen-P value

is  $5 \text{ mg kg}^{-1}$  for acid soils but  $25 \text{ mg kg}^{-1}$  for calcareous soils. Plant tissue tests are also used and are a valuable nutrient management tool, however, their use in the current season is limited as it is often too late to correct a deficiency once it has been identified. A Y-leaf sample taken at mid-tillering and containing 0.1% P is considered deficient, while values of 0.2 to 0.3% are considered optimal (Dobermann and Fairhurst, 2000). Mikkelsen and Hunziker (1971) used a different method to assess tissue P (2% HAc extractable P) and reported that values  $<1000 \text{ mg PO}_4\text{-P kg}^{-1}$  were P deficient; however this methodology has not been widely used and tested elsewhere.

Based on a 1969 survey, Mikkelsen and Hunziker (1971) reported P deficiencies in 5% of rice fields based on Y-leaf samples. Given the low number of deficient fields it is probable that there were fields where P was over applied. Growers are not often sure if P applications are necessary but apply it as an insurance measure. With rising fertilizer costs and increased concern regarding off-site pollution more growers are interested in knowing when P fertilizer applications are necessary. The objectives of study were to (i) determine the extent of P deficiencies in California rice systems, (ii) evaluate soil and tissue P tests in their ability to identify P deficiencies, (iii) field validate critical limits for soil and tissue P tests, and (iv) identify soil P fractions that contribute to P uptake with the aim of possibly refining soil tests.

## MATERIALS AND METHODS

On-farm field experiments were conducted from 2005 through 2007 to evaluate the response of rice to P fertilizer additions. In 2005, 2006, and 2007 there were 4, 12, and 48 experiments, respectively for a total of 64 site-years (Table 1). In some cases, experiments were conducted in the same field from one year to the next but the experiments were never conducted in the same area of the field. The sites were located around the Sacramento Valley and represented the major areas

B.A. Linquist, Dep. of Plant Sciences, University of California, One Shields Ave, Davis, CA 95616; M.D. Ruark, Dep. of Soil Science, 263 Soils Bldg. 1525 Observatory Drive, Madison, WI 53706. Received 31 Aug. 2010.  
\*Corresponding author (balinquist@ucdavis.edu).

Published in *Agron. J.* 103:501–508 (2011)  
Published online 3 Feb 2011  
doi:10.2134/agronj2010.0365

Copyright © 2011 by the American Society of Agronomy, 5585 Guilford Road, Madison, WI 53711. All rights reserved. No part of this periodical may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher.

**Table 1. Soil characteristics, crop management, P budget, yields, and yield response for the 64 sites where P experiments were conducted.**

Year	Field ID†	Soil order	Years in rice‡	Crop rotation§	Historical straw mgmt¶	pH	Organic C		Clay	Olsen-P	Variety (past/current) #	Y-leaf P	P budget	Grain yield††	GY response to P
							%	mg kg <sup>-1</sup>							
2007	Bh-1	Vertisol	4	R	I/B	6.6	0.90	29	29.0	M/M	0.35	0.2	10.97	-0.79	
2007	Bh-2	Mollisol	5	C	I/B	5.5	1.59	60	31.9	M/M	0.28	4.5	8.29	-0.89	
2007	By-1	Entisol	5	C	I/B	6.5	0.48	8	8.0	?/M	0.34	na	8.64	0.13	
2006	Ct-1	Vertisol	5	C	I/B	7.3	0.85	50	14.3	S/S	0.22	4.3	9.10	0.43	
2007	Dd-1	Inceptisol	0	first yr	na‡‡	7.5	0.91	31	16.3	-/S	0.33	na	10.23	-0.43	
2007	Dw-1	Mollisol	4	C/F	I/B	6.2	1.25	30	20.2	M/M	0.34	-2.8	11.77	-0.49	
2007	Ml-1	Alfisol	5	C	I/B	6.2	1.25	31	3.8	M/M	0.22	-3.7	10.76	1.22§§	
2007	Ml-2	Alfisol	5	C	I/B	6.7	1.10	32	5.0	M/M	0.25	-3.7	11.72	0.01	
2006	Rc-1	Vertisol	1	R	I/B	6.1	0.84	52	32.4	M/M	0.30	na	14.80	-0.64	
2007	Rc-2	Vertisol	1	R	I/B	5.7	0.77	57	24.7	M/M	0.29	na	14.58	0.05	
2007	Rc-3	Vertisol	1	R	I/B	5.6	0.86	54	20.7	M/M	0.40	na	13.09	-0.28	
2005	Tb-1	Vertisol	3	R	I/B	6.3	1.47	54	3.9	M/M	0.24	-12.2	8.74	0.62	
2006	Tb-2a	Vertisol	3	R	I/B	6.4	1.10	55	8.7	M/M	0.27	-12.2	11.65	0.30	
2006	Tb-3	Vertisol	4	R	I/B	6.3	1.40	55	5.3	M/M	0.34	-14.2	12.24	-0.63	
2007	Tb-4	Vertisol	3	R	I/B	6.2	1.31	54	10.7	M/M	0.27	-12.2	11.57	-0.98	
2007	Tb-2b	Vertisol	3	R	I/B	6.3	1.44	54	8.3	M/M	0.30	-12.2	13.33	-0.17	
2007	Tv-1	Vertisol	5	C	I/B	5.7	0.73	20	14.0	M/M	0.40	-9.9	12.71	-0.70	
2007	Tv-2	Vertisol	5	C	I/B	5.2	1.13	23	13.3	SM/M	0.41	-9.5	11.87	-0.41	
2007	Wl-1	Vertisol	5	C	I/B	5.2	1.29	38	14.4	M/M	0.36	3.2	11.73	-0.38	
2007	Wl-2	Vertisol	5	C	I/B	5.5	1.17	46	12.6	M/M	0.39	3.2	11.63	0.14	
2007	Ks-1	Vertisol	5	C	R	6.2	1.32	38	11.8	M/M	0.41	-6.8	10.95	0.10	
2007	Ks-2	Vertisol	5	C	B	5.7	1.42	40	19.6	M/M	0.35	0.5	9.15	1.11§§	
2007	Ks-3	Vertisol	5	C	B	6.5	1.15	41	22.1	M/M	0.38	0.5	10.93	0.68	
2007	Mb-1	Vertisol	5	C	I/B	6.3	1.93	32	6.6	M/M	0.33	-7.5	11.76	0.04	
2007	Mb-2	Vertisol	5	C	I/B	6.3	2.00	33	5.0	M/M	0.30	-7.8	11.75	0.83	
2005	Ms-1	Vertisol	5	C	I/B	5.5	2.24	37	4.7	M/M	0.31	-12.9	10.10	0.05	
2007	Vk-1	Vertisol	5	C	I/B	7.0	1.84	39	8.3	M/M	0.30	-3.1	11.12	-0.43	
2007	Vk-2	Vertisol	5	C	I/B	6.6	2.01	31	6.3	M/M	0.31	-3.1	11.91	-0.98	
2007	Bk-1	Mollisol	3	C¶¶¶	I/B	6.6	1.41	27	14.2	SL/L	0.40	10.9	10.79	-0.33	
2007	Bk-2	Mollisol	3	C¶¶¶	I/B	7.7	1.43	34	25.1	SL/L	0.37	10.9	10.99	-0.18	
2007	By-2	Vertisol	5	C	I/B	6.4	1.86	40	8.3	M/M	0.32	2.3	10.97	0.96	
2007	By-3	Vertisol	5	C	I/B	6.3	1.84	36	14.9	M/M	0.40	3.0	7.63	0.83	
2007	Ct-2	Vertisol	5	C	I/B	7.0	1.01	38	30.6	SM/S	0.36	1.3	9.49	-0.17	
2006	Ct-3a	Vertisol	5	C	I/B	5.4	0.86	38	7.4	M/M	0.22	-1.6	12.65	-0.61	
2007	Ct-3b	Vertisol	5	C	I/B	5.7	1.10	24	13.2	M/M	0.36	-1.6	11.53	-0.08	
2007	Ct-3c	Vertisol	5	C	I/B	5.4	1.14	31	7.5	M/M	0.43	-1.6	11.89	0.40	
2006	ES-1	Vertisol	5	C	I/B	4.7	1.06	52	10.0	M/M	0.28	3.4	10.80	0.36	
2006	ES-2	Vertisol	2	C/F	B	5.0	0.66	53	11.4	S/S	0.29	4.7	6.17	-0.47	
2007	Gl-1	Vertisol	5	C	I/B	5.6	1.21	53	7.1	SM/M	0.37	0.6	11.41	0.20	
2007	Hg-1	Alfisol	5	C	I/B	6.3	0.95	14	17.5	M/M	0.24	-3.6	10.24	0.38	
2006	Jk-1	Entisol	5	C	I/B	4.5	2.16	34	14.9	M/M	0.29	-3.2	11.24	0.34	
2006	Jk-2	Entisol	5	C	I/B	5.7	0.95	30	3.8	M/M	0.22	-3.6	12.14	0.67	
2007	Jk-3	Entisol	5	C	I/B	4.6	1.24	36	12.9	M/M	0.39	-2.7	12.07	0.40	
2007	Jk-4	Entisol	4	C/F	I/B	5.7	1.18	31	8.3	M/M	0.27	-3.5	11.35	0.53§§	
2005	Js-1	Vertisol	5	C	I	5.2	1.30	50	9.4	M/M	0.24	-0.7	11.64	0.72	
2007	Kg-1	Vertisol	5	C	I/B	6.1	1.46	54	7.4	M/M	0.30	-3.0	10.83	0.45	
2007	Kg-2	Entisol	5	C	I/B	5.0	1.37	42	22.8	M/M	0.40	-0.4	11.06	0.01	
2006	My-1a	Vertisol	5	C	B	5.1	1.06	58	5.3	M/M	0.23	-7.0	9.65	0.18	
2007	My-1b	Vertisol	5	C	B	5.2	1.10	59	8.5	M/M	0.17	-7.0	12.59	0.35	
2007	My-1c	Vertisol	5	C	B	5.1	1.29	60	4.4	M/M	0.12	-7.0	12.62	0.73§§§	
2006	My-2a	Vertisol	5	C	I/B	5.3	0.96	61	2.2	M/M	0.13	-8.0	12.44	0.52§§§	
2007	My-2b	Vertisol	5	C	I/B	5.0	1.28	60	2.2	M/M	0.14	-8.0	11.89	1.24§§§	
2007	My-2c	Vertisol	5	C	I/B	5.4	1.30	62	3.2	M/M	0.15	-8.0	11.79	0.13	
2007	Mz-1	Vertisol	5	C	I/B	5.1	1.45	48	5.9	M/M	0.20	2.1	9.24	-0.02	
2007	Rd-1	Mollisol	5	C	I/B	7.9	1.04	26	31.0	M/M	0.39	10.4	10.76	-0.04	
2007	Rd-2	Mollisol	5	C	I/B	6.1	1.79	30	11.7	M/M	0.30	10.4	11.00	-0.37	
2007	Sm-1	Mollisol	4	C/F	I/B	7.0	1.13	26	22.2	SM/S	0.37	-6.7	14.34	0.48	
2007	Sr-1	Vertisol	5	C	I/B	5.4	1.53	59	6.6	M/M	0.21	na	10.00	-0.85	
2007	Sr-2a	Entisol	5	C	I/B	4.8	2.02	41	23.3	M/M	0.47	na	10.97	0.26	
2007	Sr-2b	Entisol	5	C	I/B	5.0	1.43	28	14.8	M/M	0.34	na	11.54	-0.02	
2007	Mt-1	Inceptisol	5	C	I/B	4.8	1.12	20	25.7	S/S	0.33	14.8	6.92	0.25	
2007	Mt-2	Alfisol	5	C	I/B	4.8	1.00	24	11.9	S/S	0.39	13.8	5.66	0.16	
2005	Mt-3a	Alfisol	5	C	I/B	5.2	1.09	20	18.5	SM/M	0.35	12.4	9.49	0.15	
2006	Mt-3b	Alfisol	5	C	I/B	5.3	1.01	22	12.1	SM/M	0.25	11.0	12.04	0.07	

† Field ID: First letters are grower codes followed by field number. In some cases experiments were conducted in the same field but in different locations within the field and possibly in different years.

‡ Indicates the number of years rice was grown in the 5 yr preceding the P experiment.

§ Continuous rice (C), continuous rice with occasional fallow (C/F), rice rotated with other crops (R), and for one field this was the first year in rice—before rice the field was in alfalfa.

¶ Incorporated (I), burned (B), removed (R).

# Varieties grown at each site in the 5 yr before the experiment and in the current year when

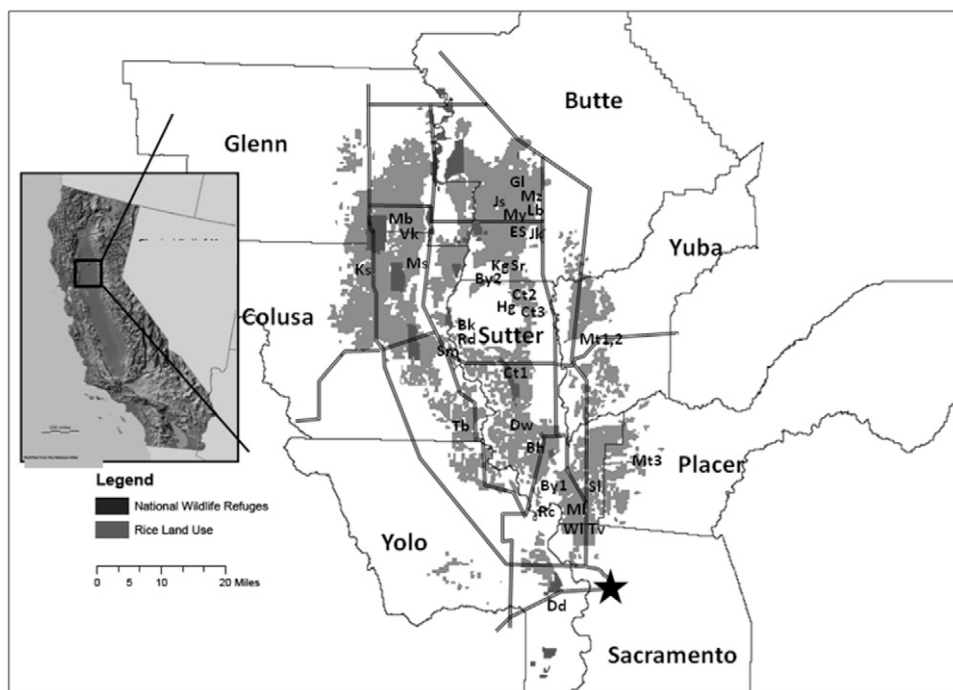
the experiment was conducted. S are specialty rice varieties (Calmochi, Kokuho Rose, Akita Komachi, Koshihikari, and Arborio), M are medium grain (M202, M205, M206, M401 and M402), and L are long grain (L206).

†† Grain yields determined from P fertilizer experiment and adjusted to 14% moisture in the treatment receiving no P.

‡‡ Not available (na).

§§ Indicates a significant yield response to the addition of P fertilizer ( $P < 0.1$ ).

¶¶¶ Fields had only been in rice for 3 yr before the P experiment.



**Fig. 1.** Map showing the California rice growing area and counties within the Sacramento Valley. The approximate study sites are shown using the Field ID in Table 1.

where rice is grown (Fig. 1). At 52 sites rice had been grown continually (or was in fallow) during the previous 5 yr. At the remaining sites rice was grown in rotation with other crops (11 sites) or was in the first year (1 site) of rice. All of the sites where rice was grown in rotation with other crops were located in the southern region of the Sacramento Valley where soils are more suitable to the production of other crops. Of the rotational sites, rice had been grown every 3 to 4 yr during the previous 5-yr period at six sites (tomato [*Lycopersicon esculentum* Mill.] and safflower [*Carthamus tinctorius* L.] were the rotational crops in these systems) while at three sites (Rc-1, Rc-2, Rc-3) rice had been grown only once in the previous 5 yr (alternate crops being maize (*Zea mays* L.), beans, melons, tomatoes, or safflower). At most sites medium grain varieties developed for California were grown (M202, M205, M206, M401, and M402); however specialty rice varieties (Calmochi, Kokuho Rose, Akita Komachi, Koshihikari, and Arborio) were grown at some locations (Table 1). These varieties are grown for specialty markets and generally have lower yields.

A field study was conducted at each site and set up as a randomized complete block design. There were two P fertilizer treatments, no P applied and P applied at 40 kg ha<sup>-1</sup> as triple superphosphate. Each treatment was replicated five times in 2005 and three times in 2006 and 2007. Plot sizes were at least 7.3 m<sup>2</sup>. All plots were within commercial rice fields (with the exception of the two ES sites which were located at the California Rice Experiment Station in Biggs), and apart from surface applications of N, P, and K, the experimental area was managed in the same way as the main part of the field. In most cases the majority of the N fertilizer was applied by the grower as aqua NH<sub>3</sub> injected 7 to 10 cm below the soil surface as was done to the rest of the field. In addition, 40 kg N ha<sup>-1</sup> (most growers apply 30 to 40 kg N ha<sup>-1</sup> in a surface application) and 50 kg K ha<sup>-1</sup> was broadcast by hand to all plots to ensure that these nutrients were not limiting. The P

fertilizer was broadcast by hand to the plots receiving P fertilizer. Following fertilizer application, all fields (except By-3 which was drill seeded) were flooded and planted by aerially applying pregerminated seed onto the field.

Approximately 35 d after seeding, 20 Y-leaf samples were taken from each experimental plot. At harvest, a 0.6 m<sup>2</sup> portion in the middle of each plot was sampled by cutting plants at ground level. Plants were oven dried and separated into grain and straw fractions. All samples were ground and analyzed for total P (Sah and Miller, 1992)

A soil sample (0–15 cm) was taken before fertilizer application at each site. The soil sample was air dried and ground for analysis. Soils were analyzed for pH (saturated paste, Richards, 1954), total N (AOAC International, 1997), soil organic carbon (Nelson and Sommers, 1982), Olsen-P (Olsen and Sommers, 1982), Bray-1 P (Olsen and Sommers, 1982), available K (Thomas, 1982), and soil texture (Sheldrick and Wang, 1993) at the UC Davis Analytical Laboratory. The soil order was determined from the Natural Resources Conservation Service web-based soil survey (<http://websoilsurvey.nrcs.usda.gov>). Most of the soils in this study were classified as Vertisols (64%) while the remaining were Entisols (eight sites), Mollisols (seven sites), Alfisols (six sites), and Inceptisols (two sites) (Table 1). Soil clay content ranged from 8 to 62% and averaged 40%. The pH of soils ranged from 4.5 to 7.9 with only four having a pH of more than 7. The organic C content of the soils ranged from 0.48 to 2.24%.

A sequential P fractionation procedure was conducted with three sequential P fractions being analyzed: NaHCO<sub>3</sub>, NaOH and HCl extractable inorganic (Pi) and organic (Po). We modified the Tiessen and Moir (1993) method by not including an initial resin P and analyzing for Po in the HCl extraction since He et al. (2006) found significant amounts of Po in this fraction. The sequential extraction procedure removes inorganic and organic P of increasing chemical stability as related to soil

P bioavailability (Hedley et al., 1982; Tiessen et al., 1984).  $\text{NaHCO}_3\text{-Pi}$  is the most biologically available Pi form,  $\text{NaOH-Pi}$  is associated with amorphous and crystalline Al and Fe phosphates, and  $\text{HCl-Pi}$  represents stable Ca bound phosphates. Sodium bicarbonate organic P ( $\text{NaHCO}_3\text{-Po}$ ) is considered to be easily mineralized and may contribute to the plant available pool while  $\text{NaOH-Po}$  is made up of chemically protected forms that involve long-term soil P transformations.  $\text{HCl-Po}$  has not been determined in most sequential P fractionation studies; however He et al. (2006) reported that the Po in this fraction is Ca bound hydrolyzable organic P. The fractionation scheme was conducted on 0.5 g of soil by sequentially extracting with 0.5 M  $\text{NaHCO}_3$ , 0.1 M  $\text{NaOH}$  and 1 M  $\text{HCl}$ . Each extraction required 16 h of shaking. The Po content of each extract was calculated as the difference between Pi and total P. The total P content of each extract was determined after digesting with ammonium persulfate and  $\text{H}_2\text{SO}_4$ . The Pi was determined on neutralized extracts (Tiessen and Moir, 1993) using the molybdate-colorimetric method of Murphy and Riley (1962).

At 56 sites where the P omission experiments were conducted an input/output P budget was developed by asking cooperating growers to provide annual P application rates, yields, and straw management practices for the 5-yr period before the experiment. The budget only accounted for the addition of P fertilizer and the removal of P in grain and straw (in cases where straw was removed). It did not account for potential losses due to leaching and runoff which we assumed to be small relative to the amount being applied (Zhang et al., 2003; Yoon et al., 2006). We also assumed no additional P losses resulting from burning of rice straw as Paul and Negi (2008) reported that in open field burning only 2.5% of the straw P is lost. At some sites this information was not available and thus was not included in the analysis. Additionally, the sites Dd-1, Rc-1, Rc-2, and Rc-3 were omitted because rice was only grown in one (or none) of the 5 yr before the experiment. For the calculation of P removal in grain and straw, we assumed a harvest index of 0.5 (the average harvest index of all sites in our study was 0.49) and grain and straw P concentrations of 0.23 and 0.09%, respectively (average of all the sites in our study). In this study the grain and straw P concentrations at harvest of specialty and the more standard medium grain varieties were identical (data not shown). The P concentrations used here are also within the range reported by Dobermann and Fairhurst (2000) for rice. At the five sites where rice was grown 3 of the 5 yr before the experiment and rotated with tomato and safflower (Tb-1, -2a, -2b, -3, and -4), tomato and safflower yields were obtained and harvestable tomato and safflower material was assigned P concentrations of 2.8 and 0.64% P, respectively. Tomato and safflower biomass was not removed from the field.

Data collected from each of the 64 P fertilizer experiments was subjected to an individual ANOVA to determine if there was a significant ( $P < 0.1$ ) yield response to P fertilizer. Simple linear and nonlinear regression analysis were used to analyze the following relationships: yield response to P vs. Olsen and Y-leaf P concentrations; and Olsen P vs. Y-leaf P concentration and the annual P budget. Pearson correlation coefficients were used to determine the degree of linear association among P fractions, soil P tests, other soil chemical properties, P uptake, Y-leaf P concentration and the annual soil P budget. Phosphorus uptake

and Y-leaf P concentrations from the “no P” treatment were used in the regression and Pearson correlation analyses.

## RESULTS

Based on the growers' field histories, P fertilizer had been applied in at least one of the previous 5 yr and at most sites it had been applied annually. Fertilizer P applications averaged  $20 \text{ kg P ha}^{-1} \text{ yr}^{-1}$  and grain yields averaged  $9.1 \text{ Mg ha}^{-1}$ . These reported historical yields were significantly correlated with plot yields from the P experiment ( $r = 0.66$ ), but were about 18% lower ( $11.1 \text{ Mg ha}^{-1}$ ) (Table 1). At sites where reported yields were  $< 7.0 \text{ Mg ha}^{-1}$  specialty rice varieties were grown. In fields where rice was the primary crop, rice straw was usually incorporated but occasionally burned. At Ks-1 straw had been removed every year. The annual soil P budget over a 5-yr period and accounting for all of the fertilizer inputs and P removal through grain and straw averaged  $-1.5 \text{ kg ha}^{-1}$  but ranged from  $-14.2$  to  $14.8 \text{ kg P ha}^{-1}$  (Table 1).

### Rice Yields and Response to Phosphorus Fertilizer

In the zero P treatment, rice grain yields ranged from  $5.7$  to  $14.8 \text{ Mg ha}^{-1}$  and averaged  $11.1 \text{ Mg ha}^{-1}$  across years, sites, and treatments. Across sites there was no yield difference between the zero and  $40 \text{ kg ha}^{-1}$  of P treatment ( $11.0 \text{ Mg ha}^{-1}$ ). All three sites (ES-2 and Mt-1 and -2) yielding below  $8 \text{ Mg ha}^{-1}$  were planted to lower yielding specialty varieties.

At 6 of the 64 sites (9%) there was a significant ( $P < 0.1$ ) and positive response to the application of P fertilizer (Table 1). Averaged across sites with a significant yield response to P, yields increased by  $0.89 \text{ Mg ha}^{-1}$  in response to P. Two of the sites with a significant yield response (My-2a,b) were in the same field but different years. In some fields there was a yield response in one year but not the other which was conducted in a separate part of the field (i.e., My-1a, c). One challenge in determining a P deficiency based on yield responses is that the magnitude of yield response was not much higher than the experimental error. The greatest yield response we observed was  $1.22 \text{ Mg ha}^{-1}$  (Ml-1) while across all sites and years the standard deviation of the grain yield response to P was  $0.54 \text{ Mg ha}^{-1}$ . At some sites visual symptoms of P deficiency were observed early in the season but disappeared as the season progressed resulting in no significant yield response.

### Indicators of Phosphorus Deficiency

Soil Olsen-P values ranged from  $2.2$  to  $32.4 \text{ mg P kg}^{-1}$  and were less than the critical value of  $6 \text{ mg P kg}^{-1}$  at nine sites (Table 1) but there was not a significant linear relationship between Olsen-P and yield response (Fig. 2). Of the six sites with significant grain yield responses, four had Olsen-P values below  $6 \text{ mg P kg}^{-1}$  and at the other P responsive sites the Olsen-P was  $8.3$  and  $19.6 \text{ mg P kg}^{-1}$  (Table 1, Fig. 2). Olsen-P was significantly correlated with P uptake (Table 2) and the P budget (Fig. 3). Bray-P ranged from  $0.3$  to  $30 \text{ mg P kg}^{-1}$  (data not shown) and was weakly correlated with Y-leaf P ( $r = 0.25$ ) but not with P uptake or the P budget. Olsen-P was correlated with all Pi fractions and  $\text{HCl-Po}$ , whereas Bray-P was not correlated with the  $\text{NaOH}$  fractions but was correlated with  $\text{HCl-Pi}$  and  $\text{Po}$ .

Y-leaf P concentrations ranged from  $0.12$  to  $0.47\%$  (Table 1). While no sites had Y-leaf P concentrations below  $0.1\%$  which is considered deficient, there were five sites where it was  $< 0.2\%$  and there was a significant yield response to added P at three of

these sites. At the other three sites where there was a significant response to P the Y-leaf values were above 0.2% (0.22, 0.27, and 0.35%). There was not a significant linear relationship between Y-leaf P and grain yield response (Fig. 2), but Y-leaf P was significantly correlated with P uptake, P budget, Bray-P and Olsen-P (Table 2). The relationship between Y-leaf P and Olsen-P was not linear as a best fit second order polynomial shows that Y-leaf P concentrations did not continue to increase when Olsen-P values exceeded 20 mg kg<sup>-1</sup> (Fig. 4).

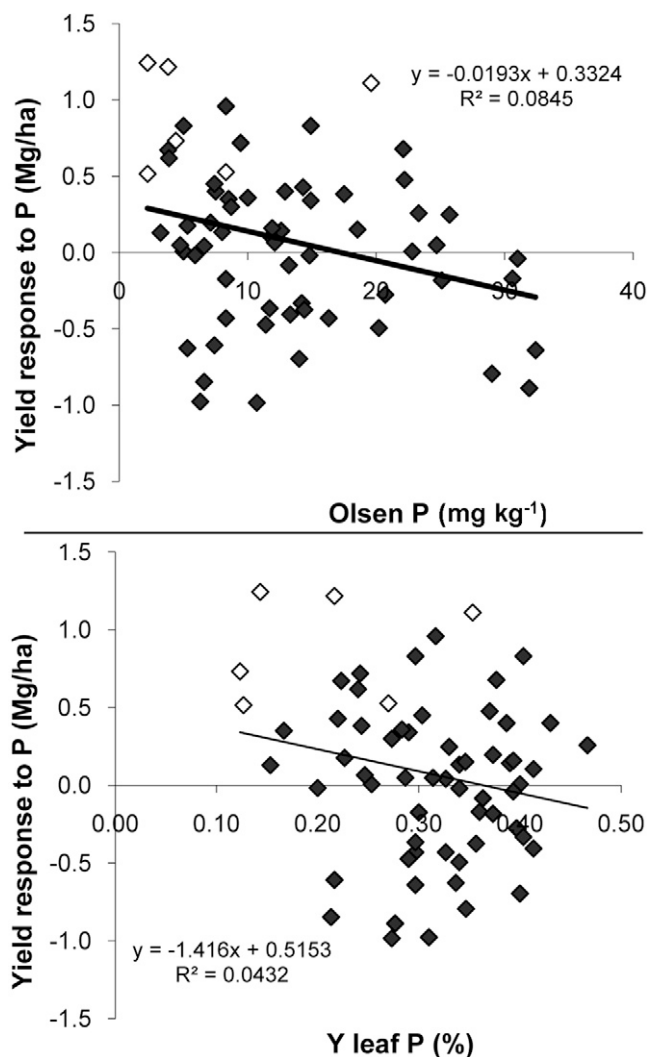
### Soil Phosphorus Fractions

The total amount of soil P in the NaHCO<sub>3</sub>, NaOH, and HCl Pi and Po fractions ranged from 125 to 640 mg kg<sup>-1</sup> and averaged 334 mg kg<sup>-1</sup> (Table 3) with 66% being Pi and 34% Po. The largest amount of P (49%) was in the HCl fraction and 37 and 14% where in the NaOH and NaHCO<sub>3</sub> fractions, respectively. There was generally a high degree of correlation among P fractions; although the HCl fractions were not correlated with NaOH fractions. Soil pH was negatively and positively correlated with NaOH-Pi and HCl-Pi, respectively. Similar relationships have been reported on elsewhere and confirm that they are extracting Fe/Al and Ca bound P, respectively (Tiessen et al., 1984). Y-leaf P, more highly correlated with soil P fractions than plant P uptake, was positively correlated with all Pi fractions and HCl-Po.

## DISCUSSION

### Phosphorus Deficiencies in California Rice Systems

Phosphorus deficiencies were not widespread in California rice systems. In this study only 9% of the sites responded to applied P fertilizer, similar to the 5% reported by Mikkelsen and Hunziker (1971) based on a 1969 survey. Unlike the southern United States where P deficiencies are primarily a problem on alkaline soils (Slayton et al., 2002; Norman et al., 2003), P deficiencies in this study all occurred on acid soils having a pH of 6.2 or less (Table 1). However, alkaline soils were poorly represented in this study with only four soils having a pH of >7. The lack of widespread P deficiency is due to increased availability of P under flooded conditions (Ponnamperuma, 1972) and because all growers in this study applied some P fertilizer. Soil P budgets for these systems show that while the “average” grower applied an optimal amount of P, many growers under applied P as demonstrated by negative P budgets. Negative P budgets resulted in lower available P (Olsen-P) and early



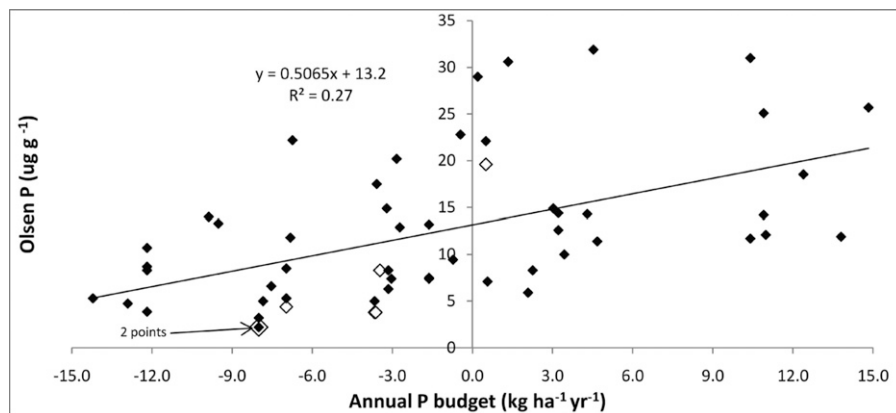
**Fig. 2.** The relationship between grain yield response (grain yield in “+P” treatment minus grain yield in “-P” treatment) and Olsen-P and Y-leaf P concentration ( $n = 64$ ). Open symbols identify sites in which there was a significant response to the addition of P fertilizer. Critical levels for Olsen-P are 6 mg kg<sup>-1</sup> and for Y-leaf P concentration 0.1% (Doberman and Fairhurst, 2000) or 0.2% (recommendation from this study).

season plant P concentration (Y-leaf P) and may lead to yield reductions in the future if P rates are not increased. The wide variation in P budgets among the fields in this study (range from -14 to +15 kg ha<sup>-1</sup> yr<sup>-1</sup>) highlights the need for improved P recommendations.

**Table 2.** Correlation coefficients (Pearson) for measured plant and soil properties and soil P fractions. Only significant ( $P < 0.05$ ) correlations are shown. For all correlations the number of cases was 64 with the exception of Annual P budget ( $n = 56$ ).

Parameter	P uptake†	Y-leaf P†	Clay	Organic matter	pH	Annual P budget	Bray-P	Olsen-P	NaHCO <sub>3</sub> Pi	NaHCO <sub>3</sub> Po	NaOH Pi	NaOH Po	HCl Pi	HCl Po
Y-leaf P	0.26													
Clay	-	-0.48												
Organic matter	-	-												
pH	-	-												
Annual P budget	-	0.29	-0.39											
Bray-P	-	0.25	-	-0.36	0.54									
Olsen-P	0.26	0.50	-	-	-	0.52		0.75						
Sod Bi Pi	0.25	0.48	-	-	-	0.53		0.73	0.96					
Sod Bi Po	-	-	0.26	-	-0.40	-		-	-					
Sod Hy Pi	-	0.49	-	-	-0.24	0.57		0.73	0.72	0.31				
Sod Hy Po	-	-	-	0.34	-0.49	-		-	-	0.51	0.46			
HCl Pi	-	0.38	-	-	0.70	-		0.56	0.49	0.50	-	-		
HCl Po	-	0.44	-	-	0.57	0.27		0.40	0.42	0.49	-	-	-	0.71

† P uptake and Y-leaf P from “no P” treatment.



**Fig. 3.** The relationship between Olsen-P and the P budget ( $n = 56$ ). The P budget is an accounting of P inputs (fertilizer) and outputs (grain and straw removal) over the 5 yr before the experiment. In the figure this value is averaged and presented as an annual P budget. Open symbols identify sites in which there was a significant response to the addition of P fertilizer. The arrow in the figure identifies two overlapping points.

Crop P deficiencies were not severe in our study. At P deficient sites, yields only increased on average by  $0.89 \text{ Mg ha}^{-1}$  and at most by  $1.24 \text{ Mg ha}^{-1}$  suggesting relatively mild P deficiencies. In contrast, P deficiencies on alkaline soils in the Arkansas were more severe with Slayton et al. (2002) reporting P responses of up to  $2.5 \text{ Mg grain ha}^{-1}$ .

### HCl-Po Fraction

Phosphorus in the HCl-Po fraction is usually not determined in most sequential P fractionation schemes as Tiessen and Moir (1993) indicated that there was usually little to no Po in this extract. In this study, the amount of P in the HCl-Po fraction averaged  $40 \text{ mg kg}^{-1}$  and ranged from 0 to  $128 \text{ mg kg}^{-1}$ . Turner et al. (2005) suggested that a quantitative analysis of organic P should include a determination of Po in both acid and alkali extracts. However, in methods proposed by Hedley et al. (1982) and Tiessen and Moir (1993) the Po is all determined in alkali extracts. He et al. (2006) reported that the 1 M HCl extraction in the Hedley sequential fractionation procedure (Hedley et al., 1982) may contain significant amounts of Po. This study confirms this and further suggests that HCl-Po may be an important fraction for plant P nutrition. In another study Linquist et

al. (2011) reported that the amount of P in the HCl-Po fraction differed among soil orders.

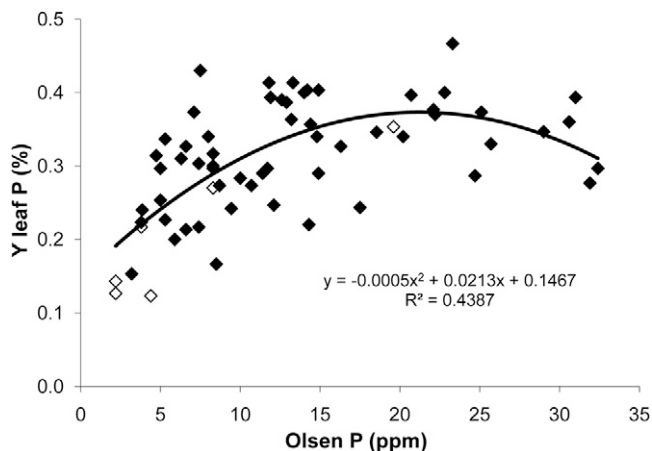
### Plant Available Fractions and Fate of Applied Phosphorus

The  $\text{NaHCO}_3\text{-Pi}$  fraction was the only fraction correlated with crop P uptake; while both  $\text{NaHCO}_3\text{-Pi}$  and  $\text{NaOH-Pi}$  were the fractions most highly correlated with Y-leaf P concentration. These fractions are associated with labile Pi and Fe/Al-Pi, respectively (Tiessen et al., 1984). Verma and Tripathi (1982) also found that Fe- and Al-P were the most important inorganic fractions contributing to rice P nutrition. Zhang et al. (2006) reported positive correlations between all Pi fractions and P uptake on a calcareous soil in China. Calcareous soils generally have higher amounts of HCl-Pi (Ca-P) (Tiessen et al., 1984) and thus this fraction may contribute more to P uptake in calcareous soils. However, correlations between HCl-Pi and P uptake were not significant in this study and may be due to the fact that calcareous soils were not well represented in this study as only four of the soils had a pH of  $>7.0$  (Table 1). HCl-Pi was correlated with Y-leaf P though, suggesting that it does play a role in supplying crop P demand. None of the Po fractions were correlated with P uptake but HCl-Po was the only Po fraction correlated with Y-leaf P concentration and the P budget, suggesting that this fraction is dynamic and deserving of further study.

The annual P budget was positively and significantly correlated with  $\text{NaHCO}_3\text{-Pi}$ ,  $\text{NaOH-Pi}$ , and HCl-Po. These are the same fractions that were most highly correlated with either P uptake or Y-leaf P concentration. The high correlation between P budget and  $\text{NaHCO}_3\text{-Pi}$  (labile P) and  $\text{NaOH-Pi}$  (Fe/Al-Pi) suggests that these Pi fractions are primary contributors to plant P nutrition and potential sinks for excess applied P fertilizer. Others have also found that the Fe/Al-Pi fraction is a sink for excess fertilizer P (Sah and Mikkelsen, 1986; Zhang et al., 2006; Saleque et al., 2004).

### Phosphorus Tests

The wide range in the annual P budget among growers indicates the need for improved recommendations and P tests to identify when P is needed. Of the two soil tests evaluated, the Bray-P performed the poorest as it was only weakly correlated with Y-leaf P concentration ( $r = 0.25$ ) and was not correlated with P uptake or the annual P budget. Olsen-P was a better indicator as it was more strongly correlated with Y-leaf P ( $r = 0.50$ ) and was correlated



**Fig. 4.** The relationship between Olsen-P and Y-leaf P concentration ( $n = 64$ ). Open symbols identify sites in which there was a significant response to the addition of P fertilizer. Critical levels for Olsen-P are  $6 \text{ mg kg}^{-1}$  and for Y-leaf P concentration  $0.1\%$  (Doberman and Fairhurst, 2000) or  $0.2\%$  (recommendation from this study).

**Table 3. Summary results of sequential P fractionation on 64 rice soils in California. "Total" refers to the sum of the three fractions determined.**

Parameter	Sodium bicarbonate		Sodium hydroxide		Hydrochloric acid		Total		Total
	Pi	Po	Pi	Po	Pi	Po	Pi	Po	Pi + Po
	mg kg <sup>-1</sup>								
Mean	33	15	63	61	123	40	219	116	334
Maximum	75	32	143	111	382	128	545	224	640
Minimum	11	5	19	30	17	0	51	61	125
Standard deviation	16	5	32	19	93	32	114	37	138

with P uptake, annual P budget, and the Fe/Al-Pi fraction which supplies plant P. The Olsen-P test was developed for crops grown on alkaline soils (Olsen et al., 1954); however, a number of studies comparing soil P tests have found the Olsen-P test superior to other tests (including Bray-1) for predicting P deficient soils and P uptake in flooded rice soils regardless of pH (Ektepe, 1976; Chang, 1976). Dobermann and Fairhurst (2000) also recommend Olsen-P for rice soils as it is more versatile across a wider pH range than other soil P tests. Why is Olsen-P a better predictor of P availability? The Fe-P fraction may be important in rice soils as Sah and Mikkelsen (1986) found that Fe-P increased when the soil was flooded while Al-P decreased, suggesting that Fe-P may be more important than Al-P for crop nutrition. Bray-P and Olsen-P extract different P fractions. The Bray extractant is acidic and contains HCl which extracts Ca-P (Williams et al., 1980) but Maida (1978) found that Bray extracted Al-P (in addition to Ca-P) but did not extract Fe-P. Maida (1978) also reported that Olsen-P extracted Fe-P and this is supported by the high degree of correlation between Olsen-P and NaOH-Pi (Table 2). Unfortunately however the sequential fractionation scheme used here does not differentiate between Fe and Al bound P as the NaOH-Pi fraction is thought to be Fe- and Al-Pi (Williams et al., 1980).

Our data confirm previous greenhouse studies (Williams, 2010) that an Olsen-P value of 6 mg kg<sup>-1</sup> is a suitable critical value. Six sites had significant yield responses to added P fertilizer and four of these had Olsen-P values below 6 mg kg<sup>-1</sup>; however there were also two sites where soil P values were above the critical level (8.3 and 19.6 mg kg<sup>-1</sup>) and there was a response to added P. Furthermore, 13 soils had P values below 6 mg kg<sup>-1</sup> but significant grain yield responses to P were found at only four of these sites. While this test is not perfect, it is a reasonable indicator of low P soils and could be used with other tools (i.e., Y-leaf P and P budget) to develop more reliable recommendations.

Y-leaf P concentration, in addition to being correlated with both soil tests and P uptake, was also correlated with the P budget, all of the Pi fractions and HCl-Po. Values between 0.2 and 0.4% are considered optimum; while <0.1% is considered deficient (Dobermann and Fairhurst, 2000). From the United States, others have reported that Y-leaf P concentrations of 0.1 to 0.27% are considered adequate (Ward et al., 1973; Jones et al., 1991). None of the Y-leaf P concentrations in this study were below 0.1%; however three of the five sites with Y-leaf P values below 0.2% responded significantly to P. The Y-leaf P concentrations at the other sites with significant yield responses were 0.22, 0.27, and 0.35%. Based on our data set with relatively few P deficient sites, a Y-leaf P concentration of 0.2% or less should be considered deficient. This critical value is higher than that suggested by other studies and should be confirmed with more data. The problem with a tissue test is that once a deficiency has been identified it is often too late to correct in the same season; however it does provide valuable information for managing P in the following season.

Developing a P budget based on P inputs and outputs can also be a valuable tool to determine potential P needs. The budget is a calculation of the P added as fertilizer minus the P removed by the grain and straw (if straw is removed). Such calculations are easy and inexpensive as fertilizer and yield records are usually readily available. While growers on average applied close to the right amount of P (average annual P budget was -1.5 kg P ha<sup>-1</sup> yr<sup>-1</sup>) the annual P budget ranged from -14 to +15 kg P ha<sup>-1</sup> yr<sup>-1</sup> and suggests that fertilizer inputs were not based on P demand, leading to excessive P build up or decline in some soils. All but one site with a significant response to P had negative P budgets (one site the P budget was 0.5 kg ha<sup>-1</sup>). As is the case with the soil and plant tissue tests, the P budget does not always predict a P deficiency as there were six cases where the P budget was -10 kg ha yr<sup>-1</sup> or less with no significant response to P. Lack of response to P additions at these sites may be due P management practices that occurred before the 5-yr period discussed in the interviews with growers. Based on our results growers should take a management approach to P that emphasizes build up and maintenance, as also suggested by Dobermann and Fairhurst (2000), using soil and tissue tests and a P budget. Growers can maintain the soil P budget and fertility by adding the amount of fertilizer that is removed by the crop (i.e., a maintenance approach to P fertility). For most California growers that do not remove their rice straw, 2.3 kg P ha<sup>-1</sup> should be applied for each Mg ha<sup>-1</sup> of grain yield to maintain soil P levels. If soil Olsen-P levels are <6 mg kg<sup>-1</sup> or if tissue P tests are low then higher rates are advisable to build up soil P. Excessively high soil P values are not advisable due to the risk of off-site contamination (Sharpley et al., 2003) and algae (Spencer et al., 2006) and P should not be applied.

Finally, P tests may be improved by including organic P. While there are many studies indicating that organic P is an important source of plant P (i.e., Yang et al., 2006; Sharpley, 1985), no routine lab tests use organic P to develop recommendations. While some have suggested that NaHCO<sub>3</sub>-Po is easily mineralizable and contributes to plant available P (i.e., Bowman and Cole, 1978) our study does not support this but rather suggests that HCl-Po may be plant available based on the correlation between this fraction and Y-leaf P (Table 2).

## SUMMARY AND CONCLUSION

The efficient management of P is crucial to ensure optimal yields while at the same time not causing P to build up excessively in soils which can lead to offsite pollution and within field algae problems. Phosphorus deficiencies are not that prevalent in California rice systems, which is in part due to a number of growers who are maintaining or increasing soil P budgets through fertilizer additions. However, there are growers who are applying less P than their crop demands and this may lead to increased deficiencies in the future. This is especially the case with growers that achieve high yields as the crop removes more P.

Both the Olsen-P soil test and the Y-leaf P test can be useful tools in identifying potential P deficiencies across a wide range of soil types. This study also highlights the utility of using an input/output P budget (based on fertilizer P inputs and crop P removal) in determining if P rates are low, adequate, or excessive. In this study the only fields with a P deficiency were those that had average annual P budgets of 0.5 kg P ha<sup>-1</sup> or less. The annual P budget was also correlated with both Olsen-P and Y-leaf P. While the focus of this manuscript has been the identification of P deficient soils (not correcting a deficiency), our data suggest that soil P can be maintained by adding the amount of P that is removed by the crop.

The P fractionation scheme, in combination with the other plant and soil data and P budget, demonstrate that it is the labile (NaHCO<sub>3</sub>-Pi) and Fe/Al-Pi fractions (NaOH-Pi) in these soils which are the most dynamic. It is primarily from these fractions that P is removed for plant uptake and to which excess fertilizer P ends up. HCl-Po was the only Po fraction correlated with other plant and soil indicators of P deficiency and with the P budget. This fraction has been ignored in most studies, but our research suggests that it is an important and dynamic P fraction and is thus deserving of further study.

### ACKNOWLEDGMENTS

We would like to acknowledge the California Department of Food and Agriculture's (CDFA) Fertilizer Research and Education Program (FREP) and the California Rice Research Board for funding this research. We thank Katie Chun for her assistance in the laboratory and the cooperation of the many rice growers that participated in this study.

### REFERENCES

- AOAC International. 1997. Official methods of analysis of AOAC International. 16th ed. Method 972.43. AOAC Int., Arlington, VA.
- Bowman, R.A., and C.V. Cole. 1978. An exploratory method for fractionation of organic phosphorus from grassland soils. *Soil Sci.* 125:95–101.
- Chang, S.C. 1976. Phosphorus in submerged soils and phosphorus nutrition and fertilization of rice. p. 93–116. *In* The fertility of paddy soils and fertilizer applications for rice. Asian and Pacific Region Food and Fertilizer Technol. Ctr., Taipei, Taiwan.
- Dobermann, A., and T.H. Fairhurst. 2000. Rice: Nutrient disorders and nutrient management. Potash & Phosphate Inst., Potash & Phosphate Inst. of Canada, and Int. Rice Res. Inst., Singapore and Los Baños.
- Ekpete, D.M. 1976. Evaluation of chemical methods for determination of available phosphorus in waterlogged soils. *Soil Sci.* 121:217–221.
- He, Z., A.M. Fortuna, Z.N. Senwo, I.A. Tazisong, C.W. Honeycutt, and T.S. Griffin. 2006. Hydrochloric fractions in Hedley fractionation may contain inorganic and organic phosphates. *Soil Sci. Soc. Am. J.* 70:893–899.
- Hedley, M.J., J.W.B. Stewart, and B.S. Chauhan. 1982. Changes in inorganic and organic soil phosphorus fraction induced by cultivation practices and by laboratory incubations. *Soil Sci. Soc. Am. J.* 46:970–976.
- Jones, J.B., Jr., B. Wolf, and H.A. Mills. 1991. Plant analysis handbook; A practical sampling, preparation, analysis, and interpretation guide. Micro-Macro Inc., Athens, GA.
- Linquist, B.A., M.D. Ruark, and J.E. Hill. 2011. Soil order and management practices control soil phosphorus fractions in managed wetland ecosystems. *Nutrient Cycl. Agroecosys.* (in press).
- Maida, J.H.A. 1978. Phosphate availability indices related to phosphate fractions in selected Malawi soils. *J. Sci. Food Agric.* 29:423–428.
- Mikkelsen, D.S., and R.R. Hunziker. 1971. A plant analysis survey of California rice. *Agrichemical Age* 14:18–22.
- Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta* 27:31–36.
- Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon and organic matter. p. 539–579. *In* A.L. Page et al. (ed.) Methods of soil analysis: Part 2. Chemical and microbiological properties. ASA Monogr. 9. ASA and SSSA, Madison, WI.
- Norman, R.J., C.E. Wilson, Jr., and N.A. Slaton. 2003. Soil fertilization and mineral nutrition in US mechanized rice culture. *In* C.W. Smith and R.H. Dilday (ed.) Rice: Origin, history, technology, and production. John Wiley & Sons, Hoboken, NJ.
- Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ. 939. U.S. Gov. Print. Office, Washington, DC.
- Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. p. 403–430. *In* A.L. Page et al. (ed.) Methods of soil analysis: Part 2. Chemical and microbiological properties. Agron. Monogr. 9. 2nd ed. ASA and SSSA, Madison, WI.
- Paul, J., and M.S. Negi. 2008. Effect of burning of rice and wheat straw on plant nutrients losses. *Crop Res. (Hisar)* 36:382–383.
- Ponnamperuma, F.N. 1972. The chemistry of submerged soils. *Adv. Agron.* 24:29–96.
- Richards, L.A. 1954. Diagnosis and improvement of saline and alkali soils. USDA Agric. Handb. 60. U.S. Gov. Print. Office, Washington, DC.
- RRB. 1980. Nutritive and environmental factors affecting high yield potential. Rice Research Board Annual Report. Available at <http://www.carrb.com/80rpt/Nutrition.htm> (verified on 25 Nov. 2010). California Rice Res. Board, Yuba City, CA.
- Sah, R.N., and D.S. Mikkelsen. 1986. Transformations of inorganic phosphorus during the flooding and draining cycles of soil. *Soil Sci. Soc. Am. J.* 50:62–67.
- Sah, R.N., and R.O. Miller. 1992. Spontaneous reaction for acid dissolution of biological tissues in closed vessels. *Anal. Chem.* 64:230–233.
- Saluque, M.A., U.A. Naher, A.B.M.B.U. Pathan, A.T.M.S. Hossain, and C.A. Meisner. 2004. Inorganic and organic phosphorus fertilizer effects on the phosphorus fractionation in wetland rice soils. *Soil Sci. Soc. Am. J.* 68:1635–1644.
- Sharpley, A.N. 1985. Phosphorus cycling I unfertilized and fertilized agriculture soils. *Soil Sci. Soc. Am. J.* 49:905–911.
- Sharpley, A.N., J.N. Weld, D.B. Beegle, P.J.A. Kleinman, W.J. Gburek, P.A. Moore, Jr., and G. Mullins. 2003. Development of phosphorus indices for nutrient management planning strategies in the United States. *J. Soil Water Conserv.* 58:137–152.
- Sheldrick, B.H., and C. Wang. 1993. Particle-size distribution. p. 499–511. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Canadian Soc. of Soil Sci., Lewis Publ., Ann Arbor, MI.
- Slayton, N.A., C.E. Wilson, R.J. Norman, S. Ntamatungiro, and D.L. Frizzell. 2002. Rice response to phosphorus fertilizer application rate and timing on alkaline soils in Arkansas. *Agron. J.* 94:1393–1399.
- Spencer, D., C. Lembi, and R. Blank. 2006. Spatial and temporal variation in the composition and biomass of algae present in selected California rice fields. *J. Freshwater Ecol.* 21:649–656.
- Thomas, G.W. 1982. Exchangeable cations. p. 159–165. *In* A.L. Page et al. (ed.) Methods of soil analysis: Part 2. Chemical and microbiological properties. ASA Monogr. 9. ASA and SSSA, Madison, WI.
- Tiessen, H., and J.O. Moir. 1993. Characterization of available P by sequential extraction. p. 75–86. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publ., Ann Arbor.
- Tiessen, H., J.W.B. Stewart, and C.V. Cole. 1984. Pathways of phosphorus transformations in soils of differing pedogenesis. *Soil Sci. Soc. Am. J.* 48:853–858.
- Turner, B.L., B.J. Cade-Menun, L.M. Condron, and S. Newman. 2005. Extraction of soil organic phosphorus. *Talanta* 66:294–306.
- Verma, T.S., and B.R. Tripathi. 1982. Evaluation of chemical methods for the determination of available phosphorus in waterlogged Alfisols: 1. Phosphate-availability indices in relation to phosphate fractions. *Soil Sci.* 134:258–264.
- Ward, R.C., D.A. Whitney, and D.G. Westfall. 1973. Plant analysis as an aid in fertilizing small grains. *In* L.M. Walsh and J.D. Beaton (ed.) Soil testing and plant analysis. SSSA, Madison WI.
- Williams, J.D.H., T. Mayer, and J.O. Nriagu. 1980. Extractability of phosphorus from phosphate minerals common in soils and sediments. *Soil Sci. Soc. Am. J.* 44:462–465.
- Williams, J.F. 2010. Rice nutrient management in California. Publ. 3516. Univ. of California, Agric. and Natural Resources, Richmond.
- Yang, C., L. Yang, and L. Jianhua. 2006. Organic phosphorus fractions in organically amended paddy soils in continuously and intermittently flooded conditions. *J. Environ. Qual.* 35:1142–1150.
- Yoon, K.S., J.K. Choi, J.G. Son, and J.Y. Cho. 2006. Concentration profile of nitrogen and phosphorus in leachate of a paddy plot during rice cultivation period in Southern Korea. *Commun. Soil Sci. Plant Anal.* 37:1957–1972.
- Zhang, H.C., Z.H. Cao, Q.R. Shen, and M.H. Wong. 2003. Effect of phosphate fertilizer application on phosphorus (P) losses from paddy soils in Taihu Lake Region. I. Effect of phosphate fertilizer rate on P losses from paddy soil. *Chemosphere* 50:695–701.
- Zhang, Q., G.H. Wang, Y.K. Feng, Q.Z. Sun, C. Witt, and A. Dobermann. 2006. Changes in soil phosphorus fractions in a calcareous paddy soil under intensive rice cropping. *Plant Soil* 288:141–154.