Final Report
Project title: Efficient phosphorus management in coastal vegetable production

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Objectives:

1) Develop efficient P fertilizer guidelines for coastal lettuce production
2) Document the relationship between soil characteristics, soil test P levels, and potential loss of P through in runoff.

Executive summary:

Decades of heavy phosphorus fertilizer application to vegetable fields in the Salinas and Pajaro Valleys have resulted in substantially increased soil P concentration. Soil test P levels now commonly exceed the threshold for expected crop response to continued P fertilization, based on commonly cited references from the University of California and other sources. While elevated soil P generally does not cause agronomic problems, it undoubtedly contributes to the undesirably high P concentration found in many coastal surface waters, including parts of the Salinas and Pajaro River systems. This project was undertaken to reexamine P management recommendations for lettuce production, and to evaluate the relationship of soil P status, P bioavailability, and the potential for P loss to the environment.

Soil was collected from 30 fields in the Salinas and Pajaro Valleys, most in long- term vegetable rotations. The P status of these soils was evaluated by a variety of analytical techniques, including the standard bicarbonate (Olsen) extraction (Pbc), calcium chloride extraction, a P bioavailability test using anion exchange membranes, and a procedure to estimate the degree of P saturation. Columns of these soils were then exposed to a simulated irrigation event under controlled conditions, and both runoff and leachate were collected and analyzed for PO4-P. The soils averaged 75 PPM Pb,, indicative of the intensity of P fertilization in coastal vegetable production. All measures of soil P status were highly correlated, and there was a strong correlation between all measures of soil P status and P concentration in both runoff and leachate. In soils with elevated Pb,, P

concentration in runoff and leachate substantially exceeded current environmental standards for surface water. In a separate experiment it was shown that the presence of a cover crop significantly reduced P04-P concentration and sediment in runoff.

Twelve trials were conducted in commercial lettuce fields in the Salinas Valley to evaluate whether P fertilization affected crop productivity in fields with moderate or high soil test P. The fields ranged from 53-171 PPM Pbc, averaging 82 PPM. In each field replicated plots were established in which the growers' preplant P application was skipped. In only one field was a significant lettuce yield response to P fertilization observed; that field was a spring planting (cool soil conditions), and had only 54 PPM Pbc. Averaged across trials, lettuce productivity was virtually identical in plots with and without preplant P. In these fields P fertilization had minimal effect on plant P uptake or tissue P status.

We conclude that current P fertilization practices for lettuce can be improved. P fertilization of fields > 60 PPM Pbc is unlikely to affect lettuce productivity. Below that soil test level, yield improvement becomes more likely, particularly under cool soil conditions. Continued fertilization of high P soils increases the potential for significant P loss to the environment. In addition to eliminating unnecessary P applications, growers can minimize P loss to the environment by eliminating or impounding tailwater, and by growing winter cover crops to minimize winter runoff and sediment loss. Those practices are best targeted toward fields with the highest Pbc, particularly if those fields have characteristics (slope or poor water infiltration rate) conducive to generating runoff.

Methods:

Soil P status:

To determine the current P status of agricultural land in the Salinas and Pajaro Valleys, soil from 30 fields, most in long-term vegetable rotations, was collected in spring, 2002. The fields, located in Monterey, San Benito, Santa Clara and Santa Cruz Counties, represented both conventionally-farmed and organically-managed land. In all fields, soil samples were collected from 0-6 inches and 6-12 inch depth. These samples were analyzed for bicarbonate (Olsen) extractable P (Pb,, Olsen and Sommers, 1982), the standard agronomic soil test procedure for neutral to alkaline agricultural soils. The 0-6 inch samples were also analyzed for pH and texture (% sand/silt/clay). Additionally, the 0-6 inch samples were evaluated by several alternative techniques to develop a more complete picture of soil P status. Those techniques were:

1) Calcium chloride extractable P (Pc,). Four grams air-dried soil was extracted in 40 ml 0.01 M CaCl2. The mixture was shaken for 1 hr, then centrifuged. The supernatant was analyzed for P04-P by a colorimetric method. The background and theory for this procedure is given in Kuo (1996).

2) P extractable by iron-impregnated paper (PFe). This technique seeks to mimic the action of plant roots by adsorption of P04-P onto chemically-treated paper strips; all P04- P thus captured in theory represents bioavailable P. Strips of ashless filter paper were immersed in 0.37 M FeC13, acidified with 1.3 M HCl for one hour, then air-dried. The paper was then dipped in 2.7 M NH4OH for 30 sec, rinsed with deionized water, then air-dried again. One of these iron-impregnated paper strips was put onto a centrifuge tube and shaken with a mixture of 1 g air-dried soil and 40 ml 0.01 M CaC12 for 16 hr. The strip was removed, rinsed in deionized water, then dried. Adsorbed P was removed from the strip by shaking in 0.1 M H2SO4 for one hr, and quantified by ICP-AES analysis. There were 3 replicate measurements per soil sample. The background and theory for this technique is given in Chardon et al. (1996).

3) P extractable by anion exchange membrane (Paem)• This technique is also purported to measure only bioavailable P. Disks of Bio-Rex AG 1-X8 anion resin membrane (Bio- Rad Laboratories, Richmond, CA) with a reactive area of 13 cm2 were eluted in 0.5 M NaHCO3, then rinsed with deionized water. Soil wetted to 2.5 times the gravimetric water content at field capacity was compressed on top of the membrane in a beaker to ensure complete contact with the reactive surface. The beakers were incubated at 20° C for 16 hr. The membranes were removed, rinsed with deionized water to remove adhering soil particles, then extracted in 40 ml 0.5 M HCl for one hr to remove adsorbed P. The extract was analyzed for PO4-P by a colorimetric method. To determine the effect of temperature on P adsorption six of the soils were chosen for further study. This anion exchange membrane procedure was conducted at 15 and 25° C (59 and 770 F), bracketing the soil temperatures encountered in the Salinas Valley in an annual production cycle. Prior to all Paem determinations the soils were leached with 0.01 M CaC12 to reduce soil NO3-N concentration below 5 PPM because N03-N suppresses P adsorption. There were 3 replicate measurements per soil sample. Background and theory for this technique is given in Cooperband and Logan (1994).

4) % P saturation (Psat). This procedure ranked the degree to which a soils' ability to sequester applied P in insoluble forms has been diminished. The capacity of soil to adsorb P was determined by shaking a 1:100 mixture of soil and 0.01 M CaC12 solution containing either 1.5 or 15 PPM PO4-P for 24 hr. The mixtures were centrifuged and the supernatants analyzed for PO4-P. Soil adsorption of P from the solution (in PPM, on a dry soil wt basis) was determined, and the % P saturation of the soil was calculated by the formula:

(Olsen P / (Olsen P + P adsorption)) * 100 = % P saturation
The higher the % P saturation, the less capacity remained to chemically bind applied fertilizer P. There were 3 replicate measurements per soil sample. Background and theory for this technique is given in Paulter and Sims (2000).

P loss potential:

The potential for loss of PO4-P in runoff or leachate was determined for each soil. Plastic columns 4 inches in diameter and 6 inches deep were filled with soil (0-6 inch sample); the columns contained a 45 µm filtration membrane, and a vacuum port to aid in the extraction of leachate. The soil columns were exposed to a simulated irrigation event in which 1 inch depth of 0.01 M CaCl2 was uniformly applied in 30 min by a moving sprayer nozzle. The high application rate was needed to ensure that runoff was generated in all soils. Runoff was captured, and the concentration of PO4-P was determined. A vacuum was then applied under the soil columns, and leachate was collected; the volume and PO4-P concentration was determined. There were 3 replicate columns of each soil.

An additional experiment was conducted to determine the effect of the presence of a cover crop on the P loss potential in runoff. Containers with a surface area of 40 in2 were filled with 6 of the soils, which ranged from 29 - 177 PPM Pb,. Half of the containers were moistened to field capacity and maintained at that moisture level at room temperature. The remaining containers were seeded with oats, which were allowed to grow until a dense canopy approximately 3 inches high was formed. At that time the containers with the oat cover crop were wetted to approximate field capacity. Containers with and without the oat cover crop were then subjected to a simulated irrigation event as previously described. The P04-P concentration and sediment content of runoff was determined. There were 3 replicate containers per treatment (cover crop or fallow) per soil.

Lettuce P requirements:

A total of twelve field trials were conducted in commercial lettuce fields in the Salinas Valley in 2002-2003 evaluating whether P fertilization affected crop productivity in fields with moderate or high soil test P levels. The fields chosen varied from 53 - 171 PPM Pbc (0-6 inch depth), averaging 82 PPM; this Pbc range encompasses the majority of vegetable acreage in the Salinas Valley. Existing recommendations rank these fields as moderate to high P availability. The fields were spread geographically from Salinas to King City, with a range of soil textures and planting dates; details are given in Table 1. In 10 of these fields the grower applied preplant P. Four plots per field were established in which this P application was skipped; the performance of these plots was compared to adjacent plots receiving the preplant P application. In fields #4 and 10 the grower did not apply preplant P fertilizer; four plots were established in each of these fields in which preplant P was applied at 130 lb P2O5 / acre. The experimental design in all fields was randomized complete

block, with each plot being 4 beds wide and 200 feet long. All data were collected in the middle 100 feet of each plot, from the middle two beds.
To document the effects of P fertilization on early plant growth the extent of plant canopy coverage prior to or at cupping was quantified by digital infrared photography, with the digital images manipulated by special software (Dycam Inc., Chatsworth, CA) to calculate the % of ground covered by foliage. Whole leaf total P and midrib P04-P concentration was monitored at cupping stage. At harvest the total P concentration of both the harvested head tissue and plant residue was determined. Just prior to commercial harvest, 30-40 whole plants per plot were randomly selected and weighed to compare total plant biomass between treatments. These whole plants were then trimmed according to market standards and the marketable weight was recorded. In 9 of the fields plant counts were also made before and after commercial harvest, and the % of marketable plants calculated.

Results:

Soil P status:

The soils collected in the field survey ranged from 15 - 177 PPM Pbc, averaging 75 PPM (Table 2). To put these numbers into perspective, soils from the Sacramento Valley that have been farmed for an equivalent period of time typically range from 10-25 PPM Pb,. The difference reflects the higher rates, and more frequent application, of P fertilizers in the coastal valleys. Despite high Pbc, many coastal vegetable growers continue to apply P before each crop (as evidenced by the grower P application in 10 of the 12 trial fields), and a substantial number also apply P in sidedressings. It should be noted that some fields under both conventional and organic management had high soil P levels; heavy use of composted manures can elevate soil P as well as heavy use of synthetic P fertilizers. The soils ranged in texture from sandy loam to clay; pH ranged from 6.1 - 7.9, with only two soils below pH 6.5

There was significant correlation among all measures of soil P status (Table 3). Pbc was highly correlated (r = 0.89) with the anion exchange membrane technique (Paem), supporting the validity of Pbc as a valid measure of bioavailable P. Calcium chloride extractable P (PeC), a simple laboratory procedure, was very closely correlated with the much more complicated Paem technique (r = 0.95). The iron-impregnated paper technique (PFe) was a complex laboratory procedure, with greater variability of result than the other techniques evaluated; the correlation of this technique to other measures of soil P status was generally poor.

The effect of temperature on P bioavailability was significant. As measured with the Paem technique, bioavailable P averaged 37% greater at 25° C (77° F) than at 15° C (590 F, Fig. 1). The range of 15 - 25° C encompasses the typical seasonal soil temperature variation experienced in the Salinas Valley.

P saturation was clearly linked to Pbc, with high Pbc soils having significantly diminished capacity to sequester additional P (Fig. 2). When incubated with a 1.5 PPM P04-P solution the P adsorption capacity of some of these soils was saturated. Pbc was a highly correlated with Psat (r = 0.90).

In the runoff / leachate trial P04-P concentration among soils ranged from 0.02 -PPM in runoff, and 0.14 - 10.8 PPM in leachate. To put these values in perspective, in their surface water quality monitoring program the Region 3 Water Quality Control Board currently considers 0.12 PPM to be the maximum acceptable P04-P concentration. The potential environmental hazard represented by such high leachate P04-P concentrations is overstated, since surface soil was used in this experiment, and P availability generally declines with depth. However, we found elevated Pbc levels (> 60 PPM) to at least 3 ft depth at some sites, suggesting that the P04-P concentration of drain tile water may be of serious concern. Conversely, the runoff P04-P undoubtedly underestimated potential P losses under field conditions. The relatively small soil columns used in this study, and the high water application rate, resulted in a short dwell time of water on the soil surface before runoff occurred; longer dwell time would tend to increase soil P solubilization. While both Pbc and Paem were highly correlated with P04-P concentration in runoff and leachate, Pcc was the best predictor of runoff and leachate P (r= 0.98 and 0.96, respectively, Fig. 3), perhaps not surprisingly since 0.01 M CaC12 solution was used in the runoff experiment to simulate irrigation water. This calcium- dominated solution is similar to irrigation water in the coastal production regions. Regardless of the soil test used, the strong linear relationship between soil test P and runoff and leachate P illustrated the importance of judicious P fertilizer management.

Factors other than soil P status can affect P loss to the environment. Field slope and soil texture affect water infiltration. The presence of a crop may have profound influence as well. In the runoff simulation experiment in which soil with a cover crop was compared to fallow soil, the presence of the cover crop reduced runoff P04-P concentration by 41%, and sediment carried in the runoff by 85% (Fig. 4). Reducing sediment losses would be particularly important in fields with elevated soil P levels, since substantial P may be solubilized from that sediment after it leaves the field in runoff.
This experiment may underestimate the overall importance of cover crops in reducing P losses to the environment, since cover crops also tend to significantly reduce runoff volume.

Lettuce P requirement:
Preplant fertilization had negligible impact on early season lettuce growth; across 12 trials the % canopy coverage was nearly identical with or without preplant P (Table 4). In field #1 there was a small but statistically significant improvement in yield with preplant P. This field was planted in early April (cool soil temperature) and had a Pbc level of 54 PPM, among the lowest of the trial sites. Field # 7 had similar conditions, and though not statistically significant,

there was a trend toward greater plant weight with P fertilization. Fields in which Pbc was substantially higher, or that were planted in warmer weather, showed no response to applied P. Excluding fields #1 and 7, plant whole and marketable weight, and % marketable plants were essentially identical in plots with and without preplant P. Field #4 exhibited low plant vigor in both treatments; the relatively small average plant weight in some other fields was due to high density planting for harvest for salad mix, and to the need to conduct the evaluation before commercial harvest.

P fertilization had minimal impact on tissue P concentration, with variability in all measures of plant P status greater among fields than between treatments within fields (Table 5). Current sufficiency standards are 0.40% for mid-season leaf P, and 3,000 PPM for midrib P04-P (Western Fertilizer Handbook, 2000). Only the no P treatment in field #10 (spring planted, 55 PPM PbJ had leaf P below the 0.40% threshold. However, several fields were near or below the 3,000 PPM P04-P midrib threshold, including fields with extremely high soil P levels; indeed, the highest midrib value recorded in either treatment in any field was only 3,540 PPM. These trials suggested that a 2,500 PPM P04-P sufficiency threshold value may be warranted.

P application had little influence on crop P uptake. The harvestable portion of the crop contained on average approximately 10 lb of elemental P / acre, and the difference between fertilized and unfertilized crops was < 0.5 lb / acre. Since the growers applied an average of 66 lb P2O5 / acre (29 lb P / acre), most of that P remained in the soil. This large difference between P application and removal over many years explains the elevated soil test P values now common in the coastal valleys.

In summary, the following conclusions can be drawn from this study:

1) The probability of obtaining a lettuce growth response from preplant P application in fields with Pb, > 60 PPM is low. Even at 50 PPM Pbc only fields planted in early spring have a reasonable probability of crop response, and only a low rate of P application could be justified. Given the modest P removal rate of lettuce, it may take a number of crop cycles of little or no P application to significantly reduce soil test P levels.
2) The Pb, test is not only a useful guide to P fertilizer management, it also provides a relative ranking of potential P loss to the environment through surface runoff. Management efforts to limit P losses can be most effectively directed at fields with elevated Pbc (perhaps those with > 80 - 100 PPM).
3) Cover **cropping is a valuable practice to minimize P loss to the environment during the winter**. This study, which **supported prior research on this topic, suggests that** cover **crops will reduce** runoff **P04-P concentration and sediment content.**

Outreach activities:

Results of this project have been widely **disseminated both through presentations at public meetings and articles in trade publications**. **In addition to presentations at the FREP Annual Conference in both 2002 and 2003, a total of 8 presentations at grower and fertilizer industry meetings have been presented. Those events were:**

1) Coastal Agronomy Conference, sponsored by the California Plant Health Association, San Luis Obispo, July 16, 2002.
2) California Agricultural Production Consultants Association annual meeting, Anaheim, October 22, 2002.
3) California Plant and Soil Conference, Modesto, February 5, 2003.
4) Irrigation and Nutrient Management meeting, Salinas, February 12, 2003.
5) Monterey Bay Ag Expo, Watsonville, February 25, 2003.
6) Western Nutrient Management Conference, Salt Lake City, March 6, 2003.
7) Vegetable Production meeting, Guadalupe, January 21, 2004.
8) Irrigation and Nutrient Management meeting, Salinas, February 10, 2004.

A written summary of the 2002 research was published in the Proceedings of the Western Nutrient Management Conference, **a biennial meeting of academic and fertilizer industry personnel from all western states. Additionally, a summary of the 2002 work for growers was printed in the Monterey County UCCE newsletter of January**, **2003. An article summarizing the entire project** (**see attachment**) **was published in Vegetables West magazine** (**January, 2004, edition), the Western Farm Press** (**February 7, 2004**, **edition), and the January, 2004**, **Monterey County UCCE newsletter. Collectively**, **these outlets will reach the majority of coastal lettuce growing operations.**

Literature cited:

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Cooperband, L. R. and T. J. Logan. 1994. Measuring **in-situ changes in labile soil** phosphorus with **anion-exchange membranes**. Soil Sci. Soc. Amer. J. 58:105-114.

Kuo, S. 1996. Phosphorus. *In D. L.* Sparks (ed.) Methods of soil analysis, part 3. Chemical methods. SSSA Series no. 5, pp 869-919.

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Table 1. Characteristics of the 2002- 2003 **trial sites.**

Field	Location	Pbc (PPM)7	P application rate (lb P205 / acre)	Planting dater
		Iceberg lettuce		
1	Salinas	54	59	Apr 3, 2002
2	Salinas	124	60	Apr 11, 2002
3	Chualar	72	42	June 12, 2002
4	Chualar	171	130	July 15, 2002
5	King City	57	80	Jan 27, 2003
6	King City	62	75	Jan 27, 2003
7	King City	53	75	Feb 19, 2003
8	King City	82	80	Feb 26, 2003
9	Salinas	81	60	May 20, 2003
		Romaine lettuce		
10	Soledad	55	130	May 11, 2002
11	Chualar	78	72	July 26, 2002
12	Salinas	98	53	Feb. 10, 2003

Z top six inches of soil r date of first water

Table 2. Soil test P in survey fields.

	Number of fields	
Pbc (PPM)Z	Conventional	Organic
< 40	5	3
40-80	9	0
80 - 120	7	l
> 120	3	2

Z 0-6 inch depth

Table 3. Correlation matrix for **techniques** to evaluate **soil P status, and P loss** potential.

	Pbc	Pcc	P	Paem	Psat	Runoff P04-P
Pbc						
Pcc	0.86					
PFe	0.78	0.77				
Paem	0.89	0.95	0.76			
Psat	0.90	0.82	0.61	0.84		
Runoff P04-P	0.83	0.98	0.72	0.93	0.79	
Leachate P04-P	0.78	0.96	0.67	0.90	0.82	0.95

Pbc = bicarbonate extraction; Pee = calcium chloride extraction; PFe = iron-impregnated paper extraction; Paem = anion exchange membrane extraction; Psat = % P saturation all correlations significant at $p < 0.01$

Table 4. **Lettuce response to P fertilization.**

Field	P treatment (lb P2O5 / acre)	% canopy cover'	% of plants marketable	Whole plant wt (lb)	Marketable plant wt (lb)
		Iceberg lettuce			
1	0	47	81Y	2.15"	1.46 Y
	59	48	87	2.29	1.56
2	0	17	93	2.42	1.58
	60	19	95	2.52	1.57
3	0	28	84	2.56	1.66
	42	28	83	2.64	1.70
4	0	31	75	1.55	1.06
	130	32	77	1.56	1.08
5	0	24	90	2.31	1.35
	80	25	92	2.29	1.34
6	0	42	76	2.52	1.49
	75	42	68	2.43	1.43
7	0	18	90	2.00	0.98
	75	22	91	2.20	1.12
8	0	18	87	2.07	1.35
	80	20	87	2.00	1.32
9	0	25	87	2.60	1.83
	60	26	83	2.49	1.65
Ave	No **P**	**28**	**85**	**2.24**	***1.42***
	Plus P	**29**	**85**	**2.27**	**1.42**
		Romaine lettuce			
10	0	25		1.55	1.07
	130	26		1.65	1.08
11	0	39		1.21	0.90
	72	38		1.17	0.88
12	0	15		2.31	1.43
	53	17		2.38	1.47
Ave	No **P**	**26**		**1.69**	**1.13**
	Plus P	27		1.73	1.14

Z early season canopy development, measurement by infrared photography Y significantly different from the applied P treatment

Table 5. Effect **of P fertilization on lettuce tissue P concentration.**

Field	P treatment (lb P2O5 / acre)	At heading: Leaf P (%)	At heading: Midrib P04-P (PPM)	% P at harvest: Harvested head	% P at harvest: Residue
		Iceberg lettuce			
1	0	0.43		0.64	0.32
	59	0.43		0.66	0.32
2	0	0.48		0.68	0.35
	60	0.51		0.71	0.39
3	0	0.51	3,480	0.78	0.41
	42	0.53	3,440	0.81	0.36
4	0	0.44	2,480	0.55	0.38
	130	0.49	2,760	0.59	0.42
5	0	0.54	2,330	0.66	0.39
	80	0.52	2,540	0.73	0.39
6	0	0.46	2,560	0.64	0.33
	75	0.47	2,530	0.65	0.35
7	0	0.62	3,100	0.72	0.37
	75	0.71	3,540	0.78	0.39
8	0	0.55	2,990	0.65	0.34
	80	0.54	3,210	0.66	0.37
9	0	0.51	3,250	0.75	0.40
	60	0.52	3,330	0.76	0.39
Ave	**No P**	**0.50**	**2,880**	**0**.67	0.37
	Plus P	**0.53**	**3,050**	**0.70**	**0.38**
		Romaine lettuce			
10	0	0.37		0.38	0.25
	130	0.40		0.42	0.23
11	0	0.56		0.56	0.30
	72	0.56		0.56	0.29
12	0	0.65	2,840	0.56	0.48
	53	0.62	2,760	0.61	0.44
Ave	No **P**	**0.53**		**0.50**	**0.34**
	Plus P	**0.53**		**0.53**	**0.32**

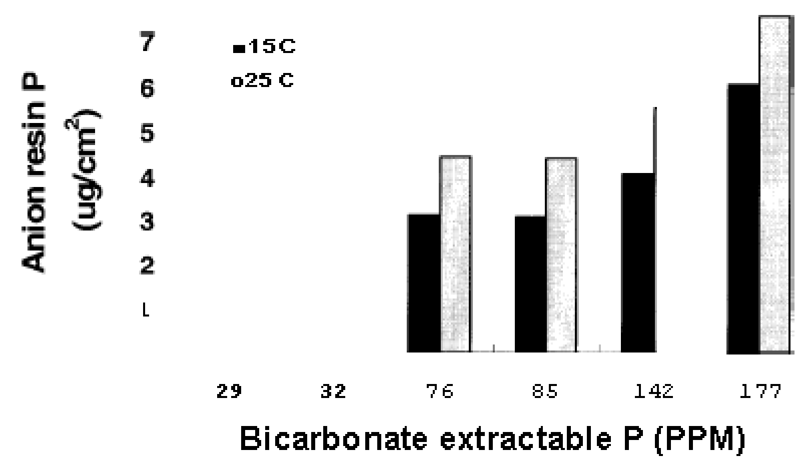

Fig. 1. Effect of temperature on soil P bioavailability , as measured by the anion exchange membrane technique.

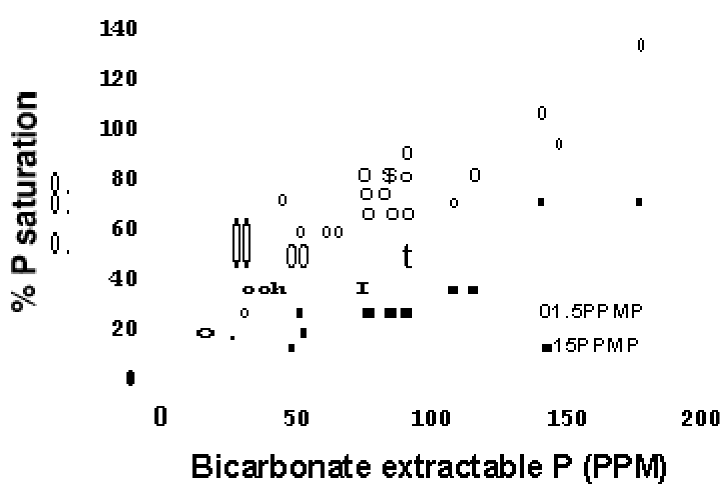

Fig. 2. Relationship between bicarbonate extractable P and % P saturation; 1.5 and 15 refer to the P04-P concentration of the enrichment solution.

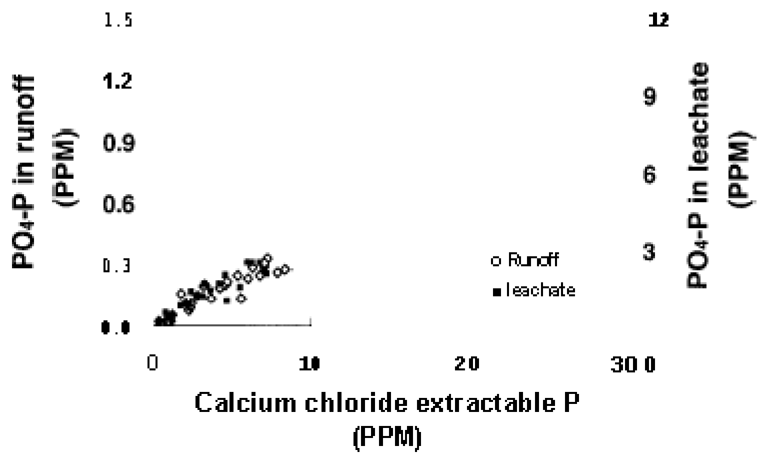

Fig. 3. Relationship between calcium chloride extractable P and the concentration of P04-P in runoff and leachate from the column study.

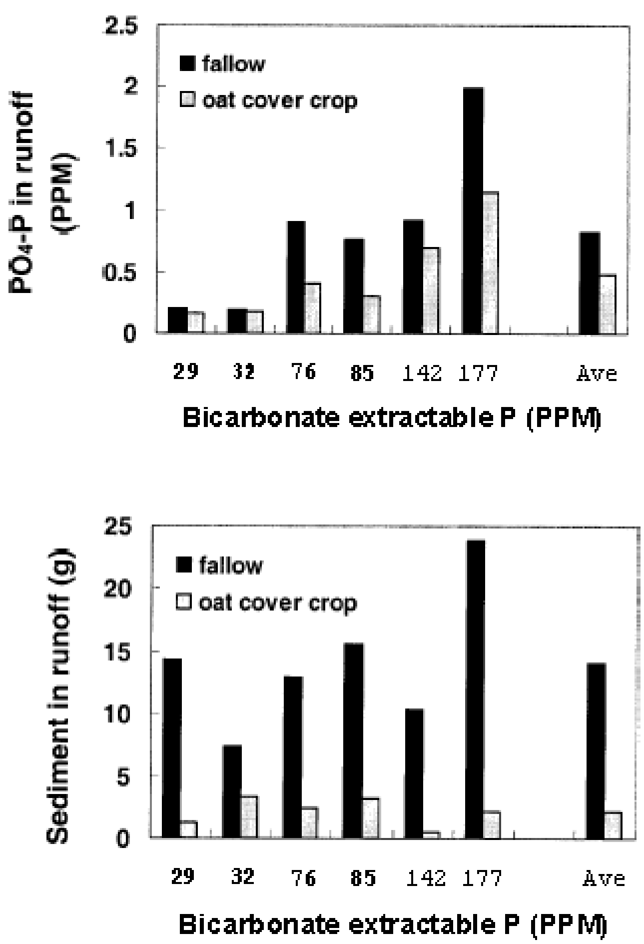

Fig. 4. Effect of oat cover crop on P04-P concentration and sediment content of runoff from six soils.