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SEDIMENT-PHOSPHORUS RELATIONS IN SURFACE RUNOFF FROM IRRIGATED LANDS

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ABSTRACT

Phosphorus and sediment concentrations were measured in irrigation and drainage waters, and phosphorus and sediment inflows and outflows computed. Relationships between phosphorus and sediment were developed. Total phosphorus and orthophosphate concentrations measured in nonfiltered samples are closely related to the sediment concentration, but dissolved orthophosphate measured in samples filtered through 0.45 µm membrane filters is independent of the sediment concentration. A net sediment inflow was found on one large tract where sediment settles in drains and the amount of surface runoff is low, but a net sediment outflow was found for another tract with steeper drains and from which more surface runoff returned to the river. Net phosphorus inflows were measured on both tracts. Particle size segregation takes place in irrigation and drainage waters whenever the flow velocity is slow enough to allow suspended sediment to settle, and the quantity of phosphorus per unit of sediment remaining suspended increases. Actually, much more phosphorus settles with that portion of the sediment that settles than remains in suspension where sediments are eroded from silt loam or loam soils. Thus, conditions favoring settling are phosphorus conserving conditions.

INTRODUCTION

Phosphorus is tightly held by most soils and sediments, and the amount solubilizing, precipitating or combining with sediments depends upon equilibria conditions between the phorphorus in the ambient solution and that attached to or held by sediments. Sediments may scavenge phosphorus from solution (Taylor and Kunishi, 1971), and many sediments have a great capacity to do so (Latterell, Holt, and Timmons, 1971). Sediments also represent a vast phosphorus reservoir that can maintain a low and nearly constant water-soluble phosphorus concentration in a lake or stream for a very long time.

Sediments carry large quantities of phorphorus into waterways each year as a result of erosion (Viets, 1971; Wadleigh, 1968). Phosphorus is a limited, valuable, natural resource required by all living organisms, and reclaiming it from ocean and lake sediments would be extremely expensive. Therefore, the phosphorus entering waterways ultimately reaching the ocean or other large water bodies represents a phosphorus loss to man, animals, and plants, except those living in aquatic environments.

Irrigated agriculture involves very complex and dynamic solution-to-solid phase equilibria for phosphorus. Irrigation waters from rivers and streams carry sediment loads and associated phosphorus that vary through the season. These waters have a dissolved phosphorus concentration that may also vary during the season. When this water is applied to close growing crops, like alfalfa and grass, the sediment and the associated phosphorus is usually deposited upon the land. Dissolved phosphorus is effectively removed from the water that percolates through the soil (Carter, Bondurant, and Robbins, 1971; Carter, Robbins, and Bondurant, 1973). In contrast when the water is applied to recently cultivated row crops, the soil may erode adding to the sediment and associated phosphorus loads in the runoff water. Surface and subsurface drainage waters from fields of various crops may enter surface drains and mix. In some cases flow velocities in drains are low or the water is passed through a sediment pond and sediments settle. In other cases, the flow velocity is high and there is no settling until the water reaches a river or a reservoir along a river, or in some cases, the ocean. All these dynamic processes can influence phosphorus equilibria.

During the past 6 years, we have been studying phosphorus inflows in the irrigation water and outflows in the drainage water from large irrigated tracts, and phosphorus-sediment relationships in irrigated agriculture in an effort to determine the extent of phosphorus losses from irrigated lands and to develop information useful for reducing such possible losses. This paper reports phosphorus and sediment concentrations in irrigation and drainage waters for two large tracts, functional relationships between sediment and phosphorus concentrations in irrigation and surface runoff waters, phosphorus inflows and outflows for two large tracts, phosphorus:sediment rations, and related information.

MATERIALS AND METHODS

The studies involved the 82,030 ha (202,700 a) Twin Falls Canal Company tract and the 65,350 ha (161,480 a) Northside Canal Company tract and the sampling sites previously described (Brown, Carter, and Bondurant, 1974). Three samples were collected at 2-week intervals at each site. They were: (1) a 200 ml sample filtered through a 0.45 μm membrane filter immediately upon sampling, (2) a 200 ml nonfiltered sample, and (3) a 10 liter nonfiltered sample. Biological activity was stopped by adding 40 mg $HgCl_2$/liter immediately as samples were collected. The 200 ml samples were refrigerated at 4 C until analyzed. The 10 liter samples were allowed to settle for 1 week in the laboratory, and then the supernatant was siphoned off and analyzed for phosphorus concentration. The sediment and a small amount of solution were transferred to weighed containers, dried at 105 C and weighed to determine sediment concentrations. The settling time exceeded that needed for 1.0 μm particles to settle the depth of the sample according to Stokes law. All samples were collected at a drop structure, culvert or turbulent zone to assure that the samples properly represented the stream and its sediment load. At some sites a fractional water-sediment sampler was used to assure representative samples (Heinemann and Brown, 1972).

All samples were analyzed for dissolved and total orthophosphate, dissolved and total hydrolyzable phosphorus and total dissolved and total phosphorus following chemical treatments previously described (Carter, *et al.*, 1974). Dissolved organic and total organic phosphorus concentrations were obtained by subtracting orthophsophate plus hydrolyzable phosphorus from total phosphorus for the dissolved and total categories. The chemical treatments used were essentially those recommended by the Environmental Protection Agency (Environmental Progection Agency, 1974). Phosphorus concentrations were measured in the solutions following chemical treatment by the ascorbic acid method (Watanabe and Olsen, 1965). The pH was adjusted before adding the ascorbic acid-ammonium molybdate solution containing potassium antimony tartrate to assure reproducible results (Carter, *et al.*, 1974).

Regression and correlation analysis were employed to evaluate sediment-phosphorus relations in irrigation and surface runoff waters. Such analyses were completed for dissolved orthophosphate and total phosphorus only because as studies progressed, hydrolyzable and organic phosphorus concentrations in irrigation and drainage waters seemed insignificant.

Sediments collected from the 10 liter samples were analyzed for total phosphorus by suspending 0.1 g subsamples in 40 ml of distilled water and following the persulfate digestion procedure for water samples (Carter, *et al.*, 1974; Environmental Protection Agency, 1974). NaCHO$_3$ extractable phosphorus was determined by extracting 5 g samples with 100-ml 0.5 M NaHCO$_3$ solution and determining the phosphorus concentration by the ascorbic acid method (Watanabe and Olsen, 1965). Where only small amounts of sediments were obtained, 0.5 g of sediment was extracted with 10-ml of the solution.

Sediment, dissolved orthophosphate and total phosphorus inflows in the irrigation water and outflows in the surface drainage water were calculated for a typical irrigation season for the two tracts. This was done by multiplying the phosphorus and sediment concentration for each 2-week sampling period by the quantity of flow for that period and accumulating the results for the season.

The relationship of phosphorus concentration to particle size was investigated by collecting samples from the surface 15-cm of field soils from certain subbasins in the two tracts, mixing soil samples with water without the aid of dispersing reagents, and allowing samples to settle for the time periods that gave an aggregate or particle size segregation into sand, silt, and clay sizes. This segregation was assumed to simulate processes taking place as eroded soil enters drainage streams and subsequently settles as the flow velocity decreases. Complete dispersion was not expected under these conditions, and some aggregates containing clay settled in the sand and silt fractions. These size fractions were analyzed for total- and NaHCO$_3$-extractable phosphorus. Surface soil samples were collected from both tracts on a grid and analyzed for total and NaHCO$_3$ extractable phosphorus so that results could be compared with those from

Table 1. Numbers of samples with sediment and phosphorus concentrations in specific ranges.

Variables	Numbers of Samples									
	Concentration Range (ppm)									
	0-50	51-100	101-200	201-500	501-1001	1001-2000	Above 2000			
Sediment	33	21	32	13	7	2	3			
	Concentration Range (ppb)									
	0-25	26-50	51-75	76-100	101-150	151-200	201-250	251-300	301-400	Above 400
Phosphorus*										
Ortho-P (F)	21	23	23	23	20	1				
Ortho-P(NF)		10	14	11	24	20	7	10	5	11
Total-P(NF)			1	4	19	20	22	12	17	16

*Ortho-P(F) is the orthophosphate measured in a sample filtered through a 0.45 µm membrane filter. Ortho-P(NF) is the orthophosphate measured in a nonfiltered sample. Total-P is the total phosphorus measured in a nonfiltered sample.

sediments collected from surface drainage streams. Additional evidence that particle size segregation takes place in drainage streams was obtained by calculating phosphorus:sediment ratios (the quantity of phosphorus per unit of sediment) for some drainage streams with flow velocities slow enough to allow settling and some with high flow velocities so that there was little or no settling. Dissolved orthophosphate concentrations were subtracted from the total phosphorus concentrations so that the phosphorus involved was that attached to the sediment.

RESULTS AND DISCUSSION

The sediment concentration in surface runoff water returning to the river from the two large irrigation tracts varied widely during the irrigation season (Table 1). The lowest concentration measured was 10 ppm in the W drain on the Northside tract in which the flow velocity was very slow allowing the drain to serve as a sediment retention basin. The highest concentration measured was 2610 ppm in the J-8 drain on the Northside tract, but concentrations as high as 2250 ppm were measured in the Filer drain on the Twin Falls tract. Generally,the sediment concentrations were highest during the period when row crop cultivations were most frequent. After July, sediment concentrations were lower in all drainage water entering the river, except from those drains where the flow velocity was slow enough to allow sediments to settle. Little changes were observed in these drains.

The total phosphorus concentration paralleled the sediment concentration (Table 1). The relationship between the two parameters is given by the first equation in Table 2. A similar relationship was found between the

Table 2. Regression equation and correlation coefficients showing relationship between sediment and phosphorus concentrations in irrigation and drainage waters.

X	Y	Equation	r^2	r
Sediment in nonfiltered samples (ppm)	Total phosphorus in nonfiltered samples (ppb P)	$Y = 140.52 + 0.72X$	0.89	0.94
Sediment in nonfiltered samples (ppm)	Orthophosphate in nonfiltered samples (ppb P)	$Y = 79.82 + 0.579X$	0.90	0.95
Sediment in nonfiltered samples (ppm)	Orthophosphate in filtered samples (0.45 um) (ppb P)	$Y = 57.71 + 0.033X$	0.10	0.32

sediment and the orthophosphate concentrations determined in nonfiltered samples. These results showed that the concentration of both orthophosphate and total phosphorus in nonfiltered water samples depends upon the sediment concentration. These equations could be used to predict the total phosphorus and orthophosphate in nonfiltered samples. Better predictive equations could likely be developed for specific surface drains or subbasins where conditions are more uniform. The third equation shows that there is no such relationship between the orthophosphate in filtered samples and the sediment concentration. Thus, the dissolved orthophosphate concentration is independent of the sediment concentration. Dissolved hydrolyzable and organic phorphorus concentrations are very low in the 111 water samples included for comparison. Only two samples had dissolved hydrolyzable concentrations above 26 ppm and only four samples had organic phosphorus concentrations above that value. Total hydrolyzable and organic phosphorus concentrations were somewhat higher and related to the sediment concentrations, but still of little significance in irrigation and drainage waters.

There was a net sediment outflow or loss of 37,790 mt (41,368 t) from the Twin Falls tract or 0.46 mt/ha (0.20 t/a), in contrast to a net sediment inflow or accumulation of 45,170 mt (49,807 t) into the Northside tract or 0.69 mt/ha (0.30 t/a) (Table 3). These two tracts had contrasting results because of different amounts of surface drainage returning to the river and different slopes and resulting flow velocities in surface drains on the two tracts (Brown, Carter, and Bondurant, 1974). The surface drains on the Northside tract were constructed to a low slope, some of which serve effectively as sediment retention basins. One drain passes through a basin. The drains on the Twin Falls tract are mostly natural, steep channels in which the flow velocity is too high to allow much sediment settling.

Net total phosphorus and dissolved orthophosphate inflows were found for both tracts even though there was a net sediment outflow on the Twin Falls tract (Table 3). These results include only the phosphorus in the irrigation and surface drainage water, and do not include the phosphorus fertilizer applied to the land. The results indicated that the sediment leaving the Twin Falls tract carried less phosphorus per unit of sediment than the sediment entering the tract in the irrigation water. The sediment in the irrigation water was likely composed of smaller-sized particles than was the sediment leaving the tract in the surface drainage water.

The $NaHCO_3$ extractable and total phosphorus concentrations were greater in sediments in drainage waters from the Northside tract than that from the Twin Falls Tract (Table 4). These results show that more particle size segregation takes place in Northside tract drains than in Twin Falls tract drains. The sediment remaining suspended in Northside tract drains contained relatively more clay than that in Twin Falls tract drains. Both total and $NaHCO_3$ extractable phosphorus concentrations in sediments from both tracts were higher than concentrations found in surface soils, but the difference was greater for the Northside tract (compare tables 4 and 5).

Table 3. Water, Sediment, dissolved ortho-P and total-P inputs and outputs for two large tracts for an irrigation season.

	Metric				English			
	Water $10^4 m^3$	Sediment	Ortho-P	Total-P	Water a ft	Sediment	Ortho-P	Total-P
		------mt------				------t------		
Inflow	Twin Falls Tract (82,030 ha)				(202,700 a)			
Diverted water	138,310	75,820	28.57	189.00	1,121,000	83,576	31.49	208.36
Outflow*								
Rock Creek	13,930	43,090	12.11	34.84	112,932	47,502	13.85	42.82
Cedar Draw	4,144	8,750	2.82	11.16	33,595	9,647	3.10	12.48
Filer Drain	1,084	11,280	1.13	10.16	8,971	12,434	6.22	18.16
Mud Creek	7,239	13,820	5.64	16.47	58,684	15,236	1.92	7.87
Deep Creek	4,732	5,630	1.74	7.14	38,363	6,208	1.25	11.25
13 small drains	6,295	31,040	2.31	15.06	51,036	34,217	2.55	16.60
Net Inflow	100,866	---	2.82	94.17	817,599	---	2.60	99.18
Net Outflow	---	37,790	--	---	---	41,368	--	---
Inflow	Northside Tract (65,350 ha)				(161,480 a)			
Diverted water	150,631	57,250	34.38	159.39	1,221,182	63,111	37.90	175.70
Outflow								
K	1,410	1,300	1.28	3.75	11,432	1,431	1.42	4.13
N-32	2,478	2,160	1.84	5.71	20,087	2,375	2.02	6.29
J-8	622	3,550	0.25	1.42	5,039	3,911	0.28	1.56
S	1,780	3,440	0.60	2.97	14,432	3,798	0.67	3.27
W-26	1,787	1,280	0.25	1.19	14,488	1,405	0.49	4.72
W	960	350	0.45	4.28	7,779	384	0.28	1.31
Net Inflow	141,594	45,170	29.97	140.08	1,147,925	49,807	32.74	154.42
Net Outflow	---	---	---	---	---	---	---	---

*Includes flow from subsurface drainage tunnels that enter the listed streams as well as water pumped from wells for industrial purposes. Surface runoff totalled 14% of the total water inflow to the tract (Carter, Bondurant and Robbins, 1971)

Table 4. $NaHCO_3$-extractable and total phosphorus concentrations in sediments collected from irrigation and surface drainage waters for two large irrigated tracts during the 1971 irrigation season (Carter, *et al.*, 1974).

	$NaHCO_3$ Extractable P (ppm)					Total P (ppm)				
Source	May	Jun	Jul	Aug	Sep	May	Jun	Jul	Aug	Sep
					Northside tract					
Diverted water	138	80	46	--	--	1,100	1,243	1,040	1,100	1,278
K	195	148	98	95	61	1,206	1,040	1,036	1,185	1,018
N-32	345	277	104	--	72	1,395	1,392	1,076	1,338	941
J-8	47	75	59	84	68	649	808	1,018	1,110	948
S	166	157	62	53	60	1,075	1,086	966	999	908
W-26	171	191	55	44	64	1,345	1,153	985	1,018	940
W	278	404	--	--	318	1,370	1,760	1,000	1,228	1,006
					Twin Falls tract					
Diverted water	133	--	66	37	63	1,160	1,600	1,040	1,025	1,047
Rock Creek	36	122	38	28	33	955	936	831	672	939
Cedar Draw	34	74	44	36	30	895	1,038	902	915	819
Filer Drain	21	52	33	29	31	895	1,006	842	940	952
Mud Creek	30	48	21	26	22	1,040	1,110	1,040	1,138	956
Deep Creek	66	96	20	28	38	912	1,070	602	840	870
Hansen Drain	39	95	32	28	41	882	1,040	870	970	988
Kimberly Drain	54	59	40	38	80	963	1,013	897	912	965

Table 5. $NaHCO_3$-extractable and total phosphorus concentration in soil samples collected from the surface 15 cm (6 in.) of fields in two large irrigation tracts, ppm (Carter, et al., 1974).

	No. of fields sampled	$NaHCO_3$ Extractable P				Total P			
		Max.	Min.	Med.	Mean	Max.	Min.	Med.	Mean
Northside tract	44	64	4	22	24	885	488	763	722
Twin Falls tract	48	55	6	20	22	1007	580	842	839

The relative total and $NaHCO_3$ extractable phosphorus concentration in the sand, silt, and clay size fractions of soils separated without the aid of dispersion agents are presented in Table 6. A comparison of the values in Tables 4 and 6 shows that particle size segregation is more complete in drains on the Northside tract than in drains on the Twin Falls tract as suggested earlier, because both total and $NaHCO_3$ extractable phosphorus concentrations in sediments from Northside tract drains are closer to the values for the clay size fraction separated from soils. Also, the data in Table 4 indicate that sediments in the diverted water are comprised mostly of clay which is as expected because the river water is stored in upstream reservoirs where settling can occur, and is then released for irrigation downstream as the demand requires.

Table 6. Total and $NaHCO_3$-extractable phosphorus for various particle and aggregate size fractions of surface soils collected from four subbasins, ppm (Carter, et al., 1974).

Drainage subbasins	Total P			$NaHCO_3$-extractable P		
	Sand	Silt	Clay	Sand	Silt	Clay
Kimberly	875	1000	1400	33	55	137
Filer	650	975	1285	13	27	67
K	550	1150	1285	21	74	125
J-8	450	1020	1325	8	45	70

The data in Table 7 show that the phosphorus:sediment ratio (the quantity of phosphorus per unit of sediment) indicates the extent of the particle size segregation. The higher the value of the ratio the more extensive was the particle size segregation. For example, ratio values for the W drain which serves as a sediment basin were 1.60 and higher. Values for the K drain which passes through a sediment retention basin also generally exceeded 1.0. When the flow velocity was too high to allow settling, as in the Filer drain, the values were generally less than unity. Values for Rock Creek and Deep Creek varied because their flows vary widely and

Table 7. The quantity of phosphorus per unit of sediment in irrigation and drainage waters.

	Sampling date, 1971							
	6/15	6/29	7/13	7/26	8/10	8/28	9/8	9/28
	Phosphorus per unit of sediment X 1000							
Northside Canal	2.24	1.60	1.42	1.60	1.97	3.14	2.97	3.24
Twin Falls Canal	--	0.75	1.96	2.39	2.21	2.77	3.13	2.93
W	1.78	3.40	1.60	2.67	3.45	3.45	--	2.65
K	1.12	0.94	1.62	2.31	1.82	2.25	2.40	4.08
Filer	0.83	0.57	0.96	0.58	0.81	0.87	0.86	1.29
Rock Creek	0.81	1.04	0.87	1.09	0.60	--	1.45	1.17
Deep Creek	1.24	0.95	--	1.00	1.34	0.81	1.02	0.91

and the amount of settling is related to the flow velocity which is a function of the flow volume. The mean value for the total phosphorus for the Northside and Twin Falls tract surface soils, calculated in the same manner as for sediments were 0.72 and 0.84, respectively. Dividing values for each tract into those presented in Table 7 for drains of the respective tracts is another method of indicating the extent of particle size segregation. The numbers presented in Table 8 are particle size segregation indices. When these values exceed 1.0, particle size segregation has taken place, and the greater the number, the more extensive was the particle size segregation.

Table 8. Indices of particle size segregation in surface drainage streams.

	Sampling date, 1971							
Drain	6/15	6/29	7/13	7/26	8/10	8/24	9/8	9/28
W	2.5	4.7	2.2	3.7	4.8	4.8	--	3.7
K	1.6	1.3	2.2	3.2	2.5	3.1	3.3	5.7
Filer	1.0	0.7	1.1	0.7	1.0	1.0	1.0	1.5
Rock Creek	1.0	1.2	1.0	1.3	0.7	--	1.7	1.4
Deep Creek	1.5	1.1	--	1.2	1.6	1.0	1.2	1.1

The data presented in Tables 7 and 8 were obtained over a broad range of soil and cropping conditions, and varying stream sizes. Greater precision could likely be attained by restricting measurements to given stream sizes, subbasins, soils, cropping conditions, land slopes, time of season, etc. Also, in our studies, there was considerable variation in the total phosphorus measured in the surface soil so the numbers should be used only as indicators not as precise measures. Also sometimes canal water is spilled into surface drains, and the index values could exceed unity because values of the phosphorus:sediment ratios in the irrigation water were generally greater than found in the surface soils.

Most of the sediment and associated phosphorus entering irrigated tracts is filtered from the water by soil as the water enters the soil or by close growing crops. Only a small fraction of that sediment entering an irrigated tract leaves that tract in drainage water, because only a small portion, 6% and 14% for the two tracts studied, applied water be-becomes surface runoff. Essentially all the sediment leaving an irrigated tract is from erosion of that tract, supplying different sediments in the drainage water than entered in the irrigation water.

CONCLUSIONS

Most of the phosphorus in irrigation water and surface drainage waters from irrigated lands is associated with or attached to the sediment. The total phosphorus concentration is directly related to the sediment concentration as is the orthophosphate measured on nonfiltered samples. Therefore, controlling the quantity of sediment returning to a stream from irrigated land controls to a large extent the quantity of phosphorus returning. The dissolved orthophosphate concentration is independent of the sediment concentration.

Sediment and phosphorus losses from irrigated tracts can be controlled by limiting the surface drainage water leaving the tract and by utilizing sediment retention basins or drains of low slope so that the flow velocity is slow enough for sediment to settle. Whenever the flow velocity is slow enough to allow settling, particle size segregation takes place. The clay size particles settle slowest and are most likely to be carried by the drainage stream to the river. These smaller particles contain higher phosphorus concentrations per unit weight so that as settling takes place the phosphorus per unit of sediment remaining in suspension increases. In a sense, this is phosphorus enrichment of the suspended sediment. However, in sediments eroded from most silt loam or loam soils the amount of phosphorus associated with the sediment that settles greatly exceeds the amount associated with the smaller size particles remaining in suspension so that conditions favoring settling are conservation conditions for both sediment and phosphorus. Ideally, preventing surface runoff from entering a river would prevent all of the sediment loss and the only phosphorus loss would be the very small quantity in subsurface drainage water.

REFERENCES

Brown, M. J., Carter, D. L., and Bondurant, J. A., 1974, Sediment in irrigation and drainage waters and sediment inputs and outputs for two large tracts in southern Idaho. J. Environ. Qual., 3, 347-351.

Carter, D. L., Bondurant, J. A., and Robbins, C. W., 1971, Water-soluble NO_3-N, PO_4-P, and total salt balances on a large irrigation tract, Soil Sci. Soc. Am. Proc., 35, 331-335.

Carter, D. L., Brown, M. J., Robbins, C. W., and Bondurant, J. A., 1974, Phosphorus associated with sediments in irrigation and drainage waters for two large tracts in southern Idaho, J. Environ. Qual., 3, 287-291.

Carter, D. L., Robbins, C. W., and Bondurant, J. A., 1973, Total salt, specific ion and fertilizer element concentrations and balances in the irrigation and drainage waters of the Twin Falls tract in southern Idaho, USDA, ARS-W-4.

Environmental Protection Agency, 1974, Methods for chemical analysis of water and wastes, 249-263.

Heinemann, W. H., and Brown, M. J., 1972, Fractional water-sediment sampler, Soil Sci. Soc. Am. Proc., 36, 376-377.

Latterell, J. J., Holt, R. F., and Timmons, D. R., 1971, Phosphate availability in lake sediments, J. Soil and Water Conserv., 26, 21-24.

Taylor, Alan W., and Kunishi, Harry M., 1971, Phosphate equilibria on stream sediment and soil in a watershed draining an agricultural region, J. Agr. Food Chem., 19, 827-831.

Viets, Frank G., Jr., 1971, Fertilizers, J. Soil and Water Conserv., 26, 51-53.

Wadleigh, C. H., 1968, Wastes in relation to agriculture and forestry, USDA Misc. Publ. No. 1065.

Watanabe, F. S., and Olsen, S. R., 1965, Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil, Soil Sci. Soc. Am. Proc., 29, 677-678.