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Phosphorus Behavior in Flooded-Drained Soils. III. Phosphorus Desorption and Availability

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ABSTRACT

Four California soils that showed wide variability in soil properties and P sorptivity under flooded-drained (FD) conditions were selected for this study. The soils were flooded for 0 to 90 d at two levels of organic matter (OM, 0 and 10 g kg^{-1}) and two temperatures (23 and 35 °C). They were subsequently drained and used for P-sorption studies at 0.3, 1.2, and 2.0 m*M* initial P concentrations. The P desorption from P-sorbed soils were carried out in three consecutive extractions with 0.1 *M* NaCl. The effect of FD conditions on P availability to corn (*Zea mays* L.), was studied at three levels of P (0, 5, and 20 mg P kg^{-1} soil). Without OM treatment, FD conditions decreased P desorption in three of four soils examined. Added OM and higher temperature further decreased P desorption and the period of flooding (FP) required to reach the minimum P desorption. Organic matter markedly decreased P desorption even in Soil 3, which was unaffected by FD conditions. Under FD conditions, plant-tissue P concentration of corn was decreased to a variable extent depending on soil type. The desorption of added fertilizer P in a given FD soil correlated well with changes in the amorphous FeA fraction under comparable conditions. Phosphorus sorption and desorption were controlled by the changes in amorphous FeA and, in some cases, amorphous FeB fractions.

Under aerobic soil conditions, addition of OM has been reported to decrease P sorption (Singh and Jones, 1976; Abbott and Tucker, 1973; Meek et al., 1979) and increase P desorption (Kuo, 1983; Singh and Jones, 1976). Application of OM to a flooded soil intensifies the soil reduction processes (Ponnamperuma, 1972), increases the transformations of soil Fe and P minerals, and leads to higher P sorption in FD soils (Sah and Mikkelsen, 1986b; Sah et al., 1989).

Excluding the possibility of precipitation and occlusion, freshly sorbed P shows greater desorption than native soil P, probably because of the orientation of sorbed PO_4 ions on the soil surface with time (Kuo and Lotse, 1974a) and a transfer of physically sorbed to chemisorbed P (Ryden and Syers, 1977). According to Hingston et al. (1974), chemisorption and bi- and multidentate ligand formation decreases P desorption (increases the irreversibility of sorbed P). Under these conditions, OH ions are desorbed in preference to the desorption of specifically sorbed PO_4 ions.

The extent of P sorption in soil appears to be dependent on the surface charge of soil particles capable of P sorption. Freshly precipitated Fe oxides, mainly gel-like highly amorphous forms, have a large surface area (Borggaard, 1982; Davis and Leckie, 1979) and play an important role in P sorption and desorption (Ghanem and Mikkelsen, 1988; Kuo and Lotse, 1974b; Sah and Mikkelsen, 1986a). Phosphate ions may be specifically sorbed on the surface of Fe oxides (Hingston et al., 1967, 1972; White, 1981) resulting in a decrease in P desorption and the zero point of charge of Fe oxides (Kuo and McNeal, 1984). Iron transformation is expected to decrease P desorption in FD soils by increasing chemisorption. It is not well understood how FP, soil OM status, and temperature, which affect Fe transformation (Sah et al., 1989) influence P desorption.

In California, wheat (*Triticum aestivum* L.), safflower (*Carthamus tinctorius* L.), corn, and sorghum [*Sorghum bicolor* (L.) Moench] have shown P deficiency following flooded rice (*Oryza sativa* L.) (Brandon and Mikkelsen, 1979; Martin et al., 1971; Peterson et al., 1972). Similar observations were also reported from Australia (Willet, 1979; Muirhead et al., 1975; Willet and Higgins, 1980). The relationships of soil properties and Fe transformations to P sorption-desorption and plant P availability under FD conditions are not well understood.

The objective of this work was to examine the effects of soil properties, temperature, and OM treatments on P desorption and its availability under FD conditions.

MATERIALS AND METHODS

Phosphorus Desorption Study

Four soils used in other studies (Sah et al., 1989; Sah and Mikkelsen, 1989) were selected to examine the effects of OM addition and temperature on P desorption. They were amended with 0 and 10 g OM (85% cellulose + 15% starch) kg^{-1} soil, and incubated under flooded conditions at 23 and 35 °C for 0 to 90 d. At the end of flooding period, the soils were drained, dried at 22 ± 2 °C, and used for P-sorption studies using 0.3 to 2.0 m*M* initial P concentration (P_i) (Sah and Mikkelsen, 1989). The P-sorbed soils at P_i = 0.3, 1.2, and 2.0 m*M* were treated (in 50-mL centrifuge tubes) with

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15 mL 0.1 *M* NaCl and shaken on a reciprocating shaker for 2 h, centrifuged at 1500 rpm for 0.16 h, and the supernatant liquid was decanted. The soil residues were treated with 15 mL 0.1 *M* NaCl twice in sequence, shaken, and centrifuged. Aliquots of the three extractions were pooled, filtered, and assayed for P.

Phosphorus was analyzed by the ascorbic-acid method (Watanabe and Olsen, 1965). The amount of P desorbed by three extractions for a given P_i was expressed as a proportion of P sorbed and plotted against the FP. The effects of OM and temperature were similarly examined. Phosphorus desorption was correlated with changes in Fe forms.

Greenhouse Assay

Nine of the ten soils used for the P-sorption study (Soil 5 was not included) (Sah and Mikkelsen, 1989) were investigated for the effects of FD conditions on P availability to corn (Pioneer 3162). The soils were flooded for 90 d, drained, and air dried at 22 ± 2 °C. The FD and unflooded soils were amended with 0, 5, and 20 mg P kg^{-1} soil and potted at 2.0 kg soil per pot. A blanket application of 50 mg N and 40 mg K kg^{-1} soil was also applied. Six corn seeds were planted per pot, thinned to four after emergence, and grown in the greenhouse for 30 d. The plants were then harvested, and dried at 70 °C for 48 h. Ground plant material (0.25 g) was digested with a mixture of nitric and perchloric acid and analyzed for P (Watanabe and Olsen, 1965) after neutralizing the digest to about pH 2.0. Phosphorus concentration and P uptake, as affected by FD conditions and soil type, were examined. The effects of FD conditions on P desorption were related to P availability to corn.

RESULTS AND DISCUSSION

Effect of Soil Type

Under unflooded conditions, Soil 1 had the highest (419 g kg^{-1} sorbed P), while Soil 3 had the lowest (115 g kg^{-1} sorbed P) P desorption and the remaining two soils had intermediate values (Fig. 1–4). In the absence of OM treatment, only three of the four soils showed a decrease in P desorption under FD conditions. The FD conditions resulted in the maximum reduction in P desorption (up to 50%) in Soil 1 and no reduction in Soil 3. In the two remaining soils, P desorption under FD conditions decreased as much as 30%.

At least two conditions are necessary for a decrease in P desorption under FD conditions: (i) a high reducible soil Fe content, and (ii) sufficient decomposable OM to accentuate soil reduction. Soil 7, a calcareous soil, is rich in OM but has a small reducible Fe content and did not show the response to FD conditions (data not shown). On the other hand, Soil 3, which is high in reducible Fe but low in OM, also showed no response to FD conditions. In the absence of OM application, soil 3 showed restricted anaerobiosis during the flooding period, and limited Fe transformations (Sah et al., 1989) and no increase in P sorption under FD conditions (Sah and Mikkelsen, 1989). The amorphous Fe content affects P sorption (Khalid et al., 1977; Willet and Higgins, 1980). However, the mechanism by which amorphous Fe affects P desorption is not understood from this study.

Effects of Organic Matter and Temperature

Organic-matter application prior to flooding decreased P desorption under FD condition (Fig. 1–4). In Soil 1, OM treatment produced a 45% reduction (compared with no OM treatment) at P_i = 0.30 m*M* (Fig. 1a), and 30 to 35% reduction at P_i = 1.2 (Fig.

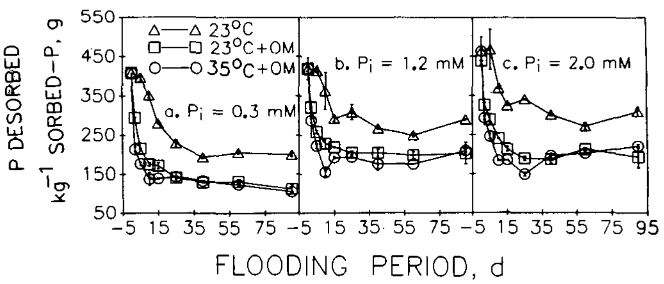

Fig. 1. Effects of organic matter (OM) and temperature during flooding period on P desorption in flooded-drained Soil 1. Prior to desorption, soil samples were allowed to sorb P at three initial P concentrations (P_i): a) 0.3 m*M*, b) 1.2 m*M*, and c) 2.0 m*M*. Vertical bars represent standard deviation for a given point.

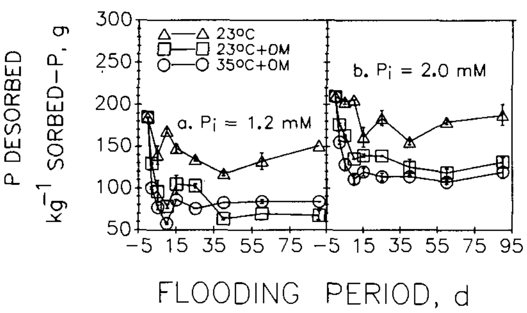

Fig. 2. Effects of organic matter (OM) and temperature during flooding period on P desorption in flooded-drained Soil 2. Prior to desorption, soil samples were allowed to sorb P at two initial P concentrations (P_i): a) 1.2 m*M*, and b) 2.0 m*M*. Vertical bars represent standard deviation for a given point.

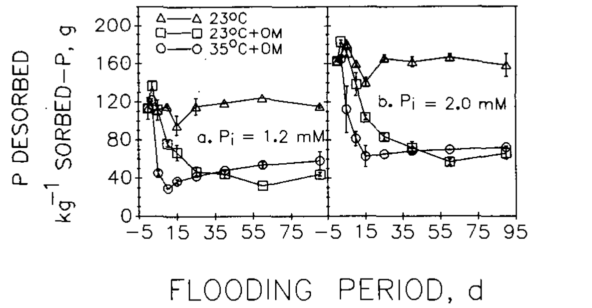

Fig. 3. Effects of organic matter (OM) and temperature during flooding period on P desorption in flooded-drained Soil 3. Prior to desorption, soil samples were allowed to sorb P at two initial P concentrations (P_i): a) 1.2 m*M*, and b) 2.0 m*M*. Vertical bars represent standard deviation for a given point.

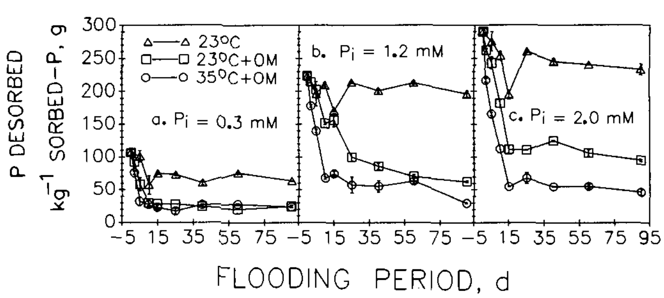

Fig. 4. Effects of organic matter (OM) and temperature during flooding period of P desorption in flooded-drained Soil 6. Prior to desorption, soil samples were allowed to sorb P at three initial P concentration (P_i): a) 0.3 m*M*, b) 1.2 m*M*, and c) 2.0 m*M*. Vertical bars represent standard deviation for a given point.

1b) and 2.0 mM (Fig. 1c). Beyond 25 d, there was no difference between temperature treatments (Fig. 1a-c).

For Soil 2 and 3, P desorption at $P_i < 1.2$ mM was at such low concentrations that P concentration could not be determined reliably. For these soils, therefore, the P desorption only at 1.2 and 2.0 mM are presented. For Soil 2, FD conditions decreased P desorption by about 30% at $P_i = 1.2$ mM and by 20 to 30% at $P_i = 2.0$ mM (Fig. 2a,b). Organic-matter treatment is Soil 2 had a larger effect than in Soil 1: P desorption was decreased by 50 to 65% at $P_i = 1.2$ mM and by about 40% at $P_i = 2.0$ mM at 23 °C, while elevated temperature treatment had only small additive effects.

Both OM treatment and elevated temperature had larger effects on P desorption i Soil 3 and 6, compared with Soil 1 and 2. In Soil 3, flooding and draining without added OM had no effect on P desorption (Fig. 3a). In this soil, OM treatment decreased P desorption by 65% at 23 °C, and even more at 35 °C for about 25- to 40-d FP. At 35 °C, OM additions resulted in a rapid decrease in redox potential (Eh), which reached a minimum value (−190 mV) after only 5 d of flooding, and then became stable (Sah et al., 1989). The mechanism of increase in P desorption after an initial decrease is not understood. Organic-matter treatment decreased P desorption through increased soil reduction at the higher temperature (Fig. 4).

These results imply that added OM and temperature are very important in affecting P desorption in FD soils, and that OM added prior to soil flooding is likely to aggravate P deficiency. Flooded, drained conditions increase amorphous Fe and P sorption (Sah and Mikkelsen, 1986c). It is not understood how amorphous Fe affects Fe precipitation, which could be an important phenomenon in apparent hysteresis in P sorption-desorption. Amorphous Fe increases the surface area of soil (Borggaard, 1982) and, therefore, increases the number of sites for P sorption.

For each soil and treatment, P desorption increased as P_i increased (Fig. 1–4). At low P_i, sorbed P is likely to occupy high-energy sites (Ryden and Syers, 1977; Hingston et al., 1974) resulting in lower sorbed-P recovery in desorbing solution. At higher P_i, the proportion of physically sorbed P is likely to increase, resulting in an increase in P desorption. This was reflected in a high correlation ($r \geq 0.90$) between P sorption and desorption. It appears that the changes in soil resulting from FD conditions primarily affects P sorption. Lower P availability to the plant may result from higher P sorption, which decreases desorbable P concentration in the soil solution. Changes in P desorption also correlated well with the changes in Fe fractions (Table 1). Amorphous FeA showed consistently high and significant correlation with P sorption for all soils and under most treatment conditions. These results suggest that both P sorption and desorption in FD soils can be explained by Fe transformations, particularly by measuring the amorphous FeA and B fractions.

Table 1. Correlation of P desorption (at 1.2 mM initial P concentration) with changes in Fe fractions. The variation in these two parameters results from flooding period (FP), organic matter (OM), and temperature treatments.

Soil† no.	OM	Temp.	Fe fractions‡: Amorphous FeA	Amorphous FeB	Free Fe oxides
	g kg⁻¹	°C	r		
1	0	23	−0.90	−0.71	0.90
	10	23	−0.93	−0.45	0.87
	10	35	−0.95	−0.50	0.83
	All treatments§		−0.93	−0.53	0.89
2	0	23	−0.78	0.81	−0.38
	10	23	−0.85	0.82	−0.62
	10	35	−0.94	0.84	−0.27
	All treatments		−0.91	0.81	−0.22
3	0	23	0.43	0.05	−0.50
	10	23	−0.98	−0.73	0.86
	10	35	−0.89	−0.40	0.56
	All treatments		−0.92	−0.68	0.78
6	0	23	−0.20	−0.46	0.63
	10	23	−0.98	−0.90	0.84
	10	35	−0.91	−0.77	0.95
	All treatments		−0.91	−0.76	0.89

† Defined in Part I of this paper, Table 1 (p. 1719).
‡ Amorphous FeA and amorphous FeB as defined by Sah et al. (1989).
§ All treatments = pooled data of the three treatments (0 and 10 g OM kg⁻¹ soil at 23 and 35 °C) for a soil.

Effect of Flooded-Drained Conditions on Plant Phosphorus Availability

Tissue Phosphorus Concentration

The FD conditions and different P levels affected tissue P concentration. However, the FD/unflooded treatment × P level interaction was not significant for any soil. Therefore, the means can be compared independently. Six of the nine soils investigated showed lower tissue P concentration under FD conditions (Table 2). Phosphorus sorption and desorption under FD conditions was not affected in Soil 3 and 9 (Sah and Mikkelsen, 1989). For Soil 8, P desorption was lower under FD conditions, but tissue P concentration was not affected.

For Soil 7 (a calcareous soil), P desorption was not affected; mean tissue P concentration under FD conditions (1.6 g kg⁻¹), however, was significantly lower than under unflooded conditions (2.3 g kg⁻¹). The better growth of corn (3.93 g dry weight) under FD con-

Table 2. Effect of flooded-drained conditions and P levels on tissue P concentration of corn (dry-weight basis).

Soil† no.	Treat-ment‡	P level, mg kg⁻¹: 0	5	20	LSD (0.05) between: FD/UF conditions	P levels
		tissue P concentration, g kg⁻¹				
1	FD	1.63	1.50	1.93	0.21	0.26
	UF	2.97	3.00	3.70		
2	FD	1.70	1.90	1.77	0.31	0.38
	UF	2.93	2.87	2.53		
3	FD	1.53	1.63	1.73	0.18	0.19
	UF	1.30	1.63	1.57		
4	FD	2.10	2.30	2.70	0.37	0.45
	UF	2.90	2.83	2.70		
6	FD	1.37	1.40	1.87	0.43	0.54
	UF	2.10	2.60	2.43		
7	FD	1.33	1.57	1.87	0.46	0.57
	UF	1.87	2.17	2.90		
8	FD	1.23	1.07	1.37	0.16	0.19
	UF	1.20	1.23	1.43		
9	FD	1.23	1.15	1.63	0.21	0.26
	UF	1.23	1.13	1.57		
10	FD	2.13	2.60	2.83	0.27	0.32
	UF	2.93	3.07	2.77		

† Defined in Part I of this paper, Table 1 (p. 1719).
‡ UF = Unflooded soils, FD = Flooded-drained soil. FD/UF treatments × P level interactions were not significant for any soil.

ditions than under unflooded soil (3.48 g dry weight) may have resulted in the dilution of tissue P concentration. Phosphorus fertilization increased tissue P concentrations in corn at harvest in all soils except 2 and 4 (Table 2). However, the effect of FD conditions was evident even in these soils: the P status of Soil 2 and 4, under unflooded conditions, was naturally high and did show a P response.

CONCLUSIONS

This study reveals that induced P deficiency under FD conditions may be expected in soils high in reducible Fe and containing a source of readily decomposable OM. Soils having less than 8 g kg^{-1} organic C did not cause a significant reduction in P desorption and P availability to corn. Flooded, drained conditions increased P sorption and decreased P desorption in soils where Fe transformations were not limited by either low OM or reducible Fe content. Organic-matter treatment prior to flooding and elevated temperature decreased P desorption; effects were much larger in soils with low OM but high reducible Fe content. Induced P deficiency in FD soil appears to be caused by high P sorptivity and lower P desorption as a consequence of Fe transformations.

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