

Phosphorus Behavior in Flooded-Drained Soils. II. Iron Transformation and Phosphorus Sorption

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ABSTRACT

Effects of flooding periods (FP), organic matter (OM) and temperature treatments during flooding on Fe transformation in flooded-drained (FD) soils were studied on four soils representing wide variations in the effect of FD conditions on P sorptivity. The soils were extracted in sequence with ammonium oxalate at pH 6 (amorphous FeA) and at pH 3 (amorphous FeB), and with dithionite-citrate-bicarbonate reagent (free Fe oxides). The amorphous FeA fraction increased with FP, OM treatment, and elevated temperature. In soils with low amorphous-Fe to free-Fe-oxide ratio, both amorphous FeA and free Fe oxides increased at the expense of amorphous FeB as the FP increased. In soils with low amorphous-Fe to free-Fe-oxide ratio, both amorphous Fe fractions (A and B) increased at the expense of free Fe oxides as FP increased. For all soils, the Fe transformation during soil flooding was accelerated by OM and high-temperature treatments, both of which contributed to a decreased redox potential in the soil. Amorphous FeA fraction correlated well with P sorption under all combinations of OM and temperature in each soil, while other Fe fractions correlated well only under certain conditions. Results suggest that the nature and the magnitude of Fe transformations in these FD soils depend on interacting effects of FP, OM, and temperature.

ACUTE P DEFICIENCY may develop in crops grown on FD soils (Brandon and Mikkelsen, 1979). Increased soil P sorption, which is believed to cause this P deficiency, may result from an increase in amorphous Fe oxides in these environments (Sah and Mikkelsen, 1986b). Soil-solution Fe concentration increases from only a fraction of a mg L⁻¹ in aerobic soils (Oborn and Hem, 1961) to up to hundreds of mg L⁻¹ in anoxic flooded soils (Gotoh and Patrick, 1974; Mandal, 1961; Howeler, 1973; Kumar et al., 1981). However, high concentrations of dissolved Fe cannot be sustained in the oxidized layer of flooded soils (Hem and Cropper, 1959). This reaction is probably the driving force in Fe pumping, a process of diffusion of Fe from the subsurface anoxic layer to the surface oxic layer of flooded soils. The process leads to a large transformation of Fe under flooded conditions and is controlled by pH (Nhung and Ponnampereuma, 1966), temperature (Cho and Ponnampereuma, 1971) and OM additions during or prior to soil flooding (Mandal, 1961; Sah and Mikkelsen, 1986b). Organic-matter addition, temperature, and pH influence the metabolic activities of anaerobic bacteria. Therefore, the redox potential (*E_h*) may be the most significant single factor affecting Fe transformations in flooded or FD soils.

The oxalate-soluble or amorphous Fe is reduced more readily than crystalline Fe under anaerobic conditions (Munch and Ottow, 1980). Fischer and Pfan-

neberg (1984) found good correlation between amorphous Fe and the rate of reduction of soils containing various ratios of amorphous to crystalline Fe. Ammonium-oxalate extracted (0.2 M at pH 3 for 2 h) amorphous Fe represents mainly ferrihydrite (Schwertmann and Fischer, 1973). It forms aggregates of various sizes (Schwertmann et al., 1986) and is present in various degrees of crystallinity and solubility (Schwertmann et al., 1982). Therefore, amorphous Fe itself may partition into several transformation products under FD conditions. Consequently, an additional fractionation of amorphous Fe (ammonium oxalate, pH 3) could be expected to give a better insight into the changes within the amorphous Fe fraction.

Iron extracted with 0.1 M sodium pyrophosphate (Na₄P₂O₇) is considered freshly precipitated gelatinous amorphous Fe (Bascomb, 1968), organically bound Fe (McKeague, 1967; McKeague et al., 1971), or both. Although pyrophosphate extraction has been used in many Fe fractionations (McKeague, 1967; Loveland and Digby, 1984; Bascomb, 1968), the inherent drawback is that it disperses the soil, making it difficult to obtain clear filtrates for Fe determination, and the residual soil is not suitable for sequential extraction of other Fe fractions. These complications are increased if the soil is high in clay and other colloidal materials. Of the four soils used in this study, we could not obtain a clear filtrate in Soil 2, 3, and 6 due to their high clay content.

Borggaard (1985) found a good correlation between pyrophosphate- and EDTA-extractable Fe forms. Earlier, Borggaard (1979, 1981) also found a good correlation between EDTA- and ammonium-oxalate-(at pH 3) extractable Fe. These findings suggest that ammonium-oxalate-extractable Fe is correlated with pyrophosphate-extractable Fe. Miller et al. (1986) reported a decrease in extractable Fe when the pH of the ammonium oxalate solution was increased from 3.5 to 5.5. This suggests the desirability of extracting soils with ammonium oxalate at a higher pH in the sequence before extracting with ammonium oxalate at pH 3.0 to differentiate amorphous Fe fractions.

The physico-chemical changes occurring in anoxic flooded soils affect the Fe fractions even after the soil is drained and the condition becomes aerobic (Willet and Higgins, 1980). A consequence of this phenomenon is an induced P deficiency in FD soils reported by several researchers (Sah and Mikkelsen, 1986a,b; Brandon and Mikkelsen, 1979; Willet and Higgins, 1980). The nature and the magnitudes of changes in Fe forms and their impact on P availability to crops in FD soils is not understood.

This study is a continuation of the work reported in Sah and Mikkelsen (1989), where the effects of OM, temperature, and flooding were examined in respect to P sorption. The objectives of this study were to: (i) examine the effect of FP, substrate OM level, and temperature during soil flooding on the nature and extent

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of Fe transformations in drained soils; (ii) relate Fe fractions with P sorption, with the objective of explaining the difference in P sorptivity based on Fe transformations in soils.

MATERIALS AND METHODS

Four soils showing variation in properties and P-sorption characteristics (Sah and Mikkelsen, 1989) were selected for this study. The soil taxonomic classification, properties and selection criteria are reported in Table 1 of Part I of this paper (p. 1719). These soils had not been flooded in the last 2 to 3 yr.

Soil Incubation

Duplicate samples of 20 g of each soil were treated with 0 and 10 g OM (85% cellulose + 15% starch) kg^{-1} soil, flooded in 50-mL polypropylene tubes, and incubated at 10, 23, and 35 °C, during the period of 0 to 90 d. During the incubation period, about 5-cm water depth was maintained in the tubes, which were kept uncapped but covered with aluminum foil to minimize evaporation of water while allowing gas exchange. Following the flooding period, the soils were air dried without draining at 22 ± 2 °C for 20 d, ground to pass a 0.5-mm sieve and used for Fe fractionation.

Iron Fractionation

One gram ground, air-dried soil samples were weighed in duplicate into 50-mL polypropylene centrifuge tubes and extracted in the following sequence: (i) with 30 mL 0.2 M

ammonium oxalate at pH 6.0 for 2 h in darkness; (ii) with 30 mL 0.2 M ammonium oxalate at pH 3.0 for 2 h in darkness (Borggaard, 1979); and (iii) with dithionite-citrate-bicarbonate reagent, DCB (Mehra and Jackson, 1960).

After the shaking period at each extraction, the tubes with extractant were centrifuged at 2000 rpm for 0.25 h, the supernatant liquid was decanted, and the tubes with moist soil (after extraction) were weighed. Iron concentrations in the extracts were measured with atomic absorption spectrometer using air-acetylene flame atomization with standardized Fe solutions in a similar background. The amount of Fe remaining in the tubes was calculated from the Fe concentration in the extract and subtracted from the subsequent Fe fraction. Soil 1, FD for 90 d with and without OM at 23 and 35 °C, was also extracted with 0.1 M sodium pyrophosphate for 1.0 h (McKeague, 1967).

The nonlinear equation $Y = A(1 - b \exp^{-cx})$, where Y = expected P sorption, A = maximum expected P sorption, x = FP, and b and c are constants, was fitted to ΔFeA (the change in amorphous FeA fraction relative to unflooded soil) as a function of FP. Two-way analysis of variance was performed for each Fe fraction and appropriate least significant differences were calculated.

The Eh of the soils for each treatment was measured as a function of FP using a combination platinum electrode calibrated with quinhydrone at pH 4 and pH 7. The combination electrode was fitted with a rubber stopper that sealed the tubes when the electrode was inserted into a flooded soil sample. Three to four measurements were made per tube.

RESULTS AND DISCUSSION

Ammonium oxalate at pH 6 extracted more Fe than did pyrophosphate, but the two methods showed excellent correlation and unit slope (Fig. 1). Our data show that ammonium oxalate at pH 3 extracted large amounts of Fe that underwent transformations (Fig. 2-5). Ammonium oxalate at pH 6 possibly extracts a portion of the amorphous Fe oxides (ferrihydrite) that was extractable by ammonium oxalate at pH 3. This fraction showed better correlation with P sorption (Table 1) than other Fe fractions for three soils (no. 1, 3, and 6) under each combination of OM and temperature treatments studied. In Soil 2 also, this Fe fraction correlated better than free Fe oxides. For convenience, we call this fraction amorphous FeA and the fraction extracted in sequence with ammonium ox-

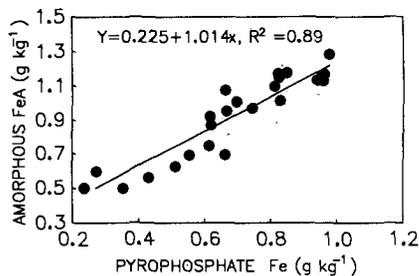


Fig. 1. Relationship of pyrophosphate-extractable Fe with amorphous FeA for soil no. 1 treated with 0 and 10 g organic matter kg^{-1} soil and incubated at 23 °C and 35 °C. The observed points represent Fe concentration in flooded-drained soils at different flooding periods.

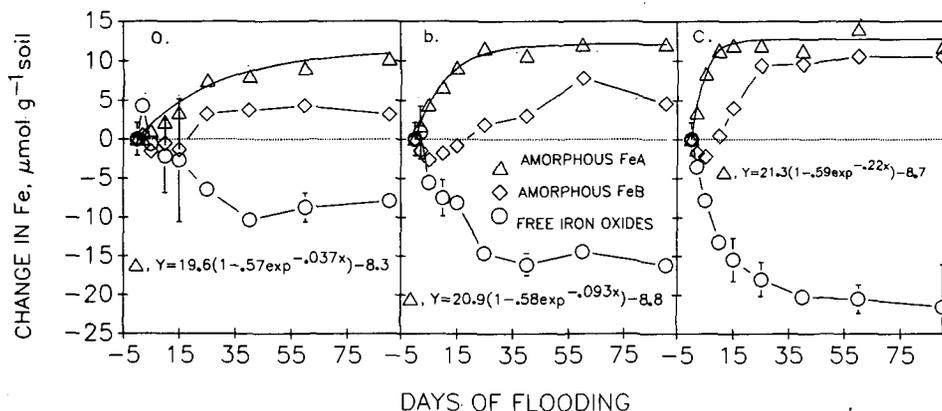


Fig. 2. Effect of added organic matter (OM) and increased temperature on changes in three Fe fractions in flooded-drained soil no. 1. (a) Without added OM incubated at 23 °C; (b) Treated with 10 g OM kg^{-1} soil and incubated at 23 °C; (c) Treated with 10 g OM kg^{-1} soil and incubated at 35 °C. LSD (0.05) between flooding-period lengths = 0.25, 0.61, and 3.28; and between treatments (a, b, c) = 0.68, and 3.61 for amorphous FeA, amorphous FeB, and free Fe oxides, respectively.

late at pH 3 as amorphous FeB. Iron extracted with DCB will be identified as free Fe oxides. It should be kept in mind that there are no clear-cut boundaries among these Fe fractions. These fractions provide only a relative grouping of a large array of Fe mineral forms in soil.

Effects of Soil Type

The nature and the magnitude of changes in the amorphous FeA, amorphous FeB, and free Fe oxide fractions in FD conditions depended on soil type, FP, OM content, and temperature during flooding. When

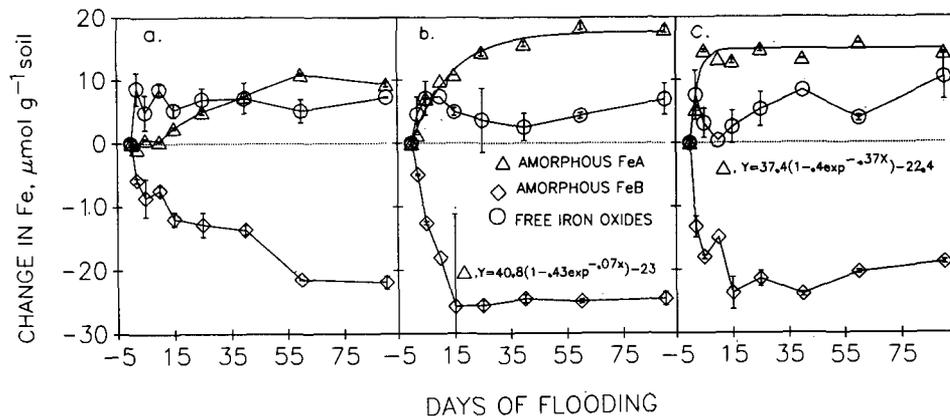


Fig. 3. Effect of added organic matter (OM) and increased temperature on changes in three Fe fractions in flooded-drained soil no. 2. (a) Without added OM incubated at 23 °C; (b) Treated with 10 g OM kg⁻¹ soil and incubated at 23 °C; (c) Treated with 10 g OM kg⁻¹ soil and incubated at 35 °C. LSD (0.05) between flooding-period lengths = 0.36, 3.91, and 2.94; and between treatments (a, b, and c) = 0.39, 4.3, and 3.22 for amorphous FeA, amorphous FeB, and free Fe oxides, respectively.

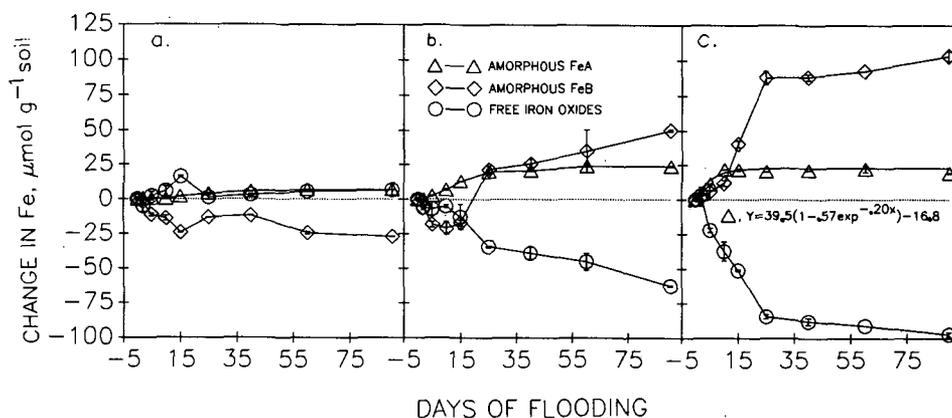


Fig. 4. Effect of added organic matter (OM) and increased temperature on changes in three Fe fractions in flooded-drained soil no. 3. (a) Without added OM incubated at 23 °C; (b) Treated with 10 g OM kg⁻¹ soil and incubated at 23 °C; (c) Treated with 10 g OM kg⁻¹ soil and incubated at 35 °C. LSD (0.05) between flooding-period lengths = 0.73, 4.92, and 4.52; and between treatments (a, b, and c) = 0.80, 5.46, and 4.97 for amorphous FeA, amorphous FeB, and free Fe oxides, respectively.

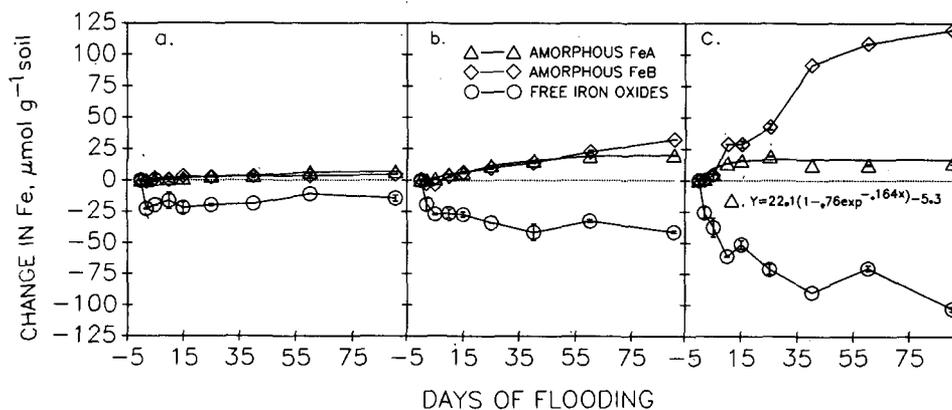


Fig. 5. Effect of added organic matter (OM) and increased temperature on changes in the three Fe fractions in flooded-drained soil no. 6. (a) Without added OM incubated at 23 °C; (b) Treated with 10 g OM kg⁻¹ soil and incubated at 23 °C; (c) Treated with 10 g OM kg⁻¹ soil and incubated at 35 °C. LSD (0.05) between flooding-period lengths = 0.36, 1.98, and 4.1; and between treatments (a, b, and c) = 0.40, 2.18, and 4.50 for amorphous FeA, amorphous FeB, and free Fe oxides, respectively.

Table 1. Correlation of changes in Fe fractions with P sorption as affected by organic matter (OM) and temperature treatments. The variation in these two variables was brought about by different flooding periods (FP).

Soil† no.	OM	Temp.	ΔFeA	ΔFeB	ΔFeD
	g Kg^{-1}	$^{\circ}\text{C}$	<i>r</i> with P sorption to maintain —50 μM final P concentration (P_f)—		
1	0	23	0.96	0.87	-0.99
	10	23	0.98	0.61	-0.94
	10	35	0.95	0.53	-0.50
	All treatments‡		0.93	0.58	-0.63
6	0	23	0.89	0.87	-0.21
	10	23	1.00	0.94	-0.81
	10	35	0.91	0.85	-0.91
	All treatments		0.92	0.84	-0.90
			<i>r</i> with P_r at 1.2 mM —initial P concentration (P_i)—		
2	0	23	-0.67	0.88	-0.51
	10	23	-0.70	0.78	+0.23
	10	35	-0.50	0.81	-0.24
	All treatments		-0.64	0.82	-0.16
3	10§	23	-0.93	-0.59	0.72
	10	35	-0.99	-0.86	0.88
	All treatments		-0.94	-0.70	0.81

† Defined in Part 1 of this paper, Table 1 (p. 1719).

‡ Combined data of the combinations of OM and temperature listed for each soil.

§ Correlation coefficients for Soil 3 at 0 added OM are not shown due to lack of response of P_r to FP.

not treated with OM, there was an apparent decrease in amorphous FeB and an increase in amorphous FeA fractions for 15-d FP in Soil 1 (Fig. 2). At FP longer than 15 d, both amorphous Fe fractions increased at the expense of the free Fe oxide fraction. A decrease in amorphous FeB for the first 15 d, however, does not provide conclusive evidence that this fraction contributed to the increase in amorphous FeA because of the large error associated with the measurements on this day (Fig. 2a). In Soil 2, unlike Soil 1, the amorphous FeA and free Fe oxides increased at the expense of amorphous FeB, regardless of the FP (Fig. 3). For this soil, if amorphous Fe was not further fractionated, the sum of the changes in the two amorphous Fe fractions would be smaller and the characterization of Fe transformation would be misleading. Without OM treatment, Soil 3 behaved like Soil 2 (the amorphous FeB fraction decreased while the two other Fe fractions increased with increasing FP, Fig. 4a) and Soil 6 behaved like Soil 1 (the two amorphous Fe fractions increased at the expense of free Fe oxides, Fig. 5a).

Effects of Organic Matter and Temperature

Amorphous FeA

The amorphous FeA fraction increased with FP in each soil regardless of OM treatment. Addition of OM resulted in a rapid and larger increase in amorphous FeA. In Soil 1, the FP required to attain 95% of the maximum ΔFeA , however, decreased from 77 d in the absence of OM to only 32 and 14 d when the soil was treated with OM at 23 and 35 $^{\circ}\text{C}$, respectively (Fig. 2). The higher temperature accelerated the rate of increase in amorphous FeA, although the magnitude of the increase was not much affected. The amorphous FeA fraction in Soil 2 also showed a similar trend (Fig.

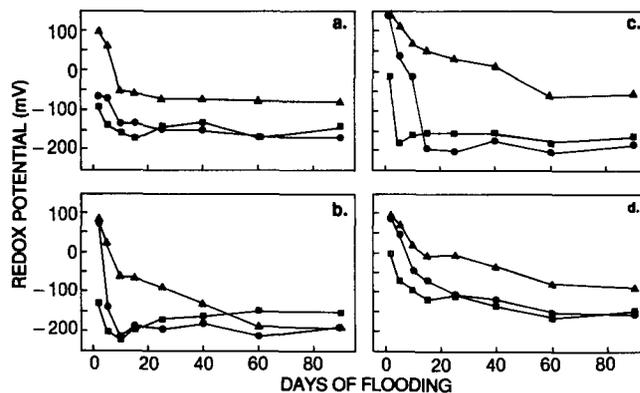


Fig. 6. Changes in the redox potentials of four soils during different flooding periods as affected by organic-matter (OM) and temperature treatment during flooding. (a) Soil 1, (b) Soil 2, (c) Soil 3, (d) Soil 6. Δ , flooded at 23 $^{\circ}\text{C}$ without OM treatment. \bullet , treated with 10 g OM kg^{-1} soil and incubated under flooded conditions at 23 $^{\circ}\text{C}$. \blacksquare , treated with 10 g OM kg^{-1} soil and incubated under flooded conditions at 35 $^{\circ}\text{C}$.

3), with larger effects of OM and temperature. In Soil 3 and 6, the increase in FeA in OM-treated soils were three times larger than the corresponding increase without added OM (Fig. 4 and 5).

Amorphous FeB

The nature of changes in the amorphous FeB fraction was different in each soil studied. The FP at which ΔFeB (amorphous FeB at a given time minus that in unflooded soil) peaked, and the magnitude of the peak, depended on OM and temperature. In the absence of OM at 23 $^{\circ}\text{C}$, the peak ΔFeB in Soil 1 was 4.0 $\mu\text{mol g}^{-1}$ soil (Fig. 2a). In OM-amended soil, this increased to 7.8 $\mu\text{mol g}^{-1}$ soil at 23 $^{\circ}\text{C}$ (Fig. 2b) and to 10.0 $\mu\text{mol g}^{-1}$ soil at 35 $^{\circ}\text{C}$ (Fig. 2c). The FP required to attain the peak amorphous FeB was decreased with an increase in temperature.

Soil 2 had the highest amorphous-Fe to free-Fe-oxides ratio (Sah and Mikkelsen, 1989), which is a measure of active Fe in soil (Schwertmann et al., 1986). If the ratio is high, amorphous FeB is presumably preferred to crystalline Fe for reduction (Munch and Ottow, 1980; Fischer and Pfanneberg, 1984). The magnitude of decrease in amorphous FeB was not much affected by OM and temperature, but the FP for 95% of the minimum ΔFeB was decreased with OM treatment (Fig. 3).

Without OM treatment, amorphous FeA and free Fe oxides increased at the expense of amorphous FeB. When Soil 3 was treated with OM, amorphous FeB content increased at the expense of the free Fe oxides, either at 35 $^{\circ}\text{C}$ or after an initial decline at 23 $^{\circ}\text{C}$ (Fig. 4b and c). In Soil 3, Fe transformations appeared to be limited by OM treatment, probably due to inadequate energy available for soil reduction. In the absence of OM, the E_h in this soil did not go below zero until 40-d FP (Fig. 6c). The other three soils attained much lower E_h values under similar conditions (Fig. 6). When treated with OM, Soil 3 showed a rapid and much larger decrease in E_h . The amorphous-Fe to free-Fe-oxide ratio in Soil 3 (0.7) was lower than Soil

Table 2. Effect of organic matter (OM) and temperature on Fe forms in flooded-drained soils for a 90-d flooding period.†

Soil‡ no.	Fe§ fraction	OM	Temperature			Between any two treatments LSD (0.05)	Between two OM treatments LSD (0.05)
			10 °C	23 °C	35 °C		
		g kg ⁻¹	Fe, μmol g ⁻¹ soil				
1	Amorphous FeA	0	5.67	10.24	10.52	0.43	0.25
		10	11.49	12.07	11.71		
	Amorphous FeB	0	-3.07	3.17	13.68	1.53	0.88
		10	-0.87	4.61	10.48		
	Free Fe oxides	0	-2.85	-7.89	-19.14	7.10	4.10
		10	-10.73	-16.16	-21.53		
2	Amorphous FeA	0	5.15	9.33	14.39	0.98	0.57
		10	19.11	18.07	14.21		
	Amorphous FeB	0	-5.95	-21.91	-22.60	1.38	0.80
		10	-16.58	-24.53	-18.89		
	Free Fe oxides	0	9.62	7.27	10.93	6.96	4.02
		10	9.28	6.96	10.38		
3	Amorphous FeA	0	0.75	6.87	14.19	0.73	0.42
		10	12.88	23.83	19.16		
	Amorphous FeB	0	-7.83	-26.97	45.28	4.52	2.61
		10	-3.94	50.24	103.21		
	Free Fe oxides	0	7.90	6.85	-47.53	8.93	5.16
		10	-4.19	-62.38	-96.98		
6	Amorphous FeA	0	3.64	6.89	10.39	1.19	0.69
		10	11.41	20.05	14.21		
	Amorphous FeB	0	5.39	5.00	60.85	4.16	2.40
		10	8.24	32.75	119.93		
	Free Fe oxides	0	-8.60	-14.48	-54.16	9.74	5.62
		10	-16.84	-41.36	-102.86		

† Soils were flooded for 90 d at respective temperature with or without OM treatment, drained and Fe was extracted from the drained soils. The Fe represents the amount extracted from 90 d flooded-drained soils minus that from the respective unflooded soils.

‡ Defined in part 1 of this paper. Table 1, p. 1719.

§ Amorphous FeA extracted with ammonium oxidase at pH 6 for 2 h; amorphous FeB determined by the method detailed by Borggaard (1979); Free Fe oxides determined by the method of Mehra and Jackson (1960).

2 (1.4) and much higher than Soil 1 and 6 (0.3). This ratio appears to be borderline for the preference of amorphous FeB; amorphous FeB was preferred only in the absence of OM.

Regardless of OM treatment, amorphous FeB and FeA fractions increased at the expense of free Fe oxides in Soil 6. When Soil 6 was flooded without added OM at 23 °C, the amorphous FeB fraction increased steadily with an increase in FP, and attained the maximum ΔFeB at 5.0 $\mu\text{mol/g}$ (Fig. 5a). When flooded with added OM, the maximum ΔFeB was increased to 31.0 $\mu\text{mol g}^{-1}$ soil at 23 °C (Fig. 5b) and to 120.0 $\mu\text{mol g}^{-1}$ soil at 35 °C (Fig. 5c). Apparently, attainment of potential Fe transformation in Soil 6 required OM treatment along with elevated temperature (35 °C).

Free Iron Oxides

The soluble Fe concentration in reduced soils increases due to dissolution of free Fe oxides, the so-called "reductant soluble" Fe (Patrick and Mahapatra, 1968). For Soil 1 and 6, free Fe oxides decreased as FP increased (Fig. 2 and 5). Both soils had lower amorphous-Fe to free-Fe-oxide ratios. Soil 6 showed about 2 to 5 times greater decrease in ΔFeD (change in free Fe oxides with respect to unflooded soil) than Soil 1 under similar conditions (Fig. 2 and 5). Soil 2, which had the highest amorphous-Fe to free-Fe-oxides ratio, showed a net increase in free Fe oxides as FP increased, regardless of OM and temperature treatment. The magnitude of ΔFeD was largest when the soil was flooded with added OM at 35 °C. Soil 3 attained the maximum ΔFeD of 16 $\mu\text{mol g}^{-1}$ soil when

flooded without OM treatment (Fig. 4a); ΔFeD decreased to -62 $\mu\text{mol g}^{-1}$ soil when flooded with OM treatment at 23 °C (Fig. 4b) and further to -97 $\mu\text{mol g}^{-1}$ soil when flooded with added OM at 35 °C (Fig. 4c). The amorphous-Fe to free-Fe-oxides ratio in Soil 3 was about two times higher than in Soil 1 and 6, but only about 50% of that in Soil 2. The amorphous-Fe to free-Fe-oxides ratio appears to indicate whether free Fe oxides will increase or decrease under FD conditions.

At 90-day Flooding Period

The Fe transformation was stabilized in all soils in about 90-d FP or less. Therefore, to eliminate the variable FP, the effects of temperature and OM were evaluated for a 90-d FP.

Amorphous FeA. For all soils, added OM produced the largest percentage increase in amorphous FeA at 10 °C. As temperature increased from 10 to 35 °C, the difference in amorphous FeA between OM treatments (0 and 10 g kg⁻¹) progressively decreased (Table 2). When treated with OM at 35 °C, the amorphous FeA in all soils decreased, compared with OM treatment at 23 °C. In untreated soils, amorphous FeA plateaued about 50 d later during flooding than in OM-treated soils (About 8-to 18-d FP, Fig. 2-5). This period may have allowed amorphous FeA in OM-treated soils to be transformed into more-stable Fe forms. The reorganization and precipitation of Fe during the soil-flooding period was also noted by Ponnampereuma (1977) and Mandal (1961).

Amorphous FeB. For Soil 1 and 2, amorphous FeB was significantly increased by temperature, but OM

addition had only minor or no effects (Table 2). For Soil 3 and 6, both temperature and OM had strong interactive effects on amorphous FeB. In the absence of OM, ΔFeB in Soil 3 was $-7.8 \mu\text{M g}^{-1}$ soil at 10°C , and increased to $45 \mu\text{mol g}^{-1}$ soil at 35°C . The OM amendment increased ΔFeB to as much as $103 \mu\text{M Fe g}^{-1}$ Soil 3.

Free Iron Oxide. At 90-d FP, there was no significant effect of temperature and OM treatment on free-Fe-oxide concentration in Soil 2. The Fe transformation in this soil occurred primarily from amorphous FeB to amorphous FeA (Table 2). In Soil 3 and 6, input of OM and a temperature higher than 23°C was essential for the dissolution of free Fe oxides and the climax Fe transformation.

Within the range of treatments applied, OM and temperature appeared to complement each other in affecting Fe fractions. However, a soil responding to OM treatment at the highest temperature (35°C) may be considered deficient in OM substrate for microbial activity (for Fe transformation) because this temperature is close to the physiological optima for many soil microbes (Cho and Ponnampetuma, 1971). The Fe fractions of Soil 1 and 2 did not respond to OM at 35°C , while Soil 3 and 6 showed a significant response at this temperature. This indicates that Fe transformations in Soil 3 and 6 were limited by the initial OM substrate level.

Relationship of Iron Transformation and Phosphorus Sorption

Table 1 shows that changes in Fe fractions were related to P sorption under similar FD conditions. The ΔFeA correlated best with the expected P sorption (Sah and Mikkelsen, 1989) for a given P concentration for both Soil 1 and 6 (only $50 \mu\text{M P}$ concentration shown in Table 1) under all treatments of OM and temperature. The ΔFeB showed lower correlation in OM-treated Soil 1, while ΔFeD had inconsistent correlation with expected P sorption. For Soil 2 and 3, Fe fractions were correlated with final P concentration (P_f) at 1.2 mM initial P concentration (P_i). In this regard, ΔFeA showed the best correlation in Soil 3, while ΔFeB was the best in Soil 2.

CONCLUSIONS

This study demonstrates that it is difficult to predict the nature, rate, and magnitude of Fe transformation in a FD soil without considering temperature and energy sources (OM), since these factors determine microbial activity and, ultimately, the *Eh* of soil during flooding. The processes that lead to changes in Fe fractions in drained soils probably originate during the anoxic flooding period of soil. The higher Fe concentration in the anoxic soil layers and Fe pumping from the anoxic to oxic layers possibly accelerates dissolution and reprecipitation of Fe minerals in flooded soils. In soils with high amorphous-Fe to free-Fe-oxide ratios, amorphous Fe was transformed to free Fe oxide, while in soils with low ratios, Fe transformations were in the opposite direction. There was evidence of Fe transformation within the amorphous Fe fraction. At suitable temperature and OM, a FP as short as 5

d may change the proportion of Fe fractions in drained soils. These could affect the availability of P and possibly other plant nutrients. The P sorptivity in FD soils is correlated with the Fe transformation.

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