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Dependence of Soil Organic Carbon on available Iron and Manganese Concentrations in Submerged Rice Soils

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Abstract

Effect of soil submergence on changes in soil organic C (SOC) and DTPA-extractable Fe and Mn and their interrelationship was studied in three texturally-different soils viz. loamy sand, clay loam and silty clay traditionally grown to rice-wheat system. Laboratory incubation experiments were conducted for 120 d under controlled temperature and moisture conditions. Soil organic C increased with incubation period up to 30-45 d and declined sharply thereafter. Similarly, concentration of DTPA-Fe was highest at 30 d and decreased sharply thereafter. However, DTPA-Mn concentration was the highest at 15 and 30 d of incubation, under submerged and field capacity moisture regimes, respectively. Soils incubated under submerged conditions exhibited higher SOC, DTPA-Fe, and DTPA-Mn than those incubated at field capacity moisture. In all the three soils under submerged conditions SOC, DTPA-Fe and Mn were higher at 40°C followed by 30°C and 20°C temperature. Irrespective of soil and incubation temperature, values of these variables did not change with incubation of air dry soil. The concentration of DTPA-Fe and Mn showed positive relationship with SOC concentration at submerged and field capacity moisture regimes. Increase in SOC with submergence was considered to be due to an increase in DTPA-Fe and Mn suggesting the need for using some chelating agents to remove their interference in SOC determination by wet digestion method.

Keywords

Rice-wheat; Soil texture; Moisture regime; Temperature regime; Soil organic C; Available iron; Available manganese

Introduction

A 25 years record of carbon (C) sequestration in soil under rice-wheat system in the North Indian state of Punjab showed 38% accrual in soil organic carbon (SOC) concentration. It was attributed to greater plant-mediated C input because of increased crop productivity and to soil submergence leading to retarded rate of organic matter decomposition [1]. In a number of studies, researchers have shown a significant relationship between SOC sequestration and C input through plant biomass and organic manures [2,3]. Recently, a comparison of three cropping systems revealed significantly higher SOC concentration in soils under rice-wheat than the maize-wheat and cotton-wheat cropping systems [4]. Rice-wheat cropping involves cultivation of wetland and upland crops in sequence and the soil experiences alternate wetting and drying, which could lead to differential stabilization of soil organic matter, compared to upland cropping systems [5]. According to Sahrawat [6] the principal mechanisms involved in soil organic matter (SOM) accumulation in soils under submergence include slower, incomplete and inefficient decomposition in the absence of oxygen.

Under submerged condition, the main electron acceptors are organic substances degraded by organic matter and other substances such as Fe^{3+}, Mn^{4+}, NO_3^-, SO_4^{2-} etc. Less energy is released by the redox reaction for synthesis of microbial cells per unit of SOC mineralization [7]. Soils under submerged rice cultivation are subjected to various changes and show decrease in oxidation-reduction [8]. Which tends to increase in iron (Fe^{2+}) and manganese (Mn^{2+}) concentrations due to decrease in redox potential. Submergence of soils tends to initially increase Fe and Mn solubility in soil, which decreases as the submergence period progresses. In well-drained soils, Mn and Fe availability for plant uptake decreases because of their lesser presence in soil solution [9,10]. Saha et al. [11] reported increase in DTPA-extractable Fe and Mn after 45 days of submergence by 3 and 1.8 times, respectively, over their initial concentrations. Mandal and Mitra [12] reported a sharp increase in water soluble and exchangeable Mn after 10 days of submergence followed by significant decline thereafter. Similar trend was observed for Fe but with smaller magnitude. Most of the studies on SOC and micronutrient availability have been conducted in relation to nutrient management and crop productivity. Not much information is available on the role of moisture and temperature regimes on changes in SOC and available Fe and Mn concentrations in soil. The present study was conducted to i) investigate the effect of moisture and temperature regimes on changes in soil organic C, available Fe and Mn in texturally different soils and ii) study relationship between SOC and Fe and Mn availability.

Methods and Materials

Soil sample collection and analyses

Three bulk soil samples (0-15 cm depth) were collected from farmers' fields under rice-wheat system. Soil samples were collected from Hoshiarpur (loamy sand soil), Rupnagar (clay loam soil) and Patiala (silty clay soil) districts of Indian Punjab. Samples were air-dried in shade, ground to pass 2 mm sieve for laboratory studies. Soil pH (1:2 soil: water suspension) was determined using a glass calomel electrode and electrical conductivity (EC) of 1:2 soil: water supernatant was determined using a conductivity meter Jackson [13]. Soil organic C was determined by wet digestion of soil sample in 1N potassium dichromate and concentrated H_2SO_4, followed by titration with N/2 ammonium ferrous sulphate using diphenylamine indictor [14]. Particle size distribution was determined by International pipette method [15]. Diethylene triamine penta acetic acid (DTPA) extractable Fe and Mn were assessed by extracting 10 g portion of soil with 20 ml of DTPA extractant (0.005M DTPA + 0.01M $CaCl_2$ + 0.1M TEA buffer, pH 7.3), followed by determination of their concentration on atomic absorption spectrophotometer (Varian Model AAS-FS) [16]. Soil moisture content (θ) at field capacity was determined in a pressure plate apparatus by applying 0.33 bar pressure.

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Laboratory incubation experiment

Laboratory incubation experiments were conducted at 20 (T1), 30 (T2) and 40^{0}C (T3) temperature and air-dry (M1), field capacity (M2) and submerged or flooded (M3) moisture regimes providing nine combinations of temperature and moisture. At each combination of temperature and moisture incubations were conducted for 15, 30, 45, 60, 90 and 120 days. Fifty g of each soil (oven dry basis) was taken in plastic vials and compacted to representative bulk density. Soils in the vials were brought to requisite moisture content by adding distilled water. The vials along with soils at field capacity were weighed and moisture was maintained by adding distilled water throughout the incubation period. For flooded conditions, 1 cm water-head was maintained at the soil surface throughout the incubation period. One set of vials did not get any water to represent air-dry conditions. Each vial was covered with a perforated polythene sheet using a rubber band to allow diffusion of gases in and out and to restrict evaporation. In order to avoid soil disturbance during sampling at the end of an incubation period, independent vials were maintained for each incubation period and temperature and moisture combination. Therefore, a total of 567 repacked vials were prepared for incubation. At the end of each incubation period, soil samples were analyzed for SOC, DTPA-Fe and Mn.

Statistical analysis

The data on different measurements were subjected to ANOVA using completely randomized factorial design (CRD) and mean separation was made at 95% confidence interval using least significant difference (LSD). Correlation analyses were performed between different measurements. All the analyses were done using locally-developed software.

Results and Discussion

General soil properties are that the soils were loamy sand, clay loam and silty clay in texture, non-saline and near neutral in reaction (Table 1). The soils were low to medium in SOC. While loamy sand soil was deficient in DTPA-extractable Mn and Fe, the other two soils were sufficient in DTPA-Mn and Fe.

Change in soil organic carbon

The effect of incubation time on SOC concentration under different moisture and temperature regimes is shown in Figure 1 and Tables 2 and 3. At field capacity moisture, SOC concentration ranged between 3.60 and 4.37 g kg^{-1} in loamy sand, 5.00 to 6.34 g kg^{-1} in clay loam and 6.60 to 8.14 g kg^{-1} in silty clay soil. Under submerged moisture, the SOC ranged between 3.60 and 4.61 g kg^{-1} in loamy sand, 5.00 and 6.70 g kg^{-1} in clay loam and 6.60 to 8.57 g kg^{-1} in silty clay soil. At both the moisture regimes, the silty clay soil showed the highest SOC concentration followed by clay loam and loamy sand soils. The SOC concentration increased significantly during initial 30 to 45 days of incubation and decreased sharply thereafter. Averaged across soils, SOC was the lowest (5.07 g kg^{-1}) at start than at subsequent incubation periods.

Averaged across soils and incubation periods SOC was significantly higher under submerged moisture than at field capacity moisture. Seven-fold greater SOC has been reported in wetland soils compared with aerobic soils [17]. Reduced soil condition leads to increase in Fe concentration and under flooded conditions SOM decomposition is governed by the availability of alternate electron acceptors such as oxidised forms of Fe and Mn [18]. Zhou [19] suggested that under submerged conditions main organisms such as anaerobes, do not completely oxidize organic substrates to CO_2 through Tri Carboxylic acid cycle (TCA), but form small molecules of organic acids, alcohols, etc. through other biochemical pathways, which decrease C mineralization. The effect of moisture on SOC concentration was more at higher temperature (40°C) than at lower temperatures (20 and 30°C) (Table 3, Figure 1). The present study was conducted with different temperature and moisture regimes. So the results of this analysis do not support the reports of Marinari et al. [20], they have reported that increase in temperature of the Mediterranean sites seems to favour microbial metabolism for C mineralization. Moreover, rise in temperaturxe enhances decomposition rate of SOM, due to favourable environment for soil microbes [21].

The silty clay soil showed significantly higher SOC concentration followed by clay loam and loamy sand soils. The SOC concentration ranged between 4.00 and 4.16 (g kg^{-1}) in loamy sand, 5.73 to 6.11 (g kg^{-1}) in clay loam and 7.32 to 7.69 (g kg^{-1}) in silty clay soils at submerged condition (Table 3). Averaged across temperatures, the three soils showed higher SOC concentration under submerged conditions than at field capacity moisture. Irrespective of the temperature, soils kept at air-dry moisture regime did not exhibited any change in SOC (Figure 1).

Changes in DTPA-Fe in soils

The effect of incubation periods on DTPA-Fe concentration under different moisture and temperature regimes is shown in Figure 2 and Tables 4 and 5. At field capacity moisture, DTPA-Fe ranged between 3.8 and 21.2 mg kg^{-1} in different soils. The DTPA-Fe increased during initial 30 days of incubation and decreased thereafter upto 60 days. Under submerged conditions, DTPA-Fe ranged between 3.8 and 23.2 mg kg^{-1} in different soils. The temporal trends of DTPA-Fe under submerged moisture were similar to that observed under field capacity moisture. Averaged across soils, DTPA-Fe was the lowest (7.3 mg kg^{-1}) at start and the highest (16.3 mg kg^{-1}) at 30 days after incubation (Figure 2). Decrease in Fe content in soil at later stages of submergence had also been reported by Mishra and Pande [22]. Gogoi et al. [23] observed a sharp increase in water soluble and exchangeable-Fe from 40 and 44 mg kg^{-1} at 0 day to 159 and 282 mg kg^{-1}, respectively, at 14 days (peak at 14 days after submergence), which decreased thereafter, as submergence period progressed. Irrespective of the temperature, soils kept at air-dry moisture regime did not exhibited any change in DTPA-Fe (Figure 2).

Averaged across soils and incubation period DTPA-Fe was higher under submerged than at field capacity moisture. Suthar et al. [24] reported that Fe availability in soil was significantly influenced by

Table 1: Important physical and chemical properties of surface (0-15 cm) soils at the start of the incubation experiment.

Soil property	Loamy sand	Clay loam	Silty clay
pH	7.4	7.4	7.3
EC (dSm^{-1})	0.26	0.29	0.24
SOC (g kg^{-1})	3.6	5.0	6.6
DTPA-Fe (mg kg^{-1})	3.84	7.62	10.5
DTPA-Mn (mg kg^{-1})	3.12	4.46	5.62
Sand (%)	85.7	63.0	29.0
Silt (%)	4.7	11.0	30.5
Clay (%)	9.6	26.0	40.5
θ¶ (%)	20.4	29.3	32.2

θ¶ = Volumetric moisture content

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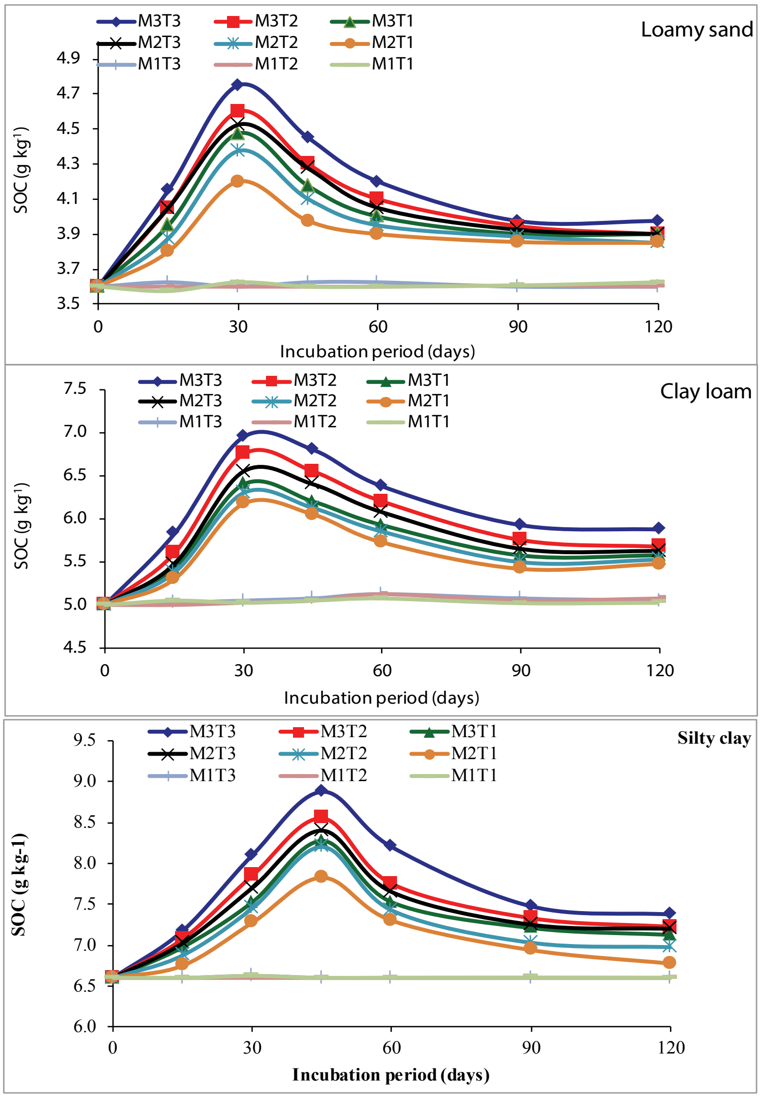

Figure 1: Effect of different moisture and temperature regimes on the concentration of soil organic carbonduring120 days incubation of three soils [M_1, M_2 and M_3 represents air-dry, field capacity and submergence moisture regimes; T_1, T_2 and T_3 represents 20, 30 and 40°C temperature regimes].

Table 2: Soil organic carbon concentration (g kg^{-1}) in three soils as affected by moisture regimes and incubationperiod (averaged across temperature).

Field capacity				Submergence		
Incubation period (days)	Loamy sand	Clay loam	Silty clay	Loamy sand	Clay loam	Silty clay
0	3.60	5.00	6.60	3.60	5.00	6.60
15	3.91	5.38	6.88	4.05	5.62	7.08
30	4.37	6.34	7.48	4.61	6.70	7.83
45	4.12	6.19	8.14	4.31	6.52	8.57
60	3.97	5.88	7.46	4.10	6.17	7.83
90	3.89	5.52	7.07	3.94	5.75	7.34
120	3.87	5.54	6.98	3.93	5.71	7.24
LSD (*p<0.05*) Soils=0.16, Moisture=0.13, Incubation period=0.24, Moisture x Incubation period=0.062, Soil x Moisture=0.22, Soil x Incubation period=0.42, Soil x Incubation period x Moisture=NS						

Table 3: Soil organic carbon concentration (g kg^{-1}) in three texturally different soils as affected by moisture and temperature regimes (averaged across incubation).

Field capacity				Submergence		
Temperature (˚C)	Loamy sand	Clay loam	Silty clay	Loamy sand	Clay loam	Silty clay
20	3.88	5.59	7.07	4.00	5.73	7.32
30	3.95	5.67	7.22	4.07	5.93	7.48
40	4.05	5.83	7.40	4.16	6.11	7.69
LSD (*p<0.05*) Soils=0.03, Temperature=0.03, Soil x Temperature=0.05, Moisture x Temperature=NS, Soil x Moisture x Temperature=NS						

moisture level. Available Fe in soil increased (by 285% over its initial value) up to 4 weeks after incubation and decreased thereafter. The magnitude of increase was greater at saturation followed by 80% and 20% of available water regimes. Similarly, Tiwari et al. [10] observed higher Fe content under waterlogged than at field capacity moisture.

The effect of moisture on DTPA-Fe was more pronounced at higher temperature (40˚C) than at the other two temperatures (Table

Table 4: Diethylene triamine pentaacetic acid extractable iron (DTPA-Fe) and Mn (mg kg^{-1}) in three soils as affected by moisture regime and incubation period (averaged across temperature).

DTPA-Fe				**DTPA-Mn**		
Incubation period (days)	**Loamy sand**	**Clay loam**	**Silty clay**	**Loamy sand**	**Clay loam**	**Silty clay**
Field capacity						
0	3.8 (0.05)‡	7.6 (0.06)	10.5 (0.09)	3.24 (0.05)‡	4.46 (0.07)	5.62 (0.09)
15	6.4 (0.20)	11.6 (0.65)	16.8 (0.26)	5.17 (0.14)	7.33 (0.27)	9.87 (0.47)
30	8.3 (0.39)	15.0 (0.70)	21.2 (0.68)	5.52 (0.13)	8.02 (0.23)	11.3 (0.32)
45	7.4 (0.38)	12.9 (0.58)	19.3 (0.36)	4.45 (0.17)	6.63 (0.16)	9.17 (0.52)
60	6.0 (0.31)	11.0 (0.30)	17.6 (0.48)	4.25 (0.08)	6.15 (0.26)	8.28 (0.43)
90	5.2 (0.27)	9.9 (0.28)	16.6 (0.46)	4.01 (0.08)	5.67 (0.29)	7.54 (0.25)
120	4.9 (0.15)	9.3 (0.36)	15.0 (0.33)	3.82 (0.09)	5.38 (0.21)	7.23 (0.30)
Submergence						
0	3.8 (0.05)	7.6 (0.06)	10.5 (0.09)	3.24 (0.05)	4.46 (0.07)	5.62 (0.09)
15	7.1 (0.33)	13.2 (0.60)	18.2 (0.66)	5.91 (0.15)	8.63 (0.22)	12.2 (0.40)
30	9.4 (0.29)	16.4 (0.59)	23.2 (0.96)	5.54 (0.13)	7.87 (0.33)	11.0 (0.33)
45	8.2 (0.32)	14.0 (0.69)	20.5 (0.43)	4.74 (0.17)	6.94 (0.18)	9.85 (0.23)
60	6.9 (0.34)	11.9 (0.34)	18.8 (0.38)	4.42 (0.11)	6.86 (0.19)	9.10 (0.29)
90	6.0 (0.36)	10.7 (0.39)	17.9 (0.46)	4.15 (0.10)	6.20 (0.24)	8.33 (0.20)
120	5.4 (0.19)	10.5 (0.37)	15.9 (0.33)	4.04 (0.07)	5.94 (0.19)	7.96 (0.22)
LSD (*p<0.05*) Soils=0.64, Incubation period=0.98, Moisture=0.52, Moisture x Incubation period=NS, Soil x moisture=NS, Soil x Incubation period=1.70, Soil x Moisture x Incubation period=NS						
LSD (*p<0.05*) Soils=0.16, Moisture=0.13, Incubation period=0.24, Moisture x Incubation period=0.34, Soil x Moisture=0.22, Soil x Incubation period=0.42, Soil x Incubation period x Moisture=NS						
‡ Values in the parenthesis indicate standard error						

Table 5: Diethylene triamine pentaacetic acid extractable iron (DTPA-Fe) and Mn (mg kg^{-1}) in three soils as affected by moisture and temperature regimes (averaged across incubation).

	DTPA-Fe				**DTPA-Mn**	
Temperature (°C)	**Loamy sand**	**Clay loam**	**Silty clay**	**Loamy sand**	**Clay loam**	**Silty clay**
Field capacity						
20	5.7 (0.51)‡	10.5 (0.79)	16.1 (1.16)	4.20 (0.27)‡	5.98 (0.44)	7.95 (0.65)
30	5.9 (0.56)	10.8 (0.89)	16.7 (1.27)	4.32 (0.29)	6.10 (0.44)	8.30 (0.69)
40	6.5 (0.67)	11.8 (1.08)	17.4 (1.41)	4.53 (0.33)	6.62 (0.50)	9.05 (0.80)
Submergence						
20	6.2 (0.63)	11.2 (0.92)	17.0 (1.32)	4.36 (0.32)	6.33 (0.46)	8.72 (0.73)
30	6.8 (0.71)	12.3 (1.12)	18.0 (1.52)	4.62 (0.35)	6.81 (0.52)	9.21 (0.82)
40	7.1 (0.74)	12.6 (1.17)	18.5 (1.66)	4.73 (0.37)	6.96 (0.56)	9.54 (0.89)
LSD (*p<0.05*) Soils=0.64, Temperature=0.64, Moisture=0.52, Soil x Moisture=NS, Soil x Temperature=NS, Moisture x Temperature=NS, Soil x Moisture x Temperature=NS				LSD (*p<0.05*) Soils=0.16, Moisture=0.13, Temperature=0.16, Soil x Temperature=0.27, Moisture x Temperature NS, Soil x Moisture=0.22, Soil x Moisture x Temperature=NS		

‡ Values in the parenthesis indicate standard error

5, Figure 2). At field capacity moisture, DTPA-Fe ranged between 5.7 and 17.4 mg kg^{-1} in different soils (Table 5). The DTPA-Fe concentration was significantly higher under submerged (by 8.0%) compared to field capacity moisture and ranged between 6.2 and 18.5 mg kg^{-1} in different soils (Table 5). The DTPA-Fe concentration increased with temperature. Increase in DTPA-Fe concentration with temperature may be attributed to increase in its diffusion in soils [25]. Higher DTPA-Fe under submerged conditions could be due to the reduction of iron from ferric (Fe^{3+}) to ferrous (Fe^{2+}) form under submerged conditions [4]. Submergence tends to decrease the redox potential and oxygen diffusion rate and increases the accumulation of CO_2, which is responsible for increased concentration of Fe in the

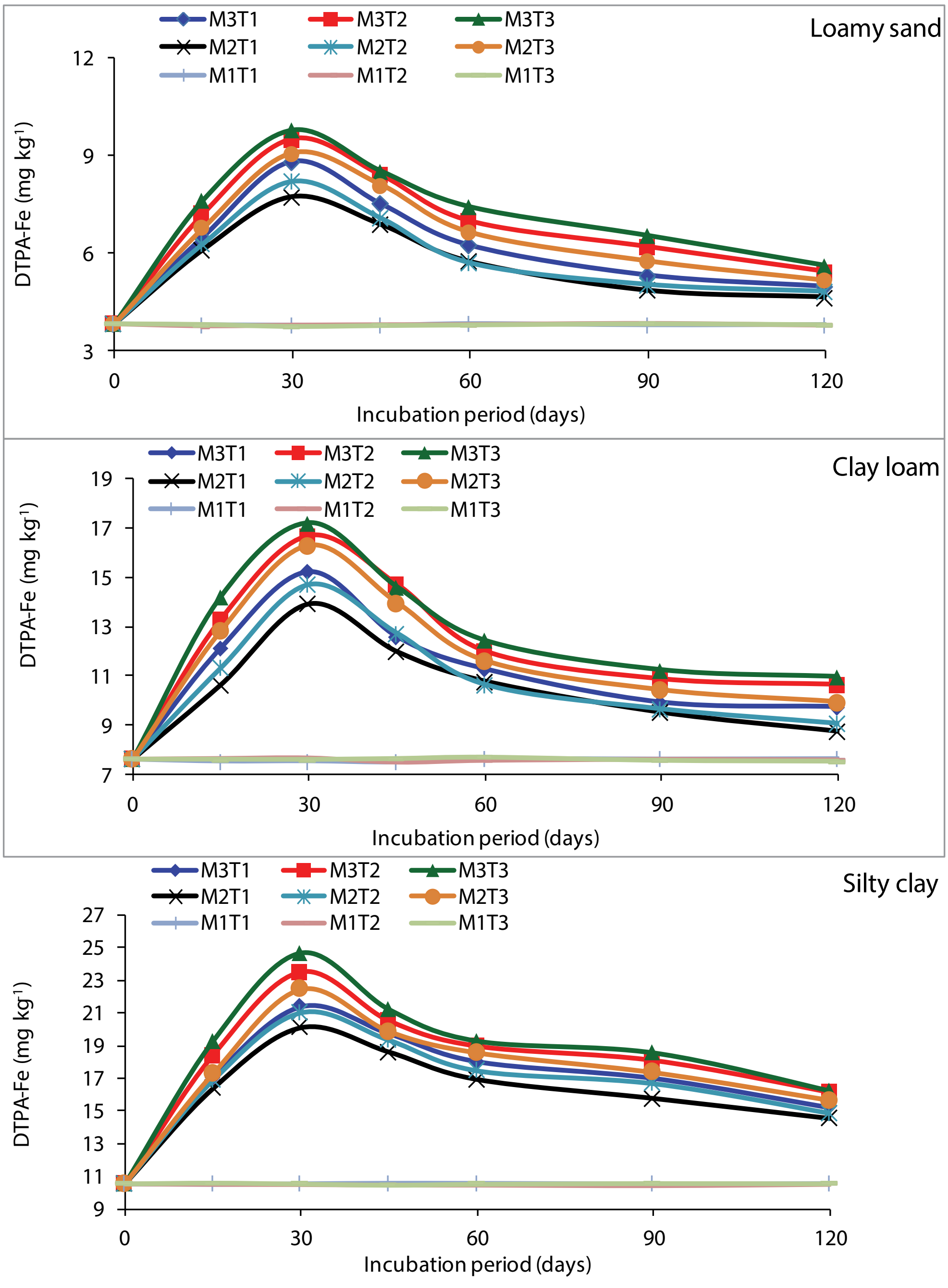

Figure 2: Effect of different moisture and temperature regimes on the concentration of DTPA-Feduring120 days incubation of three texturally different soils [M_1, M_2 and M_3 representsair-dry, field capacity moisture regime and submergence moisture regimes; T_1, T_2 and T_3 represents 20, 30 and 40°C temperature regimes].

soils [8], Bandyopadhyay and Sen [26]. The decrease in DTPA-Fe after 30 days of incubation could be because of formation of insoluble Fe compounds in soils [27,28].

Changes in DTPA-Mn in soils

The effect of incubation time on DTPA-Mn concentration at different moisture and temperature regimes is shown in Figure 3 and Tables 4 and 5. At field capacity, DTPA-Mn ranged between 3.24 and 11.3 mg kg^{-1} in different soils. The DTPA-Mn concentration increased during initial 30 days of incubation and decreased thereafter. The silty clay soils showed significantly higher DTPA-Mn followed by clay loam and loamy sand soil. Under submerged conditions, DTPA-Mn ranged between 3.24 and mg kg^{-1} in different soils. The DTPA-Mn concentration increased upto 15 days of incubation. Unlike DTPA-Fe, the decrease in DTPA-Mn concentration occurred earlier (at 15 days of incubation). It might be because of fast reduction of Mn compared to Fe [29] also reported a sharp increase in insoluble ferrous Fe in waterlogged soils and thereafter, with an increase in

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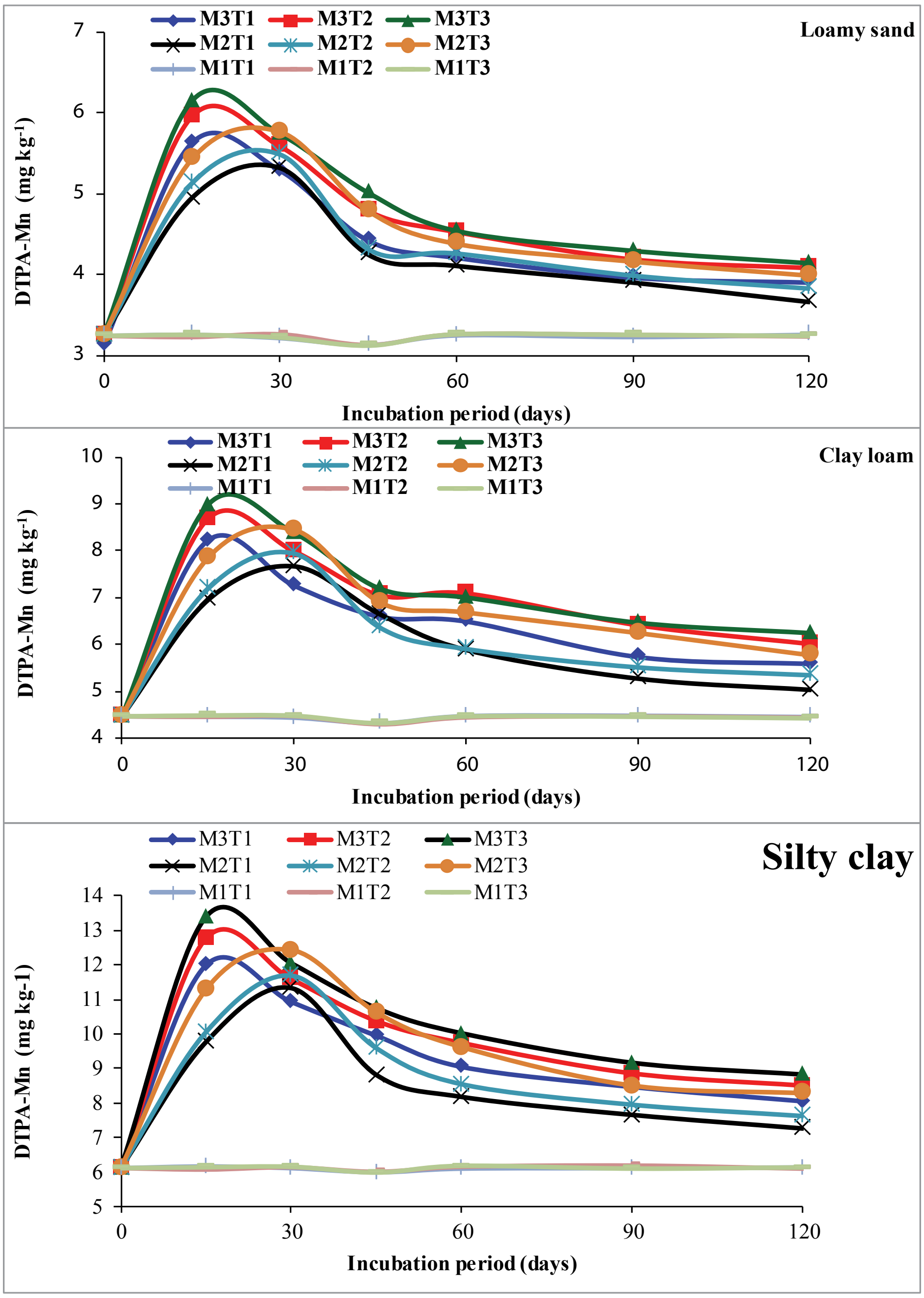

Figure 3: Effect of different moisture and temperature regimes on the concentration of DTPA-Mn during 120 days incubation of three texturally different soils [M_1, M_2 and M_3 represents air-dry, field capacity and submergence moisture regimes; T_1, T_2 and T_3 represents 20, 30 and 40°C temperature regimes].

CO_2 concentration, Fe^{++} entered into the exchangeable complex but slower than Mn where the trend was same as for Fe, It was concluded that transformation of Fe and Mn were due to direct reduction of their oxidised forms. The silty clay soils showed significantly higher DTPA-Mn concentration followed by clay loam and loamy sand soils. Averaged across soils and incubation period, DTPA-Mn was significantly higher under submerged moisture regime than at field capacity and Mitra [12] observed a sharp increase in water soluble and exchangeable Mn after 10 days of waterlogged soil moisture conditions followed by significant decline thereafter up to 85 days in alluvial soils. Increase in Mn was always greater under continuous waterlogged moisture than continuous saturated and alternate waterlogged moisture regime.

At different temperatures, DTPA-Mn concentration ranged between 4.20 and 9.05 mg kg^{-1} in the three soils. The effect of moisture on DTPA-Mn was greater at higher temperature (40°C) than at the other two temperatures (Table 5, Figure 3). The silty clay soils showed significantly higher DTPA-Mn than clay loam and loamy sand soils. Under submerged moisture, DTPA-Mn ranged between 4.36 and 9.54 mg kg^{-1} in different soils (Table 5). Averaged across

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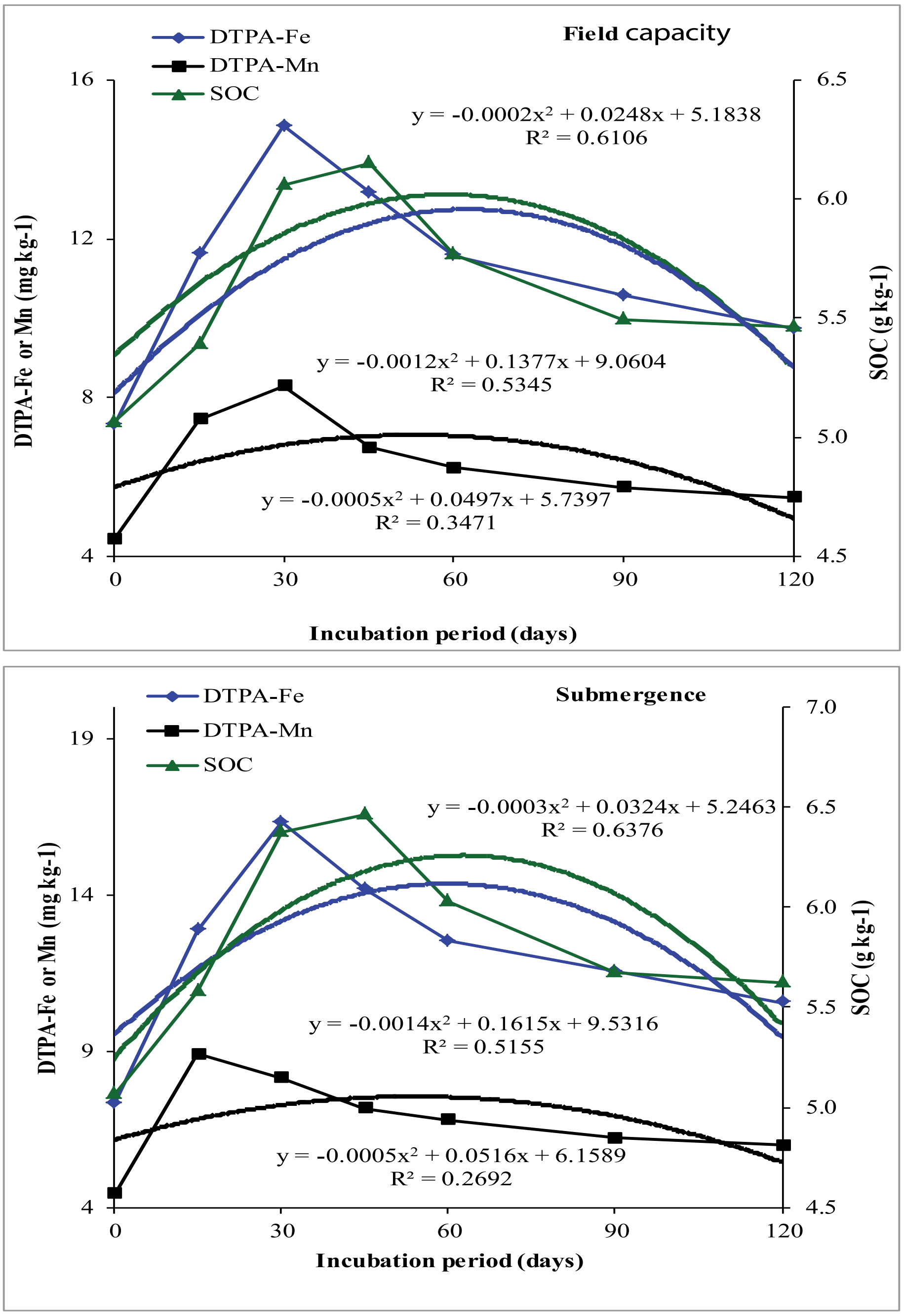

Figure 4: Scatter plot of DTPA-Fe, Mn and SOC versus incubation period under field capacity and submerged condition (*Data pooled for soils*).

different temperatures, soils showed significantly higher DTPA-Mn under submerged than at field capacity moisture. Bandyopadhyay and Sen [26] assessed the effect of 14 days of super saturated soil water condition on exchangeable Mn in silty clay soils and observed significant decrease in redox potential and oxygen diffusion rate, which led to significant increase in exchangeable Mn. Irrespective of the temperature, soils kept at air-dry moisture regime did not exhibited any change in DTPA-Mn (Figure 3).

Relationship of SOC with DTPA extractable Fe and Mn

At both the soil moisture regimes, increase in the concentration of SOC, DTPA-Fe and DTPA-Mn were positively related to incubation time (Figure 4). Soil organic C exhibited significant ($p<0.05$) correlation with DTPA-Fe (r=0.95**) and Mn (r=0.86**) (Table 6).

The reduction of $Fe^{3+}$to Fe^{2+} and Mn^{4+} to Mn^{2+} is expressed by the following equations (Ponnamperuma [30]:

$Fe(OH)_3 + 3H^+ + e^- \Leftrightarrow Fe^{2+} + 3H_2O$,

$MnO_2 + 4H^+ + 2e^- \Leftrightarrow Mn^{2+} + 2H_2O$

Because potassium dichromate ($K_2Cr_2O_7$) is used as an oxidation agent in Walkley and Black [14] method, it may oxidize the reduced

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Table 6: Correlation between different soil properties (Data pooled for soils and moisture regimes).

Variables	DTPA-Fe	DTPA-Mn
DTPA-Fe		
DTPA-Mn	0.95**	
SOC	0.95**	0.86**

**Correlation is significant at p<0.01

forms of Fe and Mn. Therefore, the increase in the concentration of Fe and Mn in submerged soils may be responsible for increase in SOC. Consequently, the determination of SOC in submerged rice soils may show higher values of SOC due to the presence of reduced forms of Fe and Mn [13] indicating pseudo rather than actual increase in SOC. To circumvent this methodological problem, the soil sample may be collected after the harvest of wheat crop, where rice and wheat crops are grown in a sequence. Alternatively, some chelating agents such as DTPA or EDTA may be used in SOC determination by Walkley and Black [14] method. This will require modification of the method which needs further investigation.

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