Comparison of Pedogenic Properties of Some Paddy and Non-Paddy Soils of Southern Iran

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ABSTRACT- Paddy soils make up the largest anthropogenic wetlands on earth. The present study was performed to investigate and compare soil formation of paddy soils with long-term rice cultivation history with non-paddy soils and study the effect of waterlogging on soil pedogenesis. Soil samples were taken from paddy and non-paddy soils derived from the same calcareous parent materials. Some pedogenic properties such as organic carbon (OC), clay content, iron fractions, pH, electrical conductivity (EC), cation exchange capacity (CEC), and calcium carbonate equivalent (CCE) were measured. Results revealed that paddy management had profound impact on soil formations and led to faster soil forming processes in paddy soils under flooded condition. In the studied paddy soils, OC and CEC content significantly increased in surface and subsurface soils; but soil pH significantly decreased. Chemical analysis revealed a significant increase of clay portion in subsurface of paddy soils and a non-significant increase of EC in surface and subsurface of paddy soils. The CCE content in surface and subsurface of paddy soils was non-significantly lower than that of non-paddy soils. Rice cropping system greatly affected different Fe forms so that paddy soils had more available Fe (Fe_{ex}), total Fe (Fe_t), and poorly crystalline Fe oxides (Fe_o), but lower pedogenic Fe (Fe_d) and crystalline Fe oxides than non-paddy soils.

INTRODUCTION

Rice is one of the world's major food resources, supporting more than 50% of the world population, and one of the most important crops that is cultivated under submerged conditions (Bouvet and Toan, 2011). Paddy soils are hydromorphic soils formed under intense anthropogenic influence, widely distributed in difference parts of the world such as Asia and Iran. They may originate from many types of soils in pedological terms or different parent materials, but are highly modified by anthropogenic managements during rice paddy cultivation (Gong, 1983).

Paddy soil formation is driven by the anthropogenic management practices that mask the soil's original characteristics (Gong, 1983, 1986). These management practices, such as plowing and puddling (tillage of flooded soil), artificial submergence and drainage and manuring, liming and fertilization, have obvious impacts on soil properties (Kirk, 2004;Yu, 1985; Ponnamperuma, 1972). The periodic redox cycles induced by specific paddy soil management strategies have strong effects on long-term biogeochemical processes and can result in permanent and temporary changes of soil properties (Kögel-Knabner et al., 2010).

Flooding, puddling and the associated development of a plow pan, change physical properties of soil. These changes are generally beneficial for rice growth because of improving nutrient availability and reducing percolation losses. Typical paddy soil-forming processes under anthropogenic managements have been identified and reviewed by Gong (1983, 1986). These important pedogenic processes and transformations include gradual profile differentiation of Fe and Mn by oxidation–reduction and eluviation–illuviation processes in the paddy soils resulting from periodic artificial submergence and drainage (Gong, 1983, 1986; Yu, 1985), changes in soil pH, specific conductance and redox potential, base leaching and re-adsorption processes, accumulation of organic matter in the surface horizon of paddy soils, nutrient transformations and associated changes in bioavailability (Ponnamperuma, 1972; Kirk, 2004), destruction of clay minerals due to ferrolysis, and formation of poorly structured cultivated horizon and a compact and slightly laminar-structured plow pan by repeated plowing and puddling (Gong, 1983, 1986).

Frequent inundation leads to anoxic conditions in the soil and reduced rates of organic matter decomposition (Sahrawat, 2004), while it intensifies mineral weathering (Nanzyo et al., 1999) and leaching processes (Gong, 1986; Ponnamperuma, 1972). High

concentrations of dissolved organic matter during flooding seasons enhance the changes as well as the release of structural Fe in clay minerals and support the formation of ferrihydrite (Kögel-Knabner et al., 2010). Frequent redox cycles may favour the formation of poorly crystalline Fe (hydr) oxides, i.e., ferrihydrite. However, Thompson et al. (2006) observed a positive correlation between the number of red ox cycles and increasing crystallinity of soil hydrous oxides in short term batch experiments. This could also result in higher total Fe oxide contents in paddy soils compared to non-paddy soils (Cheng et al., 2009).

Understanding how management practices affect paddy soil evolution is useful for improvement and sustainable use of these important soil resources (Zhang and Gong, 2003). In Fars Province (in the South of Iran), lower areas were used for a cropping sequence of flooded paddy rice followed by a non-flooded crop. The upper areas have been exclusively used for non-flooded crop production. This enables us to study the genesis of paddy and non-paddy soils in a unique way. In this area, natural soil (non-paddy soils) have often been studied to estimate changes in soil properties but few studies have examined paddy soils. Therefore, the present study was performed to investigate the effect of paddy management on some pedogenic, and physico-chemical properties of paddy soils and compare them with non-paddy soils derived from uniform parent material in ten areas.

MATERIALS AND METHODS

Study Region and Field Sampling

This study was conducted in ten areas of Fars Province. Within each area, a paddy and a non-paddy soil were selected based on historical information and current land uses. Fars Province is located in the southern part of Iran, at the 50° 30´-55° 38´ eastern longitude and 27° 3´ -31° 42´ northern latitude (Fig.1). Zagros mountains, with a north-west to south-east direction, are extended towards the central parts of the province. Elevations in the north reach higher than 3900 m above sea level, while in the southern parts, the elevations are mostly less than 500 m above sea level. Annual precipitation and potential evapotranspiration range from 50 to 1000 mm and from 800 to 3000 mm, respectively. Mean annual temperature ranges from 12 to 24 ˚C.

Parts of the selected area in Fars Province were used more than 5 months per year for irrigated paddy rice cultivation (paddy soils) and other parts were used for a variety of non-irrigated upland crops (non-paddy soils). The profiles of a paddy and a non-paddy soil within each area which had developed on calcareous parent materials, were selected in pair wise manner, and were as close as possible to each other, so as to minimize variations of parent materials between the paired profiles. Paddy fields had approximately 100 years of rice cropping history and profiles were located in the middle of each field. Profiles were dug, described and classified according to the Soil Survey Manual (Soil

Survey Staff, 1993) and Keys to Soil Taxonomy (Soil Survey Staff, 2014). The soil samples were collected from the different horizons (0–20 cm and 20–40 cm horizons) of the profiles with three replications from both horizons.

Fig.1. Location of Fars Province, southern Iran.

Laboratory Analyses

Soil samples were air-dried and passed through a 2 mm sieve. Soil pH was measured with a combined electrode in saturated soil paste using deionized water. Electrical conductivity (EC) was measured in the soil saturated extract. Organic carbon (OC) content was measured by dichromate oxidation method (Nelson and Sommers, 1996). Calcium carbonate equivalent (CCE) was determined by acid neutralization (Loppert and Suarez, 1996).Particle-size distribution (PSD) was measured by the hydrometer method (Gee and Bauder, 1986). Cation exchange capacity (CEC) was determined by saturating of soil with 1 M sodium acetate at pH 8.2 and replacing sodium by subsequent washing with 1 M ammonium acetate at pH 7 (Sumner and Miller, 1996).

Pedogenic Fe (Fe_d) was extracted by the dithionite-citrate-bicarbonate (DCB) method (Mehra and Jackson, 1960). Poorly crystalline Fe oxides Fe (Fe_o) was extracted by 0.2 M ammonium oxalate (pH 3.0) (McKeague and Day, 1966). Total Fe (Fe_t) content was quantified with a boiling 4N HNO_3 digestion (Sposito et al., 1982). Available Fe (Fe_{ex}) was extracted using DTPA (Lindsay and Norvel, 1978).The extracted Fe concentrations were determined by atomic absorption spectrophotometry (AAS). The amount of crystalline Fe oxides (Fe_{cry}) was calculated by the difference between the dithionite and the oxalate-extractable Fe ($Fe_{cry}=Fe_d–Fe_o$), (Wissing et al., 2013).

Statistics Analyses

Statistics analyses were used by SPSS package (v15). To compare the differences between paddy and non-paddy profiles, all paddy profiles were selected as one group and all non-paddy profiles as another group. In surface (0–20 cm) and subsurface (20–40 cm) soils of both groups in each area, three replications of soils from each horizon were used and analyzed by independent sample t tests.

RESULTS AND DISCUSSION

Organic Carbon Content

Organic carbon content in surface soils of paddy soils was consistently higher than that of non-paddy soils (Table 1). The average of organic carbon values in surface horizon of paddy soils was 11.41 g kg^{-1}, significantly different (p= 0.006) from the equivalent value of 8.00 g kg^{-1} in non-paddy profiles (Table 2). Also, organic carbon average of subsurface (20–40 cm)

soils of paddy soils was 7.23 g kg^{-1}, significantly different (p=0.021) from 4.79 g kg^{-1} of non-paddy soils (Table 2).

Organic carbon content of surface soils ranged from 1.34 to 15.98 and from 0.93 to 10.97 g kg^{-1} in paddy and non-paddy soils, respectively. Overall, by group comparison, paddy and non-paddy soils were significantly different in the organic carbon content in surface and subsurface soils.

Our results indicated that long-term rice cropping management (approximately 100 years) results in more organic carbon content in paddy soils (Table 1 and 2).Higher amounts of organic carbon in paddy soils are assumed to be due to higher accumulation of the surface litter, addition of rotted roots or charred material, or to the accumulation of lignin-derived compounds (Ko¨gel-Knabner et al., 2010; Wising et al., 2013).

Table 1. Some chemical and physical properties and different forms of iron of Non-paddy (NP) and Paddy soils (P).

Site	Soil	Classification	Depth (cm)	pH	Clay (%)	Silt (%)	Sand (%)	CCE (%)	CEC (cmol(c) kg^{-1})	OC (g kg^{-1})	EC (dS m^{-1})	Fe$_t$* (g kg^{-1})	Fe$_d$* (g kg^{-1})	Fe$_o$* (g kg^{-1})	Fe$_{ex}$* (mg kg^{-1})
Firouzabad 1	NP	Typic Calcixerepts	0-20	7.94	37.1	39.5	23.4	57.4	12.7	8.66	0.42	9.01	3.42	1.30	14.36
			20-40	7.85	38.2	12.6	49.2	58.9	12.5	3.85	0.57	10.72	5.42	1.06	11.09
Firouzabad 1	P	Typic Epiaquepts	0-20	7.75	39.4	47.8	12.8	54.7	14.9	11.36	0.85	13.11	2.32	1.48	37.63
			20-40	7.76	47.0	40.0	13.0	56.7	13.8	7.70	0.64	10.36	3.13	1.47	19.89
Firouzabad 2	NP	Typic Haploxerepts	0-20	7.83	23.0	32.0	45.0	70.3	10.0	10.97	0.40	8.37	5.68	0.75	4.60
			20-40	7.95	33.2	29.3	37.5	70.6	9.6	4.24	0.26	8.14	6.47	0.57	4.35
Firouzabad 2	P	Typic Epiaquepts	0-20	7.65	34.6	33.8	31.6	58.7	13.9	11.55	0.48	10.90	4.67	1.66	34.99
			20-40	7.93	37.1	29.8	33.1	57.0	13.8	6.74	0.33	7.81	5.31	1.54	29.70
Reikan	NP	Typic Haplustepts	0-20	7.87	19.3	26.7	54.0	74.5	11.3	10.78	0.40	7.44	3.18	1.08	12.34
			20-40	7.64	29.1	23.0	47.9	74.8	10.0	7.12	0.45	6.15	3.68	0.64	6.12
Reikan	P	Typic Epiaquepts	0-20	7.58	29.8	29.2	41.0	67.6	13.9	13.86	0.85	11.11	2.56	1.49	18.36
			20-40	7.60	33.5	20.1	46.4	64.9	11.3	10.40	0.43	9.97	2.79	1.09	12.03
Fathabad	NP	Typic Haplustepts	0-20	7.62	24.0	37.5	38.5	54.0	10.0	8.85	2.60	10.39	4.42	1.40	19.70
			20-40	7.43	27.4	34.0	38.6	56.0	8.8	7.51	1.24	9.95	4.92	1.26	15.11
Fathabad	P	Typic Epiaquepts	0-20	7.17	34.9	37.0	28.1	51.0	13.5	10.59	3.60	12.16	3.97	1.54	26.28
			20-40	7.32	49.0	29.9	21.1	53.0	11.3	8.66	1.86	14.44	3.91	1.39	20.50
Shaldan	NP	Typic Haplustepts	0-20	7.66	23.4	39.8	36.8	70.0	10.5	5.58	0.55	10.14	3.39	0.88	13.50
			20-40	7.60	27.4	36.6	36.0	67.4	8.8	4.04	0.85	8.58	4.72	0.72	13.17
Shaldan	P	Typic Epiaquepts	0-20	7.49	37.4	16.6	46.0	64.9	14.2	11.36	0.85	12.69	1.10	1.04	20.95
			20-40	7.53	39.4	14.6	46.0	63.4	12.0	5.58	0.79	10.29	2.32	1.23	14.16
Koshkak 1	NP	Typic Haploxerepts	0-20	7.80	50.7	31.2	18.1	47.3	15.1	10.59	0.63	13.79	5.28	2.16	21.43
			20-40	8.00	52.7	21.3	26.0	49.9	13.8	8.47	0.50	13.86	5.86	2.03	17.99
Koshkak 1	P	Typic Epiaquepts	0-20	7.37	55.9	29.1	15.0	45.3	16.4	12.13	0.93	17.13	4.08	2.50	26.67
			20-40	7.69	63.1	26.4	10.5	47.5	15.1	9.43	0.53	15.31	3.88	2.12	25.43
Koshkak 2	NP	Typic Calcixerepts	0-20	7.84	52.4	35.0	12.6	48.5	14.8	6.10	0.54	10.84	4.61	1.76	13.65
			20-40	7.91	54.0	34.0	12.0	49.2	15.0	4.80	0.40	8.75	4.81	1.50	13.31
Koshkak 2	P	Typic Epiaquepts	0-20	7.73	60.3	30.7	9.0	46.5	16.5	8.66	0.66	14.99	3.51	2.00	19.61
			20-40	7.86	57.1	32.6	10.3	50.0	15.5	6.16	0.47	10.81	3.41	1.99	19.25
Kordbal	NP	Typic Calcixerepts	0-20	8.30	44.1	40.0	15.9	51.0	15.2	4.24	3.50	10.67	5.51	1.71	8.62
			20-40	8.35	38.0	37.5	24.5	52.2	13.6	2.50	3.58	10.43	5.13	1.48	7.44
Kordbal	P	Typic Halaquepts	0-20	7.10	49.4	38.0	12.6	45.1	18.3	9.05	3.57	11.27	3.20	2.18	34.17
			20-40	7.11	49.4	37.7	12.9	45.2	18.3	8.99	3.52	11.42	3.22	2.10	17.34
Norabad 1	NP	Typic Calciustepts	0-20	7.72	40.2	44.5	15.3	59.4	16.4	4.62	1.01	8.53	4.21	1.84	13.80
			20-40	8.21	32.9	43.8	23.3	60.6	15.1	2.70	0.78	7.89	4.60	1.03	9.20
Norabad 1	P	Typic Epiaquepts	0-20	7.02	48.2	43.2	8.6	56.7	19.2	9.63	1.40	9.76	2.95	2.84	18.50
			20-40	7.55	60.9	28.5	10.6	53.7	18.3	3.85	0.85	8.17	3.15	1.73	14.93
Norabad 2	NP	Typic Haplustepts	0-20	7.92	40.6	49.9	9.5	56.0	17.8	9.63	0.93	10.06	5.81	2.10	11.16
			20-40	8.08	40.4	44.6	15.0	59.4	15.1	2.70	0.34	9.47	6.21	1.20	9.69
Norabad 2	P	Typic Epiaqualfs	0-20	7.35	44.2	44.5	11.3	55.2	19.2	15.98	2.17	11.44	4.11	3.52	19.38
	NP		20-40	7.22	48.1	42.6	9.3	57.4	17.8	4.81	0.78	9.79	4.40	2.81	11.99

*Fe$_t$=total Fe, Fe$_d$= pedogenic Fe, Fe$_o$=poorly crystalline Fe oxides, Fe$_{ex}$=available Fe

Table 2. Group comparison between non-paddy (NP) and paddy (P) profiles on selected properties (averaged surface (0–20 cm) and subsurface (20–40 cm) soils)

Soil properties	Soil	Surface (0–20 cm) soils		Subsurface (20–40 cm) soils	
		Mean	Significant level	Mean	Significant level
Organic carbon(OC) (g kg^{-1})	NP	8.00	0.006	4.79	0.021
	P	11.41		7.23	
Clay content (%)	NP	35.4	0.128	37.3	0.020
	P	43.4		48.4	
Silt content (%)	NP	37.6	0.477	31.6	0.736
	P	34.9		30.2	
Sand content (%)	NP	26.9	0.430	31.0	0.138
	P	21.6		21.3	
pH	NP	7.85	0.001	7.90	0.012
	P	7.42		7.55	
Electrical conductivity(EC) (dS m^{-1})	NP	1.09	0.394	0.89	0.782
	P	1.53		1.01	
Calcium carbonate equivalent(CCE) (%)	NP	58.8	0.291	59.9	0.158
	P	54.5		54.8	
Cation exchange capacity (CEC) (cmol(c) kg^{-1})	NP	13.40	0.035	12.25	0.056
	P	16.0		14.72	
Total Fe(Fe$_t$) (g kg^{-1})	NP	9.92	0.010	9.39	0.167
	P	12.45		10.83	
pedogenic Fe(Fe$_d$) (g kg^{-1})	NP	4.55	0.011	5.18	0.000
	P	3.24		3.55	
poorly crystalline Fe(Fe$_o$) (g kg^{-1})	NP	1.50	0.080	1.15	0.013
	P	2.03		1.75	
Available Fe (Fe$_{ex}$) (mg kg^{-1})	NP	13.32	0.000	10.75	0.003
	P	25.65		18.52	
Fe$_o$/Fe$_d$	NP	0.33	0.001	0.22	0.000
	P	0.66		0.50	
Fe$_d$/Fe$_t$	NP	0.46	0.000	0.56	0.001
	P	0.26		0.34	
crystalline Fe(Fe$_{cry}$) (g kg^{-1})	NP	3.04	0.000	4.02	0.000
	P	1.21		1.80	

Cheng et al. (2009) and Sahrawat (2004) showed positive effects of rice cultivation on topsoil organic carbon accumulation. Sahrawat (2004) indicated that both the high input of organic materials and the retarded decomposition rates under anaerobic conditions contribute to the organic carbon accumulation in paddy soils. Cheng et al. (2009) showed that 50 years of rice cultivation resulted in significant higher organic carbon content in paddy topsoil horizons than that in non-paddy. Wissing et al. (2011) demonstrated that the organic carbon accumulation in bulk soils was dominated by the silt and clay-sized fractions. Our results were also in accordance with Wu (2011), whose data indicated higher OC concentrations and stocks in paddy soils compared to other arable ecosystems.

Also Hanke et al. (2013); and Wissing et al. (2013, 2014) have studied mechanisms responsible for long-term accumulation of organic carbon. Hanke et al. (2013) assessed the redox control on organic carbon mineralization and dissolved organic matter dynamics across long term rice cultivation and demonstrated that organic carbon accumulation in paddy soils resulted from a microbial community well adapted to anoxic condition that has a low efficiency in mineralizing organic carbon during transient oxic states. Wissing et al. (2013, 2014) investigated organic carbon accumulation in organo-mineral associations during the long-term development of soils under wet paddy cultivation in comparison to non-irrigated cropping systems. Results of Wising et al. (2013, 2014) showed that paddy soils were characterized by an accelerated decalcification, higher contents of organic carbon and Fe oxides, and higher organic carbon coverage on mineral surfaces as compared with non-paddy soils. In addition, Fe oxides and organic matter in paddy soils seemed to protect each other in organo-mineral associations primarily in the fine clay-sized fraction as indicated by the selective removal of organic matter or Fe oxides (Wissing et al., 2013).

Clay Content and Soil Texture

As for clay content, our results suggest that paddy management favors clay accumulations, particularly in layers bellow 20 cm depth, as the average of clay content in surface (0–20 cm) and subsurface (20–40 cm) soils of paddy profiles as a group is statistically higher than that of non-paddy profiles (Table 1 and 2).

Average of clay content in surface (0–20 cm) soils of paddy soils (43.4%) was higher than non-paddy soils (35.4%), but difference between them was not significant (p=0.128), (Table 2). Also clay proportion in subsurface (20–40 cm) soils was significantly higher (p= 0.020) in paddy (48.4%) compared to non-paddy soil (37.3%). However, the cultivated paddy soils with

long paddy cultivation history had much higher clay content in subsurface than surface soils.

Paddy soils has 30-65% (Mean value =46%) clay in the upper solum (until 40 cm below surface), which is due to artificial accumulation of dredged fine materials on the surface. The irrigation water flowing from paddy fields contains 1.5-1.7 g L^{-1} of suspended material, which is richer in clay and fine particles (mainly smaller than 0.05 mm in average diameter) than the bulk soil (Zhang and Gong, 1998). Deposition of suspended material from irrigation water (generally fine particles) and mechanical leaching probably favors clay accumulations and differentiation. Theses process could result heavier texture in surface (0–20 cm) and subsurface (20–40 cm) soils of paddy soils. Earlier studies have showed that, in paddy soils, ploughing, puddling, flooding, and drainage could cause downward and more obviously lateral mechanical movement of soil particles (Gong, 1986). Average of silt and sand content in surface (0–20 cm) soils of all paddy profiles was 34.9 and 21.6%, not significantly different with 37.6 and 26.9%, in non-paddy profiles, respectively. Also silt and sand content in subsurface (20–40 cm) soils of all paddy and non-paddy profile was not significantly different (Table 2).

Soil pH

Soil pH is probably the most important chemical soil parameter; it reflects the overall chemical status of the soil and influences a whole range of chemical and biological processes occurring in the soil (Jaillard et al., 2003). Because of its implications in most chemical reactions in the soil, knowing the actual value of soil pH and monitoring its changes is critical for understanding the physicochemical functioning of the soil (Jaillard et al., 2003). Average of pH in surface (0–20 cm) soils was significantly lower (p= 0.001) in paddy (7.42) compared to non-paddy soils (7.85). Pairwise comparison between subsurface (20–40 cm) soils of paddy and non-paddy soils revealed that they were significantly different (p= 0.012). The pH values in subsurface (20–40 cm) soils of paddy and non-paddy soils were 7.55 and 7.90 (Table 2).

Soil reduction is accompanied by changes in the pH. The pH values of non-paddy bulk soils were neutral to alkaline and decreased significantly after water logging and continuous rice cultivation (Kirk, 2004). The pH values remained above 7 as long as carbonates were present. Without carbonates most paddy topsoils were in the range of pH 5–7. After soil waterlogging, the pH tends to converge to neutrality irrespective of initial pH, whether acidic or alkaline (Ponnamperuma, 1972; Kirk, 2004). After submergence, pH of alkaline-calcareous soils decreased initially and remained almost constant. Following submergence, CO_2 formed in respiration, escapes from the soil only very slowly, and it therefore accumulates. As CO_2 continues to accumulate during anaerobic respiration and fermentation, large partial pressures develop, typically in the range of 5 to 20 kPa.

The accumulation of CO_2 lowers the pH of alkaline soils (Kirk, 2004).

Soil EC

Salinity is the major nutritional constraint on the growth of wetland rice, because rice is more sensitive to salinity. Therefore, the monitoring of soil solution salinity is important for sustainable production of rice (Marschner, 1995). The electrical conductivity of saturation extracts tended to be Higher in paddy as compare to non-paddy soils, but showed same patterns with depth for paddy and non-paddy soils. Mean value of EC in surface (0–20 cm) soils of non-paddy and paddy profiles were 1.09 and 1.53 dS m^{-1}, respectively (Table 2). Also Average of EC in subsurface (20–40 cm) soils of paddy profiles (1.01) was higher than non-paddy soil (0.89), (Table 2). No significant (in surface and subsurface soils) were observed between paddy and non-paddy soils (Table 2). Narteh and Sahrawat (1999) found that the soil solution electrical conductivity (EC) increased initially after submergence and then decreased. The specific conductance of the solutions of most soils increases after submergence, attains a maximum, and declines to a fairly stable value, which varies with the soil. The changes in conductance reflect the balance between reactions that produce ions and those that inactivate them or replace them with slower moving ions (Ponnamperuma, 1978). The increase in conductance during the first few weeks of flooding is due to the release of Fe^{+2} and Mn^{+2} from the insoluble Fe^{+3} and Mn^{+4} oxide hydrates, the accumulation of NH_4^+, HCO_3^-, and $RCOO^-$ and (in calcareous soils) the dissolution of $CaCO_3$ by CO_2 and organic acids. An additional factor is the displacement of ions, especially cations, from soil. The decrease in conductance of calcareous soils (non-paddy) is caused by the fall in partial pressure of CO_2 and the decomposition of organic acids (Ponnamperuma, 1978).

Calcium Carbonate Equivalent (CCE)

The mean value of calcium carbonate equivalent (CCE) in surface (0–20 cm) soils of the uncultivated and rice cultivated fields was 58.8 and 54.5% respectively and difference between them was not significant (p=0.291), (Table 2). Also average of CCE in subsurface (20–40 cm) soils of non-paddy and paddy profiles was 59.9 and 54.8 and difference between them was not significant (p=0.158), (Table 2). Our results showed that rice cultivation resulted in increase of decalcification in the surface and subsurface soils compared to the non-paddy soils; although differences between them were not significant. However loss of calcium carbonate in surface soils of rice fields was more and faster than non-paddy fileds, but decalcification in the subsurface soil also were slightly accelerated.

Kalbitz et al. (2013) indicated that paddy management increased decalcification compared to the non-paddy agricultural use.

With increasing paddy cultivation age, CCE content decreases gradually, because the leaching loss of $CaCO_3$

in the calcareous soil increased with increasing cultivation age due to the artificial periodic irrigation and drainage in rice planting system. High partial pressure of CO_2 in the soil during periods of waterlogging may be considered to favor $CaCO_3$ dissolution (Van den Berg and Loch, 2000). The increased accumulation of organic matter and thereby ammonium in the water layer under paddy management in promote acidification due to higher acid production during the dry cropping phase. A larger input of nitrogen fertilizer to paddy soils may additionally contribute to a more intensive production of protons after ammonia oxidation and dissolution of carbonates (Gandois et al., 2011). Wissing et al. (2011) showed that flooding and discharge lead to a gradual carbonate loss and subsequent pH decrease during rice cultivation. Thus, they resulted that pedogenesis of paddy soils differs remarkably from that of corresponding non-inundated croplands, where decalcification is much slower and faster decalcification caused by the paddy management accelerates other pedogenic processes.

Cation Exchange Capacity (CEC)

The averaged CEC in surface (0–20 cm) soils of all paddy profiles was 16.0 $cmol_c$ kg^{-1}, significantly higher than (p=0.035) with the equivalent value of 13.4 $cmol_c$ kg^{-1} in non-paddy profiles (Table 2). Averaged of CEC in subsurface (20–40 cm) soils of paddy profiles was 14.72 $cmol_c$ kg^{-1}, and it was not significantly different (p=0.056) with non-paddy profiles (12.25 $cmol_c$ kg^{-1}), (Table 2).

Higher portion of clay content and organic matter and clays with higher CEC (specially smectite, data not shown) cause increase CEC in paddy soil compared to non-paddy soils. This higher concentration of smectite is reflected in the relative high CEC value of the clay fractions. Also reduction of structural Fe causes a net increase in the negative surface charge on the clay, resulting in increased CEC (Stucki et al., 1997). Further, in soils that undergo intermittent reduction and oxidation, a large part of the easily reducible Fe is present as coatings of oxy hydroxides on clay surfaces and these are dissolved during soil reduction. Where positively charged oxy hydroxides neutralize negatively charged sites on the clay, dissolution of the coatings will cause the net surface negative charge and hence CEC to increase (Kirk, 2004).

Iron Fractions

Average of total Fe in surface (0–20 cm) soils of paddy profiles were 12.45 g kg^{-1}, it was significantly different (p= 0.010) with 9.92 g kg^{-1} in non-paddy profiles (Table 2). Total Fe concentration in subsurface (20–40 cm) soils was similar to that of total Fe in surface soils. It was higher in all paddy profiles (mean value =10.83 g kg^{-1}) compared to non-paddy profiles (mean value=9.39g kg^{-1}) but difference between them was not significant (p= 0.167).

DTPA extract available form of iron (Fe_{ex}). The Fe_{ex} values in surface soils (mean value=25.65 mg kg^{-1}) and subsurface soils (mean value=18.52 mg kg^{-1}) of paddy soils were significantly higher (p=0.000) compared to non-paddy soils (Table 2). Iron, which is released from primary minerals during weathering, is present as Fe^{3+} under aerobic conditions. Ferric iron (Fe^{3+}) is almost entirely insoluble and therefore essentially immobile by convection or mass flow. Iron can move with the soil solution and available for plant when Fe^{3+} (ferric iron) is reduced to Fe^{2+} (ferrous iron) under anaerobic conditions (Carta et al., 2009).

The DCB dissolves crystalline forms of Fe oxides (e.g. goethite or hematite) and amorphous forms (poorly crystalline) of Fe oxide (mainly ferrihydrite) (Mehra and Jackson, 1960). Pairwise comparison between the paddy and non-paddy soils revealed that Fe_d concentrations showed significant difference in surface and subsurface soils (Table 2 and Fig. 2). Averaged Fe_d concentrations in surface and subsurface soils of all paddy profiles were 3.24 and 3.55 g kg^{-1}, significantly lower (p=0.011 and p=0.000) than 4.55 and 5.18 g kg^{-1} in non-paddy profiles respectively (Table 2). The Fe_d concentration in surface soils of paddy profiles varied from 2.32 to 5.30 g kg^{-1} and in non-paddy profiles from 3.68 to 6.47 g kg^{-1} and in subsurface soils varied from 1.10 to 4.66 g kg^{-1} and 3.18 to 5.81 g kg^{-1} in paddy and non-paddy profiles, respectively. It can be observed that rice cultivation has caused a significant decrease of Fe_d throughout the profile and obvious profile differentiation.

The depth distributions of Fe_d in paddy soils suggest a gradual illuviation of Fe_d by rice cultivation, as the Fe_d is slightly less in surface soils and slightly higher in the subsurface. The decrease of Fe_d is attributed to reduction and mobilization when artificially submerged, and increases in the subsoil result from the leaching and mobilization when artificially re-precipitation of iron. For paddy soils, the change of soil moisture regime from that in the original soils is very critical for the transformation of iron and manganese minerals (Yu, 1985). The long-term rice cultivation has caused an obvious decline of Fe_d throughout the profile and its differentiation between horizons is also obvious. Zhang and Gong (2003) reported that the decrease of Fe_d content in the paddy soil profile is more pronounced as the period of rice cultivation increases. Artificial flooding reduces iron minerals and mobilizes the iron as ferrous ions. Subsequent drainage and re-oxidation leads to re-precipitation of iron as cutans, mottles, concretions, or nodules. This cycle causes rapid differentiation of iron and manganese distributions, especially when the surface saturation is artificial. Various processes contribute to the loss of iron and other elements in paddy cultivation, including illuviation, reduction and dissolution chelation, and ferrolysis (Zhang and Gong, 2003).

Oxalate-extractable Fe (Fe_o) represents poorly crystalline Fe oxides which are nowadays denoted as short-range-ordered oxides. Ferrihydrite ($Fe_5HO_8 \cdot 4H_2O$) is the most prominent poorly crystalline Fe oxides phase (Carta et al., 2009). Paddy soils are characterized by higher Fe_o concentrations (Fig. 2), ranging from 1.04 to

3.52 g kg^{-1} (mean value =2.03) in surface soils and 1.09 to 2.81 g kg^{-1} (mean value =1.75) in subsurface soils. Statistical analyses showed that the Fe_o values in subsurface of paddy soils significantly increased while in surface soils were not significant (p=0.013 and p=0.080, respectively) (Table 2). Average of Fe_o concentrations in surface soils and subsurface soils of non-paddy profiles were 1.50 and 1.15 g kg^{-1}, ranging from 0.75 to 2.16 g kg^{-1} and 0.57 to 2.03 g kg^{-1}, respectively (Table 2). The higher Fe_o proportion in paddy soils is associated with higher OC concentrations compared to the non-paddy soils. In contrast, the non-paddy soils have lower proportions of Fe_o, resulting in lower OC concentrations. Oxalate extractable Fe oxides (e.g., ferrihydrite) are known to have a large mineral surface (Wagai and Mayer, 2007). Because of the higher Fe_o content, the potential to accumulate OC is more pronounced in paddy soils compared to soils from the same parent material but under non-paddy management. Correlations of OC with Fe_o have already been

identified as a relevant feature in paddy soils (Pan et al., 2003).

The ratio of Fe_o/Fe_d in soils reflects the different pedogenic environments, such as redox conditions, presence of organic ligands, soil forming age, and weathering degree (Wissing et al., 2013). Our data showed lower ratios of Fe_o/Fe_d (Table 2 and Fig. 2) in non-paddy soils, indicating significantly higher crystallinity compared to corresponding paddy soils. The paddy management induces the preferred formation of Fe_o in early stages of soil development, leading to a higher ratio of Fe_o/Fe_d (Fig. 2). The ratios of Fe_o/Fe_d in surface soils of non-paddy and paddy soil varied from 0.13 to 0.43 (mean value=0.33) and 0.35 to 0.96 (mean value=0.66), respectively (Table 2). Dryland soils had the lower Fe_o/Fe_d ratio values, indicating the dominance of crystalline iron oxides (hematite and goethite), (Table 2 and Fig. 2).
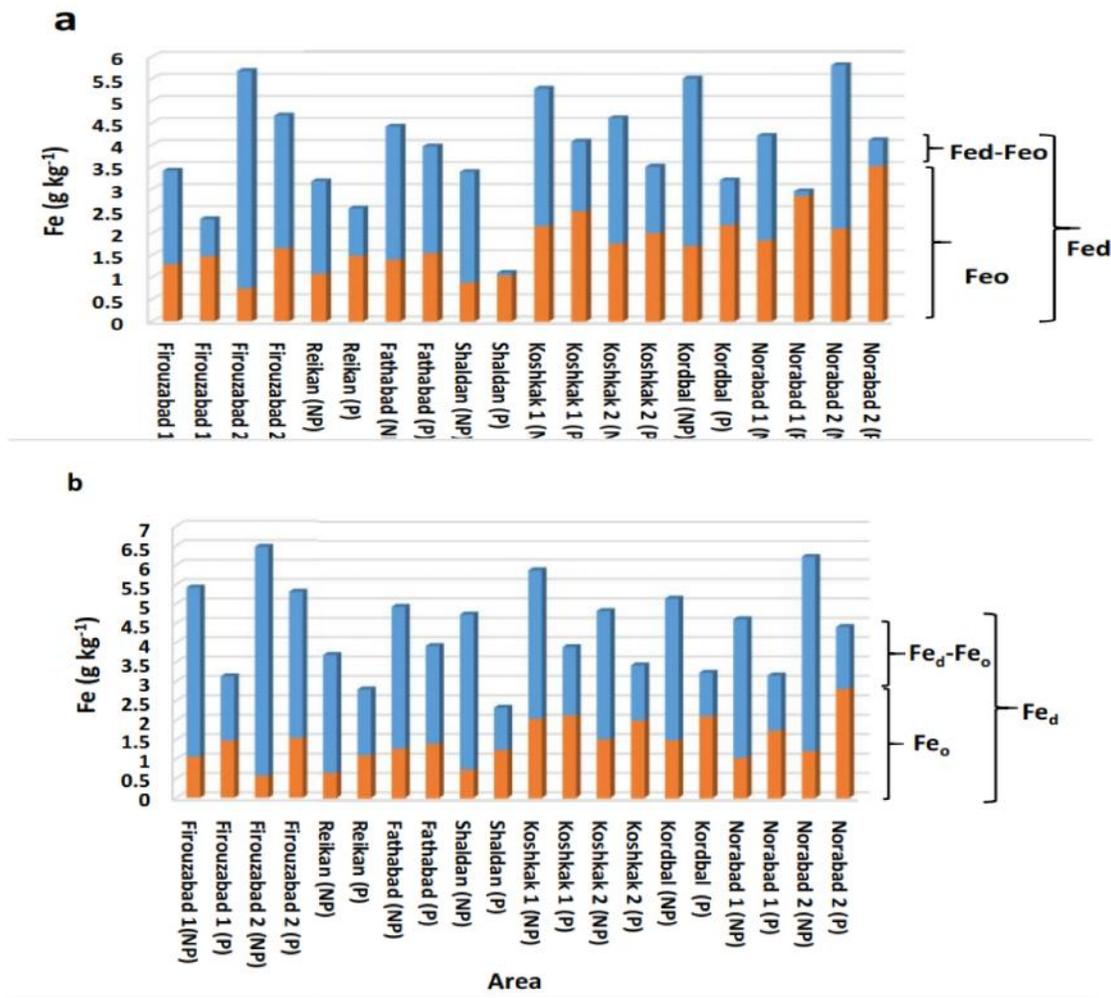

Fig. 2. Pedogenic Fe (Fe_d), poorly crystalline Fe (Fe_o) and crystalline Fe oxides (Fe_{cry}), ($Fe_{cry}=Fe_d–Fe_o$) in surface (a) and subsurface (b) soils of paddy (P) and non-paddy (NP) soils.

Results showed that paddy profiles had significant lower (p=0.000) content of crystalline Fe oxides (Fe_d-Fe_o) compared to the associated non-paddy profiles in surface and subsurface soils (Table 2 and Fig. 2). The management of the paddy soils creates an environment of Fe oxide formation which was different to those in non-paddy soils (Fig. 2). Zhang et al. (2003) reported that the paddy management led to a decreased crystallinity of soil Fe oxides, because crystalline Fe oxides can be transformed to poorly crystalline forms when artificially submerged. Fe_o oxides in non-paddy soils are formed by dissolution and precipitation reactions involving soil minerals and become more crystalline over time (Schwertmann and Taylor, 1989).

Under waterlogging condition, iron oxides are reduced to Fe^{2+} and leached downward. Fe^{2+} is rapidly oxidized in re-oxidation state and precipitated as ferrihydrite. Ferrihydrite is a short-range-ordered phase having nanometric dimensions, usually around 2–6 nm (Carta et al., 2009). It is assumed that ferrihydrite is often the first phase to form in soils, especially at rapid oxidative precipitation. Under oxidizing conditions metastable ferrihydrite is gradually transformed to more thermodynamically stable and crystalline phases like goethite or hematite. However, the presence of organic matter in soils effectively prevents the conversion of ferrihydrite to the more crystalline forms (Jones et al., 2009). Higher content of organic matter at surface soils may prevent the crystallization of iron oxides

Zhang et al. (2003) reported in incubation experiments the transformation to higher Fe_o proportions after soil flooding, resulting in a gradual reduction of the ratio of Fe_o to Fe_d with time. They also found a higher ratio of Fe_o/Fe_d with ongoing paddy soil management and higher OC contents with longer paddy rice cultivation. Soils with high OC content contain more organic acids, which may have an inhibitory effect on crystallization and lead to retardation of Fe oxide crystallization (Schwertmann et al., 1982).

The ratio of Fe_d/Fe_t in the pedons further illustrates changes in the iron oxides. Results showed that in all pedons, ratio decreased with rice cultivation, which suggests the simultaneous loss of Fe_d and the primary iron (silicate iron). The ratio of Fe_d/Fe_t in surface soils of non-paddy profiles (mean value=0.46) was higher significantly (p=0.000) than paddy soils (mean value=0.26) (Table 2). However, Fe_d/Fe_t for paddy soils is not much lower and the ratio may be higher in the subsoil of old paddy soils, which have formed a hydragric horizon. Differences of either Fe_d/Fe_t in the paddy profiles were small, which was explained by the relatively short periods of rice-cultivation.

CONCLUSIONS

Investigation of paddy and non-paddy soils evolution, derived from the same calcareous parent materials, showed specific management induced differences in surface (0–20 cm) and subsurface (20–40 cm) soils. Direct comparison of paddy soils with non-flooded soils indicated that under wetland rice cultivation, soil formation was faster. Results revealed that paddy soil management led to decrease of calcium carbonate, due to frequent flooding (although decreasing of CCE was not significant), and larger OC accumulation. This is supported by the reduced OM decomposition due to the periodically soil flooding, the paddy-specific composition of Fe oxides and the accessibility of the soil mineral surfaces for OC covering due to the enhancement of decalcification. It is concluded that long term rice cultivation significantly increases the available Fe value, clay portion, total Fe content, and electrical conductivity as compared with dryland profiles, but significantly decreased soil pH and shifted toward neutrality. Clay accumulations, particularly in subsurface (20–40 cm) soils, could result in heavier texture in paddy soils. Higher content of clay content and organic matter and clays with higher CEC (specially smectite) caused increase CEC in paddy soil as compared to non-paddy soils. Long-term rice cultivation tended to result in more diversified horizons of paddy profiles, whereas non-paddy cultivation did not have this effect. The poorly crystalline forms of Fe oxides in paddy soils were more and paddy profiles had significant lower contents of crystalline Fe oxides in surface and subsurface soils. This was in contrast to non-paddy soils, which had a different regime of Fe oxide formation, characterized by higher proportions of crystalline Fe oxides.

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مقایسه ویژگی‌های پدوژنیکی برخی خاک‌های شالیزار و غیر شالیزار جنوب ایران

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چکیده– خاک های شالیزاری جزء بیشترین اراضی غرقابی ساخته دست بشر می باشند. تحقیق حاضر با هدف بررسی تشکیل و تکامل خاک‌های شالیزاری تحت کشت طولانی مدت برنج در مقایسه با خاک‌های غیرشالیزاری و بکر و مطالعه اثر شرایط غرقابی بر این خاک ها انجام شد. نمونه‌های خاک از خاک‌های شالیزار و غیرشالیزار با مواد مادری آهکی مشابه، برداشته شد. برخی ویژگی‌های پدوژنیکی مانند کربن آلی، مقدار رس، شکل‌های مختلف آهن، پ هاش، قابلیت هدایت الکتریکی، و ظرفیت تبادل کاتیونی، اندازه‌گیری شدند. نتایج نشان داد که غرقاب شدن تأثیر زیادی بر تشکیل خاک داشت. تحت شرایط کشت برنج غرقاب، پویایی و تحول خاک‌های شالیزاری سریع تر شده؛ که منجر به تسریع تشکیل خاک‌ها در این مناطق می شود. تجمع کربن آلی در افق های سطحی خاک (۲۰ـ ۰ سانتی متری)، تسریع فرایند آهک زدایی، و افزایش معنی‌دار مقدار رس، آهن قابل استفاده، ظرفیت تبادل کاتیونی، آهن کل، قابلیت هدایت الکتریکی، اکسیدهای آهن با تبلور کم (بی شکل)، و کاهش معنی‌دار پ هاش خاک، آهن پدوژنیک، اکسیدهای آهن متبلور، فرایندهای بارز در تشکیل خاک‌های اراضی شالیزاری مطالعه شده بودند.