academicJournals

Vol. 8(18), pp. 1975 -1982, 16 May, 2013
DOI: 10.5897/AJAR10.849
ISSN 1991-637X ©2013 Academic Journals
http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

The effect of toposequence on physical and chemical characteristics of paddy soils of Guilan Province, Northern Iran, Rasht

Javad Seyedmohammadi Meresht

Department of Soil Science, Faculty of Agricultural Sciences, University of Guilan, Rasht 41635-1314, Iran.

Accepted 26 November, 2010

Paddy soils are important in Guilan province because they are the base of agriculture. So, it is necessary to recognize and analyse paddy soils for understanding of their limitations and optimum using. Sefidrood plateaus and upper terraces, river alluvial plain, lowland and Caspian sea coastal plain physiographic units in a toposequence in Sangar Dam uplands in adjacent of Rasht city to Caspian sea shore were recognized. Five profiles were studied on each physiographic unit, which one of them was selected in order to detail study as reference profile. Physical and chemical characteristics of paddy soils formed on mentioned physiographic units were studied by providing disturbed soil samples from the horizons of described soils. Results showed that soil structure was weak granular in all surface horizons and single grain in the subsurface horizons of the Coastal plain. Soil structure was subangular blocky and angular blocky in the subsurface horizons of other units. Organic matter was high in surface horizons because of accumulation of rice residues. Organic mater was the highest level in lowland due to high ground water table and lower decomposition rate. Cation exchange capacity (CEC) was high in lowland and alluvial plain due to high organic matter and clay content in soils. Clay particles in plateaus lands were lower than other units because of alteration, suitable aeration and occurrence of ferrolysis. Electrical conductivity was high in subsurface horizons of lowlands and coastal plain because of high ground water table. Exchangeable Na+ was high in subsurface horizons of coastal plain and lowlands due to sea water seepage from depth in these soils. Soil reaction was nearly neutral because of natural and artificial submerged effect.

Key words: Chemical properties, Guilan, paddy soils, physical properties, puddling.

INTRODUCTION

The study of soils evolution is very important due to study of soil processes. Rice is the staple food of approximately one-half of the world's populations. Much of the paddy is grown and consumed in Asia. Paddy is usually grown by transplanting seedlings under flooded conditions (Abubakar et al., 2010). Electrical conductivity of paddy soils was high in lowlands with respect to uplands. It was probably related to presence of Fe^{2+} and Mn^{2+} ions that were released from their oxide form reduction (Golsefidi, 2001; Goto et al., 2003). The puddling of paddy soils is the most common method of rice cultivation in these soils and results in a complete distortion of the soil structure of the puddled layer and the formation of a distinct plough pan (Eickhorst and Tippkotter, 2009). Plough pan layer was formed because of puddling and mobility of agricultural machines (Bockari et al., 2004; Abubakar et al., 2010). This layer was caused that water and nutrition elements were protected in root region for rice plant

E-mail: Javad58_sey@yahoo.com. Tel: +989366554266.

(Kirchhof et al., 2000; McDonald et al., 2006). Puddling damages soil structure in plough layer of paddy soils and decreases pores and voids in this layer (Hassannezhad et al., 2008). Soil organic carbon has an important role in improving soil quality and sustainable production. Continuous compost application increased the total soil organic carbon concentration in plough layers and improved paddy soil physical properties (Lee et al., 2009).

High concentrations of dissolved organic matter during flooding seasons enhance the changes and the release of structural iron in clay minerals, and support the formation of ferrihydrite. Repeated redox alternations lead to a translocation of iron in various directions, and particularly increase the crystallinity of iron oxides. The large accumulation of soil organic matter observed in paddy soils due to high input of plant residues associated with retarded decomposition under anaerobic conditions. Soil organic matter accumulation in paddy subsoils can be explained by downward movement of dissolved organic matter and its stabilisation by interaction with iron oxides (Kogel-Knabner et al., 2010). Organic materials decrease exponentially with increasing in depth in paddy soils (Pan et al., 2008).

Soils on an older delta (coastal plain) are more strongly developed and showed a decrease of dithionite citrate bicarbonate extractable iron in surface horizon of young paddy soils and more profoundly throughout the profile in old paddy soils. In the polder area (poorly drained), the apparent lowering of groundwater table by deposition of sediment has changed the soil hydrology and increased redox potential. With the better soil aeration, crystalline iron oxides and their ratio to total iron increase with cultivation age. On well-drained terraces (uplands), the change of soil moisture regime is overwhelming. Previously well-aerated upland soils are periodically reduced, which accelerates leaching and loss of iron oxides from surface horizons, and probably clay decrease by lateral movement and ferrolysis processes. An iron-enriched subsurface horizon has formed rapidly and it is a diagnostic feature of this type of paddy soil (Zhang and Gong, 2003).

The objective of this study was to determine the effect of toposequence, high ground water table and its alternative fluctuation on physicochemical characteristics of paddy soils in Northern Iran.

MATERIALS AND METHODS

Study area

The study area (at the east of Rasht city) is located between 49°, 31' to 49°, 45' E longitude and 37°, 7' to 37°, 27' N latitude in North of Guilan Province, Northern Iran, in the southern coast of the Caspian sea with different water table depth. The climate of the region is very humid with the mean annual precipitation of 1293.6 mm. The mean annual temperature is also 15.8°C. The soil moisture and temperature regimes of the region are Aquic, Udic and Thermic, respectively. The parent materials are derived from river sediments.

Field work

This study was accomplished from September 2003 to September 2006. Physiographic units were distinguished and separated on aerial photographs including, Sefidrood plateaus and upper terraces, river alluvial plain, lowland and Caspian sea coastal plain physiographic units (Figure 1). Five pedons on each physiographic unit were selected and sampled according to genetic horizons when the fields were drained after rice harvest, which one of them was selected in order to detail study as reference profile. Soil samples described (Soil Survey Staff, 1993) and soil horizons of studied profiles distinguished according to Keys to Soil Taxonomy including, Apg (gley ochric horizon), ABg (gley ochric horizon), Bg (gley cambic horizon), Bw (cambic horizon), BCg (subsurface horizon) then soil profiles classified, according to Keys to Soil Taxonomy (Soil Survey Staff, 2010).

Physicochemical analysis

Air-dried soil samples were crushed and passed through a 2 mm sieve. Particle-size distribution was determined after samples were dispersed using sodium hexametaphosphate for determination of sand, silt and clay fractions by hydrometric method (Klute, 1986). Organic carbon was determined by Walkley-Black method (Page et al., 1982). Bulk and particle density were measured by praphine and piknometer methods, respectively (Burt, 2004). pH in aqueous suspensions and 0.01 M $CaCl_2$, cation exchange capacity (CEC) was determined using sodium acetate (NaOAc) at a pH of 8.2, electrical conductivity (EC) of the saturated extract, exchangeable basic cations including Ca^{2+}, Mg^{2+} by titration method, exchangeable basic cations such as Na^+, K^+ by Flame photometry method, base saturation percentage was determined using of CEC and basic cations, total iron oxides using dithionite citrate bicarbonate method, amorphous iron was measured by ammonium oxalate method (Burt, 2004).

RESULTS AND DISCUSSION

Soil representative profiles description and some morphological characteristics and classification of soils are reported in Table 1. Physical and chemical properties of representative profiles are reported in Table 2. Bulk density was low in all pedons surface horizons (Table 2). It was increased with depth increasing in profile (Table 2) due to compaction as a result of agricultural machines mobility (Ghildyal, 1978; McDonald et al., 2006). Plough pan layer was observed in low part of plow layers in all pedons and its thickness was between 3 to 5 cm. plough pan layer was formed due to puddling and clay particle sedimentation in pores and mobility of agricultural machines in these soils (Jia-fang and Shi-ye, 1981; Bockari et al., 2004; Eickhorst and Tippkotter, 2009; Abubakar et al., 2010). This layer prevents from leaching of nutrition elements and protects aquatic condition for rice plant in plow horizon due to high compaction and finally causes high rice yield (De Datta and Kerim, 1974; Kirchhof et al., 2000; McDonald et al., 2006). Soil structure was granular in surface horizons (Table 1).

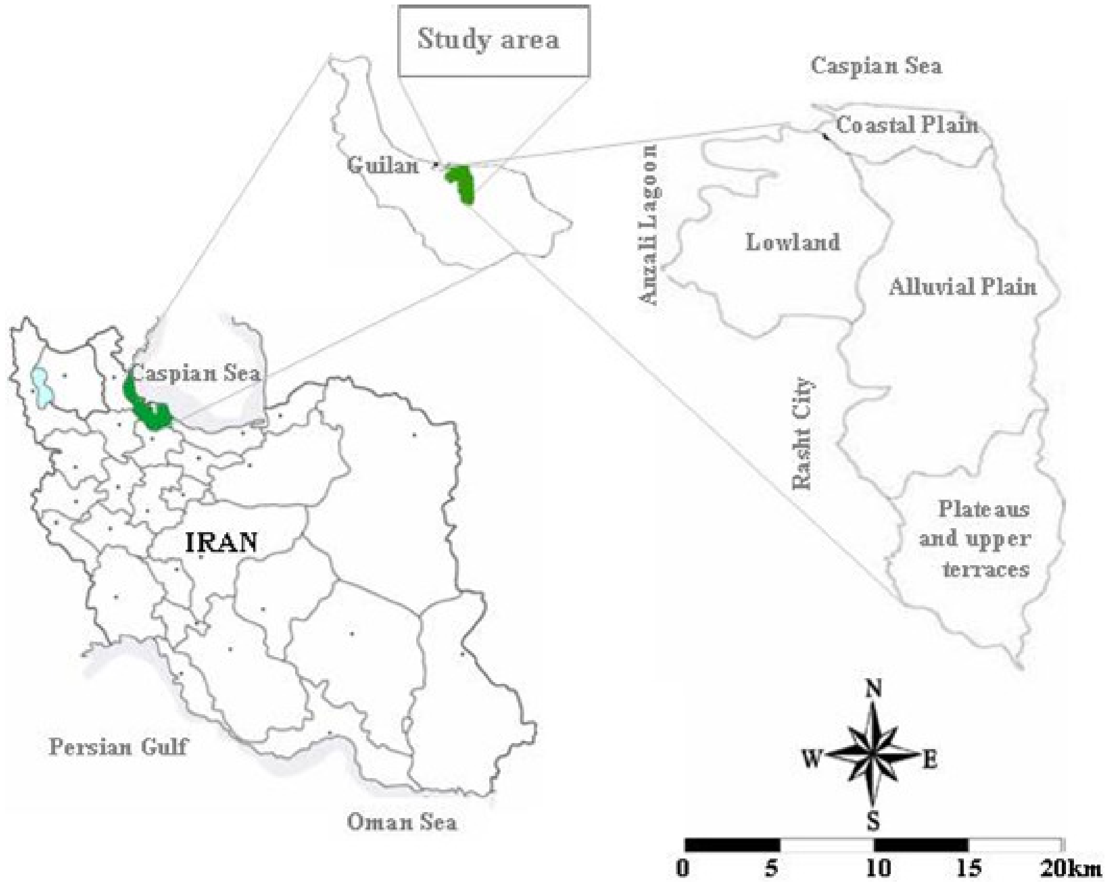

Figure 1. Location of study area in northern Iran.

This structure was formed after several months from puddling due to accumulation of organic matter that is produced from rice residues and presence of high clay content and oxides in these soils (Tarasawa 1975; Golsefidi, 2001; Hassannezhad et al., 2008). Soil structure was single grain in the subsurface horizons of the Coastal plain as well as subangular blocky and angular blocky in the subsurface horizons of other units (Table 1). The reason of abovementioned structures in subsurface horizons of plateaus and upper terraces, alluvial plain and lowland is the accumulation of organic mater (Hassannezhad et al., 2008). The large accumulation of soil organic matter observed in paddy soils surface horizons of all physiographic units (Table 2) due to high input of rice plant residues associated with retarded decomposition under anaerobic conditions (Kogel-Knabner et al., 2010). Organic carbon had the highest level in lowland with respect to other units (Table 2) because of retarded decomposition in submerged conditions.

High concentrations of dissolved organic matter during flooding seasons enhance the changes and the release of structural iron in clay minerals. Repeated redox alternations lead to a translocation of iron in various directions, and particularly increase the crystallinity of iron oxides in plateaus and upper terraces soils (uplands) (Kogel-Knabner et al., 2010). Presence of high organic matter level and reduction conditions was resulted in iron oxides reduction in plow horizon and formation of Fe^{2+} ion. This form of iron was leached due to high mobility in coastal plain soils (Table 2). Fe^{2+} associated with organic matter were caused occurrence of ferrolysis process and finally, clays were deteriorated by this process in plateaus lands (uplands) (Prihar et al., 1985; Zhang and Gong, 2003; Hassannezhad et al., 2008).

Clay content was high in alluvial plain and lowland (Table 2) but clay film was not observed in studied soils because of high ground water table, its alternative fluctuation and dry-wet alternation (Nettleton et al., 1969; Prakongkep et al., 2007). Soil reaction (pH) was neutral in these soils (Table 2) due to submerged conditions (Ponnamperuma, 1972, 1978; Goto et al., 2003).

Iron was high in plateaus and upper terraces lands (Table 2) because of weathering and suitable aeration. Fe^{2+} was released from minerals and according to ferrolysis process, associated with organic matter was caused that clays were deteriorated. Finally, clay content decreased in plateaus lands. Iron was lower in lowland

Table 1. Morphology properties and classification of soils

Horizon	Depth (cm)	Horizon boundary	Moisture matrix color	Texture	Structure	Voids	Root	Soil consistence (wet)	lime	Redox features
Representative profile of plateaus and upper terraces (Coarse-loamy, mixed, active, thermic Typic Eutrudepts)										
Apg	0-15	aw	10YR4/2	Sic	P. 2fgr S. 1fgr	3vf	2f	vs/vp	e	F1D,10YR5/6
ABg	15-42	cs	10YR4/2	Sic	P. 2mabk S.1vfgr and 1msbk	2f	1vf	s/p	e	C2D,10YR5/6
Bw	42-80	cw	7/5YR4/3	Sc	P. 3mabk S. 2mabk	2f	-	s/ps	e	C2P, 10YR5/6
C	>80		10YR4/4	S	P. sg S. sg	2f	-	-	e	-
Representative profile of river alluvial plain (Fine, mixed, active, thermic Fluventic Endoaquepts)										
Apg	0-18	aw	5Y4/2	Cl	P. 2fgr S. 1fgr	2vf-m	3f	s/p	e	F1P, 10YR5/6
AB	18-40	gs	7.5YR4/3	Sic	P. 2mabk S.1vfgr and 1msbk	2vf	1vf	s/p	e	C2P, 10YR5/6
Bg1	40-75	cs	7.5YR4/3	C	P. 3mabk S. 2mabk	2f	-	s/p	e	M2P,10YR5/6
Bg2	75-105	cw	10YR4/2	C	P. 3msbk and abk S. 2msbk and abk	1f	-	s/p	e	M2P,10YR5/6
BCg	105-160		5Y4/1	Sc	P. 1msbk and abk S. 1fsbk and abk	1f	-	ss/ps	e	M2D,5Y5/1
Representative profile of lowland (Fine, mixed, active, thermic Typic Endoaquepts)										
Apg	0-19	as	5Y4/2	Sicl	P. 2fgr S. 1fgr	2m	3f	vs/vp	e	-
ABg	19-42	cs	5Y4/2	Sic	P. 1msbk S. 1fsbk	2f	2f	vs/vp	e	M2D,5Y5/1
Bg1	42-80	cs	5Y3/2	Sic	P. 2msbk S. 1fsbk	2f	-	vs/vp	e	C2D,5Y5/1
Bg2	80-150		5GY3/1	C	P. 2msbk S. 1msbk	1f	-	vs/vp	e	C2D,5Y5/1

Table 1. Contd.

Representative profile of coastal plain (Mixed, thermic Typic Psammaquents)										
Apg	0-23	as	10YR4/2	Cl	P. 1fgr S. 1fgr	2f-m	2f	ss/ps	e	C2D,10YR5/6
Cg1	23-80	cs	10YR4/2	S	P. S. sg	2f	1vf	so/po	-	-
Cg2	>80		2.5Y3/2	S	P. S. sg	2f	-	so/po	-	-

Horizon boundary: (distinctness: a = abrupt, c = clear, g = gradual; topography: s = smooth, w = wavy). Soil texture: Cl: clay loam, Sic: silty clay, C: clay, Sc: sandy clay, S: sandy, Sicl: silty clay loam. Soil structure: P: primary structure, S: Secondary structure, (grade: 1 = weak, 2 = moderate, 3 = strong); (size: m = moderate, f = fine, vf = very fine); (type: gr = granular, sbk = subangular blocky, abk = angular blocky, sg = single grain). Voiod: 1 = few, 2 = common, 3 = many, f = fine, vf = very fine, m = moderate. Root: 1 = few, 2 = common, f = fine, vf = very fine. Wet Consistence: vs = very sticky, vp = very plastic, s = sticky, p = plastic, ss = slightly sticky, ps = slightly plastic, so = nonsticky, po = nonplastic. Lime: e = slightly effervescent. Redox features: (frequency: F = few, C = common, M = many); (size:1 = fine, 2 = moderate); (contrast: D = distinct, P = prominent). *) All of the plow horizons had plow pan layer. **) Ground water table was in depth 2 m of plateaus, in depth 45 to 85 cm of river alluvial, in depth 15 cm of lowland and in depth 20 cm of coastal plain.

due to slow speed of weathering in this land and its amount was very low in coastal plain because of light soil texture (Table 2) in these lands and leaching. Difference between extracted iron by citrate bicarbonate dithionate and extracted iron by ammonium oxalate showed the presence of pedogenic iron oxides in these soils. It was used as criteria for determination age and evolution of soils. FeO to Fed proportion was decreased with depth increasing. This proportion was very different in surface horizons with respect to subsurface horizons in coastal plain due to ground water table fluctuation and leaching. Amorphous iron was low in lowland subsurface horizons because of reduction conditions and exiting Fe^{2+} of soil or slow speed of minerals weathering in these lands (Zhang and Gong, 2003).

Electrical conductivity was high in soils of lowland (Table 2). Draining water from adjacent lands and uplands was accumulated on lowland soils and was caused high electrical conductivity. Fe^{2+} and Mn^{2+} releasing from their oxides in reduction conditions is the other reason for high electrical conductivity in these lands (Ponnamperuma, 1978; Golsefidi, 2001).

Electrical conductivity was low in plateaus lands and high in subsurface horizons of coastal plain (Table 2) that high EC in coastal plain is due to seepage of sea water in these soils. CEC was high in lowland (Table 2) because of high presence of organic matter in surface horizons and high clay content in subsurface horizons (Akef et al., 2003). In the surface horizons of plateaus and alluvial plain $CaCO_3$ was more than subsurface horizons because of lime addition to soil with calcification process by rice plant (Golsefidi, 2001). Lime was low in coastal plain due to leaching and light texture. Exchangeable basic cations including Ca^{2+}, Mg^{2+}, Na^+ and K^+ were considered in lowland and alluvial plain (Table 2) because of high clay content and low leaching in these lands. Na+ was high in subsurface horizons of coastal plain (Table 2) due to seepage of sea water in these soils. Base saturation percentage should be low in these soils due to high precipitation but, because these soils received Sefidrood river water that it is full of basic ions therefore, base saturation percentage was high in these lands (Table 2) (Golsefidi, 2001; Akef et al., 2003). Comparison of FeO to Fed proportion results showed that soils from plateaus and upper terraces and river alluvial plain units had more evolution than lowland and coastal plain units.

Conclusion

Based on the findings of the present investigations, it can be inferred that weathering of minerals was high in surface horizons particularly in plateaus lands due to high moisture and puddling of soils during soil preparation for rice cultivation. Iron released from iron minerals because of weathering during soil formation and it was caused by soil matrix impregnation in

Table 2. Physical and chemical properties of soils.

Horizon	Depth (cm)	Clay	Silt	Sand	Particle density	Bulk density	Porosity	SP	Fe_d[1] (g/kg)	Fe_o[2] (g/kg)	Fe_o/Fe_d
		%			(g/cm^3)						
Representative profile of plateaus and upper terraces											
Apg	0-15	29.1	48	22.9	2.5	1.3	49	73	38.7	25.6	0.6
ABg	15-42	17.1	52	30.9	2.5	1.3	47	61	38.8	25.4	0.6
Bw	42-80	5.1	30	64.9	2.6	1.5	42	49	37.3	14.7	0.4
C	>80	11	4	85	2.7	1.6	38	32	30.5	15.8	0.5
Representative profile of river alluvial plain											
Apg	0-18	38	37.6	24.4	2.6	1.4	46	89	39	28.4	0.7
AB	18-40	47.8	41.2	11	2.7	1.4	46	78	38.3	29.6	0.8
Bg1	40-75	40.6	36.2	23.2	2.5	1.5	41	84	39.8	24.3	0.6
Bg2	75-105	42.8	38	19.2	2.5	1.6	34	80	36	17.5	0.5
BCg	105-160	36	17	47	2.6	1.8	31	77	31.6	16.5	0.5
Representative profile of lowland											
Apg	0-19	39	44.2	16.8	2.5	1.4	44	91	30.1	16.3	0.5
ABg	19-42	39	45	16	2.6	1.5	43	69	29.8	15.1	0.5
Bg1	42-80	41.8	42	16.2	2.6	1.5	41	69	24.7	11.2	0.4
Bg2	80-150	48.2	30	21.8	2.7	1.6	39	79	19.5	9.3	0.5
Representative profile of coastal plain											
Apg	0-23	21.2	51.4	27.4	2.6	1.3	48	63	38.3	29.6	0.8
Cg1	23-80	6	4.8	89.2	2.8	1.2	45	20	30.4	5.6	0.2
Cg2	>80	6	5.6	88.4	2.9	1.7	41	21	11.8	2.5	0.2

Horizon	Depth (cm)	pH Water	pH $CaCl_2$ (0.01M)	CEC (cmol$_c$/kg)	Ca	Mg	K	Na	ECe dSm^{-1}	OC	TNV	BS
					cmol$_c$/kg					%		
Representative profile of plateaus and upper terraces												
Apg	0-15	7.6	7.3	27.6	18.3	7.9	0.3	0.09	0.3	3.8	0.8	96
ABg	15-42	7.7	7.5	15.5	9.4	4.3	0.7	0.06	0.2	1.4	2.3	93
Bw	42-80	7.7	7.4	6.4	2.8	1.3	0.1	0.08	0.4	0.7	2.8	68
C	>80	7.2	6.9	5.8	2.5	1.1	0.2	0.02	0.3	0.1	3.7	67

Table 2. Contd.

Representative profile of river alluvial plain												
Apg	0-18	7.5	7.1	27.3	17.7	9.2	0.2	0.2	1.1	2.4	6.8	99.8
AB	18-40	7.7	7.3	27.8	19.1	8.3	0.3	0.1	0.8	1.1	7.1	100
Bg1	40-75	7.6	7.2	23.7	15.4	7.1	0.6	0.4	0.5	1	7.4	99.9
Bg2	75-105	7.4	7.4	25.2	16.4	7.5	0.7	0.3	0.5	1.2	9.8	99.8
BCg	105-160	7.6	7.4	20.1	13	6	0.7	0.3	2.1	0.8	6.8	100
Representative profile of lowland												
Apg	0-19	7.2	7.2	32.2	21.8	9.6	0.5	0.1	1.2	3.9	1.3	99
ABg	19-42	7.4	7.4	22.4	14.5	6.9	0.5	0.3	1.3	1	2.6	100
Bg1	42-80	7.9	7.5	23.1	16.3	6.9	0.3	0.1	1.4	0.8	2.3	100
Bg2	80-150	8	7.4	25.1	15.8	7.6	0.5	0.2	0.9	0.5	2.3	96
Representative profile of coastal plain												
Apg	0-23	7.6	7.4	18.1	11.7	5.4	0.1	0.2	1.2	2.1	5.4	96
Cg1	23-80	7.8	7.4	4.9	2.1	1.2	0.06	0.4	1.4	0.2	-	75
Cg2	>80	7.8	7.4	3.8	1.3	0.7	0.04	0.5	2.2	0.1	-	68

1) Extracted iron by dithionite citrate bicarbonate. 2) Extracted iron by ammonium oxalate.

surface horizon of plateaus and alluvial plain. Measured iron was high in mentioned physiographic units. Iron minerals were deteriorated in lowlands and coastal plain less than other units due to high ground water table and its alternative fluctuation. Electrical conductivity was high in lowlands surface horizons because of adjacent region and uplands (plateaus and upper terraces) drainage water accumulation. Therefore, lowlands unit soils will probably be saline in future. Thus, it is vital to prevent from salinity problems. On the whole, the presence of ground water has prevented from soil evolution in lowlands and coastal plain in this toposequence.

ACKNOWLEDGMENTS

The authors wish to express their sincere thanks to the Department of soil science, University of Guilan for supporting field studies and samplings. We would also like to thank all the members of the Soil Science Laboratory of Faculty of Agriculture, University of Guilan, for providing the facilities to carry out this work and for their suggestions.

REFRENCES

Abubakar MS, Ahmad D, Othman J, Sulaiman S (2010). Mechanical properties of paddy soil in relation to high clearance vehicle mobility. Aust. J. Basic Appl. Sci. 4(5):906-913.

Akef M, Mahmoodi S, Eghbal KM, Sarmadian F (2003). Studying the changes of physicochemical and micromorphological characteristics of soils in converted natural forests to paddy soils in foumanat region in Guilan province. (In Persian). J. Iran Nat. Resour. 56(4):407-423.

Bockari M, Ishak W, Azimi Y, Chan C (2004). Effect of rotary tillage on soil physical properties and energy consumption in a Malaysian paddy field. Malays. J. Soil Sci. 8:25-38.

Burt R (Ed.) (2004). Soil Survey Laboratory Methods Manual. United States Department of Agriculture, Natural Resources Conservation Service, USA. P. 700.

De Datta SK, Kerim MSAA (1974). Water and nitrogen economy of rainfed rice as affected by soil puddling. Soil Sci. Soc. Am. Proc. 38:515-518.

Eickhorst T, Tippkotter R (2009). Management-induced structural dynamics in paddy soils of south east China simulated in microcosms. J. Soil Till. Res. 102:68-178.

Ghildyal BP (1978). Effect of Compacting and Puddling on Soil Physical Properties and Rice Growth. International Rice Research Institute, Los Banos, Philippines. pp. 317-336

Golsefidi TH (2001). Genesis, Classification and suitability evaluation of wetland soils for rice cultivation on different landforms in Guilan Province, Northern Iran. Isfahan Thesis Ph.D. University of Technology, (In Persian). pp. 485.

Goto E, Miura S, Nomura M (2003). The present condition of chemical properties of paddy soils in hokkaido. Jpn. J. Soil Sci. Plant Nutr. 74(4):475-483.

Hassannezhad H, Pashaee A, Khormali F, Mohammadian M (2008). Morphology and micromorphology of paddy soils under different soil moisture regime and ground water table in mazandaran province, Northern Iran. Amol. Int. J. Soil Sci. 3(3):149-156.

Jia-fang C, Shi-ye L (1981). Some characteristics of high fertility paddy soils. In Proceedings of the Symposium on Paddy Soils. (SPS'81), Institute of Soil Science, Academia Sinica, Nanjing, China. pp. 20-30

Kirchhof G, Priyono S, Utomo WH, Adisarwanto T, Dacanay EV, So HB (2000). The effect of soil puddling on the soil physical properties and the growth of rice and post-rice crops. Soil Till. Res. 56:37-50.

Klute A (1986). Methods of Soil Analysis, Part I. Physical and Mineralogical Methods. 2nd Edn., ASA and SSSA, Madison, WS, USA. P. 1189.

Kogel-Knabner I, Amelung W, Cao Z, Fiedler S, Frenzel P (2010). Biogeochemistry of paddy soils. Geoderma 157:1-14.

Lee SB, Lee CH, Jung KY, Park KD, Lee D, Kim PJ (2009). Changes of soil organic carbon and its fractions in relation to soil physical properties in a long-term fertilized paddy. J. Soil Till. Res. 104:227-232.

McDonald AJ, Riha SJ, Duxbury JM, Steenhuis TS, Lauren JG (2006). Soil physical responses to novel rice cultural practices in the rice-wheat system: Comparative evidence from a swelling soil in Nepal. Soil Till. Res. 86:163-175.

Nettleton WD, Flash KW, Brasher BR (1969). Argillic horizons without clay skins. Soil Sci. Soc. Am., 33:121-125.

Page AL, Miller RH, Keeney DR (1982). Methods of Soil Analysis Part 2: Chemical and Microbiological Properties. 2nd Edn., ASA and SSSA, Madison, WI., USA. P. 1159.

Pan G, Wu L, Li L, Zhang X, Gong W, Wood Y (2008). Organic carbon stratification and size distribution of three typical paddy soils from Taihu Lake Region, China. J. Environ. Sci. 20(4):456-463.

Ponnamperuma FN (1972). The chemistry of submerged soils. Adv. Agron. 24:29-96.

Ponnamperuma FN (1978). Electrochemical Change in Submerged Soil and the Growth of Rice. IRRI, Los Banos, Philippines. pp. 421-441

Prakongkep N, Suddhiprakarn A, Kheoruenromne I, Gilkes RJ (2007). Micromorphological properties of Thai paddy soils. Kasetsart J. Nat. Sci. 41:42-48.

Prihar SS, Ghildyal BP, Painuli DK, Sur HS (1985). Physical Properties of Mineral Soils Affecting Rice-Based Cropping Systems. IRRI, Los Banos, Philippines. pp. 57-70.

Soil Survey Staff (1993). Soil Survey Manual. 1st Edn, United States Department of Agriculture Washington, DC., USA.

Soil Survey Staff (2010). Keys to Soil Taxonomy. 11th Edn., United States Department of Agriculture, Natural Resources Conservation Service, Washington DC., USA.

Tarasawa S (1975). Physical properties of paddy soils in Japan. JARQ 9:18-23.

Zhang GL, Gong ZT (2003). Pedogenic evolution of paddy soils in different soil landscapes. J. Geoderma 115:15-29.