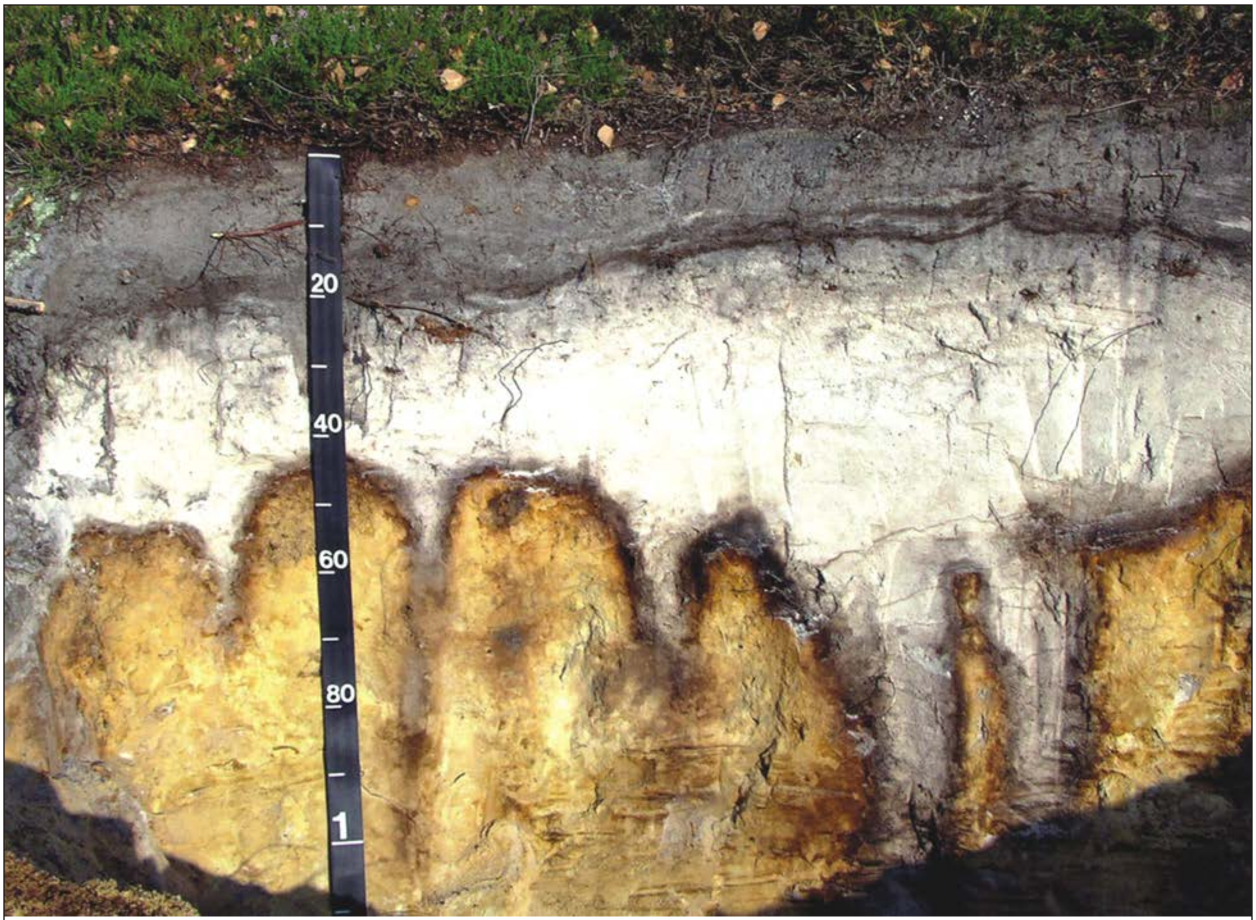

International Journal of Soil Science

ISSN 1816-4978

Academic
Journals Inc.

www.academicjournals.com

OPEN ACCESS International Journal of Soil Science

ISSN 1816-4978
DOI: 10.3923/ijss.2016.79.86

Research Article
Sealing Index, Air-filled Porosity and Hydrological Behaviour of a Tropical Ultisol as Affected by Incidental Flooding and Soil Disturbance

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Abstract

Background: Soil sealing, surface runoff and soil erosion in friable soils are typical consequences of soil disturbances due to anthropogenic activities on the soil environment. The impacts of incidental flooding and soil disturbances on physical quality index of a sandy soil in the oil producing Niger Delta region of Nigeria were studied. **Methodology:** Ninety two bulk and core soil samples were collected at 0-25, 25-40 and 40-65 cm depths in 6 locations occupying a total of 12,000 ha. **Results:** Results showed that incidental flooding increased the soil Sealing Index (SI) in Obite 1, Obite 2 and Obagi locations; 4.94, 5.53 and 5.42, respectively. In Okwuzi soil increased in sealing index was due mainly to soil disturbances. Generally, low sealing index, higher air-filled porosity and macro-aggregate stability were found in soils that were not prone to flooding and excessive disturbances. Although total porosity was moderate high in most of the soils, air-filled porosity was significantly low in Obite1, Obite 2 and Obagi 1 soils occasioned by flooding and soil disturbance. This would have serious negative effects on soil quality for agricultural production. Air-filled porosity showed significant positive relationship with soil organic matter content (0.614, $p<0.05$) and saturated hydraulic conductivity (0.709, $p<0.01$). The high silt+clay content and low soil organic matter were linked to high susceptibility of the soil to sealing. **Conclusion:** High silt deposits during peak periods of rainfall reduced the saturated hydraulic conductivity (Ksat) of soil with possible deformation of soil structure and restricted aeration. With adequate soil and watershed management practices, large area of the land can be made available for agriculture.

Key words: Macro-aggregate stability, water movement, organic matter, structural deformation

Received: January 12, 2016 Accepted: March 17, 2016 Published: June 15, 2016

Citation: B.E. Udom and O.J. Kamalu, 2016. Sealing index, air-filled porosity and hydrological behaviour of a tropical ultisol as affected by incidental flooding and soil disturbance. Int. J. Soil Sci., 11: 79-86.

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Soil quality decline due to ecosystem disturbance can impact negatively on world food security and the environment. Soil sealing and air-filled porosity control water movement and retention in soils and determine the amount of water stored in the soil for plant use[1]. Soil properties that promote soil sealing are texture, organic matter content, structural stability and sodium adsorption relationship[2].

The effects of seal formation on total porosity, size-distribution and continuity of pores have been reported[3]. Limitations in seedling emergence, root development and nutrient uptake by plants have also been reported as among the negative impacts of soil sealing[4-6]. In fine-textured soils[7], deformation of soil structure and aggregates due to cultivation increased ponding of water and surface runoff.

In the Niger Delta region of Nigeria, deforestation and construction of access roads to flow stations and oil wells are extensive and often lead to flooding during heavy rainfall[8]. The effects are presently disturbing especially in low-activity clay soils which organic matter is important to soil physical properties[9-11]. Construction of oil pipelines and cutting down of trees for fuel wood and timber often lead to increased surface runoff, soil erosion and surface crusting in such areas.

Soil sealing and its effects on air-filled porosity and a wide range of soil physical properties has not been widely reported in literature[6]. Previous studies have elucidated that surface soil disturbance altered soil hydrological properties[12-14]. In most tropical soils, where seasonal flooding is common, explanation of its effects on sealing index and air-filled porosity are not well known. For example, Servadio *et al.*[3] and Durr and Aubertot[4] reported of inconsistencies in total porosity and bulk densities in seasonally flooded soils. Also, the free soil particles during flooding and its effects on inter-aggregate pore spaces are not clearly understood. The objective of this study, therefore, was to examine the wet season flooding effects on soil sealing and related hydrological properties of soils of deltaic alluvium deposits. This will provide information on the management of such soils to increase the area of land available for crop production.

MATERIALS AND METHODS

Study area and sampling: The study was carried out in selected locations in Obite, Obagi, Okwuzi and Omoku in Ogba-Egbema-Ndoni in Rivers State, Nigeria (latitude 4°39[1] and 5°33[1]N, longitude 6°30[1] and 7°00[1]E). The area occupied about 12,000 ha on the Sombreio Warri Deltaic deposits and classified as Arenic Kandiustulf[15]. The climate is the tropical hot humid climate, with mean annual minimum and maximum temperatures of 28 and 30°C, respectively. Rainfall is usually high[16], with mean annual in excess of 2400 mm. Representative soil samples were collected in 6 locations viz., (1) Obite 1, Obite 2 and Obagi 1: Located in areas under intensive removal of vegetation for access roads onto oil wells, (2) Obagi 2 and Okwuzi: Located in areas with cases of incidental flooding for more than 8 weeks during peak periods of rains and (3) Omoku: Located in area with no flooding history (control). Bulk and core soil samples were collected in duplicates at 0-25, 25-40 and 40-65 cm depths. A total of 92 core and bulk soil samples were collected and used for laboratory analysis.

Laboratory analysis: Determination of particle-size distribution: Particle-size distribution was determined by the hydrometer method[17] after dispersing the soil with sodium hexametaphosphate.

Organic matter and sealing index: Total Organic Carbon (TOC) was determined by the walkey and black wet dichromate oxidation method[18] and was converted to organic matter by multiplying the TOC values by the Van Bemmelen factor of 1.724[19]. Sealing index was used to relate the values with susceptibility indicators of sealing, depending on soil characteristics[20] cited by Van der Watt and Claassens[21]. Sealing Index (SI) was calculated as:

$$\mathrm{SI} = \frac{\mathrm{OM} \times 100}{\mathrm{Silt} + \mathrm{Clay}} \tag{1}$$

where, OM is the organic matter content, clay and silt are clay and silt content (%), respectively. Sealing index value ≤5% was considered high crusting or sealing risk, while, a value over 9% represents a low sealing risk and 7% was considered the threshold value.

Air-filled porosity and aggregate stability: Air-filled porosity which constitutes pore size >50 µm (indicator of soil aeration and drainage) was calculated using the method of Flint and Flint[22]:

$$\text{Air-filled porosity} = \frac{\text{Volume of water drained at} - 6\ \text{kpa}}{\text{Volume of bulk soil}} \tag{2}$$

Capillary porosity which constitutes pore size <50 µm was calculated as:

$$\text{Capillary porosity} = \frac{\text{Volume of water retained at} -6 \text{ kpa}}{\text{Volume of bulk soil}} \qquad (3)$$

Aggregate stability by Mean Weight Diameter (MWD) was measured by the wet-sieving procedure[23]. In this procedure, 50 g of 2.0-4.75 mm air-dried aggregates were evenly distributed on the upper most nest of sieves 2, 1, 0.5 and 0.25 mm and were oscillated 25 times in deionized water for 1 min. Aggregates retained in the sieves were oven-dried at 50°C and weighed. The weight fractions of aggregates remaining on each sieve, relative to the initial aggregate weight of 50 g were the Water Stable Aggregates (WSA). Mean Weight Diameter (MWD) of water stable aggregates was calculated as:

$$\text{MWD} = \sum\nolimits_{l-1}^{n} \text{XiWi} \qquad (4)$$

where, Xi is the mean diameter of any particular size range of aggregates separated by sieving and Wi is the weight of aggregates in that size range as a fraction of the total dry weight of the sample analyzed. The proportion of stable aggregates ≥0.25 mm in diameter are defined as macro-aggregates and proportion of aggregates <0.25 mm in diameter are defined as micro-aggregates.

Bulk density, water holding capacity and hydraulic conductivity: The core samples were oven- dried at 105°C to determine the bulk density by the method of Grossman and Reinsch[24] as:

$$\text{Bulk density} = \frac{\text{Mass of oven - dried soil}}{\text{Volume of bulk soil}} \qquad (5)$$

Water holding capacity was calculated as:

$$\text{WHC (g g}^{-1}) = \frac{\text{Mw-Md}}{\text{Md}} \qquad (6)$$

where, WHC is the water holding capacity, Mw is mass of wet soil and Md is mass of dry soil. The soil cores were saturated for measurement of saturated hydraulic conductivity using the constant head core method[25].

Data analysis: Analyses of variance were carried out using the SAS software[26]. Significance differences between means were according to the least significant difference using Fisher's protected test at 5% probability.

RESULTS

Texture, bulk density and organic matter: The soil is mainly sandy loam to sandy clay loam in the topsoil, with scanty clay loam in Omoku subsoil (Table 1). Silt+clay content were more than 20% in the flooded soils indicating tendencies for flooding during heavy rains. In Obite 1, Obite 2 and Obagi 1, where there were extensives oil disturbance and vegetation degradation, the mean bulk density values were higher, ranging from 1.49-1.52 g cm^{-3}. In the seasonally flooded Obagi 2 and Okwuzi, mean bulk densities were 1.44 and 1.41 g cm^{-3}, respectively (Table 1). There were non-significant ($p>0.05$) differences in bulk densities with depth.

Soil Organic Matter (SOM) was low in Obite 1, Obite 2 and Obagi 1, ranging from 8.4 g kg^{-1} in the subsoil to 16.81 g kg^{-1} in the surface soil. Soils under seasonal flooding showed high organic matter in the topsoil probably due to the contributions from fine particles fractions associated with the flood water. On the other hand, SOM was higher (21.03 g kg^{-1}) in non-flooded soils of Omoku especially at the top 0-25 cm soils. This value was 61, 84 and 26% higher, compared to that of Obite 1, Obite 2 and Obagi 1, respectively, where natural vegetation has been greatly reduced.

Gravimetric water content, total porosity and saturated hydraulic conductivity: Water holding capacity of the soils at 0 kpa matric potential, as a measure of the soil hydrological characteristics were generally lower in flooded soils. The relatively high water content of 0.30 g g^{-1} in Omoku soils was probably due to the high organic matter recorded in this soil, which indirectly improved the water retention capacity of the soil (Table 2). Total porosity was generally higher in the top 0-25 cm soil but did not translate into corresponding increases in saturated hydraulic conductivity. Total porosity in the top 0-25 cm soil in Obite 2, Obagi 1 and Obagi 2 were 30, 29 and 27%, respectively, whereas, the corresponding saturated hydraulic conductivity values were 14.2, 8.9 and 15.7 cm h^{-1}, respectively (Table 2). Permeability class ranged from very slow to moderately slow in most soils under vegetation degradation and flooding. Saturated hydraulic conductivity of 70.2 and 33.3 cm h^{-1} were obtained in Okwuzi and Omoku where flooding did not occur.

Air-filled porosity and sealing index: Air-filled porosity was low in soils under extensive disturbance and flooding

Table 1: Texture, bulk density and organic matter of the soils

Soil	Depth (cm)	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Texture	Bulk density (g cm^{-3})	Organic matter (g kg^{-1})
Obite 1	0-25	840	20	140	SL	1.50	13.09
	25-40	770	50	180	SL	1.51	8.40
	40-65	790	50	160	SCL	1.55	6.39
	Mean	800	40	160	SCL	1.52	9.56
	LSD(0.05)	NS	25	24.3	-	NS	2.16
Obite 2	0-25	820	40	140	SL	1.46	11.43
	25-40	820	30	150	SL	1.49	11.10
	40-65	760	50	190	SCL	1.55	9.74
	Mean	800	40	160	SCL	1.50	10.76
	LSD(0.05)	NS	NS	23.7	-	NS	2.03
Obagi 1	0-25	800	50	150	SL	1.43	16.81
	25-40	760	60	180	SCL	1.50	11.43
	40-65	740	60	200	SCL	1.53	8.07
	Mean	767	57	176	SCL	1.49	12.14
	LSD(0.05)	NS	NS	23.8	-	NS	2.11
Obagi 2	0-25	760	40	200	SCL	1.40	25.58
	25-40	760	40	200	SCL	1.43	16.69
	40-65	790	50	160	SCL	1.48	13.57
	Mean	770	43	167	SCL	1.44	18.61
	LSD(0.05)	NS	NS	24.6	-	0.16	2.13
Okwuzi	0-25	850	30	120	SL	1.40	11.20
	25-40	820	40	140	SL	1.45	7.40
	40-65	760	60	180	SCL	1.40	5.73
	Mean	810	43	147	SCL	1.41	8.11
	LSD(0.05)	NS	24.6	27.2	-	0.18	2.55
Omoku	0-25	800	60	140	SCL	1.41	21.03
	25-40	600	120	280	SCL	1.47	11.78
	40-65	580	200	220	CL	1.52	9.10
	Mean	660	127	213	CL	1.47	13.97
	LSD(0.05)	150	74	264	-	0.11	2.46

SL: Sandy loam, SCL: Sandy clay loam, CL: Clay loam and NS: Non significant at $p>0.05$

(Table 3). Air-filled porosity, as low as 6% was obtained in Obagi 2 soils. On the other hand, capillary porosity consisting of pores <50 µm were dominant in most of the soils. Air-filled porosity were 9, 12, 8, 8 and 10% in Obite 1, Obite 2, Obagi 1, Obagi 2 and Omoku, respectively, whereas, the corresponding capillary porosity were 20, 18, 21, 19 and 22%, respectively. Pore-size distribution rather than total porosity was reliable index that can be used to define the soil health in flooded soils.

Sealing index was above critical values in most of the soils under vegetation removal and seasonal flooding. Subsoil sealing index ranged from 2.17-4.76, indicating high incidence of subsoil sealing. Seasonal flooded areas of Okwuzi and Obagi 1 showed sealing risk value of 2.40 and 3.10, respectively, at 40-65 cm depth. Surface soil sealing risk was low in non-flooded Omoku and Obagi 2 (10.5 and 10.66), respectively.

Aggregate stability: Water stability of aggregates ranged from 0.502 mm in Obite 2-1.412 mm in Omoku. Water stability at the macro-aggregate fractions was higher in Omoku and Okwuzi (Table 3). There was no significant difference ($p>0.05$) in water stability of aggregates with depth in Obite 1 and Obite 2 probably due to the effects of vegetation removal which gradually reduced the volume of air-filled porosity and organic matter of the topsoil. The highest water stability of aggregates (1.356 mm) in macro-aggregate fractions found in Omoku soil, were indication of the absent that intensive oil-field activities and flooding.

Relationships among air-filled porosity, sealing index and some soil physical properties: Relationships showed significant negative correlation between Sealing Index (SI) and Air-filled Porosity (AP) (-0.713, $p<0.01$) and positive relationships with clay and silt, 0.683 and 0.647, $p<0.05$, respectively (Table 4). There was also significant (-0.754, $p<0.01$) negative correlation between air-filled porosity and capillary porosity. There were positive relationships between air-filled porosity and SOM (0.614) and saturated hydraulic conductivity (0.709). On the other hand, capillary porosity showed positive relationships with sealing index, clay and silt content (Table 4), whereas, SI correlated negatively with hydraulic conductivity and SOM.

Table 2: Water holding capacity, total porosity and saturated hydraulic conductivity of the soil

Soil	Depth (cm)	WHC (g g^{-1})	Total porosity (%)	Ksat (cm h^{-1})	Quality assessment
Obite 1	0-25	0.27	29	25.00	Permeability is moderately rapid, plant roots may be restricted
	25-40	0.29	31	18.10	Permeability is moderately rapid
	40-65	0.28	31	14.40	Permeability is moderately slow
	Mean	0.28	30.3	19.20	
	LSD(0.05)	NS	NS	3.95	
Obite 2	0-25	0.28	30	14.20	Permeability moderately slow
	25-40	0.28	29	7.40	Permeability very slow
	40-65	0.29	26	7.30	Permeability very slow
	Mean	0.28	28	9.60	
	LSD(0.05)	NS	2.11	2.46	
Obagi 1	0-25	0.28	29	8.90	Permeability very slow
	25-40	0.21	26	20.50	Permeability moderately rapid
	40-65	0.19	26	12.30	Permeability moderately slow
	Mean	0.22	27	13.90	
	LSD(0.05)	0.88	2.38	4.67	
Obagi 2	0-25	0.21	27	15.70	Permeability moderately slow
	25-40	0.20	29	21.70	Permeability moderately rapid
	40-65	0.21	24	10.70	Permeability slow
	Mean	0.21	27	16.10	
	LSD(0.05)	NS	4.2	4.79	
Okwuzi	0-25	0.29	32	70.20	Permeability is rapid
	25-40	0.28	30	40.00	Permeability is rapid
	40-65	0.23	28	21.80	Permeability moderately rapid
	Mean	0.27	30	44.00	
	LSD(0.05)	NS	3.6	5.63	
Omoku	0-25	0.29	30	33.30	Permeability is rapid
	25-40	0.31	29	47.00	Permeability is rapid
	40-65	0.29	29	46.10	Permeability is rapid
	Mean	0.30	29	42.10	
	LSD(0.05)	NS	NS	5.63	

NS: Not significant at p>0.05, WHC: Water holding capacity and Ksat: Saturated hydraulic conductivity

DISCUSSION

The silt+clay of the soil showed that the soil was susceptible to flooding during periods of high rainfall. Indiscriminate cutting down of trees in on such soils according to Udom and Nuga[6] usually altered the soil properties and exposed the soils to flooding. High bulk densities in soils with extensive disturbances and seasonal flooding incidence were not surprising; explaining the fact that these activities reduced soil organic matter which was associated with increases in the soil bulk density. The free fine particles during flooding may have sealed the inter-aggregate pore spaces and impacted negatively on soil hydrological behaviours. Hydraulic conductivity and water content of the soils were very low, similar to earlier report by Servadio *et al.*[3] and Caravaca *et al.*[13]. Similarly, roots of many arable crops may be restricted[27,28]. The slow to moderately slow permeability found in soils under excessive disturbance and incidental flooding was related to sealing effect, high bulk density and very low air-filled porosity. Pore size distribution rather than total porosity was reliable index for measuring the soil physical health[6]. The low air-filled porosity found in the degraded soils will have deleterious implications on soil water characteristics which invariable will lead to reduction in number and diversity of soil micro-organisms[12] and consequently, poor yield of crops[14]. Such values of air-filled porosity were an indication that water movement into and within the soil would be impeded, leading to flooding during peak of rains. Low sealing risk found in Omoku and Obagi 2 with high SOM explained the role of SOM in reducing soil sealing, similar to earlier report by Barthes and Roose[1], Bricchi[2] and Udom and Adesodun[29]. Also, the low water stability of aggregates in Obite and Obagi soils was an indication the soil structure was destroyed leading to disruption in soil aggregates as direct and indirect effects of soil disturbance and incidental flooding. Relationships showed that as sealing index, clay and silt content increased, air-filled porosity decreased. Therefore, disruption of soil aggregates into fine particles fractions increased soil sealing and reduced air-filled porosity. On the other hand, sealing index increased with increase in micro-porosity and decreased in SOM. This

Table 3: Air-filled porosity, capillary porosity, sealing index and aggregate stability of the soils

Soil	Depth (cm)	Air-filled porosity (>50 µm)	Capillary porosity (>50 µm)	Sealing index	MWD (mm)
Obite 1	0-25	9	20	8.13	0.843
	25-40	12	19	3.65	0.626
	40-65	9	22	3.04	0.686
	Mean	10	20.3	4.94	0.719
	LSD(0.05)	2.01	2.52	2.16	NS
Obite2	0-25	12	18	6.35	0.675
	25-40	8	21	6.17	0.761
	40-65	8	20	4.06	0.502
	Mean	9.3	19.67	5.53	0.646
	LSD(0.05)	2.35	2.16	1.39	0.110
Obagi 1	0-25	8	21	8.41	0.711
	25-40	8	18	4.76	0.704
	40-65	7	19	3.10	0.649
	Mean	7.67	19.3	5.42	0.688
	LSD(0.05)	NS	2.16	1.68	NS
Obagi 2	0-25	8	19	10.66	0.838
	25-40	6	23	6.95	0.655
	40-65	6	18	6.46	0.685
	Mean	6.67	20	8.02	0.726
	LSD(0.05)	NS	2.66	1.66	0.124
Okwuzi	0-25	10	22	7.47	1.226
	25-40	8	18	4.11	1.412
	40-65	8	20	2.40	1.269
	Mean	8.67	20	4.66	1.302
	LSD(0.05)	NS	2.19	1.72	0.130
Omoku	0-25	14	16	10.50	1.356
	25-40	12	17	3.00	1.109
	40-65	12	17	2.17	0.948
	Mean	12.67	16.67	5.22	1.138
	LSD(0.05)	NS	NS	1.84	0.205

NS: Not significant at p>0.05 and MWD: Mean weight diameter

Table 4: Relationships among air- filled porosity, sealing index and some physical properties of the soils

	Correlation coefficient (r)						
Soil parameters	A_P (%)	C_P (%)	OM	SI	Ksat (cm h^{-1})	Clay (g kg^{-1})	Silt (g kg^{-1})
A_P (%)	1.0						
C_P (%)	-0.758**	1.0					
OM	0.614*	0.695*	1.0				
SI	-0.713**	0.759**	-0.816**	1.0			
Ksat (cm h^{-1})	0.709**	-0.617**	0.742**	-0.698*	1.0		
Clay (g kg^{-1})	-0.684*	0.691*	0.518*	0.647*	-0.619*	1.0	
Silt (g kg^{-1})	-0.647*	0.614*	0.631*	0.683*	-0.633*	-0.619*	1.0

A_P: Air filled porosity, C_P: Capillary porosity, OM: Organic matter, SI: Sealing index and Ksat: Saturated hydraulic conductivity, **significant at p<0.01, *significant at p<0.05

further confirmed the assertion of Six *et al.*[10] and Spaccini *et al.*[11]. The highly positive relationship between air-filled porosity and saturated hydraulic conductivity was an indication that the rate of water movement within the soil is usually determined by the proportion of air-filled to capillary porosity of the soil.

CONCLUSION

Significant issues addressed in this study are seasonal flooding and soil disturbance reduced the soil physical qualities such that, the air-filled porosity, hydraulic conductivity, organic matter were very low. High bulk densities were dominant and may negatively affect roots of many arable crops, whereas, high sealing index may affect the soil-air-diffusion pathways. Soil organic matter content played positive role in macro-aggregate stability, air-filled porosity and saturated hydraulic conductivity particularly, in non-flooded soils or soils with excessive removal of vegetation. Contributions of fine silt particles during flooding and disruption of macro-aggregates into fine particle fraction due to soil disturbance increased the risk of soil sealing.

SIGNIFICANT STATEMENT

Incidental flooding caused by human activities increased soil sealing and related soil properties thereby reducing the soil physical quality for agriculture. Incidental flooding yielded high silt+clay in the soil which invariably affected the soil hydraulic conductivity with negative consequences on soil aeration capacity. The positive relationship between air-fill porosity and saturated hydraulic conductivity was an indication that enhancement of macro porosity controlled water movement within the soil. The article addressed major soil science issues affecting global soil health.

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