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Assessment of Soil Physical Conditions: Evaluation of a Single Value Index

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ABSTRACT

Soil physical quality index *S*, the slope of the soil water retention curve at the inflection point, provides a scale that can be used to compare different soils or the effects of different management practices on soil physical properties. Our study indicates a downward trend in *S* value with increasing clay content and bulk density but higher values of *S* were observed with increasing organic matter content. In addition to this, different management practices (balanced application of fertilizers in conjunction with soil amendments (organic manures, fly ash, biogas slurry) and soil conditioners (*jalshakti*) and the combinations of conventional, reduced and no tillage practices) led to optimizing bulk density and increase in soil organic carbon, available water capacity, which resulted in higher values of *S* and improved soil physical quality. The index is understood to have potential for general assessment of soils or its temporal changes and thus, can help in making decision of agri-management practices.

Key words: Soil physical quality index, Tillage, Soil amendments, Soil conditioners, Long-term fertilizer experiment, Bulk density, Organic C

Introduction

With the increasing evidence of fatigue and degradation of agricultural soils, a need is felt for sustaining the soil resource base and enhancing its quality. The concept of soil quality is centred on the ability of the soil to perform the functions necessary for its intended use. Soil quality is defined as the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (Karlen *et al*., 1997). Though a large number of indicators (physical, chemical and biological) might need be integrated to quantify the soil quality, the necessity of emergence of a single value soil physical quality (SPQ) index can be proposed, as it is the soil physical environment that serves as the key to modifications of chemical and biological functions of soils. Efforts have been made since long to quantify the soil physical environment, but one parameter found sensitive to a particular soil may not be suitable for in another soil. In this context, a single value soil physical quality index, which is likely to be unique for a particular soil type or sensitive to different agri-management practices, has been proposed (Dexter, 2004a). This soil physical quality index, *S*, is defined as the slope of the soil water retention curve at its inflection point (Dexter, 2004a). In some preliminary studies, this index was found to decrease with increasing bulk density (Cavalieri *et al*., 2009) and is consistent with observations on soil compaction, effects of soil organic matter and root growth but appears to be independent of soil texture. Larger values of *S* are indicative of more root growth, less compaction and greater

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organic matter contents in soil (Dexter, 2004a). The value of S=0.035 was suggested as the boundary between good and poor soil physical conditions and were later supported by observations on friability and tillage (Dexter, 2004b). This is a new concept and need to be evaluated in diverse soils. Moreover, the soil physical environment as modified by different management practices like inorganic and organic inputs, tillage practices as well as soil amendments need to be evaluated in terms of this index, S. Thus, an attempt was made to explore its possible use in differentiating the soil physical conditions as influenced by the management practices.

Materials and Methods

In order to include representative soils from different prevailing textural classes across the country, exhaustive data on soil physical properties as texture (per cent sand, silt, and clay), bulk density, organic matter content and water retention for major soil groups/series/associations in India were collected and compiled from published literatures, various reports on AICRP on tillage (1967-1996), published reports of various ICAR institutions like NBSS&LUP, data gathered from different experiments and other relevant literature. The data broadly represented 8 major soil groups (alluvial, black, red, mixed, red and black lateritic, desert, mountain and hill, and foothills and *tarai* soils). Altogether, 274 data points with moisture retention at 4 or more suction values (10-15000 cm suction range) were selected, and analyzed to compute *S* and its subsequent relation with rest of the physical parameters.

Computation of S

The van Genuchten-Mualem (VG-M) equation was fitted on soil moisture retention data and the parameters (θ_s, the saturated and θ_r, the residual water contents; α, the inverse of suction at the inflexion point of the moisture curve; m and n, shape parameters) were estimated, through a non-linear least-squares optimization approach based on Marquardt's algorithm. Following this, the soil physical quality index *S* was computed, by using the following relation (Dexter, 2004a):

$$S = -n(\theta_s - \theta_r)\left[\frac{2n-1}{n-1}\right]^{\frac{1}{n}-2}$$

Subsequently, relations between the corresponding basic soil parameters i.e., clay content, bulk density and organic matter and *S* index were worked out. Data from various experiments depicting various agri-management (tillage, fertilizer and organic manure, soil amendments) practices were analyzed to retrieve *S* from the soil physical parameters mostly affected by the treatments. Dexter (2004a) suggested that *S* can be used as an index of soil physical quality to compare different soils or the effect of different soil physical conditions and management practices.

In the present study, experimental field data of various combinations of conventional reduced and no tillage as well as bed planting practices on a silty loam soil (38% sand, 26% silt and 36% clay) in rice-wheat cropping system continuing since 2002 at Sardar Vallabha Bhai Patel University of Agriculture and Technology, Modipuram (Meerut), India was used. Similarly, it is also interesting to judge results from the effects of soil amendments and conditioners on the value of this index. The physical index S was evaluated in another experiment in IARI, New Delhi farm area, where fly ash and biogas slurry were used for improving soil physical properties and wheat yield. This paper also explores the use of the index *S*, to predict the effects of long-term fertilizer experiment in a sandy loam soil (sand, silt and clay, 71.7, 12.0 and 16.3%, respectively) at IARI, New Delhi (after 34 years of continuous cereal based cropping system) on soil physical quality. In LTFE, the experiment consisted of 10 treatments in a randomised block design with 4 replications; 5 contrasting treatments were selected for the analysis i.e., control (no N,P,K,S or manures); 100% of recommended dose of nitrogen (N), phosphorus (P) and potassium (K) fertilizers as urea (or diammonium phosphate), diammonium phosphate and muriate of potash, respectively; 150% recommended N,P,K dose; 100% recommended N,P,K + sulphur through single super phosphate (as P source) containing 12% sulphur; and 100% recommended N,P,K +

farm yard manure (FYM) @15 Mg ha^{-1} yr^{-1} before the *kharif* season. The recommended practice is 120 kg N, 60 kg P_2O_5 and 40 kg K_2O ha^{-1} for both maize and wheat. Full dose of P and K are applied as basal, while 50% N was applied as basal and rest as top dressing.

Results and Discussion

Variation of S with clay content in soils

The soil physical index *S* representing the slope of water retention curve at the inflection point, is mostly affected by the pore size distribution, one of the dynamic properties of soil, which is management dependent. However, the pore size distribution is primarily governed by the inherent texture of the soil *i.e.*, the relative proportions of major soil separates (sand, silt and clay). The soils were classified following USDA system and the estimated values of *S* for the 9 textural classes along with the parameters used in its calculation are given in Table 1. There has been an apparent increase in bulk density as the texture changes from fine to coarse. The physical quality index was better in the range, where clay, silt and sand are near equally distributed in soils. As the texture changes towards finer and coarser ends, the value of index starts decreasing. This suggests the sensitivity of *S* on relative distribution of sand, silt and clay contents in soil, thereby indicating its potential in deciphering inherent soil properties, which is management independent. An additional attempt was made to quantify the above-mentioned effects of texture on *S* by using soil clay contents. In the entire range of clay, number of data points above 60% clay content was few; hence our analysis was limited up of clay content falling within 50-60%.

Average effect of soil texture on the soil physical quality index, *S* was examined directly (Fig. 1). No apparent relation between *S* and clay content in soil was perceptible. This might be due to wide variability in clay content as well as the dependence of *S* on factors other than clay content. However, when the proportion of clays was averaged and grouped into classes like 5-10, 10-15, 15-20, 20-25, 25-30, 30-35, 35-40, 40-45,

Table 1. Mean (M) and range (R) of clay, silt and organic carbon (OC) content; bulk density (BD) and van Genuchten parameters (θ_{sat}, α, n) along with the physical quality index values for 9 soil textural classes used in the present study

Textural class	Clay (%)		Silt (%)		OC (%)		BD (Mg m^{-3})		θ_{sat} (m^3 m^{-3})		α		n		S	
	M	R	M	R	M	R	M	R	M	R	M	R	M	R	M	R
Clayey	53.9	40.3-81.0	24.5	6.0-39.4	0.60	0.06-1.86	1.35	1.10-1.80	0.45	0.20-0.65	0.08	0.00-1.03	1.24	1.12-1.61	0.055	0.031-0.089
Silty clay	52.0	38.6-57.0	31.2	41.0-59.0	0.78	0.39-2.63	1.41	1.06-1.67	0.44	0.34-0.64	0.06	0.00-0.57	1.26	1.11-1.43	0.056	0.034-0.096
Sandy clay	38.0	35.0-41.3	10.1	2.5-16.4	0.34	0.06-0.90	1.43	1.06-1.55	0.38	0.20-0.53	0.13	0.00-0.73	1.36	1.11-1.80	0.053	0.031-0.068
Clay loam	34.9	28.0-39.4	27.8	20.5-38.3	0.48	0.08-1.60	1.35	1.09-1.51	0.41	0.25-0.58	0.06	0.00-0.43	1.30	1.13-1.50	0.062	0.030-0.091
Silty clay loam	33.1	27.0-38.9	51.5	22.4-69.0	0.59	0.52-0.70	1.41	1.11-1.65	0.40	0.29-0.53	0.07	0.00-0.45	1.35	1.14-1.51	0.063	0.046-0.095
Sandy clay loam	26.7	20.0-34.5	17.1	3.0-27.2	0.39	0.10-1.50	1.41	1.14-1.70	0.35	0.20-0.61	0.05	0.00-0.81	1.39	1.16-2.00	0.058	0.034-0.089
Loam	19.9	8.5-25.3	34.0	29.2-44.5	0.63	0.10-1.37	1.38	1.14-1.61	0.37	0.26-0.53	0.03	0.00-0.27	1.31	1.15-1.45	0.060	0.037-0.088
Sandy loam	14.4	8.0-20.1	14.4	4.5-30.6	0.34	0.06-1.73	1.50	1.17-1.73	0.26	0.20-0.60	0.01	0.00-0.19	1.48	1.18-2.11	0.049	0.030-0.075
Loamy sand	8.7	6.1-12.5	7.2	1.5-13.2	0.31	0.02-2.20	1.55	1.39-1.82	0.28	0.23-0.47	0.01	0.00-0.16	1.50	1.11-2.22	0.034	0.031-0.071

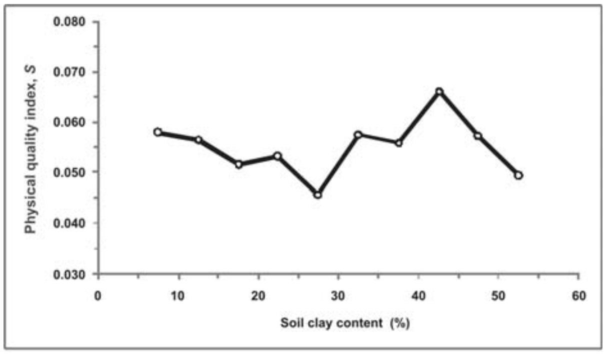

Fig. 1. Slope *S* of the soil moisture characteristic curve at the inflection point, as a function of the mean clay content in soils

45-50, 50-55 and 55-60%, some trends were noticed. Initially, there was decrease in *S* with increase in average clay content up to 20-30%, but thereafter, *S* started increasing steadily and then decreased drastically, once the average clay content exceeds 45%. When the clay content is low, formation of aggregates is difficult and the soil structure is likely to be poor. The optimum range of soil clay content was 35-45%, where the *S* has its highest value (0.066). In this range, the soil structure is generally superior as found in silty clay loam soils (average clay content is 35%). Higher clays makes the soil difficult to manage and *S* was found to reduce with increase in clay and recorded 0.049 with average clay content >50%. Results revealed that clay content in soil *vis-a-vis* its texture is one of the key factors in controlling the soil physical properties, and thus the soil physical quality, S.

Effect of long-term tillage in rice-wheat system

In the experiment on the effect of various alternate tillage practices in rice-wheat system on a silty loam soil (38, 26 and 36% sand, silt and clay content, respectively) at Modipuram, Uttar Pradesh, different values of bulk densities were obtained as a result of same tillage operations performed continuously on the same plots since last 6 years. Data revealed that the bulk density at surface (0-10 cm) was the maximum in zero till system (1.59 Mg m^{-3}) due to normal settling process of soil in absence of any tillage operations, whereas conventional tillage recorded lower bulk density (1.51 Mg m^{-3}) owing to loosening of surface soils. Minimum bulk density in 0-10 cm was obtained in bed planted rice-wheat system. The surface compaction under zero tillage has also been reported by others (Mallick and Nagarajarao, 1972, Cassel *et al*., 1995; Monneveux *et al*., 2006). The relation between *S* and bulk density of the corresponding depths is shown in Fig. 2a, in which *S* decreased with increasing bulk density. Increase in bulk density is accompanied by decrease in pore space, mostly the macro-pores, which are reduced to intermediate size (between macro and micro pore size). Change in relative proportion of transmission, storage and residual pores due to differential tillage practices brought changes in water retention-release behaviour of soil, which has been subtly reflected in *S* values. Bulk density is considered as one of the useful indices for soil structure, its change has been perceived by others as a possible reflection of change in soil physical environment *vis-a-vis* soil quality (Logsdon and Karlen, 2004). Results suggested that management (tillage) practices had significant effect in changing the inherent bulk density of soils, which was reflected in *S* values. Increased bulk density caused a decrease in S and thereby, indicating a possible decline in soil physical quality, as argued by others (Machado, 2006, Tormena *et al*., 2008 and Cavalieri *et al*., 2009).

Soil organic carbon (SOC) content has also been recognized as a key indicator of soil quality and crop productivity due to its favorable effects on soil's physical, chemical, and biological properties (Gupta and Germida, 1988; Elliott, 1986; Dormarr, 1983; Tisdall and Oades, 1982). It plays critical roles on nutrient cycling, water retention, root growth (Sainju and Good, 1993; Sainju and Kalisz, 1990), erosion control, plant productivity, and environmental quality. Excessive tillage may negatively impact both the physical structure and microbial components of the soil, and reduces soil organic C by increasing residue degradation, disrupting soil aggregation, and increasing aeration (Cambardella and Elliott, 1993; Balesdent *et al*., 1990; Dalal and Mayer, 1986). In contrast, practices that reduce residue incorporation and aggregate degradation, such as no-till or strip tillage may conserve and/or maintain soil organic

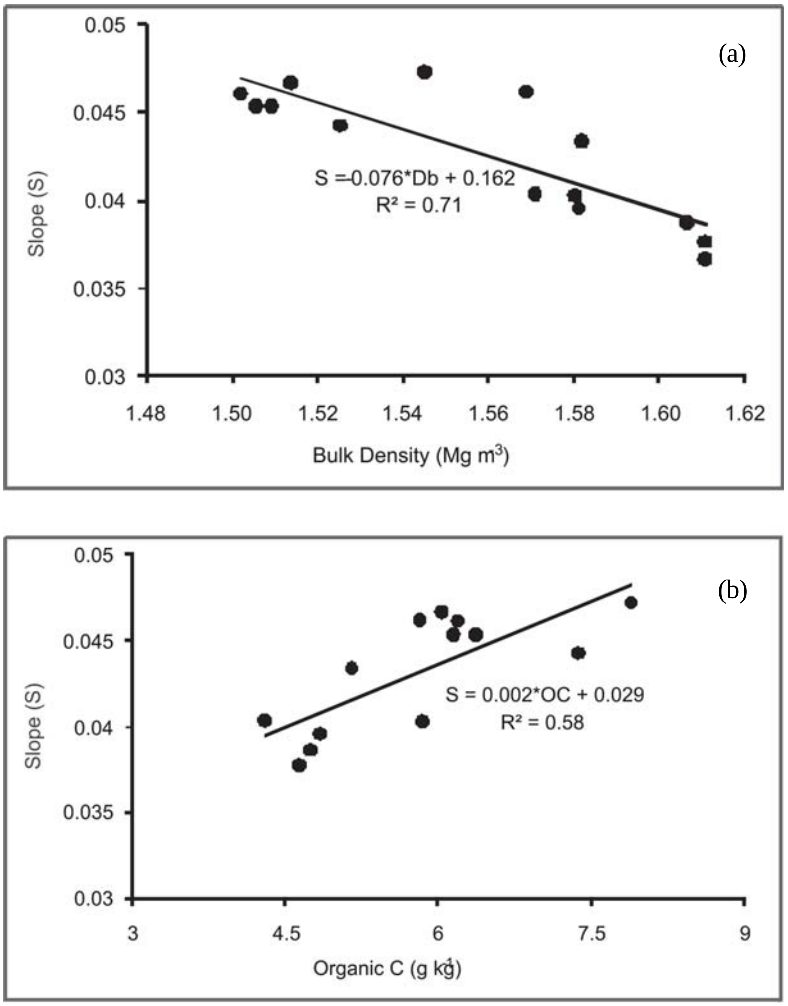

Fig. 2. Relation between physical quality index *S* and bulk density (a) and organic carbon (b) for a silty clay loam soil as influenced by long term tillage practices in rice-wheat system

C (Franzluebbers *et al*., 1995; Havlin *et al*., 1990; Doran, 1987) and increase microbial biomass (Caesar-TonThat *et al*., 2001; Drury *et al*., 1991). Higher cropping intensity also minimizes organic matter loss by sustaining annual residue returns to the soil (Shaver *et al*., 2003). Conservation tillage, particularly no tillage, generally leads to greater retention of soil organic C than conventional tillage. Data in Fig. 2b representing a range of tillage practices on a single soil, clearly shows effects of long-term tillage practices on restoring/degrading soil organic C and corresponding *S* values. The specific tillage practice leading to greater amount of organic matter in the soil and lower bulk density also resulted in higher *S* values and thus, better soil physical quality. Soil organic carbon was substantially higher in zero tillage systems and more so in top 0-5 cm soil, possibly due to increased retention of crop residues on surface and slow decomposition of the same leading to build up in SOC over time. Greater values of *S* were associated to no tillage practices with lower use of machinery inputs.

Effect of soil amendments and conditioners

Soil amendments like biogas slurry and fly ash improved the soil physical environment. The soil of the experimental field was alluvial, sandy loam (*Typic Haplustept*). Incorporation of soil amendments such as biogas slurry (@4.0 and 16.0 Mg ha^{-1}), and fly ash (0.5, 1.0 and 1.5 Mg ha^{-1})

Table 2. Values of slope *S* together with the soil parameters (bulk density, hydraulic conductivity, and root length density) as influenced by soil amendments (biogas slurry and fly ash) in a sandy loam soil

Treatments	Slope (*S*)	Bulk density (Mg m^{-3})	Hydraulic conductivity (cm hr^{-1})	Root length density (cm cm^{-3})
Control	0.046^{a}	1.52^{a}	0.51^{c}	0.47^{a}
Biogas slurry				
@ 4 Mg ha^{-1}	0.062^{c}	1.40^{b}	0.65^{b}	0.76^{b}
@ 16 Mg ha^{-1}	0.064^{cd}	1.32^{c}	1.01^{a}	0.95^{c}
Fly ash				
@ 0.5 Mg ha^{-1}	0.051^{b}	1.46^{ab}	0.61^{b}	0.84^{b}
@ 1.0 Mg ha^{-1}	0.052^{b}	1.44^{b}	0.66^{b}	0.86^{b}
@ 1.5 Mg ha^{-1}	0.059^{c}	1.41^{b}	0.90^{a}	0.89^{cd}

a-d: values followed by similar letters within a column are not significantly different at P=0.05

had significant effect on bulk density at wheat harvest (Table 2). The bulk density was recorded 1.32 and 1.41 Mg m^{-3} with applications of biogas slurry and fly ash @16 Mg ha^{-1} and 1.5 Mg ha^{-1}, respectively, as against 1.52 Mg m^{-3} in control plots. The lowering in bulk density of soil was attained due to low density of these amendments (Chatterjee *et al.*, 1988). The native soil was sandy loam (sand >70% and clay 15-20%) in texture, while the texture of fly ash was silt loam (particle size varied between 0.002-0.02 mm) with less particle and bulk densities compared to bulk soil. Application of amendments also increased the soil hydraulic conductivity of the surface layer from 0.51 (control) to 1.01 (biogas slurry @16 Mg ha^{-1}) and 0.9 (fly ash @1.5 Mg ha^{-1}) cm h^{-1} and this might be attributed to improvement in soil structure (Shakweer *et al.*, 1998). Application of amendments enriched the soil of certain nutrients, encouraging the biological activity and thereby, resulted in increased moisture retention, better aeration and drainage and reduction in bulk density. Plant root growth and other biological activity in the soil created a better pore connectivity, improving the hydraulic conductivity. Value of *S* increased from 0.046 to 0.062 and 0.064 with application of biogas slurry @ 4 and 16 Mg ha^{-1}, respectively (Table 2). Application of fly ash also improved the *S* value, and difference was not significant between the rates 0.5 and 1.0 Mg ha^{-1}, but significantly more with fly ash application @1.5 Mg ha^{-1}. As the soil physical parameters improved through soil amendments, values of *S* tended to be optimum, showing a highly positive correlation between soil quality and the slope *S* at the inflection point of the soil water function. The root length density in wheat was twice as compared to control, which suggested better soil physical environment followed by application of soil amendments, as argued by Dexter *et al.* (2004a) who reported that larger values of *S* implied a better soil physical condition for root development. Results showed that the root length density in wheat also increased by two-fold to 0.95 and 0.89 cm cm^{-3} with applications of biogas slurry @16 Mg ha^{-1} and fly ash @1.5 Mg ha^{-1}, respectively over control. It was reported that root growth would seriously be hampered with *S* values less than 0.030 (Dexter, 2004a). In the present experiment, the *S* values were well above the prescribed value and the improved root growth was in addition to the improvement in soil physical environment, also due to additional nutrients available through the soil amendments. Thus, the sensitivity of *S* with change in soil physical parameters and root growth could imply the possible use of *S* in defining and quantifying soil physical quality.

The influence of different conditioners (FYM @50 Mg ha^{-1}, factory waste @6 Mg ha^{-1}, fertilade 0.1 Mg ha^{-1}, polyvinyl acrylate (PVA) @ 0.4 Mg ha^{-1}, and basic H-concentrate @ 4 Mg ha^{-1}) on *S* was investigated using the experimental data of AICRP on tillage (1987) for two soils namely clay loam of Jind (Kaul series), and sandy loam of Hisar (Ladwa series) (Fig. 3). Addition of soil conditioners resulted in increased plant available water capacity (PAWC; difference between field

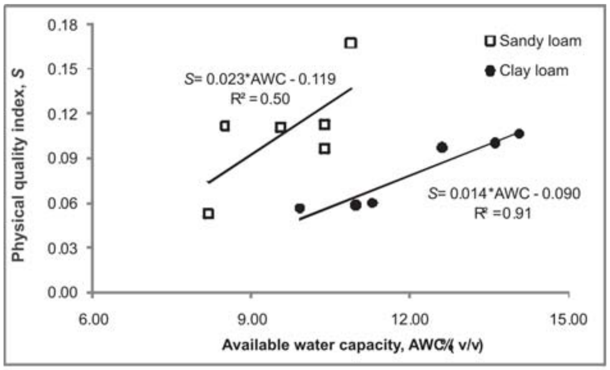

Fig. 3. Experimental values of *S* as a function of available water capacity for sandy loam (Hisar) and clay loam (Jind) soils in Haryana as influenced by soil applications of factory-waste, farm yard manure, basic H-conc., fertilade and polyvenyl acrylate in various quantities

capacity and wilting point water content) in soil and larger values of *S* over control, indicating improvement in soil structure and physical quality of the soil. In another follow up experiment, other soil properties like bulk density, hydraulic conductivity and cumulative infiltration was modified through application of these conditioners, which had positive impact on crop growth and yield. Incorporation of crop residues, manures, organic substances, and other synthetic organic materials alter the soil environment, which in turn improves the soil structure or soil physical conditions and thereby increasing the infiltration and reducing the runoff. In general, use of soil conditioners improves the soil physical quality and promotes plant growth (Wallace and Terry, 1998). This increase in PAWC might be attributed to increased number of micro pores and decreased number of macro pores as compared with the control. Similar observations were reported by Asghari *et al.* (2009). Many studies have reported that soil conditioners improved the soil physical properties under different conditions. (Barzegar *et al*., 2002; Nyamangara *et al*., 2001; Bryan, 1992; Pagliai *et al*., 1981).

It is interesting to consider the results obtained using *jalshakti* in loamy (63% sand, 19.8% clay) and loamy sand (80.8% sand, 10.0% clay) soils. Here, the effect of *Jalshakti* on *S* has been investigated using the experimental data of AICRP on tillage (1987) on water retention at different suctions ranging from 10 to 1500 kPa. The organic C status in the loamy soil of Hisar was better (5.0 g kg^{-1}) compared to loamy sand soil of Sahpur with average organic C of 2.2 g kg^{-1}. Application of *Jalshakti* @ 0.1, 0.5, 1.0 and 2.0 g kg^{-1} of soil increased the water retention substantially at all the suctions values. Available water capacity in soil for pea crop also increased with increasing amount of *jalshakti* due to increase in field capacity water content. In a similar fashion, calculated values of *S* (by fitting the moisture retention values to van Genuchten curve) also increased with additional rates of *jalshakti* (Fig. 4). Increase in available water capacity and consequently increase in *S* could be undoubtedly referred to increase in soil porosity, aggregate stability, and overall improvement in soil structure.

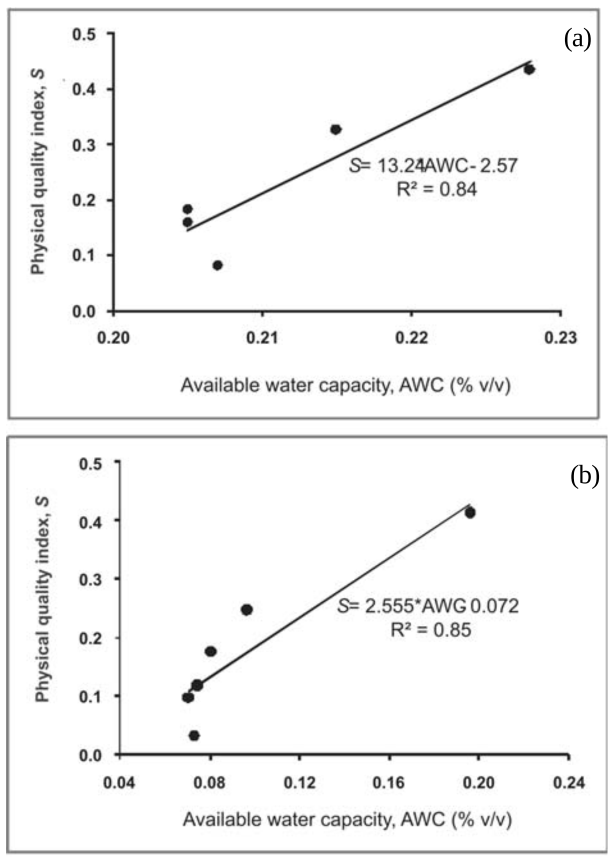

Fig. 4. Estimated values of the index *S* as a function of available water capacity in Hisar loam (a) and Sahpur loamy sand (b) as influenced by different levels of soil conditioner, *jalshakti*

Table 3. Effect of long term application of fertilizers and organic manures on soil organic carbon, hydro-physical properties and root growth (0-15 cm) in a sandy loam soil at IARI, New Delhi

Treatments	SOC (g kg^{-1} of soil)	BD (Mg m^{-3})	MWD (mm)	Pores Macro (>0.25 mm)	Pores Micro (<0.25 mm)	Ks (cm hr^{-1})	PAWC (cm)	RWD (mg cm^{-3})	S
Control	4.5^{a}	1.63^{a}	0.51^{a}	0.26^{a}	0.14^{a}	1.19^{a}	1.71^{a}	1.12^{a}	0.038^{a}
100%NPK	5.9^{b}	1.57^{b}	0.55^{b}	0.31^{b}	0.17^{b}	2.38^{b}	2.19^{b}	1.88^{b}	0.045^{b}
150%NPK	6.7^{c}	1.53^{b}	0.62^{c}	0.31^{b}	0.16^{b}	2.96^{b}	2.26^{b}	1.94^{bc}	0.047^{b}
100%NPK+S @45 kg ha^{-1}	6.3^{b}	1.57^{b}	0.61^{c}	0.32^{b}	0.16^{b}	2.38^{b}	2.38^{b}	1.99^{c}	0.048^{b}
100%NPK+FYM @15 Mg ha^{-1}	6.8^{c}	1.55^{b}	0.67^{d}	0.34^{c}	0.16^{b}	2.54^{b}	2.70^{c}	2.16^{d}	0.053^{c}

SOC=Soil organic carbon; BD=Bulk density, MWD=Mean weight diameter of aggregates; Ks=Saturated hydraulic conductivity; PAWC=Plant available water capacity; RWD=Root weight density; S=Soil physical index; within a column; Values with different letters in a column are significantly different at P=0.05.

Effect of long-term fertilization in maize-wheat rotation

Valuable information regarding soil physical quality in the most active soil layer (0-15 cm) was obtained by evaluating dynamic soil physical properties like soil organic carbon (SOC), bulk density (BD), mean weight diameter (MWD), macro-pores and micro-pores, saturated hydraulic conductivity (Ks) and plant available water capacity (PAWC) and root weight density (RWD) (Table 3). The SOC content was significantly influenced by fertilizer treatments. There was an improvement in SOC in all the treatments over control and significantly higher amount of organic carbon (6.8 g kg^{-1} of soil) was recorded with the application of FYM, closely followed by 150% NPK application than 100%NPK with sulphur or 100%NPK. Role of manure in improving the organic C in soil was also reflected in other soil physical properties. Increase in SOC with fertilizer application higher than the recommended dose could be explained by better crop growth, enlarged rooting system, and higher biomass production which ultimately increased the below- and above-ground plant residues return to soil. Integrated use of manure with mineral fertilizers in accumulating higher amount of organic carbon and subsequently improvement in physical parameters has been reported in the same experiment (Hati *et al*., 2007) and also elsewhere (Zhangliu, 2009).

In 0-15 cm, among the various treatments, there was no significant difference in bulk density, though it was significantly lower compared to control plots (1.63 Mg m^{-3}), mean weight diameter (MWD) of aggregates showed significant improvement in manure plots (0.67). Sulphur application coupled with recommended NPK also resulted in significantly higher MWD (0.61) than even recommended NPK (without S) application (0.55) and was at par with 150% NPK (0.62). This clearly demonstrated better aggregation status with increase in SOC content due to high level of biotic activity, as also evidenced by root biomass, which was significantly higher in manure plots (2.16 mg cm^{-3}) and than in sulphur and 150% NPK (1.99 and 1.94 mg cm^{-3}, respectively). Increase in MWD due to increase in SOC content have been reported by many researchers (Acharya *et al*., 1988, Rasool *et al*., 2008). Effects were also clearly visible in relative proportion of macro-pores and micro-pores, Ks and PAWC (Table 3). Manure treatment significantly increased macro pores while no significant differences were observed among the fertilizer treatments as also observed by Pagliai *et al.* (2004) and Zhangliu *et al*. (2009). Compared to control, all the fertilizer treatments improved hydraulic conductivity and available water capacity but there were no significant differences among them. This result was consistent with Subbian *et al*. (2000) who reported that available water capacity was high but not significantly affected by fertilizer levels. In consistent with the larger macro pores in manure plots, PAWC was also significantly higher (no difference in micro pores). Higher values of Ks may be attributed to type, arrangement and shape of pores. Increasing SOC not only improves soil structure and tilth but also improves the available water capacity.

The previous discussion conclusively proved the effect of long-term application of manures and fertilizers on SOC and soil physical properties including BD, aggregation, Ks and PAWC. Simultaneously, the *S* values were calculated and was found between 0.038 (control) and 0.053 (manure treatment). All the calculated S values were well above the critical limit (0.035), as proposed by Dexter (2004b), indicating no apparent degradation in soil physical quality with long-term application of NPK with or without sulphur or manures. Maximum *S* value was associated with manure treatment, precisely indicating substantial improvement in soil physical quality, as also evidenced by other parameters. Additionally, mineral fertilizer also helped in enhancing the index values, but the improvement is less as compared to manure application. This manure application has contributed to increase in SOC concentration and improved soil structure, resulting in overall improvement of soil physical quality.

Differences in SOC indicated that highest MWD and better root growth resulted in maximum root density. Although application of fertilizer alone did not add organic materials directly but resulted in better rooting system than control and as a result, improved SOC concentrations while application of FYM not only supplied additional nutrients for crop production, it also acted as a valuable source of SOC. The data fitted by the linear equations gave a coefficient of determination of 32% with *S* values negatively correlated with bulk density and a coefficient of determination of 31% with *S* positively correlated with SOC (Fig. 5). It can be concluded that different treatments that led to a greater contents of organic matter in the soil also led to better soil physical quality as indicated by relatively higher values of *S*. This increase in SOC affects the soil

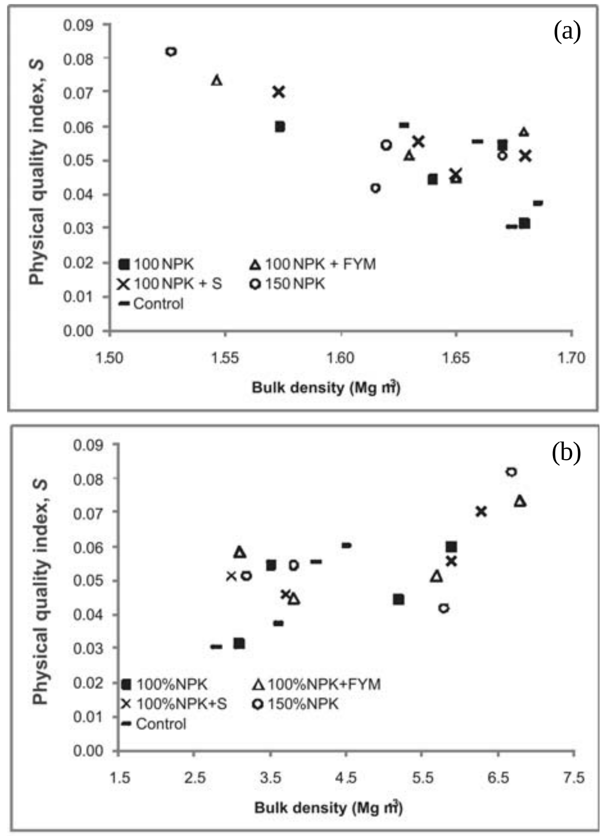

Fig. 5. The *S* value as a function of bulk density (a) and soil organic matter content (b) as calculated from the data of 34 years of cereal based cropping system at New Delhi, India (sandy loam soil)

physical quality through its positive effect on development of stable soil aggregates. Highly aggregated soils thus formed have increased pore space and infiltration resulting in improved soil physical quality.

Conclusions

Results thus support the hypothesis that the index *S* provides a scale that can be used for comparative and rapid differentiation of soils or the effects of different soil physical conditions and management practices. From these studies, it is clear that different management practices that lead to decrease in bulk density and increase in organic carbon content, available water capacity resulted in larger values of *S*, indicating improvement in soil physical quality. Increased values of *S* are obtained in zero tillage where there was minimal disturbance of soil and greater accumulation of organic matter due to incorporation of greater volume of roots. This zero tillage might have contributed to greater macro-porosity, enhancing soil structure and consequently improved soil physical quality. Similarly the long-term use of manure application resulted in increased organic carbon content, aggregation and pore connectivity with higher values of *S* indicating good structure and physical quality. Therefore, these results support *S* as an indicator of soil physical quality and it will contribute greatly to the overall assessment of soil quality.

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