Soil physical quality as influenced by long-term fertilizer management under an intensive cropping system

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Abstract: In China's major rice (*Oryza sativa* L.) production regions, the traditional fertilization modes are challenged by the continued decrease in manure and increase in mineral fertilizer. However, limited information exists on the influences of long-term fertilizer management on soil organic carbon (SOC) and soil physical properties under the intensive rice production system in southern China. The objective of this study was to characterize the changes of soil physical properties as related to mineral fertilizer, crop residues, and manure application based on a long-term field experiment. The experiment, initiated in 1986, has five treatments: unfertilized, mineral fertilizer alone, rice residues plus mineral fertilizer, low manure rate plus mineral fertilizer, and high manure rate plus mineral fertilizer. The cropping system consists of barley (*Hordaum vulgare* L.), early rice, and late rice, three crops in a year. In May 2006, after barley harvest, soil samples were collected from the 0～10 cm and 10～20 cm layers to determine SOC concentration, aggregate size distribution, bulk density (ρ_b), saturated hydraulic conductivity (K_s), and soil water characteristic curves (SWCC). The results indicated that manure significantly reduced ρ_b, increased SOC concentration, soil aggregation, K_s, transmission and storage porosity, as well as water retention capacity. Combined application of crop residue and mineral fertilizer also improved soil physical properties, but the improvement by mineral fertilizer alone was limited. Correlation analysis demonstrated that *S*, the slope of the SWCC at its inflection point, was closely associated with the selected physical parameters, suggesting *S* was an effective parameter for soil physical quality evaluation. Nevertheless, in applying the S-theory, a unified approach to define the residual water content should be considered.

Key words: Mineral fertilizer, crop residue, manure, soil physical quality, soil water characteristic curve, *S*-theory

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1 Introduction

Soil quality is a key component of sustainable agriculture. The inherent attributes of soil quality is "the capacity of soil function"[1], which can be assessed by soil physical, chemical, and biological properties indicators. The physical quality of agricultural soils primarily refers to soil strength, water transmission and storage properties in the crop root zone, which plays an integral role in controlling chemical and biological processes[2], and its evaluation must be developed using parameters describing physical behaviors. Measurement of a few selected physical properties may not adequately characterize soil quality due to their spatial-temporal variability and their strong interdependence. Integrated soil quality indicator based on a combination of soil properties can better reflect the status of soil quality than individual parameters. The *S* value, proposed by Dexter[3-5], is such an index that can effectively quantify the modifications of soil physical quality by management practices. Based on soil water characteristic cure (SWCC), *S* is defined as the slope of the SWCC at its inflection point. In most cases, SWCC used to calculate *S* is

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established from pedotransfer functions[3-5], only a few studies applied SWCC measurements on undisturbed soil cores[6].

Soil organic matter (SOM) has been identified as a key factor in maintaining soil quality and crop production[1]. It contributes directly to plant and microbial growth through its influences on soil chemical, physical and biological properties[7]. Tisdall and Oades (1982) presented a hierarchical conceptual model of aggregate formation and SOM turnover, emphasizing the importance of organic matter to soil structural stability[8]. A high proportion of stable aggregates is desirable, as they can sustain a range of pore sizes and promote aeration, water infiltration, and drainage[9]. Hence, a decline in SOM content may result in poor soil physical quality, especially under intensive cropping systems.

It has been well established that long-term application of organic materials (manure and/or crop residues) can increase SOM concentration, decrease bulk density (ρ_b)[10-12], improve pore size distribution[13,14] and saturated hydraulic conductivity (K_s)[12, 13], and increase water retention capacity[11,15]. These studies have indicated the beneficial effects of organic matter on improving physical properties. However, relevant information is limited under intensive rice cropping systems in China.

The middle and lower Yangtze River Plain is one of the most important rice (*Oryza sativa* L.) production bases in China. Since the 1980s, traditional fertilizer management practices have been altered considerably. With the continuous increase of mineral fertilizer application rates, manure inputs have been declining dramatically. Meanwhile, returning crop residue to field is being accepted gradually. There is a growing concern that the new fertilization systems may not be sustainable due to their detrimental effects on soil properties. Does mineral fertilizer alone reduce soil organic matter content and negatively affect soil aggregation, water retention capacity and hydraulic conductivity? Is crop residue application a viable option to maintain soil organic matter content and physical quality?

The first objective of this study was to compare the consequences of long-term application of manure, crop residue, and mineral fertilizer on soil organic carbon (SOC) and selected soil physical properties. The second objective was to apply the *S*-theory to quantitatively assess soil physical quality using a long-term fertilizer experiment.

2 Materials and methods

2.1 Site and cropping system

The experiment was established in 1986. It locates in Ning Xiang County (28°07'N, 112°18'E, and altitude 36 m) of Hunan Province, China. Under a continent monsoon climate, the annual mean precipitation is 1553 mm and potential evapotranspiration is 1354 mm. The monthly mean temperature is 17.2°C. Soil texture of the plough layer (0～20 cm) is silt clay loam with 13.71% sand and 57.73% silt. At the beginning of the study, the soil had an organic matter concentration of 30.9 g/kg. There are three crops in a year, barley (*Hordeum vulgare* L.), early rice, and late rice. Barley is sown in the middle of November and is harvested in early May of the following year. Early rice is then transplanted, and harvested in the middle of July. The growing season of late rice lasts from late July to the end of October.

2.2 Experiment design

The experiment had five treatments: control (without fertilizer input, CK), mineral fertilizer only (F), crop residue plus mineral fertilizer (RS+F), low manure rate plus mineral fertilizer (M_1+F), and high manure rate plus mineral fertilizer (M_2+F). The design made all the fertilize treatments receiving the same N rate (the amount of N in mineral fertilizer plus that from rice residue or manure). The mineral fertilizers included urea, ordinary superphosphate, and potassium chloride. Details about the fertilizer management are listed in Table 1. Before crop seeding or transplanting seedling, air-dried rice residue and fresh pig manure was incorporated into the soil manually with a spade. The cultivation depth was about 20 cm. For early rice, late rice, and barley, 40%, 30%, and 30% of mineral nitrogen fertilizer was applied at seeding, and the remaining nitrogen fertilizer was applied by top dressing in the growth periods. All the phosphorus and potassium fertilizers were applied at seeding. There were three replications and each plot size was 66.7 m^2.

Table 1 Nutrient supply from rice straw, fresh pig manure, and mineral fertilizer under different fertilizer treatments. The treatments are no fertilizer (CK), mineral fertilizer alone (F), crop residue plus mineral fertilizer (RS+F), lower manure rate plus mineral fertilizer (M_1+F), and high manure rate plus mineral fertilizer (M_2+F). The numbers are in kg·hm^{-2}

Treatment	Early rice			Late rice			Barley			Total		
	N	P	K	N	P	K	N	P	K	N	P	K
CK	0+0†	0+0	0+0	0+0	0+0	0+0	0+0	0+0	0+0	0	0	0
F	143+0	12+0	56+0	157+0	16+0	52+0	157+0	16+0	52+0	457	44	160
RS+F	117+26	12+20	0+54	131+27	12+4	0+57	131+27	12+4	0+57	459	48	168
M_1+F	92+52	12+20	26+37	111+47	18+18	18+34	111+47	0+18	18+34	460	86	167
M_2+F	39+104	0+39	0+75	62+95	36+36	0+68	62+95	0+36	0+68	457	147	211

† input from mineral fertilizer + input from organic fertilizer.

Note: 1) For the RS+F treatment, rice straw return rate (air dry) was 2.85, 3.0, and 3.0 t/(hm^2·a) for early rice, late rice, and barley, respectively. 2) For the M_1+F treatment, manure application rate (fresh) was 11.25, 10.23, and 10.23 t/(hm^2·a) for early rice, late rice, and barley, respectively. 3) For the M_2+F treatment, manure application rate (fresh) was 22.50, 20.55, and 20.55 t/(hm^2·a) for early rice, late rice, and barley, respectively. 4) The N, P, and K content of air-dry rice straw was 9.1, 1.3%, and 18.9 g/kg, respectively, and N, P, and K content of fresh pig manure was 4.61, 1.75, and 3.32 g/kg, respectively.

2.3 Soil sampling and measurements

Soil samples were taken from the 0～10 and 10～20 cm layers in May 2006, after barley harvest. Two samples were taken from each plot. Undisturbed samples were 120.7 cm^3 (4 cm high and 6.2 cm in diameter), 100 cm^3 (5 cm high and 5 cm in diameter), and 22.9 cm^3 (1 cm high and 5.4 cm in diameter) for determination K_s, ρ_b, and SWCC, respectively. Soil K_s was measured using the constant head method[16]. Soil ρ_b was determined by oven-drying the samples at 105℃ for 24 h. For the SWCC, the low-pressure portion (0, 0.5, 1, 2, 4, 6, and 8 kPa) was measured using the sand box, and the high-pressure portion (10, 30, 50, 100, 300, 500, 700, 1000, and 1500 kPa) was measured using the pressure plate method[17].

Field-moist soil samples were gently broken to pass an 8-mm sieve and air-dried. Part of the samples was further passed a 2-, 0.25-mm sieve to determine particle size distribution[18], and SOC concentration[19], respectively.

Water stable aggregates were determined by the wet sieving method[9]. Briefly, a 50 g air-dried subsample (＜8 mm) was rapidly submerged for 2 min in deionized water, on top of the 5-mm sieve with a sieve mesh sequence of 5, 2, 1, and 0.25 mm. Aggregate separation was achieved by mechanically moving the sieve up and down 6 cm with 130 repetitions during a period of 5 min. All aggregate fractions were oven-dried (60℃) for 48 h and weighed. Sand content (＞53 m) of the aggregates was determined on a sub-sample of aggregates that were dispersed with sodium hexametaphosphate (5 g/L).

2.4 Calculation and data analysis

Soil water content at water suction of 33 kPa (approximately pF = 2.5) and 1500 kPa (approximately pF = 4.2) was defined as field water capacity (FWC) and permanent wilting point (PWP), respectively. Available water content (AWC) was the difference between FWC and PWP[20].

The van Genuchten (1980) equation was applied to describe the relationship between soil suction and water content[21]:

$$\theta = \theta_r + (\theta_s - \theta_r)\left[1 + (\alpha h)^n\right]^{-m} \tag{1}$$

where θ was water content, kg/kg; θ_r was the residual water content, kg/kg; θ_s was the saturated water content, kg/kg; h was soil suction (cm of water); α was a scaling factor for h, and m and n were shape parameters (α＞0, m = 1−1/n, n＞1, 0 < m＜1). The variables θ_r, θ_s, α, and n were estimated by fitting Eq. (1) to the experimental data using the Solver optimization procedure in Microsoft Excel. Then S value was calculated from

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

The proportion of water stable macroaggregate (WSMA) and mean weight diameter (MWD) based on sand-free aggregates were determined by following equations[9],

$$\text{WSMA}\,(\%\text{ of soil} > 250\ \mu\text{m}) = \frac{\text{weight of dry aggregates - sand}}{\text{weight of dry soil - sand}} \times 100\% \quad (3)$$

$$MWD = \sum_{i=1}^{n} w_i \bar{x}_i \quad (4)$$

where $\bar{x}_i$ was the mean diameter (mm) of the aggregate size fractions and w_i was the proportion of each aggregate size with respect to the total sample weight.

Mean pore diameter at a given suction was estimated from water retention data using the following equation[22]:

$$\delta = (4\sigma\cos\varphi)/(\rho_w g h) = 3000/h \qquad (h>0) \quad (5)$$

where δ was the equivalent diameter of the pore, μm; σ was the surface tension (7.36×10^{-2} J/m^2 at 22℃); φ was the contact angle between the water and pore wall (assumed to be zero); ρ_w was the density of water; g was the gravitational acceleration, and h was matric suction (cm of water). According to their functions in water retention and conduction, soil pores were divided into three groups: the volume of pores drained between 20～100 cm of water was transmission pores (P_t, with diameter between 30 and 150 μm), pores drained between 100～15000 cm of water was termed as storage pores (P_s, with diameter between 0.2 and 30 μm), whereas the portion of pores less than 0.2 μm was defined as mircopores (P_m)[23].

2.5 Statistical analysis

One-way analysis of variance (ANOVA) was performed for each depth (0～10 and 10～20 cm) using the SPSS 11.0 software[24]. All differences discussed are significant at the $P<0.05$ probability level. Fisher's protected least significant difference (LSD) was calculated only when the analysis of variance F-test was significant at $P<0.05$.

3 Results and discussion

3.1 Soil organic carbon

The concentration of SOC was significantly influenced by fertilizer treatments (Table 2). In the 0～10 cm layer, SOC concentration of F, RS+F, M_1+F, and M_2+F was 12.7%, 33.7%, 61.7%, and 99.8 % higher than that of CK. Similar trends were also shown in the 10～20 cm layer. These differences demonstrated that manure was most effective in enhancing SOC accumulation, followed by rice residue. These results agreed with other findings[13,25]. Though mineral fertilizer alone did not input organic materials directly, it did enlarge rooting system and as a result improved SOC concentration[10,26]. Nevertheless, SOC increase from mineral fertilizer alone was limited in comparing to manure and rice residue.

Table 2 Influences of long-term mineral fertilizer, rice residues and manure application on soil organic carbon (SOC) concentration, bulk density (ρ_b), mean weight diameter (MWD), proportion of water stable macroaggregates (WSMA), saturated hydraulic conductivity (K_s), field water capacity (FWC), plant available water content (AWC), and S index of the 0～10 and 10～20 cm soil layers

Soil layer /cm	Treatment	SOC /g・kg^{-1}	ρ_b /mg・m^{-3}	MWD /mm	WSMA /kg・kg^{-1}	K_s /cm・h^{-1}	FWC /kg・kg^{-1}	AWC /kg・kg^{-1}	S
0～10	CK	15.77e	1.25a	1.99e	0.61d	0.84c	0.32c	0.12c	0.041c
	F	17.76d	1.21a	2.39d	0.63d	1.17c	0.32c	0.12c	0.043bc
	RS+F	21.08c	1.02b	2.69c	0.72c	1.87b	0.37b	0.14b	0.047b
	M_1+F	25.50b	0.99b	3.35b	0.81b	3.32a	0.41a	0.17a	0.061a
	M_2+F	31.51a	0.91c	3.71a	0.88a	3.80a	0.41a	0.18a	0.065a
10～20	CK	14.60e	1.29a	2.62b	0.67b	0.51c	0.32d	0.12d	0.039d
	F	16.26d	1.26a	2.60b	0.70b	1.23b	0.34c	0.13cd	0.043cd
	RS+F	20.54c	1.08b	2.98ab	0.74ab	1.47b	0.36b	0.14c	0.048c
	M_1+F	24.90b	1.03c	3.24a	0.82a	2.38a	0.40a	0.16b	0.057b
	M_2+F	29.22a	0.94d	3.41a	0.84a	2.78a	0.40a	0.18a	0.070a

Numbers in the same column for each soil layer followed by the same letter are not significantly different according to LSD ($P>0.05$).

3.2 Soil bulk density

The results of ρ_b varied in the order of CK＞F＞RS+F＞M_1+F＞M_2+F (Table 2). The treatments with organic inputs (RS+F, M_1+F, and M_2+F) significantly reduced ρ_b, but the influence of mineral fertilizer alone was insignificant in both layers. Additionally, M_2+F had significantly lower ρ_b than M_1+F, indicating that not only the organic materials, but also their application rates were determining factors for ρ_b. Correlation analysis also revealed that ρ_b was negatively related to SOC concentration in the 0～20 cm soil layer (r^2 = 0.92).

A decrease in ρ_b through manure addition has been reported elsewhere[10-12]. It is likely that the increase in SOM by organic inputs results in greater biological activities, which in turn increases porosity[26].

3.3 Soil aggregate distribution and stability

In the 0～10 cm layer, fertilizer treatments generally increased the proportion of aggregates in the ＞5, 2～5, and 1～2 mm size ranges, and decreased aggregates in the 0.25-1 and ＜1 mm fractions (Figure 1). Again the magnitude of increases under manure was larger than that under mineral fertilizer alone, and crop residues incorporation ranked intermediate between the manure and mineral fertilizer alone treatments. In the 10～20 cm layer, treatment effect on aggregate size distribution showed the same trend as in 0～10 cm layer, but the differences became smaller.

Soil aggregation expressed by MWD and proportion of WSMA was significantly affected by fertilizer treatments (Table 2). Compared to CK, the RS+F, M_1+F, and M_2+F treatments significantly increased MWD and WSMA. In addition, the M_2+F had higher MWD and WSMA than those in the M_1+F in 0～10 cm layer, indicating the positive effect on soil aggregation by high manure rate. The effect of crop residues on aggregation was also significant relative to F and CK in the 0～10 cm layer. Addition of mineral fertilizer alone increased MWD, but there was no difference in WSMA between F and CK, showing the role of mineral fertilizer was limited. The differences in MWD and WSMA among the treatments were less pronounced in the 10～20 cm layer.

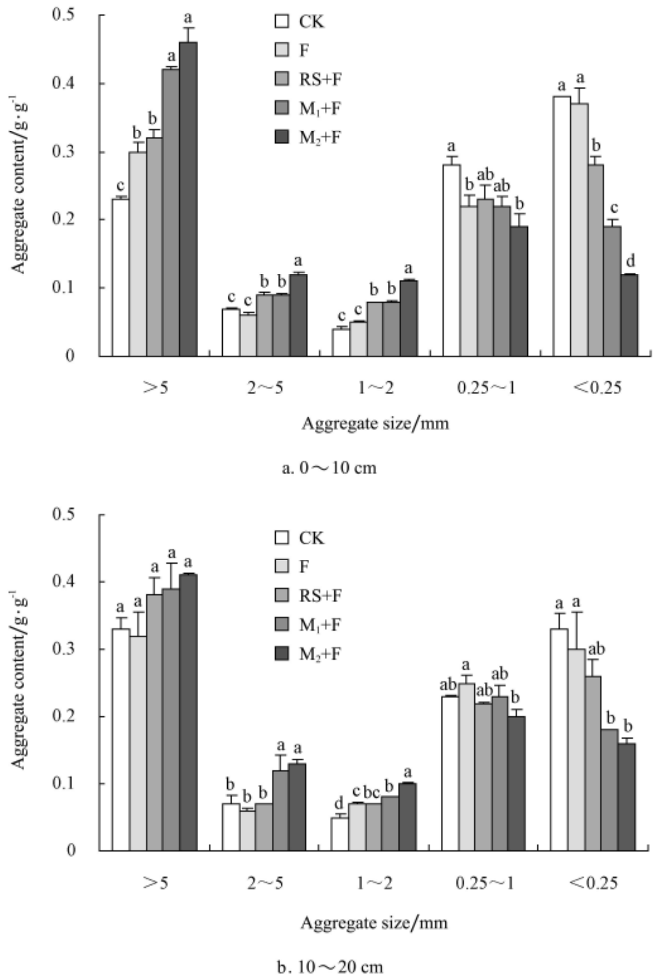


Figure 1 Fertilizer management influences on the sand-free aggregate distribution (mean ± standard error). Values followed by a different lowercase letter among management treatments within an aggregate size are significantly different at ＜0.05 according to least significant difference (LSD)

Correlation analysis revealed that MWD and WSMA were positively related to SOC concentration in the 0～10 cm soil layer (r = 0.984, P = 0.003; r = 0.988, P = 0.001, respectively), indicating the importance of SOM in soil aggregation. Similar results have been reported by others[12,13]. It is likely that constant organic matter supply through manure or crop residue application favors high level of microbial activities and production of binding agent in the macroaggregates[26].

3.4 Soil pore indicators

The transmission pores and storage pores are important in maintaining soil structure and holding available water in soil-plant-water system. For all the treatments, P_s and P_m accounted the majority of the pore volumes (＞70%) (Table 3). No significant differences were observed between RS+F, F, and CK, but manure significantly increased the fractions of transmission and storage pores at the expense of micropores. The M_2+F treatment tended to have a higher portion of transmission and storage pores, and lower micropores than the M_1+F, but the differences were generally insignificant. These results supported the findings of Pagliai et al. (2004) that compost and manure addition increased the percentage of elongated pores (50～500 μm, or transmission pores)[14]. Furthermore, the improvement in soil aggregation could increase inter-and intra aggregates pores, which might be responsible for increase in water transmission and storage pores.

Table 3 Influences of long-term mineral fertilizer, rice residues, and manure on the proportion of transmission pores (P_t), storage pores (P_s), and micropores (P_m)

Soil layer/cm	Treatment	P_t /m^3·m^{-3}	P_s /m^3·m^{-3}	P_m /m^3·m^{-3}
0~10	CK	0.12b	0.37b	0.43a
	F	0.13ab	0.36b	0.42a
	RS+F	0.13ab	0.35b	0.42a
	M_1+F	0.14a	0.39a	0.38b
	M_2+F	0.14a	0.42a	0.36b
10~20	CK	0.12c	0.37b	0.45a
	F	0.12c	0.38b	0.43ab
	RS+F	0.13bc	0.37b	0.41ab
	M_1+F	0.14b	0.39ab	0.39b
	M_2+F	0.16a	0.40a	0.32c

Numbers in the same column for each soil depth followed by the same letter are not significantly different according to LSD ($P>0.05$).

3.5 Saturated hydraulic conductivity

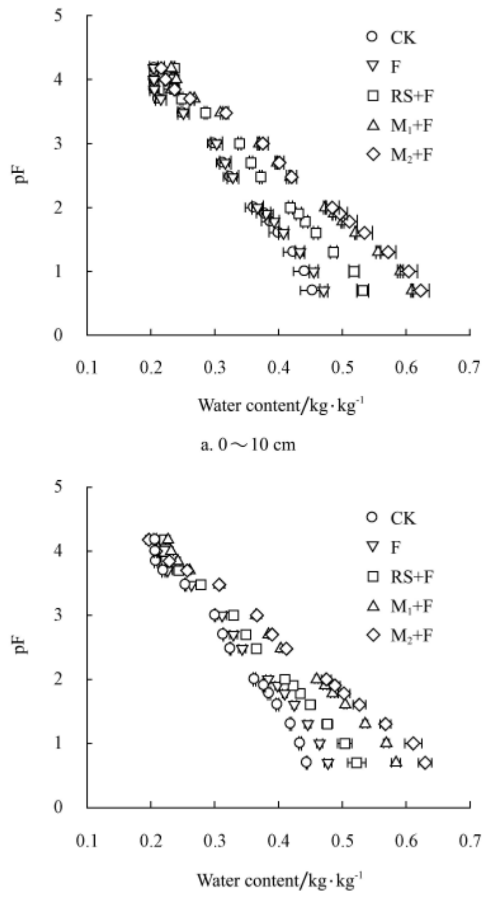
Comparing to the control, all the fertilizer treatments improved K_s, but the largest increase was from M_2+F and M_1+F (Table 2). Although crop residue and fertilizer alone also improved K_s, the extent of the changes was much less than the manure treatments. In the 0～10 cm layer, for example, the K_s of M_2+F treatment was 2.0, 3.3, and 4.5 times than that of the RS+F, F, and CK, respectively. Other studies had obtained similar results[11,13, 14].

Organic materials affect soil hydraulic conductivity by modifying soil structure, porosity, and aggregate stability. Soils with high portion of transmission pores generally give higher K_s values. Correlation analysis indicated that there was a positive relationship between K_s and P_t (r = 0.947, P = 0.035) in the 0～10 cm layer. Schjønning et al. (2002) attributed the increased K_s on soils receiving animal manure to the larger volume of pores greater than 30 μm[15].

There was significant correlations between K_s and MWD (r = 0.992, P = 0.001) and WSMA (r = 0.992, P = 0.001) in the 0～10 cm layer. Hence, SOM accumulation improves aggregation and soil structure stability, and accordingly increases hydraulic conductivity.

3.6 Soil water characteristic curves and water holding capacity

The SWCC displayed two distinct features. First, at a given soil water suction, the M_1+F and M_2+F treatments showed the highest water contents, followed by RS+F, and F and CK had the lowest water contents (Figure 2). However, the differences between M_1+F and M_2+F and between F and CK were insignificant. Second, the difference in water content between fertilizer treatments became smaller with the increase of soil water suction.



a. 0～10 cm

b. 10～20 cm

Figure 2 Soil water characteristic curves as influenced by long-term fertilizer management for the 0～10, 10～20 cm soil layers. The horizontal bars indicate ± one standard error

In the 0～10 cm layer, for example, the FWC of treatments with manure (M_2+F and M_1+F) and crop residue (RS+F) was 0.09 kg/kg and 0.05 kg/kg higher than that of the F and CK (Table 2). However, the PWP only varied slightly, from 0.23 kg/kg for M_2+F, M_1+F, and RS+F to 0.20 kg/kg for F and CK. Consequently, M_2+F and M_1+F had considerably higher AWC than those of RS+F, F, and CK, but no significant differences were observed between M_2+F and M_1+F, and between F and CK (Table 2). Similar trends were also observed in the 10～20 cm layer. These results agree with the findings from other studies[11,13,26].

3.7 Soil physical quality indicator S

In the 0～10 cm layer, S varied from 0.041 to 0.065, following the order of M_2+F＞M_1+F＞RS+F＞F＞CK, but no statistical difference was observed between M_1+F and M_2+F, RS+F and F, and F and CK (Table 2). Similar trend was also found in the 10～20 cm except that the differences between M_1+F and M_2+F became significant (P＜0.05). Clearly, manure was most effective in improving the overall soil physical quality. Crop residue and mineral fertilizer also enhanced soil physical quality, but the improvement is limited.

Table 4 was the correlation matrix between SOC, S, and other physical parameters. The correlation between S and MWD, WSMA, K_s, FWC, AWC, P_t, P_s were positive, whereas the correlation between S and ρ_b, P_m was negative. Except for P_s, all other parameters correlated with S significantly (P＜0.05), indicating that the S index could well represent these physical parameters and was a good indicator of soil physical quality. While SOC concentration also correlated well with these parameters (Table 4), the S index had the advantage of having the same meaning and consequences for different soils[3].

Table 4 Correlation matrix of soil organic carbon (SOC) concentration and physical properties in the surface layer (0～10 cm). ρ_b: bulk density; MWD: mean weight diameter of aggregates; WSMA: water-stable macroaggregates; K_s: saturated hydraulic conductivity; S: physical quality indicator (Dexter, 2004a); FWC: field water capacity; AWC: available water content; P_t: transmission pores; P_s: storage pores; P_m: micropores

	SOC	ρ_b	MWD	WSMA	K_s	S	FWC	AWC	P_t	P_s
ρ_b	-0.94*									
MWD	0.98**	-0.94*								
WSMA	0.99**	-0.97**	0.99**							
K_s	0.98**	-0.94*	0.99**	0.99**						
S	0.98**	-0.91*	0.98**	0.99**	0.99**					
FC	0.95*	-0.97**	0.97**	0.98**	0.98**	0.97**				
AWC	0.97**	-0.90*	0.98**	0.98**	0.99**	0.99**	0.97**			
P_t	0.90*	-0.85ns	0.96**	0.91*	0.95*	0.94*	0.91*	0.93*		
P_s	0.82ns	-0.60ns	0.79ns	0.79ns	0.82ns	0.86ns	0.72ns	0.87ns	0.75ns	
P_m	-0.96*	0.83 ns	0.97**	-0.94*	-0.97**	-0.98**	0.90*	-0.98**	-0.96*	0.90*

"ns" indicates not significant at the 0.05 probability level. * Significant at the 0.05 probability level. ** Significant at the 0.01 probability level.

The results of S are affected by the values of residue water content θ_r (Eq. (2)). Some previous studies set θ_r to zero[3-5]. This may not cause significant errors on course texture soils. On soils with higher clay or organic matter contents, water exists as thin films in soil particle surface even at larger matric suctions (＞1500 kPa), which may introduce substantial errors in the calculated S. In this study, the researchers set $0 \leqslant \theta_r <$ PWP to obtain the van Genuchten (1980) parameters. The fitted θ_r values were zero for all the treatments, considerably lower than the PWP values (0.20～0.23 kg/kg). If θ_r was set to PWP, S would be increased by 19%～35%, though the general tendency of S between treatments did not change. Therefore, further studies are required to investigate appropriate θ_r values for soils of different textures and organic matter contents.

4 Conclusions

Manure plus mineral fertilizer was most effective in improving SOC concentration, soil aggregation and stability, saturated hydraulic conductivity, water retention capacity, and transmission and storage porosity. Combined application of crop residue and mineral fertilizer was also beneficial to soil physical conditions, but the enhancement was smaller than that of manure. Soil quality improvement from mineral fertilizer alone was limited. The analysis emphasized the essential function of SOM in improving soil physical properties. Under the experimental condition, a combination of manure and mineral fertilizer is encouraged. If manure source is limited, mineral fertilizer should be accompanied by crop residue.

The *S* index was closely associated with SOC concentration and selected physical parameters, indicating *S* was an effective indicator of soil physical quality. Meanwhile, in application of *S* theory, a unified approach for determining soil residue water content should be considered.

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