



Poor physical structural components restrict soil fertility and crop productivity for wheat–maize cropping

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Abstract Improving poor physical structural components has been gaining increasing recognition for its role in enhancing soil fertility. This study was conducted to identify the key physical structural barriers for soil fertility and their effects on crop productivity in Aquic Inceptisol. Based on the strip sampling in Fengqiu County, arable soils from 0–0.40 m profile pits were collected to determine the physical structural components including plough layer thickness, textural composition, soil aggregation and bulk density, as well as stocks of soil organic matter (SOM), total nitrogen (TN) and total phosphorus (TP). The grain yields of wheat and maize and amounts of fertilizer applications were also investigated. The tested soil was dominated by a plough layer of 0.15–0.18 m and sandy loam texture, which

constituted 50% and 59%, respectively, of the studied profile pits. Compared to the soil with < 0.15 m plough layer, the bulk density was 4–11% lower in the plough layer and 4–12% lower in subsoil with increasing the thickness of plough layer. The soil with ≥ 0.15 m plough layer had over 21-fold macroaggregation at the expense of microaggregation, whereas the high content of sand particle in soil restrained macroaggregation. Increasing the plough layer thickness averagely improved the stocks by 176% in SOM, 153% in TN and 59% in TP at the 0–0.40 m depth. Soil macroaggregation was also significantly positively correlated with these nutrient accumulations. The factor analysis revealed that soil fertility was significantly influenced by the plough layer thickness and soil texture. The soil with 0.20–0.25 m plough layer and loam clay texture displayed the highest integrated fertility index and consequently, was beneficial to increasing the grain yields of wheat and maize and nutrient use efficiency from applied N fertilizer in the study area. These results would be informative to improve soil fertility and then crop productivity during a long-term cultivation.

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Introduction

The North China Plain is the second largest plain in China which produces almost 60–80% of national wheat and 35–40% of national maize every year (Kong et al. 2014). Cultivated tracts in the plain are dominated by fluvo-aquic soil, which accounts for 13.6 million hectares at present. Due to the parent material derived from alluvial sediments, the soil fertility is restrained by poor physical structural components and meanwhile, the poor physical structure is concurrent with a low level of soil organic matter (SOM) (Zhang et al. 2017). The global population growth has led to intensive farming systems aiming to achieve a high level of food security. In past several decades, however, the intensive soil use has further degraded the soil and deteriorated its environment, resulting in an unsustainable crop productivity. According to the latest investigation initiated by Shi et al. (2010), nearly two-thirds of arable soils were characterized by medium and low fertility in the North China Plain. In order to enhance crop productivity, improving poor soil physical structural components for integrated fertility management is especially pertinent for the North China Plain where soil structure degradation is considered the most important constraint to soil fertility.

Soils provide major ecosystem services such as food production, water retention and sequestration of soil organic carbon (C). The physical structure of soil plays a crucial role in the processes that facilitate these soil functions (Regelink et al. 2015). Generally, soil texture (Plante et al. 2006; Soh et al. 2010), aggregation (Six et al. 2002), plough layer thickness (Al-Kaisi 2001) and bulk density (White et al. 2015) are regarded as the important physical structural components, and their poor statuses could be defined as the physical structural barriers to restrict soil fertility and crop productivity. It was reported by Angst et al. (2018) that soil textural composition was largely dependent on the respective parent material and took a central role in shaping differences in organic C stocks among the investigated sites by affecting SOM stabilization via organo-mineral association and aggregation. The fine-textured soils display a capacity to stabilize new inputs of soil nutrients chemically in association with silt and clay particles, whereas the coarse-textured soils have a lower capacity to stabilize

those inputs, presumably due to their smaller amount of silt and clay surfaces available for nutrient stabilization (Stewart et al. 2008). Soil macroaggregation can physically protect SOM through compartmentalizing substrates and microbial biomass, reducing microbial activity within aggregates because of the low oxygen diffusion, and separating microbial biomass from predators (Six et al. 2002). By contrast, the increased bulk density and soil compaction associated with a decline of plough layer thickness, are found to decrease soil porosity, hydraulic conductivity and infiltration (Schwen et al. 2011), which can affect crop growth and yield (White et al. 2015; Al-Kaisi 2001).

Irrespective of agricultural management practices, various soil physical structural components are closely related through dynamic feedback mechanisms. Regelink et al. (2015) had suggested that the texture had effects on fractions of soil aggregates through changing the clay fraction that could promote macroaggregation by interacting with SOM and leading to the formation of organic-mineral assemblages. Consequently, the transition from coarse-textured to fine-textured soils may have twofold positive effects on bulk SOM stocks through affecting SOM stabilization via soil aggregation and organo-mineral association (Angst et al. 2018). To some extent, the thickness of plough layer determines the capacity of soil providing plants with water, nutrients, oxygen, heat. Accumulated evidence shows that increasing the thickness of plough layer is generally favorable for root development to the deeper part of soil profile (Guaman et al. 2016), root nutrient absorption from subsoils (Xue et al. 2015) and consequently soil nutrient redeposition to the upper part of soil profile as residues (Wang et al. 2015a). Thus, ploughing deeper has positive effects on decreasing soil bulk density and penetration resistance due to both the physical disturbance and accumulation of SOM (Celik et al. 2010; Aitkenhead and Coull 2016).

To date, although concern about the long-term sustainability of agroecosystems has generated much research on integrated soil fertility managements (Vanlauwe et al. 2010; Gentile et al. 2013), there is a lack of understanding of the improvement of poor physical structural components for increasing soil fertility and crop productivity. In the absence of replacing with other soils, soil textural composition is

hardly influenced by any management practice due to the mineralogical characteristics of parent material (Angst et al. 2018), but suitable agricultural managements are effective and feasible to affect other soil physical structural components. Liu et al. (2018) had found significant effects of adding organic amendments on increased porosity and reduced compaction in fine-textured soil. Whereas, in the coarse-textured soil, the organic amendments have been also reported to accelerate soil aggregation (Obia et al. 2016) that could alter internal soil pore structure by reducing the fraction of macro-pores and increasing meso-pore amount (Villagra-Mendoza and Horn 2018). Therefore, in this study, the strip sampling was done along the transect of agricultural area around Yellow River in Fengqiu County, which was further subjected to sub-divisions of different soils with various plough layer thicknesses and textural compositions. Further, considering the fact that crop yields on fluvo-aquic soil are limited by poor physical structure and low levels of soil nutrients (Zhang et al. 2018a), the integrated soil fertility was evaluated based on the mentioned 4 physical structural components and stocks of SOM, total nitrogen (TN) and total phosphorus (TP), although soil fertility is an integration of soil physical, chemical and biological properties. Our primary objectives were to (1) identify the key physical structural components for soil fertility in Aquic Inceptisol, (2) quantify soil fertility level under the respective plough layer thickness as well as soil texture, and (3) investigate the effects of integrated soil fertility determined by 4 poor physical structural components and SOM as well as 2 nutrient stocks on crop productivity in rainfed agricultural ecosystems.

Materials and methods

Study layout and area

For this study, strip sampling was done along the transect of agricultural area around Yellow River in Fengqiu County, Henan province, China (Online Resource 1), which is representative of the North China Plain. Along the vertical direction of the Yellow River towards the northern direction, the content of sand generally decreased with increasing distance. Soil samples from the sixty-six profile pits were collected through the strip sampling in this study.

According to the international classification of soil texture, four types of textures including sandy loam, sandy clay loam, clay loam and loam clay were recognized through determining the distribution of particle sizes (Online Resource 2).

The study area has a semi-arid warm temperate continental monsoon climate with mean annual precipitation of 615 mm and mean annual temperature of 13.9 °C. Predominant soil of the area is an Aquic Inceptisol based on the Chinese soil classification or Entisol according to the U.S.A. taxonomy, respectively (Soil Survey Staff 1996; Zhang et al. 2017). Due to the usually uniform parent material from alluvial sediments of the Yellow River, the soil is dominated by sandy loam texture (Online Resource 2). The agricultural production is focused on the rotation of winter-wheat and summer-maize annually.

Sampling

At each sampling site, a 0–0.40 m soil profile pit was excavated in early October 2016 immediately after maize harvest, and the thicknesses of plough layer and subsoil were recorded. Mixed samples were collected from the plough layer and subsoil, respectively, to determine the contents of SOM, TN and TP. The bulk clod soil samples at the whole 0–0.40 m depth were collected to investigate the aggregate distribution in response to various plough layer thicknesses and soil textures. Also, to measure soil bulk density, the volumetric samples were taken from the plough layer and subsoil by using a cylindrical metal core of 100 cm³. All samples were taken with three replications per site.

In order to investigate the crop production and estimate the nutrient utilization from fertilizers, the grain yields of wheat and maize and the amounts of N and P fertilizer applications during the rotation of wheat and maize were obtained from local farmers in each site. For details see the Online Resource 3.

Soil aggregate fractionation and analysis

All bulk clod samples were gently sieved to pass through a 10-mm sieve, and plant and organic debris in soils were identified and removed with forceps. The sieved soils and mixed soils were all air-dried at room temperature. According to the wet-sieving protocol of Elliott (1986), the tested soil was fractionated into

macroaggregates ($> 250 \mu\text{m}$), microaggregates ($250\text{--}53 \mu\text{m}$), and the silt + clay fraction ($< 53 \mu\text{m}$). All separated aggregates were oven-dried at 60°C for determining their properties.

By dividing each mixed sample into two subsamples, one subsample was carefully sieved to pass through a 2-mm sieve for soil particle-size analysis by using the pipette method (Buchan et al. 1993). The other was ground and passed through $< 0.15\text{-mm}$ sieve, and the contents of soil nutrients mentioned above were measured following the protocols described by Carter and Gregorich (2008).

Soil fertility index

Soil fertility takes into consideration several soil physical, chemical and biological properties. For a consistent and accurate assessment of soil fertility, a systematic method is required to interpret and measure soil properties. However, crop productivities on various soils are generally limited by special factors such as pH, water or nutrient limitation, P sorption, Na content, etc. For that the fluvo-aquic soil is characterized by poor physical structure and a low level of SOM, in the present study, we established the minimum data set and integrated index to quantify soil fertility that was determined by 4 physical structural components (plough layer thickness, textural composition, soil aggregation and bulk density) and SOM as well as 2 nutrient (TN and TP) stocks within the 0–0.40 m profile pit following various plough layer thicknesses and soil textures.

Five steps were executed to evaluate the integrated soil fertility (Shukla et al. 2006): Firstly, extracting the factors from the measured soil attributes using the method of principal components; Secondly, performing the Varimax with Kaiser Normalization for rotation to minimize the number of variables with the highest loading in each factor and thus to simplify the interpretation of factors; Thirdly, selecting the representative principal components to establish the minimum data set through factor analysis technique; Fourthly, scoring the integrated indicators in the minimum data set according to a regression method; And lastly, integrating the scores of indicators into a comparative index for soil fertility based on their weight factors. According to Wander and Bollero (1999) and Brejda et al. (2000), the factors with eigenvalues > 1.0 and those that explained at least 5%

of the variation in the dataset were selected as the representative principal components. The individual percentage of total variation in total data set explained by the representative principal components were termed as their weight factors.

The scoring function was used to calculate the scores of indicators in the minimum data set and their integrated score:

$$Z_i = r_{i1}x_1 + r_{i2}x_2 + \dots + r_{ij}x_j + \dots + r_{ip}x_p \quad (1)$$

$$F = \sum w_i Z_i \quad (2)$$

where Z_i is the score of the i th integrated indicator in the minimum data set; x_j is the normalization for the j th measured soil attribute derived from the factor analysis ($j = 1, 2, \dots, p$); r_{ij} is the component score coefficient matrix that could be directly obtained by the factor analysis; w_i is the weighting factor for the i th integrated indicator; and F is the integrated score of all indicators in the minimum data set and it is regarded as soil fertility index. Higher F values were assumed to mean better soil fertility.

Calculation and statistical analysis

According to Wang et al. (2015b), the stability of aggregates was assessed by the mean weight diameter (MWD) and the geometric mean diameter (GMD). The stocks of SOM, TN and TP were calculated by multiplying their contents with the bulk density and soil depth interval. The partial factor productivities from applied N (PFP-N) and P (PFP-P) fertilizers were calculated by dividing the amounts of N and P fertilizer applications, respectively, by the grain yields.

Statistical analysis was performed with the SPSS 17.0 software package for Windows (SPSS Inc., Chicago, IL, USA) and data were transformed as needed to meet the assumptions of normality and homogeneity of variances. Two-way ANOVA was used to determine the main effects and interactions of plough layer thickness and soil texture on the physical structural components, nutrient stocks and soil fertility index. A one-way ANOVA was used to test for significant differences among different thicknesses of plough layer or soil textures based on the least significant difference (LSD) calculations at 5% level. Factor analysis was performed to establish the

minimum data set and integrated index for soil fertility. Regression analyses were used to determine relationships between the mass proportion of aggregates as well as their stability and soil particle size distribution, between nutrient stocks and soil macroaggregation, and between grain yields of wheat and maize as well as partial factor productivity from applied N or P fertilizer and the integrated scores for soil fertility.

Results

Key physical structural components in Aquic Inceptisol

As shown in Fig. 1a, the most common plough layer thickness in the study area was 0.15–0.18 m constituting 50% of the studied soil profile pits. The 0.18–0.20 and 0.20–0.25 m plough layers constituted 21% each, of the studied profile pits (Fig. 1a). Across all sampling sites, the proportions of soil profile pits with < 0.15 and > 0.25 m plough layers were the least abundant (4% and 4%, respectively; Fig. 1a). Soil bulk density depended on the thickness of plough layer rather than textural composition (Table 1). A lower bulk density was generally found in both plough layer and subsoil with increasing plough layer thickness across all soil profile pits (Fig. 1b). In the plough

layer, the bulk density within soil profile pit with > 0.25 m plough layer was 10.9% lower ($P < 0.05$) than that with < 0.15 m plough layer (Fig. 1b). Whereas, 7.8–11.8% differences ($P < 0.05$) of bulk density in subsoil were observed between soil profile pits with plough layer thicknesses of < 0.18 and > 0.25 m (Fig. 1b).

The thickness of plough layer, soil texture and their interaction significantly affected the aggregate formation (Table 1). The soil with ≥ 0.15 m plough layer had over 21-fold ($P < 0.05$) macroaggregation at the expense of microaggregation than did that with a plough layer thickness of < 0.15 m at the 0–0.40 m depth when averaged all soil textures (Fig. 2a). And consequently, the aggregate stability was also improved by 173.6–234.3% for MWD ($P < 0.05$) and 22.7–40.1% for GMD ($P < 0.05$) in terms of the corresponding contrasting soils (Fig. 2b). By contrast, a greater impact on soil aggregation was observed in soil texture rather than the thickness of plough layer. 59% of profile pits in the study area were characterized by sandy loam soil (Online Resource 2), and a significantly ($P < 0.05$) higher microaggregate mass proportion was found in the sandy loam soil than other soil textures, whilst the opposite pattern was observed in the amount of macroaggregates at the 0–0.40 m depth (Fig. 2c). The regression analysis showed that the macroaggregate mass proportion was significantly ($P < 0.001$) and negatively correlated to the sand

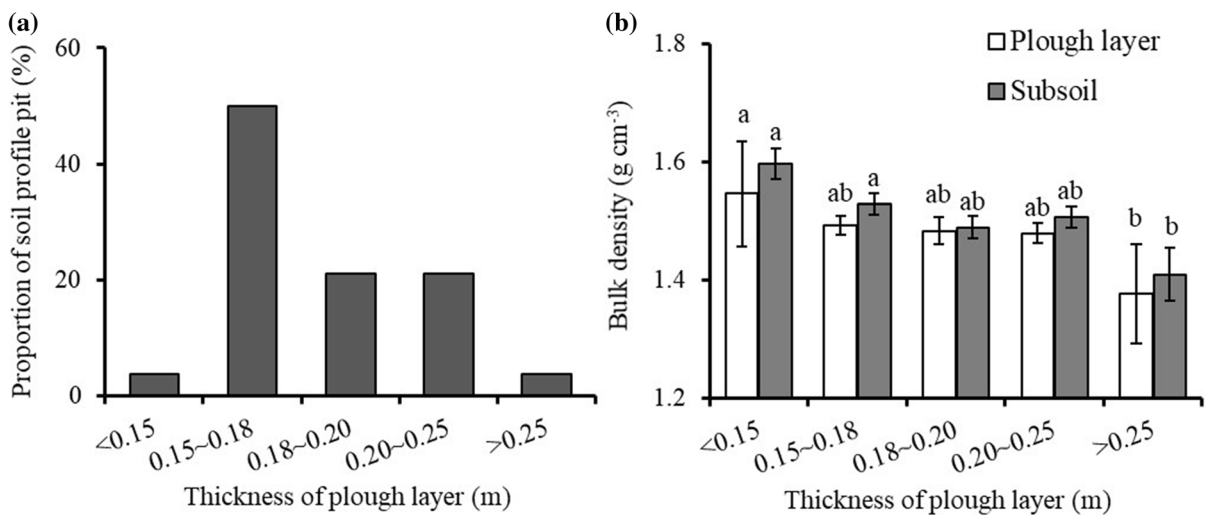


Fig. 1 Proportion of soil profile pits with various thicknesses of plough layer (a) and the corresponding bulk density in plough layer and subsoil across all soil profile pits (b). Data are means

with standard error. Different lowercase letters indicate significant differences among thicknesses of plough layer at $P < 0.05$

Table 1 Analysis of variance (ANOVA) for bulk density, soil aggregation and stocks of soil organic matter (SOM), total nitrogen (TN) and total phosphorus (TP) in plough layer,

subsoil or 0–0.40 m profile following various thicknesses of plough layer and soil textures

Source of variation	Bulk density		Mass proportion of aggregates (0–0.40 m)			Aggregate stability (0–0.40 m)	
	Plough layer	Subsoil	> 250 μm	250–53 μm	< 53 μm	MWD	GMD
Thickness of plough layer (p)	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	ns	$P < 0.001$	$P < 0.01$
Soil texture (t)	ns*	ns	$P < 0.001$	$P < 0.001$	ns	$P < 0.001$	$P < 0.001$
p \times t	ns	ns	$P < 0.05$	$P < 0.01$	ns	$P < 0.05$	$P < 0.05$

Source of variation	SOM stock			TN stock			TP stock		
	Plough layer	Subsoil	0–0.40 m	Plough layer	Subsoil	0–0.40 m	Plough layer	Subsoil	0–0.40 m
Thickness of plough layer (p)	$P < 0.001$	$P < 0.05$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$
Soil texture (t)	$P < 0.001$	$P < 0.001$	$P < 0.001$	ns	$P < 0.001$	ns	$P < 0.001$	$P < 0.001$	$P < 0.001$
p \times t	$P < 0.05$	$P < 0.01$	$P < 0.05$	$P < 0.001$	$P < 0.05$	$P < 0.01$	$P < 0.01$	$P < 0.001$	ns

* ns represents no statistical significance at the $P = 0.05$ level

content (Fig. 3a), whereas significantly and positively correlated to the silt and clay contents ($P < 0.001$ and 0.001 , respectively, Fig. 3b, c). Conversely, these correlations were reversed between the microaggregation and soil particle size distribution (Fig. 3a–c). In contrast of the sand particle, increasing the silt and clay particles could significantly ($P < 0.001$) enhance the MWD and GMD values (Fig. 3d, e), and the aggregate stability was ranked as loam clay > clay loam > sandy clay loam > sandy loam (Fig. 2d).

Linkage between soil nutrient accumulations and physical structural components

In general, the stocks of SOM, TN and TP within the 0–0.40 m profile pit were also significantly influenced by the thickness of plough layer, soil texture and their interaction (Table 1). Apart from the TP in subsoil, the nutrient stocks of soil with ≥ 0.15 m plough layer were averagely increased by 179.7% for SOM, 125.5% for TN and 116.1% for TP in the plough layer, as well as 164.9% for SOM and 248.5% for TN in subsoil, if compared to the soil with < 0.15 m plough layer (Fig. 4a). For the soil with ≥ 0.15 m plough layer, those accumulations of SOM and soil nutrients mentioned above at the 0–0.40 m depth generally increased with the thickness of plough layer, which predominantly resulted from the expansions of

soil nutrient reservoirs in the plough layer (Fig. 4a). By contrast, the mean stocks of SOM, TN and TP within the 0–0.40 m profile pit with sandy loam texture amounted to 49.48, 4.47 and 4.12 Mg ha^{-1} , respectively, which were significantly ($P < 0.05$) lower than those under other soil textures, with the highest stocks of 76.55, 5.61 and 5.06 Mg ha^{-1} , respectively, in clay loam soil (Fig. 4b). As shown in Fig. 5, a significant, positive and power-function-dependent relationship was also revealed between SOM ($P < 0.001$), TN ($P < 0.001$) or TP ($P < 0.001$) stock and the mass proportion of macroaggregates at the 0–0.40 m depth across all soil profile pits.

Soil fertility and crop productivity influenced by poor physical structural components

The results of factor analysis showed that the soil attributes differed significantly with changing the thickness of plough layer and soil texture (Table 2). The first three factors extracted using 4 soil physical structural components and SOM as well as 2 nutrient stocks had eigenvalues > 1.0 and explained more than 88.1% of the variability in the soil data (Table 2). The textural composition, macroaggregate, microaggregate and SOM stock had highly weighted loadings (≥ 0.50) under the first factor, which explained 54.3% of total variability (Table 2). By contrast, the second and third

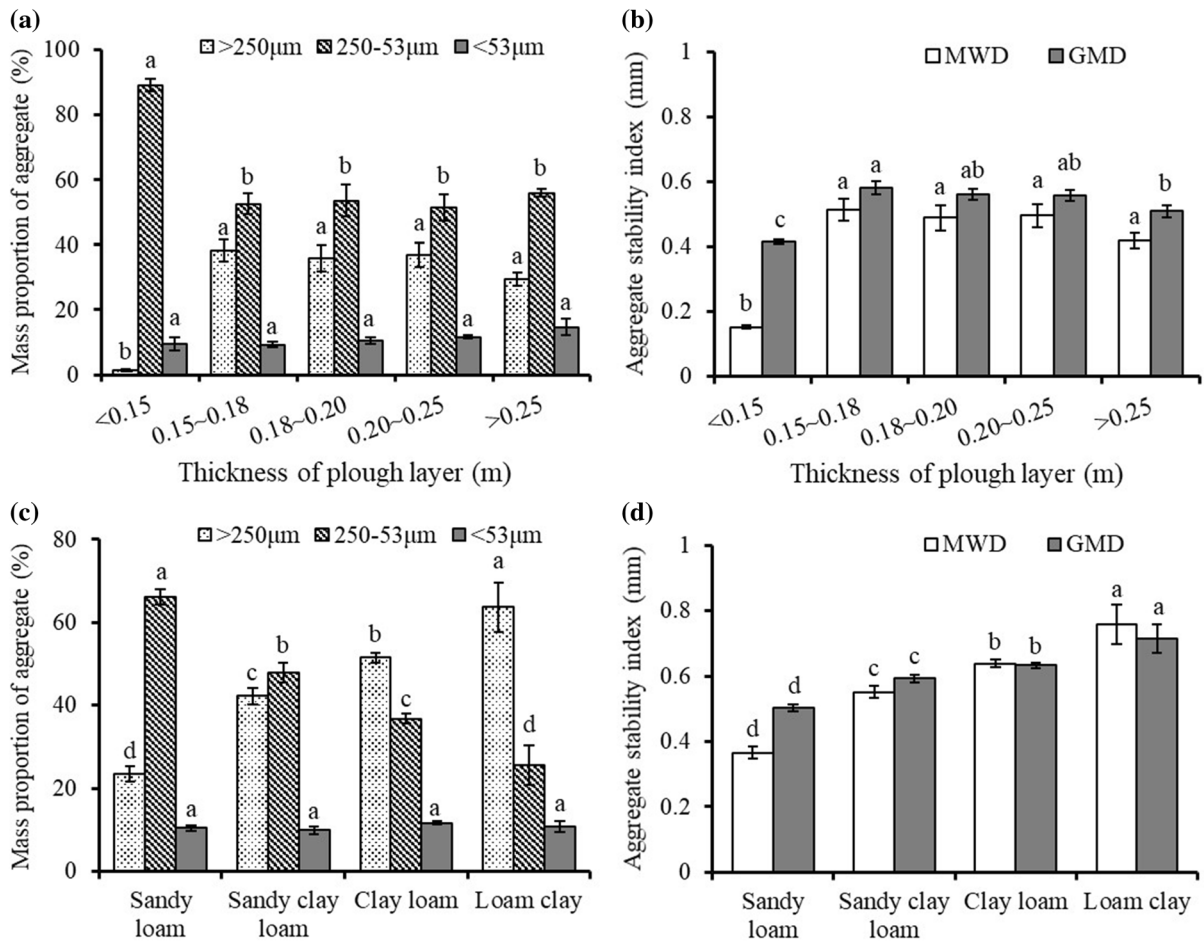


Fig. 2 Mass proportion of aggregates (a, c) and their stability (b, d) at the 0–0.40 m depth as affected by various thicknesses of plough layer and soil textures. Data are means with standard

error. Different lowercase letters indicate significant differences among thicknesses of plough layer or soil textures within the same aggregate fraction or aggregate stability index at $P < 0.05$

factors accounted for 18.7% and 15.1% of the variation in the data, respectively, and were highly loaded with the plough layer thickness and soil nutrient stocks (for the second factor) as well as the silt + clay fraction and bulk density (for the third factor) (Table 2). Thus, the first three factors were selected as the integrated indicators for the minimum data set to evaluate soil fertility determined by the mentioned 4 physical structural components and stocks of SOM, TN and TP at the 0–0.40 m depth.

The scores of integrated indicators in the minimum data set were calculated to quantify soil fertility following various thicknesses of plough layer and soil textures. The average score of the first factor in soil with 0.15–0.25 m plough layer amounted to 0.14, which was significantly ($P < 0.05$) higher than that

with plough layer thicknesses of < 0.15 and > 0.25 m, with the lowest score of $- 1.15$ in soil with > 0.25 m plough layer (Table 3). Also, the soil with ≤ 0.25 m plough layer had a significantly ($P < 0.05$) higher score of the third factor than with > 0.25 m plough layer (Table 3). Whereas, a significantly ($P < 0.05$) higher score of the second factor was observed with increasing the thickness of plough layer (Table 3). By contrast, soil texture exerted significant effects only on scores of the first and second factors (Table 3). Apart from the score of the second factor in loam clay soil, increasing the silt and clay contents was favorable to improve the scores of the first and second factors across all soil textures (Table 3).

Similar to the score of the first factor, the same pattern of the integrated score of the first three factors was

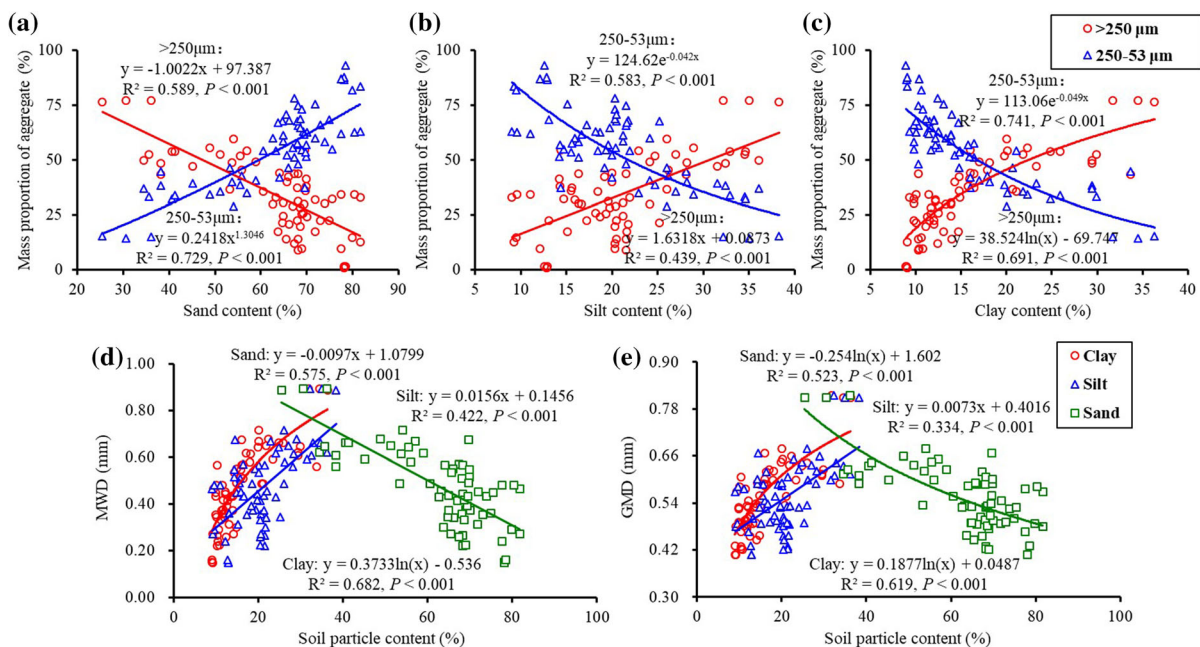


Fig. 3 Effects of soil particle size distribution on the mass proportion of aggregates (a–c) and their stability (d, e) at the 0–0.40 m depth based on the significant interactions observed in the analysis of variance (ANOVA) for soil aggregation

observed with changing the plough layer thickness and soil texture, which was presented the largest integrated scores in soils with 0.20–0.25 m plough layer and loam clay texture, respectively (Table 3). The regression analysis further showed that the grain yields ($P = 0.001$ and $P < 0.001$ for wheat and maize, respectively) and partial factor productivities from applied N fertilizer ($P < 0.001$ and $P = 0.002$ for wheat and maize, respectively) for wheat and maize were significantly and positively correlated to the integrated scores for soil fertility across all profile pits (Fig. 6a–c). Despite slight increases were found in partial factor productivities from applied P fertilizer for wheat and maize with improving soil fertility, there was no statistical significance ($P = 0.208$ and $P = 0.378$ for wheat and maize, respectively) in their correlations (Fig. 6d).

Discussion

The key physical structural barriers for soil fertility in Aquic Inceptisol

In this study, the tested Aquic Inceptisol was derived from alluvial sediments of the Yellow River, which had undergone the soil-forming processes of

pseudogleyization and dry-tillage ripening influenced by anthropogenic activities. Accumulated evidence (Angst et al. 2018) has shown that the mineralogical characteristics of parent material determine the weathering and thus textural composition of the respective soil. On the other hand, the dry-tillage ripening especially tillage and irrigation managements, could largely affect the plough layer thickness in the long term (Chen et al. 2013). Consequently, the predominant tillage regimes from the rotary- and no-tillage in the North China Plain dominated by sandy loam soil (Online Resource 2), resulted in a thin plough layer (Fig. 1a) with poor physical structural components that restrict soil fertility.

Besides increasing the plough layer thickness, deep ploughing or deep cultivation is found to generally break up soil crusts and dense layers and to increase the porosity and aeration, thus reducing soil bulk density and compaction (Schwen et al. 2011). Additionally, a series of agricultural management practices (e.g., adding organic amendments to soil for the cultivation of fertile plough layer) could be beneficial to accumulating SOM, which in turn enhances the positive effect and duration of tillage on bulk density because SOM would act as a binding or flocculating agent to prevent recompaction and help re-forming the

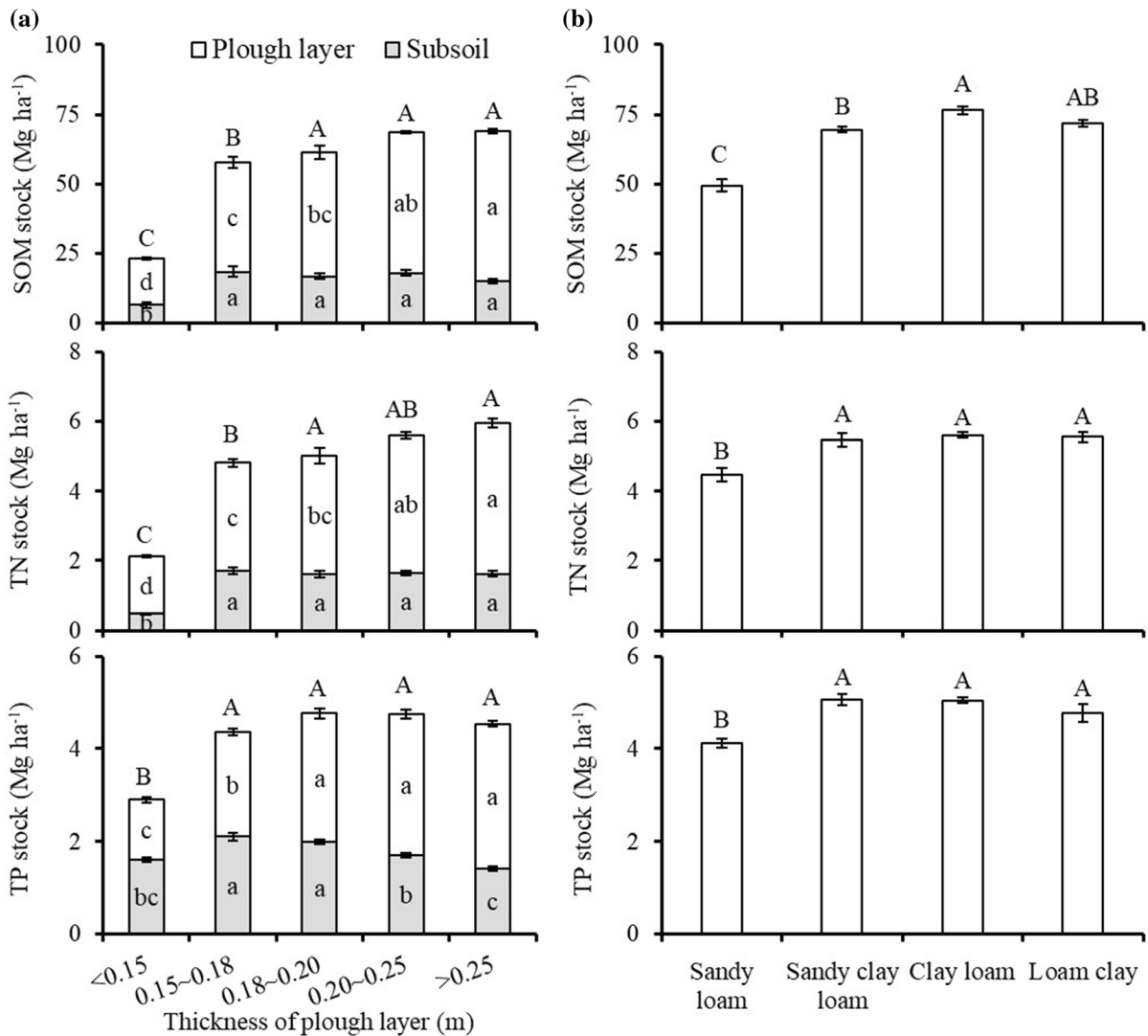


Fig. 4 Stocks of soil organic matter (SOM), total nitrogen (TN) and total phosphorus (TP) in plough layer, subsoil and/or 0–0.40 m profile as affected by various thicknesses of plough layer (a) and soil textures (b). Data are means with standard error. Different lowercase letters indicate significant differences

among thicknesses of plough layer within the plough layer or subsoil, and different capital letters indicate significant differences among thicknesses of plough layer or soil textures within the 0–0.40 m profile at $P < 0.05$

structure of ripped soil (Hamza and Anderson 2005). Ruehlmann and Körschens (2009) and Aitkenhead and Coull (2016) had demonstrated that SOM was one of the most dominating factors to decrease bulk density and soil compaction. As a result, a larger bulk density was observed in both plough layer and subsoil with reducing the thickness of plough layer (Fig. 1b) because the shallow plough layer, to some extent, restricts SOM accumulation (Fig. 4a).

In the present study, the thickness of plough layer had a significant and positive impact on macroaggregate formation and aggregate stability (Table 1; Fig. 2a, b), which might be also primarily attributed to the accumulated SOM with increasing the plough layer thickness within 0–0.40 m profile pit (Fig. 4a). Zhang et al. (2017, 2018b) suggested that the accumulations of soil organic C fractions including labile and humic components, could act as important binding agents to accelerate macroaggregation. On the other

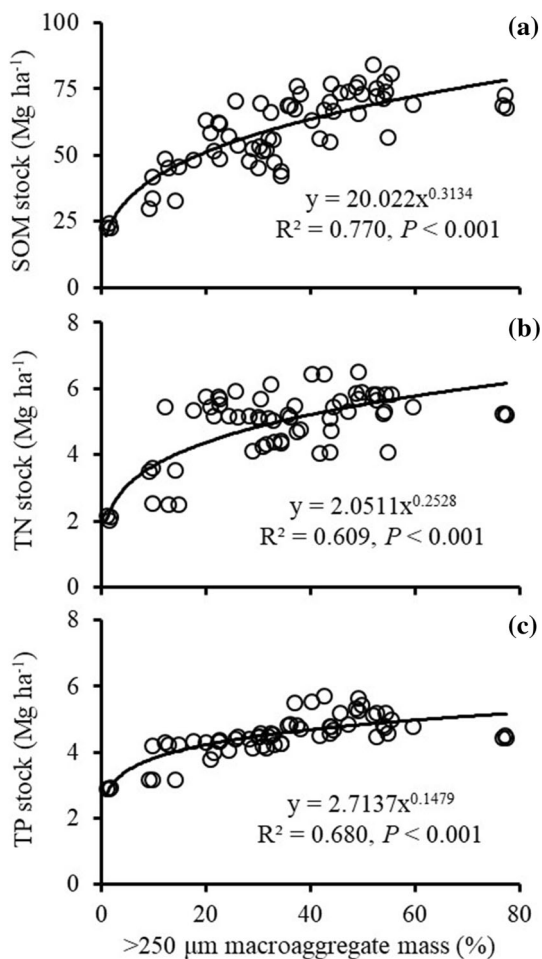


Fig. 5 Regressions between stock of soil organic matter (SOM) (a), total nitrogen (TN) (b) or total phosphorus (TP) (c), and the mass proportion of > 250 µm macroaggregates at the 0–0.40 m depth across all soil profile pits

hand, the effect of soil texture on macroaggregation (Table 1; Fig. 2c, d), to some extent, could be explained by the following reasons: Firstly, the fine-textured soil has a greater macroaggregation through providing larger surface for mineral-to-organics interactions, leading to the formation of organo-mineral assemblages (Regelink et al. 2015); Secondly, the aggregate disruption through wetting–drying cycles is expected to be more severe in coarse- than fine-textured soils (Gentile et al. 2013); The next but not last, the higher moisture and C content in fine-textured soil may have also supported a large microbial population that could promote aggregate formation and stability (Gentile et al. 2013). Therefore, in contrast of the sand particle, elevating the contents

of silt and clay particles could effectively accelerate soil macroaggregation (Fig. 3).

Soil nutrient accumulations influenced by poor physical structural components

Generally, the variation in thickness of plough layer can result in changes in soil physical, chemical and biological properties. For example, a looser soil structure could be obtained through increasing the plough layer thickness, which has positive effects on plant root penetration, root proliferation throughout the soil and root development to the deeper part of the soil profile (Celik et al. 2010; Guaman et al. 2016). These effects improve the root system capacity to absorb water and nutrients while reduce nutrient leaching (Wang et al. 2015a; White et al. 2015), leading to soil nutrient redistribution to the upper part of soil profile (Wang et al. 2015a). White et al. (2015) reported that the adequate rooting was favorable for the resource capture and crop growth and yield. Considerable amounts of N, P and potassium (K) that have been absorbed by roots from the deep soil are translocated to shoots and topsoil roots and then are deposited in the topsoil as residues (Kautz et al. 2013), which might be responsible for the increased SOM and soil nutrient stocks within 0–0.40 m profile pit predominantly originating from the plough layer with increasing its thickness (Fig. 4a). Our previous study (Zhang et al. 2018a) showed that the tested soil was rich in K and a marginal K contribution to soil K in the form of retained residues was observed in the investigated wheat–maize rotation system. Therefore, an insight was only devoted into the changes in stocks of SOM, TN and TP in response to various plough layer thicknesses.

From the soil texture perspective, it has been shown to be a major controlling factor of stabilizing soil organic C fractions (Plante et al. 2006). In general, the C, N and P cycles are closely coupled through SOM decomposition and ecosystem respiration due to the constrained proportions of these elements required by organisms. We found that SOM, TN and TP stocks generally increased with increasing the proportions of silt and clay particles (Fig. 4b) partially because of the greater reactive surface areas of these particles enhancing the soil's capacity to stabilize SOM chemically (Gonçalves et al. 2017). Simultaneously, the larger accumulations of these nutrients in fine than

Table 2 Variable loading coefficients (eigenvectors) of the first three factors extracted using 4 physical structural components and soil organic matter (SOM) as well as 2 nutrient

stocks at the 0–0.40 m depth, their eigenvalues, and individual and cumulative percentages of total variance explained by each factor

Soil attribute	Factor 1	Factor 2	Factor 3	Communality ^b
Plough layer thickness	– 0.250	0.804	– 0.317	0.810
Textural composition				
Sand particle	– 0.963 ^a	– 0.095	0.136	0.955
Silt particle	0.905	0.098	– 0.306	0.923
Clay particle	0.937	0.084	0.052	0.889
Soil aggregation				
> 250 µm macroaggregate	0.865	0.294	0.259	0.903
250–53 µm microaggregate	– 0.894	– 0.323	– 0.065	0.908
< 53 µm silt + clay fraction	0.207	0.163	– 0.892	0.866
Bulk density	0.108	0.104	0.915	0.860
SOM stock	0.618	0.700	0.142	0.892
TN ^c stock	0.423	0.791	– 0.051	0.807
TP ^d stock	0.453	0.745	0.352	0.883
Eigenvalue	5.969	2.060	1.666	9.695
Individual variance (%)	54.26	18.72	15.14	88.12
Cumulative variance (%)	54.26	72.98	88.12	

^aBoldface factor loadings (≥ 0.50) are considered highly weighted. Factor loadings are considered highly weighted when within 10% of variation of the absolute values of the highest factor loading in each factor

^bThe communality of a variable represents the amount of variance in the variable that is accounted for. The larger the communality for each variable, the more successful a factor analysis model is

^cTotal nitrogen

^dTotal phosphorus

coarse-textured soils (Fig. 4b), to some extent, are also attributable to a lack of preservation and rapid turnover of microbial biomass in coarse-textured soil due to the increased availability of substrates and higher susceptibility to predation (Six et al. 2006). In addition, the greater reactive surface areas of clay and silt particles probably increase both chemical stabilization (Gonçalves et al. 2017) and physical stabilization of SOM through the increased aggregation (Six et al. 2002). Angst et al. (2018) found that the fine-textured soil with larger clay and silt contents tended to form more water-stable macroaggregates than coarse-textured soil, which was in accordance with our results (Figs. 2, 3). Consequently, a significant and positive correlation was revealed between SOM, TN or TP stock and the mass proportion of macroaggregates across all soil profile pits in the present study (Fig. 5), since a higher degree of soil aggregation may have favored stabilization (Angst

et al. 2018) and led to larger amounts of the occluded particulate organic matter fractions (Virto et al. 2008).

Furthermore, Gentile et al. (2013) and Bosshard et al. (2008) had elucidated that the fine-textured soil as well as the increased formation of macroaggregates resulted in a greater retention of soil nutrients (e.g., soil nitrogen) from exogenous applied fertilizers. In view of the variations in the amounts of N and P fertilizer applications among different sampling sites, it might be suspected that the differences in those nutrient stocks mentioned above resulted from the different amounts of applied fertilizers. In our study, however, no remarkable relationships were observed between soil nutrient stock and the amount of N or P fertilizer application for the rotation of winter-wheat and summer-maize (Online Resource 3), suggesting that the accumulations of these nutrients were primarily derived from the pedogenesis.

Table 3 Scores of the first three factors extracted using 4 physical structural components and soil organic matter (SOM) as well as 2 nutrient stocks, and their integrated score for soil fertility at the 0–0.40 m depth following various thicknesses of plough layer and soil textures

Variable	Score			Integrated score
	Factor 1	Factor 2	Factor 3	
Thickness of plough layer (m)				
< 0.15	– 1.06b*	– 2.53e	– 0.38a	– 1.11c
0.15–0.18	0.14a	– 0.40d	0.31a	0.05a
0.18–0.20	0.02a	0.24c	0.01a	0.06a
0.20–0.25	0.27a	0.75b	– 0.26a	0.25a
> 0.25	– 1.15b	2.20a	– 1.67b	– 0.47b
Soil texture				
Sandy loam	– 0.64d	– 0.26c	– 0.12a	– 0.42d
Sandy clay loam	0.14c	0.70a	0.45a	0.27c
Clay loam	1.02b	0.34b	– 0.09a	0.60b
Loam clay	2.05a	– 0.34c	– 0.04a	1.04a
ANOVA				
Thickness of plough layer (p)	$P < 0.01$	$P < 0.001$	$P < 0.05$	$P < 0.001$
Soil texture (t)	$P < 0.001$	$P < 0.001$	ns**	$P < 0.001$
p × t	$P < 0.05$	$P < 0.05$	ns	ns

*Different lowercase letters within a column indicate significant differences among thicknesses of plough layer or soil textures at $P < 0.05$

**ns represents no statistical significance at the $P = 0.05$ level

Integrated soil fertility and its association with crop productivity

The C, N and P in soil are important elements for all life forms and are also critically needed nutrients for plant growth and crop productivity. According to previous reports (Soh et al. 2010; Six et al. 2002; Al-Kaisi 2001; Ruehlmann and Körschens 2009), soil physical structural components including the textural composition, aggregation, plough layer thickness and bulk density were all important soil quality attributes. The variations in these attributes could alter the air–soil and water–soil interactions and then further affect microbiological activity, nutrient uptake and water retention. Although the tested soil is enriched with K due to the parent material of alluvial sediments, the C, N and P have been being the important limiting elements for soil fertility and meanwhile, the soil is characterized by poor physical structural components with predominant sandy loam texture (Online Resource 2), thin plough layer (Fig. 1a), large bulk density (Fig. 1b) and poor aggregation (Fig. 2). Therefore, it was reliable and meaningful to evaluate

soil fertility on the basis of mentioned 4 physical structural components including the textural composition, aggregation, plough layer thickness and bulk density, and SOM as well as 2 nutrient stocks in the present study (Tables 2, 3).

In our study, the factor analysis showed that the first three factors explained more than 88.1% of the variability in soil fertility (Table 2). Because only the factors with eigenvalues > 1 and those that explained at least 5% of the variation in the dataset can be selected (Wander and Bollero 1999; Brejda et al. 2000), the first three factors could be used as the integrated indicators for the minimum data set to evaluate soil fertility level and the scores of these indicators were calculated to quantify the integrated soil fertility. It was found that increasing the thickness of plough layer generally enhanced the integrated score for soil fertility within the 0–0.40 m profile pit (Table 3). Surprisingly, a sharp decline in the score was observed when the plough layer thickness was larger than 0.25 m (Table 3), which might be highly connected to the textural composition in which the soil profile pits with such plough layer thickness are

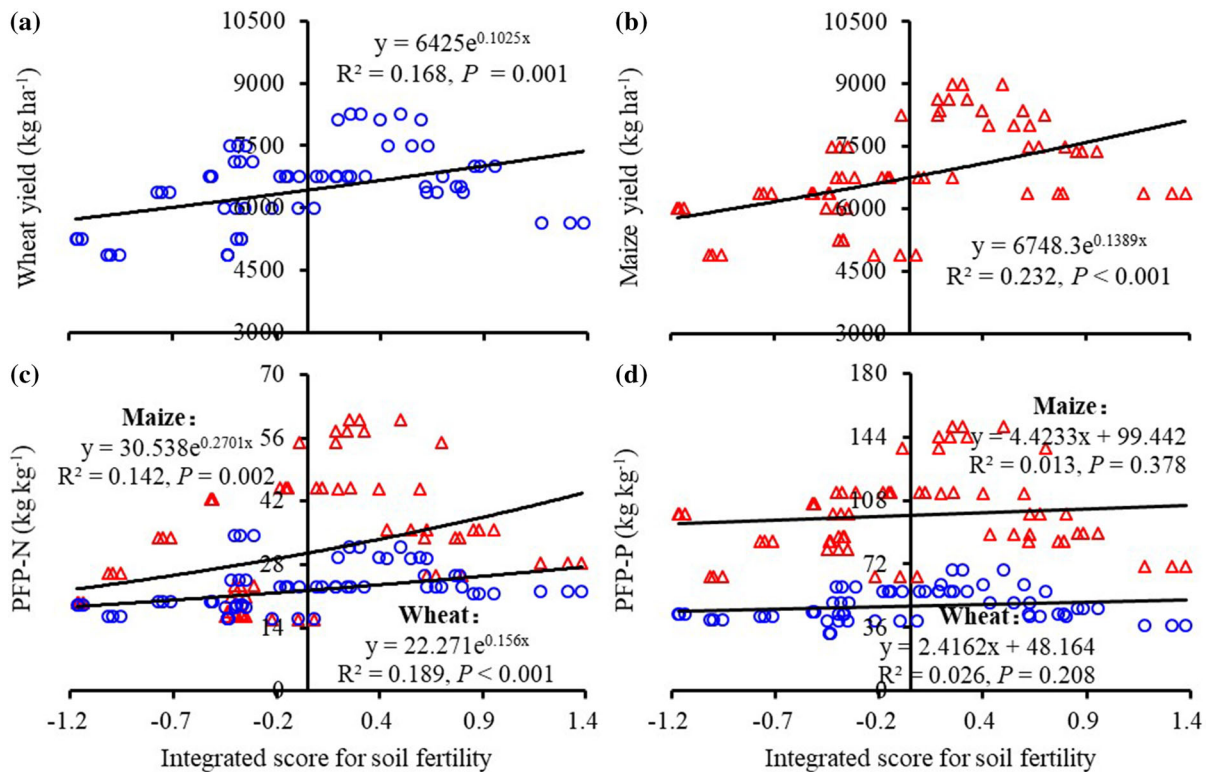


Fig. 6 Relationships between grain yields (a, b), partial factor productivities from applied N fertilizer (PFP-N) (c) or P fertilizer (PFP-P) (d) for wheat and maize, and the integrated

scores for soil fertility that was determined by 4 physical structural components and soil organic matter (SOM) as well as 2 nutrient stocks at the 0–0.40 m depth across all soil profile pits

involved. In this study, the soil with > 0.25 m plough layer was largely classified as sandy loam texture following a higher content of sand particle (data not given), so that the macroaggregation was less whilst the formations of microaggregate and silt + clay fraction were more than other soils with a plough layer thickness of 0.15–0.25 m (Fig. 2a). As a result, the scores of the first factor highly loaded with the sand particle and microaggregation as well as the third factor highly loaded with the silt + clay fraction, were significantly lower within soil profile pit following > 0.25 m plough layer than following 0.15–0.25 m plough layer (Table 3). Therefore, the integrated fertility of soil with > 0.25 m plough layer was intermediate between soils with plough layer thicknesses of < 0.15 and 0.15–0.25 m (Table 3). By contrast, the fine-textured soil had a significantly higher integrated score than did the coarse-textured soil, with the highest score under the loam clay texture coupling with 0.20–0.25 m plough layer (Table 3). These results suggested that shaping a suitable plough

layer by deep ploughing in adaptation to soil texture could effectively improve soil fertility level. Regardless of the plough layer thickness, intensive deep ploughing could bring about negative effects related to soil erosion, losses of soil nutrients, and increased cost of production. Alternatively, there are lots of other studies available also demonstrating positive effects of reduced- or no-tillage practices on soil properties and crop yields in the North China Plain (Zhang et al. 2017, 2018a). Thus, considering the presented physical structural barriers for soil fertility in Aquic Inceptisol, the intermittent deep-tillage in combination with reduced/no-tillage might be a promising approach for sustainable agricultural productivity in the long-term cultivation, which deserves further research.

Furthermore, significant and positive correlations were found between the grain yields, partial factor productivities from applied N fertilizer for wheat and maize, and the integrated scores for soil fertility (Fig. 6a–c). These results could explain the responses

of crop productivity to various thicknesses of plough layer and soil textures in the study area (Online Resource 3). Vanlauwe et al. (2010) had reported that the integrated soil fertility management was an approach to optimize the application of all available resources in adaptation to local conditions to maximize the nutrient use efficiency and crop yields. However, the slight changes in partial factor productivities from applied P fertilizer for wheat and maize with improving soil fertility in our study (Fig. 6d) indicated that the nutrient utilization of applied P fertilizer was not significantly enhanced by improving physical structural barriers for integrated soil fertility.

Conclusions

The results obtained have suggested that the thin plough layer and sandy loam texture were the predominated physical structural barriers for soil fertility in the Aquic Inceptisol. These identified poor physical structural components affected the bulk density, macroaggregate formation and consequently accumulations of SOM, TN and TP in soil. Irrespective of the textural composition, it is possible to increase soil macroaggregation and nutrient stocks as well as decrease the bulk density through expanding plough layer thickness using deep-tillage, which favors enhancing soil fertility and then crop productivity. These findings emphasize the importance of improving poor physical structural components on the integrated soil fertility managements in rainfed agricultural ecosystem of the North China Plain. Considering the negative effects and increased costs caused by intensive deep ploughing, further research should be directed towards the improvement of key physical structural components linking to increased soil fertility, crop productivity and agricultural sustainability using the intermittent deep-tillage coupling with reduced/no-tillage in adaptation to specific regional conditions.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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