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Effects of strip rotary tillage with subsoiling on soil enzyme activity, soil fertility, and wheat yield

*Jianning He, Zhenwen Yu, Yu Shi**

Key Laboratory of Crop Ecophysiology and Farming System, Ministry of Agriculture, College of Agronomy, Shandong Agricultural University, Tai'an, Shandong Province, P.R. China

**Corresponding author: shiyu@sdau.edu.cn*

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Abstract: Inappropriate tillage and soil compaction threaten farmland sustainability in the Huang-Huai-Hai Plains of China. We aimed to explore the impact of plowing tillage, rotary tillage, strip rotary tillage, and strip rotary tillage coupled to a two-year subsoiling interval (STS) on soil quality at various soil depths and on wheat yield. Soil bulk density was substantially lower in the 30–45 cm depth under STS than under any other treatment, resulting in lower soil penetration resistance. Highest soil particle macro-aggregation was observed under STS in the 15–45-cm soil layer. Consistently with greater nutrient availability, key enzymes associated with soil fertility (urease, invertase, phosphatase, and catalase) showed higher activity in STS plots. Concomitantly, highest yields were recorded for STS at 10 451 and 10 074 kg/ha in 2014–2015 and 2015–2016, respectively. STS significantly improved soil physical structure and enhanced soil enzyme activity, thereby stimulating soil nutrient release and increasing winter wheat yield.

Keywords: nutrient cycling; soil profile; soil properties; crop productivity; *Triticum aestivum* L.

The Huang-Huai-Hai Plain (3HP) in China is a highly productive area that contributes ~68% of the national, annual wheat yield (Man et al. 2015). However, soil structural stability and nutrient content in the region has been severely affected by intensive and continuous conventional tillage, causing crop productivity to drop substantially (He et al. 2019). Before the 1990s, plowing tillage significantly decreased energy use efficiency and economic benefit. After the 1990s, due to its cost-effectiveness, rotary tillage gradually replaced plowing tillage, shifting tillage depth from 25 cm to 15 cm (Kong et al. 2013). However, subsoil compaction remediation due to rotary tillage and tractor wheel 0–15 cm depth and subsequent machinery traffic associated with seeding, chemical and fertilizer spreading, and harvesting, is more complex and expensive than topsoil compaction (Mu et al. 2016), causing hard-pans to develop that limit water absorption and root growth, ultimately reducing yield and agricultural sustainability. Therefore, suitable tillage to restore farmland ecosystems and substitute sustainable cropping for mismanagement are urgently needed.

Traditional tillage enhances soil penetration resistance, reduces macro porosity, and water and nutrient availability, thus reducing crop yield (Gajda et al. 2017). In contrast, conservation tillage is known to effectively improve soil structure. Reduced or no-tillage increased soil stability due to less physical disruption of aggregates and promoted soil fertility due to increased soil enzyme activity, macro porosity and water infiltration rate (Huang et al. 2012). Subsoiling is a method used to loosen the hardpan and break up deep, compacted soil layers without bringing the infertile subsoil to the top layer (Wang et al. 2019). Furthermore, subsoiling benefited soil carbon storage by enhancing soil organic matter turnover, aggregate stability, and microbial abundance (Peigné et al. 2007). Subsoiling also improved soil catalase and urease activities from re-greening to maturity, and soil alkaline phosphatase activity during grain filling (Yin et al. 2015).

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Previous research focused the study of single-type tillage effects on soil properties; however, continuous single-type, inappropriate tillage may simply shift the problem of compaction down to a deeper layer, without improving soil environment for wheat growth (TerAvest et al. 2015). Up to present, information about the effects of mixed tillage regimes on soil ecology, sustainable productivity, and their interactions in 3HP, is nonexistent. Hence, we conducted a field study based on a continuous 9-year tillage experiment. We compared conventional tillage with 'mixed-tillage practice' – strip rotary tillage coupled to a two-year subsoiling interval, which presumably combines the advantages of strip rotary tillage with those of subsoiling. Soil physical properties, enzyme activity, available nutrient content, and yield were studied to determine the most suitable tillage regime for winter wheat culture in the region. Moreover, we used principal component analysis (PCA) to score soil properties into quality indices that represent their soil functions and evaluated the responses of soil quality indicators and grain yields of wheat to various tillage practices.

MATERIAL AND METHODS

Experimental site. The study began in 2007 in the village of Shijiawangzi, Shandong province, northern China (35°40'N, 116°41'E). The village is located in the center of the 3HP, and its environment is representative of the region. Geographic, climate, and soil information is summarized in Table 1.

Experimental design. Four tillage schemes were tested: plowing tillage (PT); rotary tillage (RT); strip rotary tillage (ST); and strip rotary tillage with a two-year subsoiling interval (STS). Operational procedures for each tillage scheme are shown in Table 2. All treatments were triplicated in a completely randomized design. Each plot was 40 m × 4 m.

Crop management. Winter wheat cv. Jimai 22 was sown on October 8 in 2014 and on October 16 in 2015. Harvest dates were June 13, in 2015 and June 12, in 2016. For fertilization, 105.0, 65.5, and 124.5 kg/ha of N, P, and K were applied at sowing, respectively, and an additional 135 kg N/ha at jointing stage. Irrigation was applied at the jointing and anthesis stages.

Data collection. Soils were sampled at 15-cm intervals to a depth of 45 cm using a soil auger. Samples were collected at sowing, jointing, and maturity stages from three sampling points randomly selected within each plot, in each growing season. Bulk density (BD) and three phase ratio were determined using the cutting-ring method. Aggregate-size separation was performed using a dry (DS) and a wet sieving (WS) method. Penetration resistance (PR) was determined to a depth of 45 cm at 2.5-cm intervals using an electronic cone penetrometer (Model SC-900, Spectrum Technologies Inc., Chicago, USA).

Soil urease (URE); invertase (INV); phosphatase (PHO); and catalase (CAT) activities were assayed as described by Ren et al. (2016). Hydrolysable nitrogen (HN), available phosphorus (AP), and available potassium (AK) were measured after Guo et al. (2017). Grain yield (GY) was estimated from a 3-m^2 area in each plot.

Statistical analysis. Soil properties and GY were analyzed for differences among tillage regimes using analysis of variance (ANOVA; $\alpha = 0.05$) followed by the least significant difference (*LSD*). PCA was conducted to establish the minimum data set and integrated indices for soil quality. Data were analyzed through PCA using factor extraction with an eigenvalue > 1 and varimax rotation. All analyses were conducted using SPSS 22.0 (SPSS Inc., Chicago, USA).

RESULTS AND DISCUSSION

Soil physical properties. The interaction between tillage and soil depth significantly affected BD, solid

Table 1. General description of the experimental site

Basic information	Yanzhou
Elevation (m a.s.l.)	55
Climate	warm-temperate, semi-humid continental monsoon climate
Average temperature (°C)	13.6
Annual precipitation (mm)	621.2
Accumulated sunshine hours (h)	2460.9
Groundwater depth (mm)	25
Soil texture	Loam
FAO soil classification	Haplic luvisols
Clay content (%)	29.6
Silt content (%)	37.3
Sand content (%)	33.1
pH	7.6
Cropping system	double-cropping, maize/wheat annually
Tillage practices	rotary or plowing tillage

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Table 2. Operational procedures of different tillage practices

Tillage	Operational procedures
Plowing tillage (PT)	returning corn straw to the field → spreading base fertilizer → moldboard plowing once with ILFQ330 turnover plough (working depth was 25 cm) → rotary cultivating two times with IGQN-200K-QY rotary cultivator (working depth was 15 cm) → harrowing two times → forming the border-check → seeding with common seeder
Rotary tillage (RT)	returning corn straw to the field → spreading base fertilizer → rotary cultivating two times with IGQN-200K-QY rotary cultivator (working depth was 15 cm) → harrowing two times → forming the border-check → seeding with common seeder
Strip rotary tillage (ST)	returning corn straw to the field → completing rotary cultivation of sowing row (working depth was 15 cm), application of base fertilizer, seeding and forming border-check at the same time with the 2BMYF-10/5 multifunctional direct seeder in stubble (The row spacing of 2BMYF-10/5 multifunctional direct seeder in stubble was designed to be 9 cm + 16 cm, in which the sowing row spacing was 9 cm, so that the area of rotary cultivation took up 36 percent of the border check's total area.)
Strip rotary tillage after subsoiling (STS)	returning corn straw to the field → subsoiling once with the ZS-180 vibration subsoiler (working depth was 38 cm) → Completing rotary cultivation of sowing row (working depth was 15 cm), application of base fertilizer, seeding and forming border-check at the same time with the 2BMYF-10/5 multifunctional direct seeder in stubble

phase ratio (SPR), DS, and WS (Table 3). ANOVA showed there were significant differences in soil physical properties among tillage and soil depths, except for liquid and gaseous phase ratio. BD and SPR were markedly lower in STS than in any other tillage regime. Further, STS enhanced macroaggregates content to a larger extent than any other treatment. Regarding soil depth, the highest BD and DS were obtained at 30–45 cm depth, followed by 15–30 cm, and then 0–15 cm. WS followed the opposite pattern. Additionally, SPR was higher at 15–30 cm and 30–45 cm than at 0–15 cm.

Average PR in 0–15 cm layer in ST was 1277 KPa, which was higher than in any other treatment (Figure 1). At 15–30 cm, RT and ST showed higher PR than PT or STS. However, at 30–45 cm, STS had the lowest PR, whereas it did not differ for PT, RT, and ST. Notably, the level of PR under STS was lower than under other tillage schemes, probably because of the reduction in BD and the increase in macroaggregates

Table 3. Tillage effects on soil physical properties

Treatment		Bulk density (g/cm^3)	Three phase ratio (%)			Macroaggregates content $R_{0.25}$ (%)	
			solid	liquid	gaseous	dry sieving	wet sieving
Tillage (T)	PT	1.47^{c}	55.84^{b}	21.20^{a}	22.96^{ab}	80.66^{bc}	18.08^{c}
	RT	1.49^{b}	56.56^{b}	21.23^{a}	22.21^{ab}	78.72^{c}	16.57^{c}
	ST	1.54^{a}	58.20^{a}	22.28^{a}	19.52^{b}	81.68^{b}	21.66^{b}
	STS	1.43^{d}	53.97^{c}	20.85^{a}	25.19^{a}	87.66^{a}	24.31^{a}
Depth (D, cm)	0–15	1.44^{c}	53.61^{b}	21.23^{a}	25.16^{a}	80.11^{b}	28.94^{a}
	15–30	1.48^{b}	56.99^{a}	20.35^{a}	22.66^{ab}	81.37^{b}	18.46^{b}
	30–45	1.52^{a}	57.82^{a}	22.58^{a}	19.59^{b}	85.05^{a}	13.06^{c}
ANOVA table (*LSD* protected, *P* ≤ 0.05)	F_T	75.20**	51.68**	0.41^{ns}	1.47^{ns}	96.50**	58.25**
	F_D	82.81**	111.44**	1.79^{ns}	2.78^{ns}	56.84**	414.68**
	$F_T \times F_D$	10.36**	9.26**	0.19^{ns}	0.35^{ns}	18.47**	18.94**
	CV	0.04	0.05	0.13	0.37	0.06	0.39

$R_{0.25}$ means aggregates of diameter > 0.25 mm (dry/wet sieving). Means followed by different letters within columns are statistically different (ANOVA) at $P < 0.05$. F_T, F_D, and $F_T \times F_D$ are *F*-values of tillage, depth, and their interaction in variance analysis, respectively; $^{**}P < 0.01$; ^{ns}not significant. PT – plowing tillage; RT – rotary tillage; ST – strip rotary tillage; STS – strip rotary tillage after subsoiling; *CV* – coefficient of variation

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content (Wang et al. 2019). Subsoiling improved soil structure by loosening the soil; concomitantly, strip rotary tillage enhanced soil aggregation and increased aggregate stability; thus, STS seemingly caused significant, positive changes in soil structure.

Soil enzyme activity. Soil enzyme activity has been proposed as a suitable proxy of the degree to which soils are altered in both natural ecosystems and in agroecosystems (Mbuthia et al. 2015). Here, URE, INV, and PHO activities decreased with soil depth, whereas CAT activity increased (Figure 2). Average URE activity under PT, RT, and ST was lower than under STS by 21.1, 31.6, and 26.3%, respectively. INV, PHO, and CAT activities under STS were highest in the 0–45-cm depth range, consistently with Yin et al. (2015), who found that CAT and URE activities were higher under subsoiling than under RT. Hence, STS improved soil enzyme activity and thus, soil ecological environment.

Soil nutrient availability. Tillage significantly affected HN, AP, AK, and nutrient availability in a depth-dependent fashion (Table 4) as shown by the greater nutrient levels at the topsoil layer, compared to the 15–45 cm layer. Kibet et al. (2016) reported that untilled soils showed 5-fold greater nutrient content than soils plowed to a depth of 10 cm. However, plowing resulted in greater nutrient amounts than in no-tillage at 10–20 cm. Our results are in line with those of other studies that suggest that reducing or eliminating tillage may help the accumulation of soil nutrients near the soil surface but not at greater depths. Mean HN, AP, and AK in the 0–15 cm soil layer did not differ between STS and ST, and was higher than in PT or RT. Interestingly, at 15–45 cm depth STS still showed the highest values for HN, AP, and AK. Seemingly, STS increased soil available nutrients in both surface and subjacent soil layers. This may have resulted from improvement in soil structure and enzyme activity (He et al. 2019).

Grain yield. Growth season and tillage had distinct, non-cumulative effects on GY (Figure 3). Tillage ef-

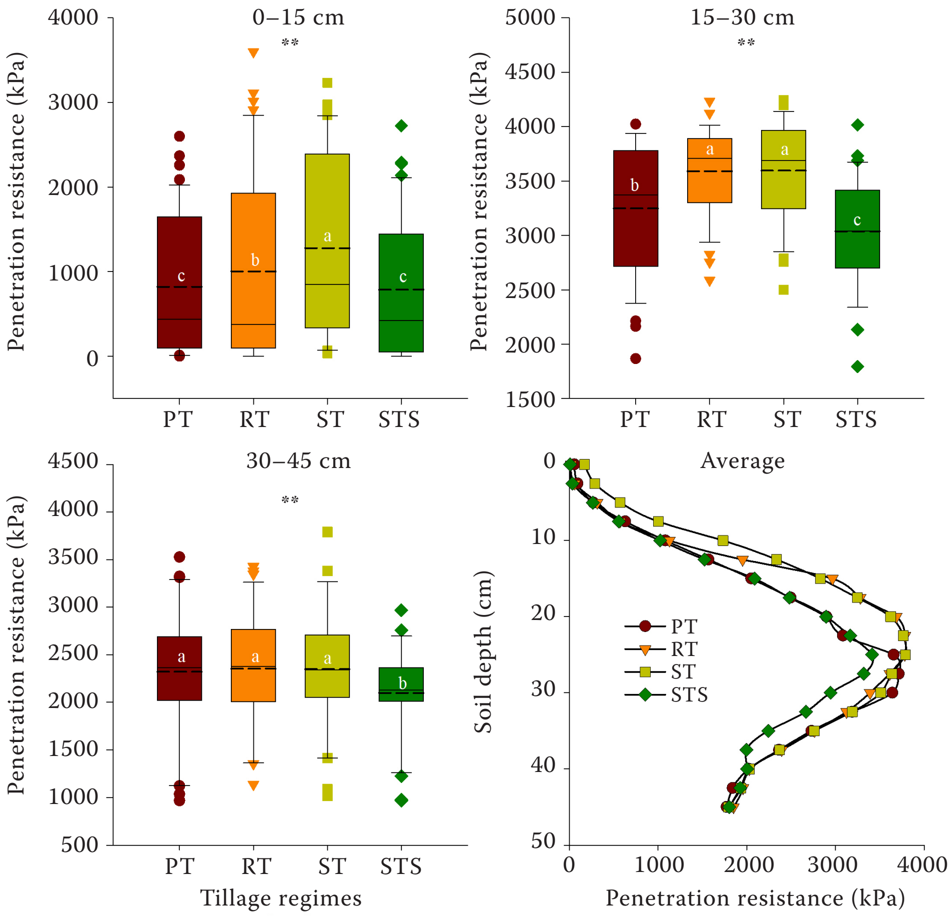

Figure 1. Soil penetration resistance under various tillage regimes. Data are means ± standard error. Different letters indicate statistical differences among treatments; $^{**}P < 0.01$. PT – plowing tillage; RT – rotary tillage; ST – strip rotary tillage; STS – strip rotary tillage after subsoiling

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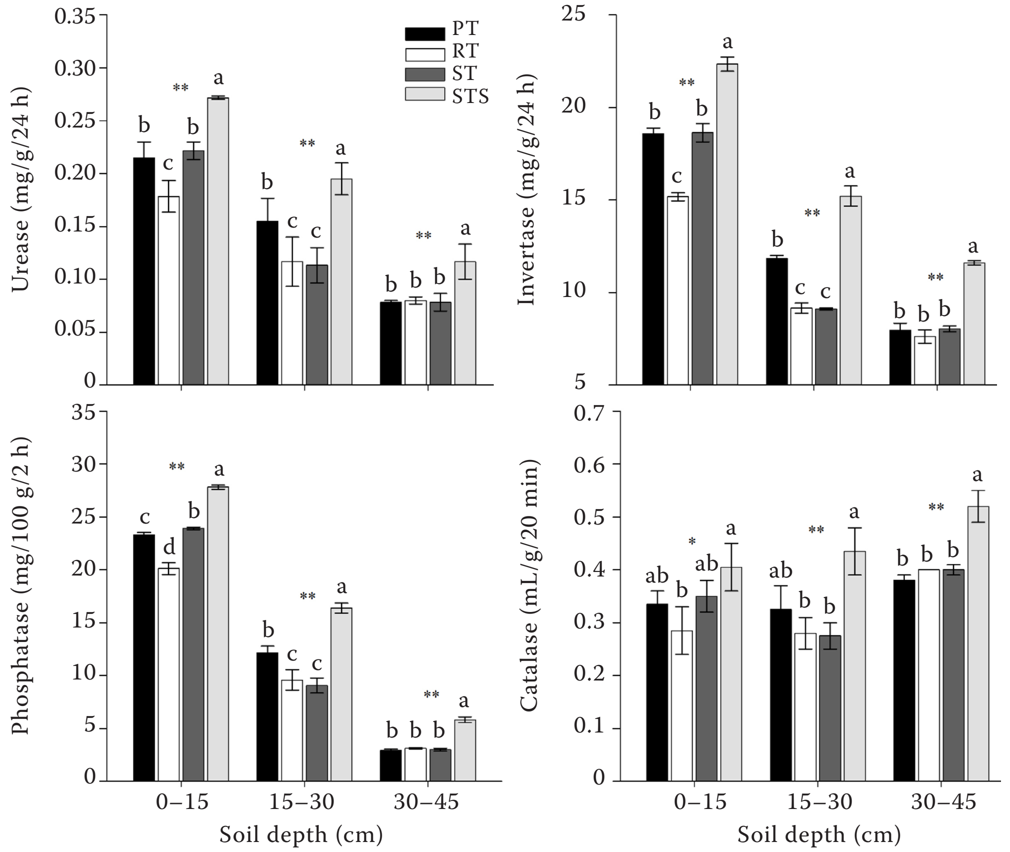

Figure 2. Soil urease, invertase, phosphatase and catalase activities under various tillage regimes. Error bars represent standard error of the mean (SEM). Different letters indicate statistical differences among treatments. $^{*}P < 0.05$; $^{**}P < 0.01$. PT – plowing tillage; RT – rotary tillage; ST – strip rotary tillage; STS – strip rotary tillage after subsoiling

fects were independent of growth season. The highest GY was observed for STS; PT had the second greatest value, whereas RT and ST showed the lowest GY. In contrast, GY was similar for no-tillage and PT in the

Table 4. Tillage effects on soil nutrient availability

Treatment		Hydrolysable nitrogen	Available phosphorus	Available potassium
		(mg/kg)		
Tillage (T)	PT	60.10[b]	21.38[c]	89.67[c]
	RT	56.89[b]	21.17[c]	89.22[c]
	ST	59.98[b]	23.60[b]	97.16[b]
	STS	69.35[a]	27.58[a]	104.73[a]
Depth (D, cm)	0–15	94.46[a]	34.20[a]	130.45[a]
	15–30	56.55[b]	22.37[b]	83.38[b]
	30–45	33.73[c]	13.72[c]	71.74[b]
ANOVA table (*LSD* protected, $P \leq 0.05$)	F_T	48.01**	115.27**	23.49**
	F_D	2071.47**	1833.91**	564.01**
	$F_T \times F_D$	12.90**	14.12**	8.28**
	CV	0.42	0.39	0.29

Means followed by different letters within columns are statistically different (ANOVA) at $P < 0.05$. F_T, F_D, and $F_T \times F_D$ are *F*-values of tillage, depth, and their interaction in variance analysis, respectively; $^{**}P < 0.01$. PT – plowing tillage; RT – rotary tillage; ST – strip rotary tillage; STS – strip rotary tillage after subsoiling; *CV* – coefficient of variation

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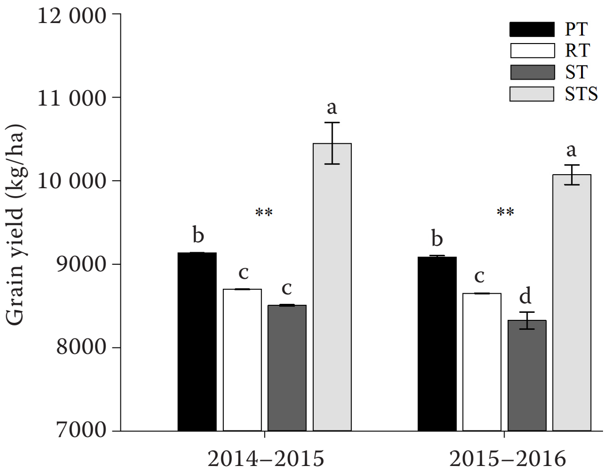

Figure 3. Grain yield of winter wheat under various tillage regimes. Error bars represent standard error of the mean. Different letters indicate statistical differences among treatments. $^{**}P < 0.01$. PT – plowing tillage; RT – rotary tillage; ST – strip rotary tillage; STS – strip rotary tillage after subsoiling

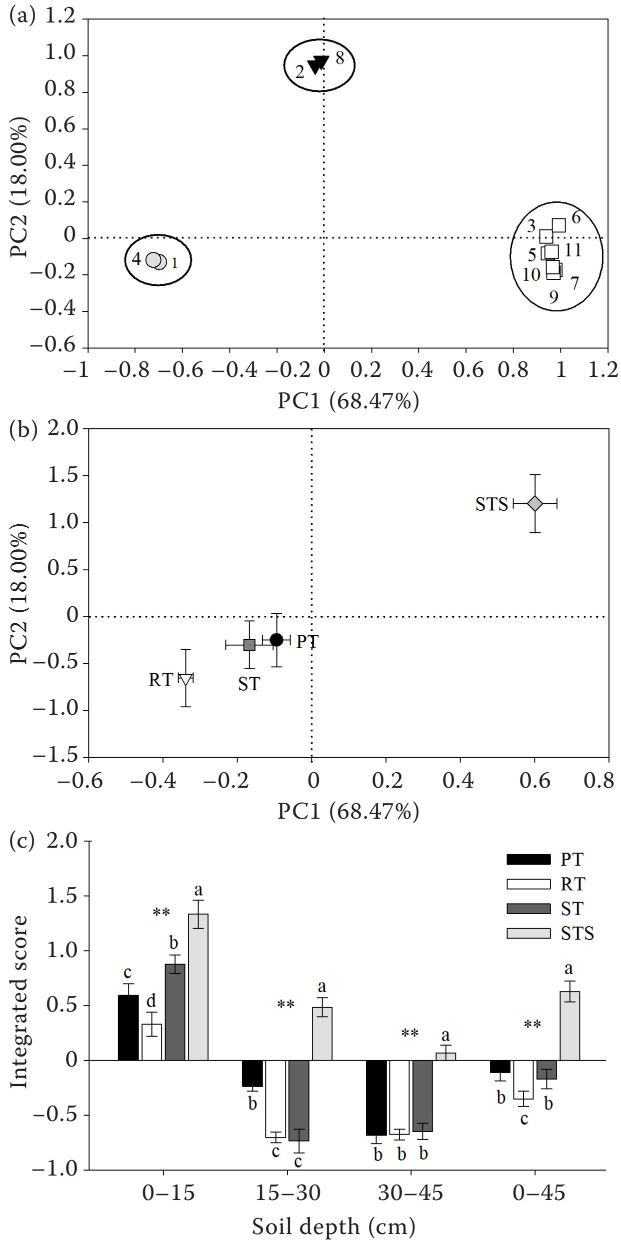

Figure 4. (a) Loading plot; (b) score plot and (c) integrated score plot of principal component analysis (PCA) of 11 soil variables for the 0–45-cm depth range under various tillage regimes. Different letters indicate statistical differences among treatments; $^{**}P < 0.01$. PT – plowing tillage; RT – rotary tillage; ST – strip rotary tillage; STS – strip rotary tillage after subsoiling; 1 – bulk density; 2 – dry sieving; 3 – wet sieving; 4 – penetration resistance; 5 – urease; 6 – invertase; 7 – phosphatase; 8 – catalase; 9 – hydrolysable N; 10 – available P; 11 – available K

first two years, whereas in the third year, PT showed greater GY (4.6 t/ha) than no-tillage (2.9 t/ha) (De Vita et al. 2007). This may be due to a positive effect resulting from the elimination of tillage during the first several years. However, a long-term reduction in tillage or no-tillage tends to increase BD and PR, which results in reduced crop productivity (He et al. 2007). In this study, the mixed-tillage practice of STS significantly increased GY, possibly because of the combination of the advantages of strip rotary tillage with those of subsoiling.

Principal component analysis. PCA showed that soil properties differed strikingly among tillage regimes. From PCA for tillage (KMO = 0.76), we identified two PCs, each with an eigenvalue greater than 1 (Figure 4a); PC1 and PC2 explained 86.5% of the total variability recorded. The eigenvalue for PC1 was 12.2 and explained 76.2% of the variability. PC1 was a contrast of WS, URE, INV, PHO, HN, AP, and AK with positive loadings against the negative loadings of BD and PR. On the other hand, PC2 explained 18.0% of the total variability (eigenvalue = 2.0) and consisted of only positive loadings for DS and CAT. Therefore, the first two factors were selected as the integrated indices for the minimum data set to evaluate soil quality determined by 11 soil properties in the 0–45 cm depth range.

The corresponding scores were calculated to quantify soil quality under various tillage regimes tested; scores were extracted for each PC to evaluate their ability to separate tillage practices (Figure 4b). For PC1, scores were greatest for STS, followed by PT

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and ST, and the smallest scores corresponded to RT; PC2 followed a similar trend. The integrated score was highest for STS, suggesting greater overall soil quality under this treatment (Figure 4c). Further, regression analysis indicated that GY was distinctly, positively, and linearly correlated to the integrated score for soil quality, which might explain GY response to various tillage regimes tested. Although ST stimulated enzyme activities and available nutrient accumulation in the topsoil layer, it did not enhance soil quality in the 0–45 cm depth as a whole.

Our study suggests that STS improved soil structure and enhanced soil enzyme activities significantly, thereby stimulating the release of soil nutrients and increasing wheat yield. Our data offer a sound basis for methodological development to measure soil physicochemical and biological characteristics to reduce wheat productivity risks. Under the experimental conditions used here, STS was the most effective tillage regime to revert the decline of farmland sustainable productivity in the 3HP region.

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REFERENCES

De Vita P., Di Paolo E., Fecondo G., Di Fonzo N., Pisante M. (2007): No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture content in southern Italy. Soil and Tillage Research, 92: 69–78.

Gajda A.M., Czyż E.A., Stanek-Tarkowska J., Dexter A.R., Furtak K.M., Grządziel J. (2017): Effects of long-term tillage practices on the quality of soil under winter wheat. Plant, Soil and Environment, 63: 236–242.

Guo W., Andersen M.N., Qi X.B., Li P., Li Z.Y., Fan X.Y., Zhou Y. (2017): Effects of reclaimed water irrigation and nitrogen fertilization on the chemical properties and microbial community of soil. Journal of Integrative Agriculture, 16: 679–690.

He J., Li H.W., Wang X.Y., McHugh A.D., Li W.Y., Gao H.W., Kuhn N.J. (2007): The adoption of annual subsoiling as conservation tillage in dryland maize and wheat cultivation in northern China. Soil and Tillage Research, 94: 493–502.

He J.N., Shi Y., Yu Z.W. (2019): Subsoiling improves soil physical and microbial properties, and increases yield of winter wheat in the Huang-Huai-Hai Plain of China. Soil and Tillage Research, 187: 182–193.

Huang M., Zou Y.B., Jiang P., Xia B., Feng Y.H., Cheng Z.W., Mo Y.L. (2012): Effect of tillage on soil and crop properties of wet-seeded flooded rice. Field Crops Research, 129: 28–38.

Kibet L.C., Blanco-Canqui H., Jasa P. (2016): Long-term tillage impacts on soil organic matter components and related properties on a Typic Argiudoll. Soil and Tillage Research, 155: 78–84.

Kong F.L., Yuan J.C., Zhang H.L., Chen F. (2013): Effect of tillage practice on growth and development and yield of winter wheat in double cropping area in North China. Acta Agronomica Sinica, 39: 1612–1618.

Man J.G., Shi Y., Yu Z.W., Zhang Y.L. (2015): Root growth, soil water variation, and grain yield response of winter wheat to supplemental irrigation. Plant Production Science, 19: 193–205.

Mbuthia L.W., Acosta-Martínez V., DeBruyn J., Schaeffer S., Tyler D., Odoi E., Mpheshea M., Walker F., Eash N. (2015): Long term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality. Soil Biology and Biochemistry, 89: 24–34.

Mu X.Y., Zhao Y.L., Liu K., Ji B.Y., Guo H.B., Xue Z.W., Li C.H. (2016): Responses of soil properties, root growth and crop yield to tillage and crop residue management in a wheat-maize cropping system on the North China Plain. European Journal of Agronomy, 78: 32–43.

Peigné J., Ball B.C., Roger-Estrade J., David C. (2007): Is conservation tillage suitable for organic farming? Soil Use and Management, 23: 129–144.

Ren C.J., Kang D., Wu J.P., Zhao F.Z., Yang G.H., Han X.H., Feng Y.Z., Ren G.X. (2016): Temporal variation in soil enzyme activities after afforestation in the Loess Plateau, China. Geoderma, 282: 103–111.

TerAvest D., Carpenter-Boggs L., Thierfelder C., Reganold J.P. (2015): Crop production and soil water management in conservation agriculture, no-till, and conventional tillage systems in Malawi. Agriculture, Ecosystems and Environment, 212: 285–296.

Wang S.B., Guo L.L., Zhou P.C., Wang X.J., Shen Y., Han H.F., Ning T.Y., Han K. (2019): Effect of subsoiling depth on soil physical properties and summer maize (*Zea mays* L.) yield. Plant, Soil and Environment, 65: 131–137.

Yin B.Z., Zhen W.C., Guo L.G. (2015): The soil ecological-environment characteristics in wheat growing season under different tillage treatments in Haihe Lowland Plain. Journal of Soil and Water Conservation, 29: 186–194.

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