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Long-term no tillage alleviates subsoil compaction and drought-induced mechanical impedance**

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A b s t r a c t. No tillage was introduced to Northeast China to prevent the soil degradation caused by conventional tillage systems. However, there are concerns that no tillage will result in soil mechanical impedance. In this study, we investigated the effects of conventional tillage and no tillage on soil strength properties using a long-term field study initiated in 2011 on a silt clay loam soil. In 2018 and 2019, soil bulk density, water content, the degree of compactness, and penetrometer resistance were measured before tillage and after planting, and also, the changes in soil profile water content and penetrometer resistance were monitored during drying periods. Results showed that conventional tillage led to the formation of a compacted zone beneath the cultivated layer, with higher bulk density, degree of compactness, and penetrometer resistance values. After converting from conventional tillage to no tillage for 8 to 9 years, the bulk density, penetrometer resistance, and degree of compactness were increased to a moderate extent in the topsoil but were lowered in the subsurface soil. During drying periods, as compared to conventional tillage plots, the no tillage plots maintained higher water contents, which resulted in lower penetrometer resistances below a 15 cm depth and the later arrival of the threshold penetrometer resistance of 2 MPa. Long-term no tillage alleviated subsoil compaction and retarded drought-induced soil strength development.

K e y w o r d s: no tillage, subsoil compaction, soil penetrometer resistance, soil drying

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INTRODUCTION

Subsoil compaction induced by improper tillage operations and the growing weight of machinery is becoming a major threat to sustainable crop production worldwide (Hamza and Anderson, 2005; Cao *et al*., 2017; Pulido-Moncada *et al*., 2019). Subsoil compaction increases soil bulk density (ρ_b) and penetrometer resistance (PR), it leads to poor soil aeration, reduced hydraulic conductivity, and also restricts root proliferation and distribution (Batey, 2009; Schjønning *et al*., 2013; Björklund *et al*., 2016; Obour *et al*., 2017), and hence adversely affects crop growth and development (Hamza and Anderson, 2005; Arvidsson and Håkansson, 2014). As opposed to topsoil compaction that may be relieved by ploughing, soil quality degradation due to subsoil compaction is more persistent (Etana and Håkansson, 1994; Håkansson and Reeder, 1994). In general terms, subsoil compaction is identified indirectly by measuring ρ_b, PR, hydraulic conductivity, and air permeability (Batey and McKenzie, 2006), or alternatively, it is assessed directly through the visual evaluation of subsoil structure (SubVESS) in the field (Obour *et al*., 2017). Among the multiple characterization methods, the measurement methods of ρ_b and PR are frequently adopted due to their simplicity and ease of operation (Hamza and Anderson, 2005).

The Mollisols, which cover a large land area of Northeast China, produce more than 40% of the national maize in China (Cai *et al*., 2014). The prevalent long-term conventional tillage (CT) system, which consists of removing crop residue, rotary tillage, ridging, and packing each year, has however led to soil degradation as indicated by the loss of soil organic matter (SOM), soil structure deterioration, and soil erosion by wind and water (Liang *et al*., 2010; Liu *et al*., 2010). There are also concerns that the intensive usage of machinery associated with long-term CT has resulted in a shallow soil rooting depth, and the formation of a plough pan underneath the cultivated layer (Cai *et al*., 2014; Wang *et al*., 2017; Feng *et al*., 2018). In recent years, deep ploughing and subsoiling have been promoted as the mainstream techniques used to alleviate the adverse effects of the CT system (Cai *et al*., 2014; Wang *et al*., 2017). These tillage practices, however, are time-consuming and labour-intensive, and the benefits are usually short-lived (Olesen and Munkholm, 2007). Moreover, deep ploughing leads to the breakdown of soil aggregates, stimulates SOM decomposition, and often increases the risk of soil erosion (Liu *et al*., 2010).

Alternatively, with minimal soil disturbance and year-round crop residue coverage on the soil surface, conservation tillage systems (*i.e.*, no tillage, NT) may be introduced as viable alternatives to the CT system for sustainable maize production in Northeast China, that is because these systems are effective at increasing soil organic carbon content, water-holding capacity, and aggregate stability (Alvarez and Steinbach, 2009; Soane *et al*., 2012; Zhang *et al*., 2015), and also reduce soil erosion (Yang *et al*., 2003; Lal *et al*., 2007). Eventually, the NT system may produce higher crop yields than the CT system (He *et al*., 2011, Zhang *et al*., 2015; You *et al*., 2017). However, there are doubts about whether the NT system can mitigate soil compaction and reverse soil degradation caused by intensive long-term CT operations (Zhai *et al*., 2017; Zhang *et al*., 2017).

In theory, long-term NT soils are less likely to be compacted than CT soils because of (1) the minimal usage of vehicular traffic (Hernández *et al*., 2019); (2) the buffering effect of surface mulch on wheel traffic (Blanco-Canqui and Lal, 2007); (3) the increase in SOM concentration, which makes the NT soil more resilient to traffic-induced compaction (Blanco-Canqui and Ruis, 2018). However, after conversion from CT to NT systems, the changes to soil properties are gradual, and a transitional period (about 3-5 years) is usually required to convert the CT system into a fully functional NT system (Moreira *et al*., 2016; Castellini *et al*., 2019). During the transitional phase, greater soil strengths (*i.e.*, increased ρ_b and PR) are often observed (Gao *et al*., 2016; Blanco-Canqui and Ruis, 2018). As the short transition elapses, progressive improvements in soil properties will emerge because the new system provides the same ecosystem services as the "true" no-tillage methods (Grigar *et al*., 2018). For example, Vogeler *et al*. (2009) observed an increase in ρ_b at the initial transition from CT to NT, but a lower or equal ρ_b value after 6 years. Reichert *et al*. (2016) reported similar results, *i.e.*, the initial physical conditions of the topsoil layer under the NT treatment could be worse than that under the CT system but improved gradually with time and the benefits were even transferred to the deeper layers. Grigar *et al*. (2018) pointed out that long-term NT soils had more pore space and lower ρ_b values than those of the CT soils. In order to formulate an appropriate soil management strategy, it is important to assess the changes to soil physical properties by using long-term tillage experiments.

In Northeast China, due to the lack of the long-term field tillage experiments, little is known about the effects of converting from CT to NT on soil mechanical impedance, and how soil strength varies under continuous wetting and drying processes. Our objective in this study was to investigate the changes to soil strength parameters (*i.e.*, ρ_b and PR) after the conversion from CT to NT in a Mollisol based on a long-term tillage experiment. We hypothesized that (1) the long-term NT system would have the ability to alleviate subsoil compaction due to minimal soil disturbance, surface cover, alterations in soil physical processes (*i.e.*, wetting/drying cycles, and freezing/thawing cycles), and enhanced bioturbation; (2) during prolonged drying periods, the soil under long-term NT would be resilient to changes in soil strength due to the favourable and stable soil moisture condition.

MATERIALS AND METHODS

The field experiment was conducted at the Lishu Experimental Station (43°16′N 124°26′E) of China Agricultural University, located in Lishu County, Jilin Province, China. The site has a sub-humid temperate monsoon climate, which is dry and windy in spring and hot and rainy in summer. Over the past 30 years, the average annual temperature has been 5.9°C, and the annual precipitation has been 556 mm with more than 73% occurring from June to September. The main crops in this area are maize (*Zea mays* L.) and soybean (*Glycine max* L. Merr.), and monocropping maize is the prevalent cropping system. The soil has a silt clay loam texture consisting of 24.1% sand, 44.9% silt, and 31.0% clay in the 0-20 cm layer (Table 1). Prior to the initiation of the field experiment, conventional tillage had been practiced continuously for more than 30 years.

The experiment was established in 2011 as a randomized split-plot design with three tillage treatments (main plots: CT, conventional tillage; NT, no tillage; RT, rotational tillage) and three crop rotation systems (subplots: continuous maize, maize-soybean 2-year rotation, and maize-maize-soybean 3-year rotation). Each tillage treatment was repeated three times, with a total plot number of 27. The plot size was 21.6 by 63 m. In this study, the CT and NT plots under continuous maize were selected to

Table 1. Soil particle size distribution, organic matter (OM) content and reference bulk density (ρ_{ref}) of the 0-40 cm soil layer under the conventional tillage (CT) and no tillage (NT)

Tillage system	Soil layer (cm)	Soil particle size distribution (g kg^{-1})			OM (g kg^{-1})	ρ_{ref} (g cm^{-3})
		Sand (2.0-0.05 mm)	Silt (0.05-0.002 mm)	Clay (< 0.002 mm)		
CT	0-5	237.8	448.7	313.5	21.13	1.66
	5-10	243.5	447.8	308.7	20.04	1.67
	10-20	244.3	449.4	306.3	14.99	1.69
	20-40	206.2	443.7	350.1	10.08	1.68
NT	0-5	244.4	440.1	315.5	30.88	1.63
	5-10	240.1	455.4	304.5	17.97	1.68
	10-20	234.0	452.1	313.9	14.74	1.68
	20-40	210.1	443.3	346.6	9.74	1.68

investigate the effects of tillage treatments on soil strength. The CT treatment consisted of: (1) post-harvest removal of above-ground maize residue; (2) spreading fertilizers on the soil surface, followed by rotary tillage to a depth of about 10 to 12 cm, and making ridges (20 cm wide, 12-15 cm high, with 60 cm spacing between adjacent ridges) with a machine in early May; (3) firming the seedbed with a field roller; (4) planting maize on the raised beds. For the NT plots, the field operations included: (1) harvesting maize with a combine, leaving 30 to 40 cm long standing stubble, and the rest of the maize residue was spread evenly in the field; (2) planting maize in spring with a no-tillage seeder, which completed planting, fertilizer application and packing in one pass. In both 2018 and 2019, the tillage operation was conducted on May 8, and maize was planted on May 10. The precipitation rate was monitored with a tipping bucket rain gauge (Model AV-3665R, Yugen Scientific Limited, Beijing, China) located nearby the field plots.

In order to examine the effects of tillage and planting operations on soil strength properties, ρ_b, PR, and volumetric water content (θ_v) were determined before tillage (on April 27 of 2018 and April 29 of 2019) and after the maize was planted (on May 31 of 2018 and May 16 of 2019) in spring. Intact soil cores were collected with 100 cm^3 stainless steel cylinders from the 0-5, 5-10, 10-20, 20-30 and 30-40 cm soil layers. A total of 30 samples (2 treatments x 5 layers x 3 replications) was collected each time. The samples were sealed tightly with plastic wrap and brought back to the laboratory to determine ρ_b and gravimetric water content (θ_m). Additionally, an SC900 Soil Compaction Meter (Field Scout^{TM} SC900, Spectrum Technologies Inc, Aurora, Colorado, USA) was used to determine the PR distribution with soil depth. The SC900 meter was positioned in the crop zone, and PR values were measured at a 2.5 cm interval in the 0 to 45 cm soil profile. Each time, four replicated PR measurements were made for each treatment.

The changes to soil profile strength and the extent to which they were affected by tillage treatment were investigated by measuring PR changes during two long-term drying processes in 2018 (from July 15 to 25, 5 times) and 2019 (from July 2 to 16, 5 times). Meanwhile, undisturbed soil samples were collected from the 0-5, 5-10, 10-20, 20-30 and 30-40 cm soil layers at the locations where PR was measured, and then oven-dried at 105°C for 48 h to determine the soil water contents.

In the laboratory, the intact soil cores collected in the field were oven-dried at 105°C for 48 h to a constant weight. Soil ρ_b was calculated by dividing the dry mass of the soil by the cylinder volume (100 cm^3), and θ_m was obtained as the ratio of the mass of lost water to the dry soil mass. Finally, θ_v was estimated as the product of ρ_b and θ_m. Additional disturbed soil samples were collected to determine soil particle-size distribution following Gee and Or (2002) and organic matter content following Nelson and Sommers (1982).

The degree of compactness (DC) was used as a parameter to describe the state of soil compaction:

$$DC = \frac{\rho_b}{\rho_{ref}} 100 \, , \tag{1}$$

where: DC is the degree of compactness (%), ρ_b is the measured (field) bulk density (g cm^{-3}), and ρ_{ref} is the Proctor reference bulk density (g cm^{-3}) that was estimated following Naderi-Boldaji *et al*. (2016):

$$\rho_{ref} = 1.90 - 3.42\ 10^{-3} OM - 5.29\ 10^{-4}\ CC \, , \tag{2}$$

where: OM is the soil organic matter content (g kg^{-1}) and CC is the clay content (g kg^{-1}).

The *t*-test was applied to assess the effects of tillage treatments and soil drying on soil physical parameters (ρ_b, θ_v, and PR) using the SPSS statistics 22.0 software (IBM SPSS, 2013). The differences were considered statistically significant at the $p<0.05$ level.

RESULTS

Figure 1 presents the monthly precipitation of the experimental site from April to September. The total precipitation was 499.6 mm in 2018 and 539.2 mm in 2019, it is 5.8 and 14.1% higher than that of the 30-year average (472.4 mm). However, precipitation varied considerably among the different seasons and between the two years. For example, the total precipitation in May 2018 was 35.8 mm, which was 32.5% lower than the 30-year average (53.0 mm), while the total precipitation in May 2019 (115.4 mm) was 118% higher than the 30-year average. For both years, the monthly precipitation in July was about the same as that of the 30-year average. Yet, in terms of daily values, the precipitation in July varied significantly. In July 2018, two heavy rainfalls on July 12 (52.4 mm) and July 26 (59.4 mm) (Fig. 1a) accounted for more than 80.5% of the total monthly precipitation (138.8 mm). Similarly, the accumulated precipitation from July 25 to 30 in 2019 was 101.8 mm, which accounted for about 78.2% of the total monthly precipitation.

Soil texture under the CT and NT treatments were similar in the 0 to 40 cm soil layer (Table 1). For example, in the 0-20 cm soil layer, the sand and clay contents of the CT treatment were 241.9 and 309.5 g kg^{-1}, respectively, and the corresponding values of the NT treatment were 239.5 and 311.3 g kg^{-1}, respectively. For both treatments, the clay contents of the 20 to 40 cm soil layer (350.1 for CT and 346.6 g kg^{-1} for ZT) were higher than that of the 0 to 20 cm layer (Table 1). This may lead to substantial differences in soil mechanical behaviours because soil texture has a substantial effect on the mechanical properties during wetting and drying processes.

The soil physical environments may differ considerably under CT and NT treatments due to the variations in surface cover and mechanical disturbance to soil structure. In this section, the changes to soil bulk density (ρ_b), water content (θ_v), penetrometer resistance (PR), and degree of compactness (*DC*) were examined before soil tillage and after maize planting in the spring seasons of 2018 and 2019.

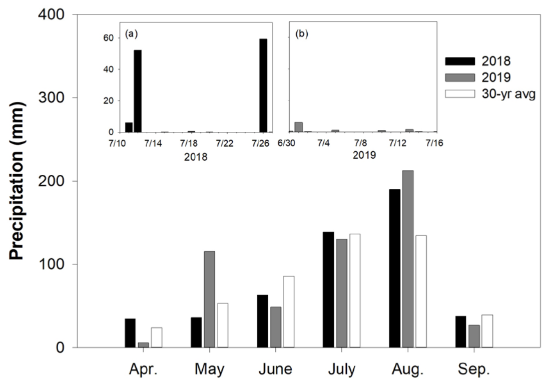

Fig. 1. Monthly precipitation at the experimental site from April to September in 2018 and 2019 as compared with that of the 30-year average. The subplots (a) and (b) show the daily precipitation from July 10 to 26 in 2018 and from June 30 to July 16 in 2019, respectively.

In general, long-term NT management significantly changed the ρ_b values of the 0-20 cm soil layer. In both 2018 and 2019, either before tillage (Figs 2a and 3a) or after planting (Figs 2b and 3b), NT had significantly higher ρ_b values than CT in the 0-10 cm soil layer, and the opposite was true for the 10-20 cm soil layer where significantly greater ρ_b values were observed in the CT plots. In the 20-40 cm soil layer, soil ρ_b values ranged from 1.42 to 1.47 g cm^{-3}, and no significant differences were observed between the NT and CT treatments.

The CT treatment displayed a significant variation in ρ_b values with soil depth in both years: It was low in the tilled soil zone, and increased linearly with depth, reached its maximum value (1.58 g cm^{-3} in 2018 and 1.52 g cm^{-3} in 2019) at about the 15 cm depth, decreased gradually to a value about 1.44 g cm^{-3}, and remained almost constant thereafter. By contrast, the NT treatment had a relatively low ρ_b value (ranging from 1.28 to 1.36 g cm^{-3}) in the 0 to 5 cm soil layer as compared to the deep layers, but had relatively small ρ_b changes (ranging from 1.44 to 1.49 g cm^{-3} in 2018 and from 1.42 to 1.45 g cm^{-3} in 2019) at soil depths below 5 cm. Clearly, long-term rotary tillage under CT created a compacted layer just

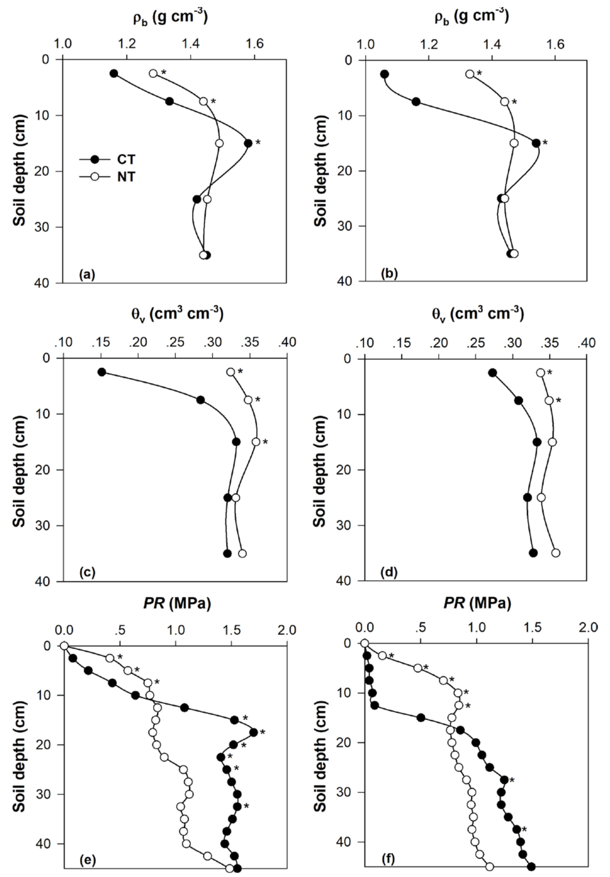

Fig. 2. Comparisons of soil bulk density (ρ_b), water content (θ_v), and penetrometer resistance (PR) between conventional tillage (CT) and no tillage (NT) measured before tillage (a, c, e) and after planting (b, d, f) in 2018. The symbol * indicates significant difference ($p<0.05$) between CT and NT at the same soil depth.

below the loose topsoil. After converting from CT to NT for 8 to 9 years, however, the compaction zone in the subsurface layer had diminished.

The tillage and planting operations under the CT treatment also induced significant temporal ρ_b variation in the tilled soil layer. In 2018, for example, the 0 to 10 cm soil layer under CT had an average ρ_b value of 1.25 g cm^{-3} before spring tillage, and the corresponding ρ_b value was reduced to 1.11 g cm^{-3} after planting. In April 2019 (*i.e.*, before tillage), the corresponding ρ_b value of the 0 to 10 cm soil layer was increased to 1.29 g cm^{-3}. By contrast, no significant seasonal ρ_b variation was observed under the NT treatment. In the deeper soil layers (>10 cm), short-term soil mechanical disturbance and planting operations produced insignificant effects on temporal ρ_b changes for both CT and NT treatments.

Either before tillage or after planting, NT produced significantly higher θ_v values than CT in the 0 to 20 cm soil profile in both years (Fig. 2c and 2d; Fig. 3c and 3d). In 2018, the average θ_v values of the 0 to 20 cm soil layer under the NT treatment were 31% (before tillage) and 17% (after planting) higher than those under the CT treatment. In 2019, the corresponding θ_v values of the NT treatment were 50% (before tillage) and 35% (after planting) higher than those under the CT treatment. At soil depths greater than 20 cm, the NT treatment tended to produce higher θ_v values than CT, but no statistically significant θ_v differences were observed between the two tillage treatments, except for April 29, 2019 when the θ_v value of the NT treatment was significantly higher than that of the CT treatment in the 30 to 40 cm soil layer.

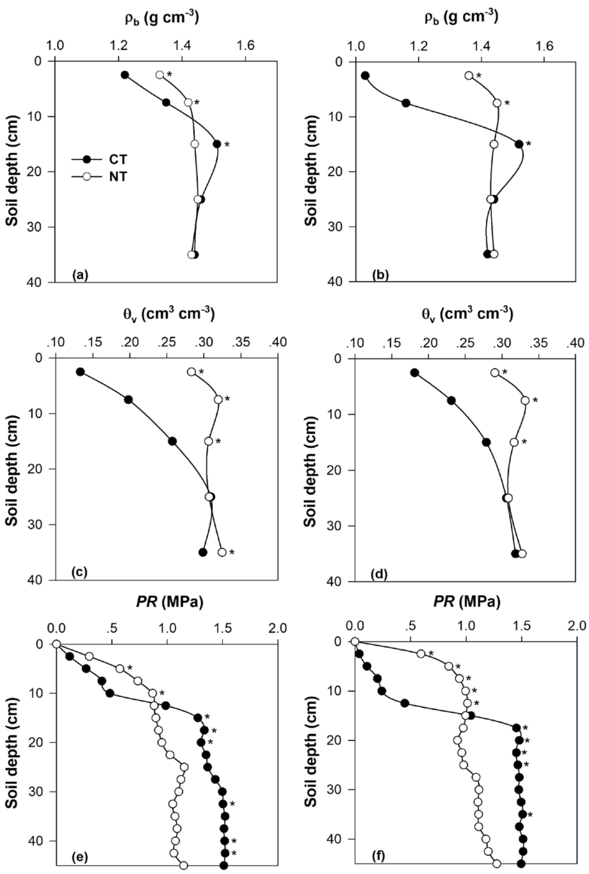

Fig. 3. Comparisons of soil bulk density (ρ_b), water content (θ_v), and penetrometer resistance (PR) between conventional tillage (CT) and no tillage (NT) measured before tillage (a, c, e) and after planting (b, d, f) in 2018. The symbol * indicates significant difference (p<0.05) between CT and NT at the same soil depth.

The two tillage systems displayed consistent PR differences before tillage and after planting in both 2018 (Fig. 2e and 2f) and 2019 (Fig. 3e and 3f). In the case of the measurements obtained before soil tillage, the NT treatment had significantly higher PR values than those of the CT treatment in the 0 to 10 cm soil layer. At soil depths greater than 10 cm, the PR values under the CT treatment tended to be higher than those of the NT treatment, and the differences were mainly significant around the 20 cm depth. A similar trend was observed in the measurements obtained after planting, but the dividing depth moved from 10 cm down to about 12.5 cm, *i.e.*, the NT treatment produced higher PR values than those of the CT treatment in the 0 to 12.5 cm soil layer and the trend was reversed at soil depths below 12.5 cm.

It is worth noting that the shapes of the PR *vs.* depth curves differed considerably between the two tillage systems. For the NT treatment, PR increased rapidly with depth in the 0 to 10 cm soil layer, but only very minor changes were observed at greater depths (Figs 2e, 2f, 3e, and 3f). For the CT treatment, the PR *vs.* depth curve showed three distinct stages: PR increased gradually with depth in the 0 to 10 cm layer, very rapidly in the 10 to 17.5 cm layer, and then increased slightly (Figs 2f and 3e) or varied little with soil depth (Figs 2e and 3f).

The variation in *DC vs.* soil depth generally followed similar trends to that of ρ_b changes in both 2018 and 2019 (Table 2). For the CT treatment, the *DC* values were relatively

Table 2. Comparisons of degree of compactness (*DC*) between conventional tillage (CT) and no tillage (NT) measured before tillage and after planting in 2018 and 2019

Sampling time	Tillage system	Degree of compactness (*DC*, %) 0-5 (cm)	5-10	10-20	20-30	30-40
Before tillage						
2018	CT	70^b	80^b	94^a	85^a	86^a
	NT	79^a	86^a	89^b	86^a	86^a
2019	CT	73^b	81^b	90^a	87^a	86^a
	NT	82^a	85^a	86^b	86^a	85^a
After planting						
2018	CT	64^b	70^b	91a	85^a	87^a
	NT	82^a	86^a	87^b	86^a	87^a
2019	CT	62^b	70^b	90a	86^a	85^a
	NT	84^a	86^a	86^b	85^a	86^a

Different letters in the same column indicate significant difference (p<0.05) between CT and NT for the same sampling time.

low and varied considerably (from 62 to 81) in the 0 to 10 cm soil layer and relatively stable (from 85 to 87) in the deeper layers (20-40 cm), and the maximum value (from 90 to 94) was obtained in the 10 to 20 cm soil layer. For the NT treatment, by contrast, relatively low *DC* values (from 79 to 84) were obtained in the 0 to 5 cm soil layer, and the other soil layers (>10 cm) generally had relatively stable *DC* values (from 85 to 89). Additionally, the tillage and planting operations of the CT system decreased the *DC* values in the 0 to 10 cm soil layer (Table 2). However, the planting operation of the NT treatment did not cause significant changes in soil *DC*.

Under field conditions, the wetting/drying process is a key factor that alters soil strength and mechanical properties. The variations in soil profile θ_v and PR in response to soil drying were compared under the contrasting tillage systems. A heavy rainfall (52.4 mm) occurred on July 12, 2018, followed by a 13-day drying period with only a 1 mm rainfall (Fig. 1a). Similarly, a prolonged drought event occurred from July 2 to July 16, 2019, during which there was only 4.4 mm of rainfall (Fig. 1b).

When the soil was subjected to drying, generally the PR value increased with decreasing θ_v under both CT and NT treatments (Figs 4 and 5). The rate of soil water loss and the corresponding changes in PR, however, varied substantially between the two tillage treatments. At the beginning of the drying process on July 15, 2018, both CT and NT treatments had high water contents: from the soil surface to the 40 cm depth, θ_v ranged from 0.25 to 0.35 $cm^3\ cm^{-3}$ under the CT treatment and varied from 0.32 to 0.37 $cm^3\ cm^{-3}$ under the

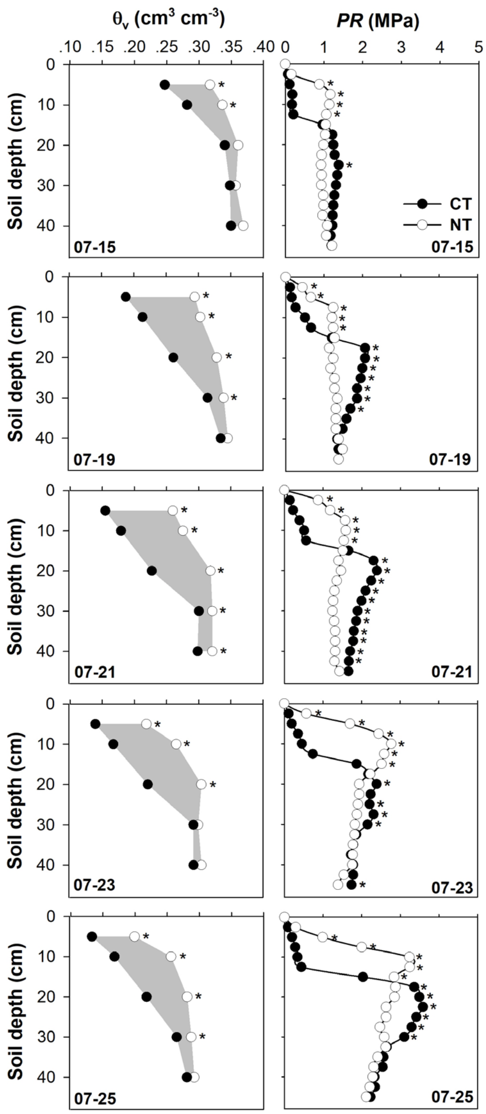

Fig. 4. Changes in soil water content (θ_v) and penetrometer resistance (PR) under conventional tillage (CT) and no tillage (NT) during a drying process in 2018. The symbol * indicates significant difference (p<0.05) between CT and NT at the same soil depth. The shadowed area represents the θ_v difference between NT and CT.

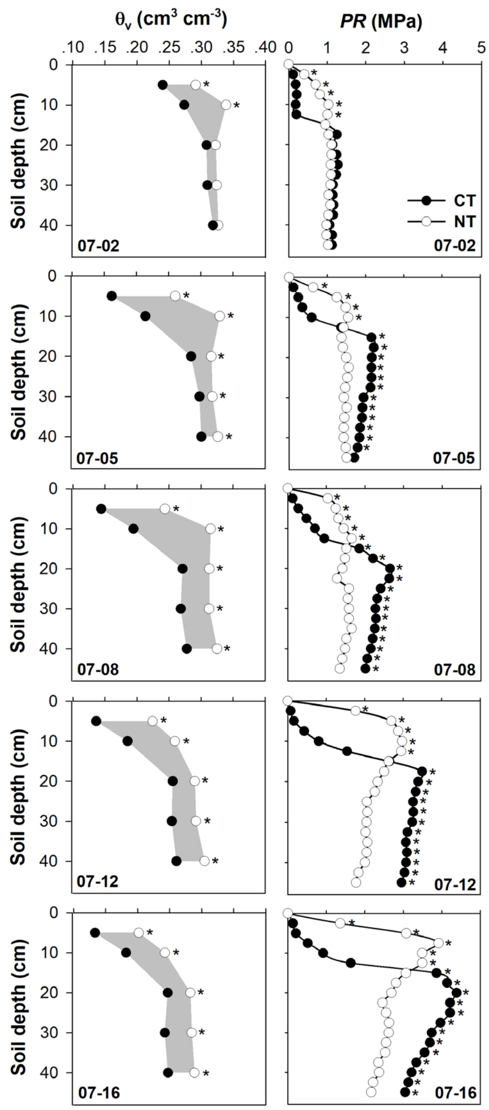

Fig. 5. Changes in soil water content (θ_v) and penetrometer resistance (PR) under conventional tillage (CT) and no tillage (NT) during a drying process in 2019. The symbol * indicates significant difference (p<0.05) between CT and NT at the same soil depth. The shadowed area represents the θ_v difference between NT and CT.

NT treatment (Fig. 4). In the 0 to 10 cm soil layer, the NT treatment had significantly higher θ_v values than those of the CT treatment.

Under this high-water content condition, the soil profile PR values were low (with maximum PR values of 1.21 and 1.38 MPa for NT and CT, respectively), and significant differences between the two treatments appeared in the 0 to 12.5 cm soil layer, where NT had greater PR values than those of CT (Fig. 4). At soil depths greater than 12.5 cm, CT tended to have higher PR values than NT, but the differences were not statistically significant except at a soil depth of 25 cm.

At the early drying stage, soil water loss in the CT treatment occurred far more rapidly than those in the NT treatment (Figs 4 and 5). From July 15 to July 21, 2018, the θ_v values of the CT treatment were reduced by 37, 36, 33, 14, and 15% in the 0-5, 5-10, 10-20, 20-30, and 30-40 cm soil layers, respectively, and the corresponding θ_v reductions of the NT treatment were 18, 18, 12, 10, and 13%, respectively. The more rapid loss of soil water under the CT treatment induced a more rapid increase in the peak PR value as compared to the NT treatment (Figs 4 and 5). For example, under the NT treatment, with an 18% decrease in θ_v from July 15 to July 21, 2018, the PR value was increased by 35% (from 1.16 to 1.57 MPa) at the 7.5 cm soil depth. During the same period, the θ_v of the CT treatment was decreased by 33% at the 20 cm depth, and the PR value was increased by 93% (from 1.24 to 2.39 MPa). In addition, as compared to the NT treatment, the CT treatment had lower PR values at soil depths above 12.5 cm, but larger PR values at soil depths greater than 17.5 cm.

With further drying of the soil, the rate of water loss from the NT plots exceeded those of the CT plots, which was reflected in the greater θ_v decrease under the NT treatment (12% in NT *vs.* 8% in CT) in the 0-40 cm soil layer. Accordingly, the PR values of the NT treatment increased rapidly, while the rate of PR change of the CT treatment seemed to be slowing down. For example, from July 21 to July 25, 2018, the soil PR of the NT treatment was increased by 104% (from 1.59 to 3.24 MPa) at the 10 cm soil depth, whereas the PR of the CT treatment at the 20 cm soil depth was increased by 46% (from 2.39 to 3.49 MPa). Even so, when severe drought occurred on July 25, 2018, the maximum PR value of the CT treatment (3.59 MPa) was 11% higher than that of the NT treatment (3.24 MPa).

Similar changes in θ_v and PR appeared during the drying period in July 2019 (Fig. 5). At the initiation of the drying process (July 2), both NT and CT had high soil water contents, and the θ_v and PR values of the NT treatment were significantly higher than those of the CT treatment in the 0 to 10 cm soil layer, but no significant θ_v and PR differences were observed between the two tillage treatments at soil depths greater than 12.5 cm. In the early drying stage (*i.e.*, from July 2 to July 8), the CT treatment had a more rapid soil profile θ_v loss and also a more rapid PR increase than the NT treatment. Under the CT treatment, for instance, with a 20% decrease in soil profile θ_v, the PR was increased by 100%. For the NT treatment, the average θ_v of the soil profile was decreased by 6%, and the average PR was increased by 49%. With further soil drying from July 8 to July 16, both tillage treatments showed a rapid PR increase, with PR values as high as 3.92 MPa (at 7.5 cm) under NT and 4.39 MPa (at 20 cm) under CT on July 16.

DISCUSSION

The state of soil compactness, which can be characterized by its ρ_b, PR, and *DC* values (Batey and McKenzie, 2006; De Oliveira *et al*., 2016), is of vital importance to crop growth. While soil compaction increases ρ_b and PR, and restricts water movement and air flow, and thus adversely affects root growth and crop yields (Bengough and Mullins, 1990; Hamza and Anderson, 2005; Arvidsson and Håkansson, 2014), an extremely loose soil could reduce root-soil contact and also has negative effects on root growth (Reichert *et al*., 2009). Many studies have shown that a soil PR greater than 2 MPa negatively affects root growth and crop yield (da Silva *et al*., 1994; Bueno *et al*., 2006; Bengough *et al*., 2006, 2011). Reichert *et al*. (2009) pointed out that the highest crop yields were usually obtained with a *DC* value of between 80 and 90. Nascimento *et al*. (2019) used relative bulk density, which may be expressed as the *DC* value we used herein to evaluate the state of soil compaction. According to Nascimento *et al*. (2019), soils with *DC* values greater than 90 are considered to be compacted, and soils with *DC* values of between 80 and 90 are normal and produce no impedance to root growth. Thus, herein we used a PR value of 2 MPa and a *DC* value of 90 as the threshold values to assess the state of soil compactness under the long-term application of CT and NT systems.

Our results showed that conversion from CT to NT generally increased the ρ_b, PR, and *DC* values of the 0-10 cm soil layer (Figs 2 and 3, Table 2), thereby indicating a greater topsoil compactness under the NT system. However, the measured increase in topsoil compaction was relatively small, since all of the PR and *DC* values under the NT treatment were lower than the critical values (PR value of 2 MPa and a *DC* value of 90) except under severe drought conditions. Similar results were also reported by Blanco-Canqui and Lal (2007). Their regional assessment of soil compaction showed that the long-term NT system did indeed cause moderate increases in soil compaction but this was not likely to adversely impact crop production because the values of compaction indicators were below the high threshold levels of compaction.

In comparison with the NT treatment, the long-term application of CT increased ρ_b and *DC* values significantly in the 10 to 20 cm soil layer (Figs 2 and 3, Table 2). The abrupt increase in PR beneath the tilled layer indicated that the long-term application of CT had resulted in a compacted zone in the subsurface layer, which agreed with some previous findings (Chen *et al.*, 2005; You *et al.*, 2017). For the NT treatment, in contrast, relatively lower ρ_b and *DC* values were observed in comparison to those of CT in the 10 to 20 cm soil layer, and there was no distinctive boundary (where soil PR increased suddenly) in PR measurements between the top and the subsurface layers (Figs 2 and 3, Table 2). Thus, the intensively tilled soil was more susceptible to compaction, while the long-term application of NT had effectively alleviated soil compaction in the subsurface layer. Under an intensive tillage system, frequent soil disturbance generally leads to degradation of the soil structure due to the breakdown of aggregates and the dispersion of clay particles (Keller *et al.*, 2013). The degree of degradation is determined by, in addition to tillage technique and crop rotation, the interaction of several factors (*e.g.*, soil texture, mineralogical composition, water content, bulk density, and penetrometer resistance). Similar to our results, Hernández *et al.* (2019) observed a sudden PR surge at the 20 cm soil depth under plough tillage, while the PR values under the NT treatment were generally consistent around the 20 cm depth and were significantly lower than those produced by plough tillage. They suggested that plough tillage had formed a hardened pan below the plough depth while long-term NT application avoided subsurface compaction. This may be explained by the fact that (1) with less traffic in the field, the NT system avoided subsurface compaction from farm machinery (Hernández *et al.*, 2019); and (2) under the NT system, maize residue cover on the soil surface may act to effectively buffer the impact of compression forces from no-till planter, sprayer, and combine (Blanco-Canqui and Lal, 2007).

In general, the soils under the NT systems are undisturbed and covered with crop residues, which favours SOM accumulation and soil aggregation, and thus improve soil physical conditions in the long run (Blanco-Canqui and Lal, 2007; Blanco-Canqui and Ruis, 2018). Moreover, over the long-term, NT systems can mitigate soil compaction (*i.e.*, plough pan formation) through natural processes such as bioturbation (Blanco-Canqui and Ruis, 2018), wetting/drying cycles, and freezing/thawing cycles (Hernández *et al.*, 2019). In a previous study carried out at our experimental site in 2012 and 2013, Gao *et al.* (2016) reported different soil strength properties from the results presented here, *i.e.*, the NT treatment produced significantly higher (8.5%) ρ_b values than the CT treatment in the 10-20 cm soil layer, and the PR values of the NT treatment were similar or greater than those of the CT treatment in soil depths below 15 cm. We consider that these contrasting results are related to the duration of the NT and CT treatments. During the early years (*i.e.*, the first 2-3 years in Gao *et al.* (2016)) of conversion from CT to NT, the physical conditions of the soil were largely determined by the residual effects of conventional rotary till-based management, and the beneficial effects of the NT system had not been fully established at this stage. Results from this study support previous findings that instead of short-term NT management, it is the long-term NT system that has conducive effects on soil properties (Blanco-Canqui and Lal, 2007; Vogeler *et al.*, 2009; Reichert *et al.*, 2016; Grigar *et al.*, 2018).

Furthermore, a significant reduction in the ρ_b and *DC* values of the topsoil (0-10 cm) appeared in the CT treatment after tillage in 2018 (Fig. 2b and Table 2), but the values returned to their previous levels before tillage in 2019 (Fig. 3a and Table 2), thereby demonstrating that the loosening effects of conventional tillage practice were short-lived. This is caused by the fact that in a plough-based tillage system, the loose topsoil layer is most susceptible to collapse and re-consolidation due to the impacts of rainfall and its associated wetting/drying cycle events (Or and Ghezzehei, 2002; Pare *et al.*, 2011).

Soil bulk density and water content are two key factors that determine soil PR under field conditions (Unger and Jones, 1998). In general, PR correlates positively with ρ_b and negatively with θ_v (Kumar *et al.*, 2012). In this study, the NT treatment had greater ρ_b, θ_v, and PR values than the CT treatment in the 0-10 cm soil layer (Figs 2-5), thereby suggesting that compared to the CT treatment, the role of ρ_b became more important in determining the PR of the topsoil layer after converting from CT to NT for 8 and 9 years. In the subsurface layer (> 20 cm), however, neither ρ_b nor θ_v alone could explain the PR changes due to tillage induced soil disturbance, because the NT treatment had significantly lower PR values than those of the CT treatment at most soil depths below 20 cm, while the differences in ρ_b and θ_v between the two tillage systems were rarely significant (Figs 2 and 3). Further research is required to understand the collective influences of bulk density and water content, as well as other soil parameters that determine the PR dynamics of the subsurface soil layer.

In both years, the soil PR of the CT and NT treatments displayed consistent trends in response to soil drying. At the beginning of the experimental period, when the soils were relatively wet, significant PR differences between the two tillage treatments only occurred in the 0 to 12.5 cm layer (Figs 4 and 5) where NT had higher ρ_b values than CT (Figs 2 and 3). In the following period (*i.e.*, from July 15 to July 21, 2018, and from July 2 to July 8, 2019), the PR differences between CT and NT became larger and progressively extended even to the 40 cm depth due to greater soil drying rates under the CT treatment (Figs 4 and 5). At this stage, the CT treatment had PR values exceeding the critical value of 2 MPa around the 20 cm soil depth, while all PR data of the NT treatment were lower than 2 MPa. With further drying of the soils (*i.e.*, July 23, 2018 and July 12, 2019 and later), the PR values of the NT treatment exceeded 2 MPa at soil depths above 20 cm, while the CT treatment had PR values much greater than 2 MPa at soil depths below 15 cm (Fig. 5). Overall, when a prolonged drought (>10 days) occurred, the NT treatment retained a relatively favourable soil moisture condition and delayed the arrival of threshold PR for at least 6 days in comparison with the CT treatment. This may be explained by the fact that the NT treatment had crop residue cover on the soil surface, which led to a reduction in evaporative water loss (Blanco-Canqui and Ruis, 2018). Thus, the conversion from CT to NT treatment alleviated the deterioration effect of drying on soil strength development, especially at greater depths (>15 cm), which could be of vital importance to crop root proliferation.

CONCLUSIONS

1. Converting from the conventional tillage system to the no tillage system caused an increase in topsoil (0-10 cm) compactness. The increase, however, was moderate since the values produced were well under the threshold levels except during severe drought conditions.

2. A dense soil layer was observed beneath the tilled topsoil under conventional tillage treatment, this was diminished after the application of no tillage for 8 to 9 years. Thus, the long-term no tillage system alleviated subsoil compaction effectively.

3. During long-lasting drying periods, the subsoil strength under conventional tillage treatment was increased rapidly and soon exceeded the threshold penetrometer resistance value of 2 MPa for crop root growth. The no tillage treatment, in contrast, was able to maintain higher soil water contents and a relatively lower soil strength for at least 6 more days. Thus, the soil under long-term no tillage had a strong resistance to changes in soil strength.

Conflict of interest: All authors declare no conflict of interest.

REFERENCES

Alvarez R. and Steinbach H.S., 2009. A review of the effects of tillage systems on some soil physical properties, water content, nitrate availability and crops yield in the Argentine Pampas. Soil Tillage Res., 104, 1-15, https://doi.org/10.1016/j.still.2009.02.005

Arvidsson J. and Håkansson I., 2014. Response of different crops to soil compaction- short-term effects in Swedish field experiments. Soil Tillage Res., 138, 56-63, https://doi.org/10.1016/j.still.2013.12.006

Batey T., 2009. Soil compaction and soil management-a review. Soil Use Manage., 25, 335-345, https://doi.org/10.1111/j.1475-2743.2009.00236.x

Batey T. and Mckenzie D.C., 2006. Soil compaction: identification directly in the field. Soil Use Manage., 22(2), 123-131, https://doi.org/10.1111/j.1475-2743.2006.00017.x

Bengough A.G. and Mullins C.E., 1990. Mechanical impedance to root growth: a review of experimental techniques and root growth responses. Eur. J. Soil Sci., 41, 341-358, https://doi.org/10.1111/j.1365-2389.1990.tb00070.x

Bengough A.G, Bransby M.F, Hans J., McKenna S.J., Roberts T.J., and Valentine T.A., 2006. Root responses to soil physical conditions: growth dynamics from field to cell. J. Exp. Bot., 57, 437-447, https://doi.org/10.1093/jxb/erj003

Bengough A.G., McKenzie B.M., Hallett P.D., and Valentine T.A., 2011. Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. J. Exp. Bot., 62(1), 59-68, https://doi.org/10.1093/jxb/erq350

Blanco-Canqui H. and Lal R., 2007. Regional assessment of soil compaction and structural properties under no-tillage farming. Soil Sci. Soc. Am. J., 71, 1770-1778, https://doi.org/10.2136/sssaj2007.0048

Blanco-Canqui H. and Ruis S.J., 2018. No-tillage and soil physical environment. Geoderma, 326, 164-200, https://doi.org/10.1016/j.geoderma.2018.03.011

Björklund M.M., Arvidsson J., Keller T., Koestel J., Lamandé M., Larsbo M., and Jarvis N., 2016. Effects of subsoil compaction on hydraulic properties and preferential flow in a Swedish soil. Soil Tillage Res., 156, 91-98, https://doi.org/10.1016/j.still.2015.09.013

Bueno J., Amiama C., Hernanz J.L., and Pereira J.M., 2006. Penetration resistance, soil water content, and workability of grasslands soils under two tillage systems. Trans. ASAE, 49, 875-882, https://doi.org/10.13031/2013.21727

Cai H.G., Ma W., Zhang X.Z., Ping J.Q., Yan X.G., Liu J.Z., Yuan J.C., Wang L.C., and Ren J., 2014. Effect of subsoil tillage depth on nutrient accumulation, root distribution, and grain yield in spring maize. Crop J., 2(5), 297-307, https://doi.org/10.1016/j.cj.2014.04.006

Cao Q.J., Li G., Jiang X.L., Diallo L., and Chen X.F., 2017. Plough pan impacts maize grain yield, carbon assimilation, and nitrogen uptake in the corn belt of Northeast China. Emir. J. Food Agric., 29(7), 502-508, https://doi.org/10.9755/ejfa.2016-12-1975

Castellini M., Fornaro F., Garofalo P., Giglio L., Rinaldi M., Ventrella D., Vitti C., and Vonella A.V., 2019. Effects of no-tillage and conventional tillage on physical and hydraulic properties of fine textured soils under winter wheat. Water, 11, 484, https://doi.org/10.3390/w11030484

Chen Y., Cavers C., Tessier S., Monero F., and Lobb D., 2005. Short-term tillage effects on soil cone index and plant development in a poorly drained, heavy clay soil. Soil Tillage Res., 82, 161-171, https://doi.org/10.1016/j.still.2004.06.006

da Silva A.P., Kay B.D., and Perfect E., 1994. Characterization of the least limiting water range of soils. Soil Sci. Soc. Am. J., 58, 1775-1781, https://doi.org/10.2136/sssaj1994.03615995005800060028x

De Oliveira P.D., Sato M.K., De Lima H.V., Rodrigues S., and Silva A.P., 2016. Critical limits of the degree of compactness and soil penetration resistance for the soybean crop in N Brazil. J. Plant Nutr. Soil Sci., 179(1), 78-87, https://doi.org/10.1002/jpln.201400315

Etana A. and Håkansson I., 1994. Swedish experiments on the persistence of subsoil compaction caused by vehicles with high axle load. Soil Tillage Res., 29, 167-172, https://doi.org/10.1016/0167-1987(94)90053-1

Feng X.M., Hao Y.B., Latifmanesh H., Lal R., Cao T.H., Guo J.R., Deng A.X., Song Z.W., and Zhang W.J., 2018. Effects of subsoiling tillage on soil properties, maize root distribution, and grain yield on Mollisols of Northeastern China. Agron. J., 110(4), 1607-1615, https://doi.org/10.2134/agronj2018.01.0027

Gao W., Whalley W.R., Tian Z., Liu J., and Ren T., 2016. A simple model to predict soil penetrometer resistance as a function of density, drying and depth in the field. Soil Tillage Res., 155, 190-198, https://doi.org/10.1016/j.still.2015.08.004

Gee G.W. and Or D., 2002. Particle-size analysis. In: Methods of Soil Analysis. Part 4. Physical Methods (Eds J.H. Dane and G.C. Topp). SSSA Book Ser. 5. SSSA, Madison, WI. 255-293, https://doi.org/10.2136/sssabookser5.4.c12

Grigar J., Hatfield J.L., and Reeder R., 2018. Transitional no-till: what is it and how does it differ from 'true' no-till? Crops & Soils., 51, 28-36, https://doi.org/10.2134/cs2018.51.0603

Håkansson I. and Reeder R.C., 1994. Subsoil compaction by vehicles with high axle load-extent, persistence and crop response. Soil Tillage Res., 29, 277-304, https://doi.org/10.1016/0167-1987(94)90065-5

Hamza M.A. and Anderson W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Tillage Res., 82, 121-145, https://doi.org/10.1016/j.still.2004.08.009

He J., Li H.W., Rasaily R.G., Wang Q.J., Cai C.H., Su Y.B., Qiao X.D., and Liu L.J., 2011. Soil properties and crop yields after 11 years of no tillage farming in wheat-maize cropping system in North China Plain. Soil Tillage Res., 113, 48-54, https://doi.org/10.1016/j.still.2011.01.005

Hernández T.D.B., Slater B.K., Corbalá R.T., and Shaffer J.M., 2019. Assessment of long-term tillage practices on physical properties of two Ohio soils. Soil Tillage Res., 186, 270-279, https://doi.org/10.1016/j.still.2018.11.004

Keller T., Lamande M.́, Peth S., Berli M., Delenne J.-Y., Baumgarten W., Rabbel W., Radjaï F., Rajchenbach J., Selvadurai A.P.S., and Or D., 2013. An interdisciplinary approach towards improved understanding of soil deformation during compaction. Soil Tillage Res., 128, 61-80, https://doi.org/10.1016/j.still.2012.10.004

Kumar A., Chen Y., Sadek M.A.A., and Rahman S., 2012. Soil cone index in relation to soil texture, moisture content, and bulk density for no-tillage and conventional tillage. Agric. Eng. Int. CIGR J., 14(1), 26-37.

Lal R., Reicosky D.C., and Hanson J.D., 2007. Evolution of the plow over 10.000 years and the rationale for no-till farming. Soil Tillage Res., 93, 1-12, https://doi.org/10.1016/j.still.2006.11.004

Liang A.Z., Zhang X.P., Yang X.M., Mclaughlin N.B., Shen Y., and Li W.F., 2010. Estimation of total erosion in cultivated black soils in Northeast China from vertical profiles of soil organic carbon. Eur. J. Soil Sci., 60, 223-229, https://doi.org/10.1111/j.1365-2389.2008.01100.x

Liu X.B., Zhang X.Y., Wang Y.X., Sui Y.Y., Zhang S.L., Herbert S.J., and Ding G., 2010. Soil degradation: a problem threatening the sustainable development of agriculture in Northeast China. Plant Soil Environ., 56, 87-97, https://doi.org/10.17221/155/2009-PSE

Moreira W.H., Tormena C.A., Karlen D.L., da Silva Á.P., Keller T., and Betioli E.Jr., 2016. Seasonal changes in soil physical properties under long-term no-tillage. Soil Tillage Res., 160, 53-64, https://doi.org/10.1016/j.still.2016.02.007

Naderi-Boldaji M., Weisskopf P., Stettler M., and Keller T., 2016. Predicting the relative density from on-the-go horizontal penetrometer measurements at some arable top soils in Northern Switzerland. Soil Tillage Res., 159, 23-32, https://doi.org/10.1016/j.still.2015.12.002

Nascimento D.M.D, Cavalieri-Polizeli K.M.V., da Sliva A.H., Favaretto N., and Parron L.M., 2019. Soil physical quality under long-term integrated agricultural production systems. Soil Tillage Res., 186, 292-299, https://doi.org/10.1016/j.still.2018.08.016

Nelson D.W. and Sommers L.E., 1982. Total carbon, organic carbon, and organic matter. In: Methods of Soil Analysis. Part. 2 (Ed. A.L. Page). 2nd ed. ASA and SSSA, Madison, WI. Agron. Monogr., 9, 539-579, https://doi.org/10.2134/agronmonogr9.2.2ed.c29

Obour P.B., Schjønning P., Peng Y., and Munkholm L.J., 2017. Subsoil compaction assessed by visual evaluation and laboratory methods. Soil Tillage Res., 173, 4-14, https://doi.org/10.1016/j.still.2016.08.015

Olesen J.E. and Munkholm L.J., 2007. Subsoil loosening in a crop rotation for organic farming eliminated plough pan with mixed effects on crop yield. Soil Tillage Res., 94, 376-385, https://doi.org/10.1016/j.still.2006.08.015

Or D. and Ghezzehei T.A., 2002. Modeling post-tillage soil structural dynamics: a review. Soil Tillage Res., 64, 41-59, https://doi.org/10.1016/S0167-1987(01)00256-2

Pare N., Andrieux P., Louchart X., Biarnes A., and Voltz M., 2011. Predicting the spatio-temporal dynamic of soil surface characteristics after tillage. Soil Tillage Res., 114, 135-145, https://doi.org/10.1016/j.still.2011.04.003

Pulido-Moncada M., Munkholm L.J., and Schjønning P., 2019. Wheel load, repeated wheeling, and traction effects on subsoil compaction in northern Europe. Soil Tillage Res., 186, 300-309, https://doi.org/10.1016/j.still.2018.11.005

Reichert J.M., Rosa V.T., Vogelmann E.S., Rosa D.P., Horn R., Reinert D.J., Sattler A., and Denardin J.E., 2016. Conceptual framework for capacity and intensity physical soil properties affected by short and long-term (14 years) continuous no-tillage and controlled traffic. Soil Tillage Res., 158, 123-136, https://doi.org/10.1016/j.still.2018.11.005

Reichert J.M., Suzuki L.E.A.S., Reinert D.J., Horn R., and Håkansson I., 2009. Reference bulk density and critical degree-of-compactness for no-till crop production in subtropical highly weathered soils. Soil Tillage Res., 102, 242-254, https://doi.org/10.1016/j.still.2008.07.002

Schjønning P., Lamandé M., Berisso F.E., Simojoki A., Alakukku L., and Andreasen R.R., 2013. Gas diffusion, non-Darcy air permeability, and computed tomography images of a clay subsoil affected by compaction. Soil Sci. Soc. Am. J., 77, 1977-1990, https://doi.org/10.2136/sssaj2013.06.0224

Soane B.D., Ball B.C., Arvidsson J., Basch G., Moreno F., and Rogerestrade J., 2012. No-till in Northern, Western and South-Western Europe: a review of problems and opportunities for crop production and the environment. Soil Tillage Res., 118, 66-87, https://doi.org/10.1016/j.still.2011.10.015

Unger P.W. and Jones O.R., 1998. Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum. Soil Tillage Res., 45, 39-57, https://doi.org/10.1016/S0167-1987(97)00068-8

Vogeler I., Rogasik J., Funder U., Panten K., and Schnug E., 2009. Effect of tillage systems and P-fertilization on soil physical and chemical properties, crop yield and nutrient uptake. Soil Tillage Res., 103, 137-143, https://doi.org/10.1016/j.still.2008.10.004

Wang Q.J., Liu F., Gao Z.C., Jia H.B., Zhang J.S., Zhang C.F., Chang B.C., and Jiang H., 2017. Effect of improving black soil and crop yield by using soil layer up-down fallow technology. Trans. CSAE, 33(6), 100-106.

Yang X.M., Zhang X.P., Deng W., and Fang H.J., 2003. Black soil degradation by rainfall erosion in Jilin, China. Land Degrad. Dev., 14, 409-420, https://doi.org/10.1002/ldr.567

You D., Tian P., Sui P., Zhang W., Yang B., and Qi H., 2017. Short-term effects of tillage and residue on spring maize yield through regulating root-shoot ratio in Northeast China. Sci. Rep., 7(1), 1-11, https://doi.org/10.1038/s41598-017-13624-5

Zhai L., Xu P., Zhang Z., Li S., Xie R., Zhai L., and Wei B., 2017. Effects of deep vertical rotary tillage on dry matter accumulation and grain yield of summer maize in the Huang-Huai-Hai Plain of China. Soil Tillage Res., 170, 167-174, https://doi.org/10.1016/j.still.2017.03.013

Zhang S., Chen X., Jia S., Liang A., Zhang X., Yang X., Wei S., Sun B., Huang D., and Zhou G., 2015. The potential mechanism of long-term conservation tillage effects on maize yield in the black soil of Northeast China. Soil Tillage Res., 154, 84-90, https://doi.org/10.1016/j.still.2015.06.002

Zhang Y., Wang R., Wang S., Wang H., Xu. Z., Jia G., Wang X., and Li J., 2017. Effects of different sub-soiling frequencies incorporated into no-tillage systems on soil properties and crop yield in dryland wheat-maize rotation system. Field Crop. Res., 209, 151-158, https://doi.org/10.1016/j.fcr.2017.05.002