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RESEARCH ARTICLE

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The effect of tire inflation pressure and tillage systems on soil properties, growth and yield of maize and soybean in a silty clay loam soil

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Abstract

Soil compaction causes adverse effects on soil structure and the performance of crops. There is significant literature supporting the hypothesis that reducing tire inflation pressure can help to minimize compaction, but there is no data on the potential benefits of high flexion tires operating at reduced tire pressures in Midwestern United States agriculture. Hence, a field-scale study was established in Illinois to determine the potential benefits of high flexion tires at low tire pressure (LTP) in comparison with those operated at standard tire inflation pressure (STP) on soil condition, crop growth and yield of maize and soybean for three tillage systems; deep tillage (450 mm), shallow tillage (100 mm) and no-till. Two adjacent experiments were established in typical maize/soybean and soybean/maize rotations, respectively. The experiment used a 2×3 factorial design with five completely randomized blocks. The results showed that the use of LTP tires resulted in lower soil penetrometer resistance for three tillage systems in 2017 and 2018 in the maize field and 2018 in the soybean field. This improved plant establishment and the number of plants per hectare of maize in both 2016 ($*p \leq .05$) and 2018 ($**p \leq .01$) and plant establishment ($***p \leq .001$) and the number of plants per hectare ($***p \leq .001$) of soybean in 2018. The penetrometer resistance was higher in the no-till plots compared to deep and shallow tillage plots in maize and was higher in the deep tillage plots compared to the shallow tillage in the soybean field. The use of LTP tires resulted in an increased grain yield of maize by 4.31% (15.02 Mg ha^{-1}) and 2.70% (14.76 Mg ha^{-1}) in 2017 ($**p \leq .01$) and 2018 ($*p \leq .05$), respectively, and soybean by 3.70% (4.25 Mg ha^{-1}) in 2018 ($*p \leq .05$). The depth of tillage had a significant effect on soybean and maize yields in 2017 ($***p \leq .001$) and 2018 ($***p \leq .001$), respectively, with higher yields of both soybean and maize in the deep and shallow tillage compared to no-till plots. The study concludes that the use of the LTP systems can be a potential means of

addressing soil compaction and maintaining soil porosity while increasing crop productivity in silty clay loam soils in Central Illinois.

KEYWORDS

crop growth and yield, crop rotation, high flexion tires, reduced tire inflation pressure, soil compaction, tillage depth

1 | INTRODUCTION

Soil compaction caused by the use of heavy farm equipment adversely affects soil conditions and the performance of crops (Batey, 2009; Godwin et al., 2022; Hamza & Anderson, 2005; Keller et al., 2019; Shaheb & Shearer, 2021; Shaheb et al., 2023). It is estimated that more than 33% of European subsoils are highly susceptible to soil compaction (Jones et al., 2003) while in the USA, soils in all regions are designated as susceptible (USDA NRCS, 2004). Soil compaction occurs when soils are subjected to loads and stresses that exceed the soils' inherent strength (Soehne, 1958). Soane et al. (1980) defined soil compaction as 'the modification of the pore volume and pore structure of the soil in which the size and number of macropores are reduced, and shape and continuity of pores are changed'. The total mass of combine harvesters has increased by nearly 10-fold, at present (36 Mg) compared with 1958 (4 Mg) (Keller & Or, 2022). The increase in equipment mass, accompanied by multiple field traffic, increases the severity of soil compaction and, thus, reduces soil productivity and crop yield (Botta et al., 2007; Chamen, 2015; Hula et al., 2009; Pulido-Moncada et al., 2019).

Soil compaction causes a reduction in pore size and total soil porosity restricts root growth and the accessibility of nutrients and water because of an increase in bulk density (*BD*), penetrometer resistance (PR) or shear strength of soil, which, in turn, affects crop growth and leads to loss of yield (Hula et al., 2009; Nawaz et al., 2013; Shaheb & Shearer, 2021; Whalley et al., 2008). High tire contact pressure (>0.10 MPa) and conventional wheel system loads can cause the compaction of soil (Soane et al., 1981). The relative effects of the tire inflation pressure and the wheel load change with soil depth. Tire inflation pressure accounts for the variation in the Söhne-predicted vertical stresses (Söhne, 1953) in the upper soil layers and the wheel load for the stresses at lower parts of the subsoil. Jones et al. (2003) *assessed* the risk of soil compaction by assessing soil strength and suggested identifying soil susceptibility (texture and packing density) and vulnerability by integrating the 'likely' soil water content. However, compaction risk assessment requires evaluating stress and strength, as estimation of soil strength and stress are considered a critical aspect of mechanistic risk assessment of soil compaction (Schjønning et al., 2012). According to the concept of soil pre-compression stress (p_{pc}), strain to soil layers up to the (p_{pc}) level is considered elastic; exceeding this causes further soil deformation (Hartge & Horn, 1984). When exposed to stresses $<p_{pc}$ in the soil profile, soil functions and productivity are affected (Mosaddeghi et al., 2007). Keller et al. (2012) studied a wide range of Scandinavian soils trafficked and highlighted that subsoil deformation at near field capacity was generally not found for vertical stresses of ca. <0.04 MPa, but it tended to increase with further increases in stress. Schjønning et al. (2012) reported that high inflation pressure and the small contact area were the reasons for the highest values of vertical stress (0.55 MPa) in the centerline 200 mm below under the narrow tire. So, the knowledge of the stress levels imposed on soil profile without causing soil deformation or compaction when using tires, wheel loads and inflation pressures is essential.

Hoeft et al. (2000) reported that field traffic with high inflation pressure tire systems (0.17 MPa) caused a significant reduction in soil porosity compared with the use of tracks and low tire pressure systems (0.04 MPa). A field study in Quebec showed that the effects of compaction as a result of high contact pressures and multiple traffic events caused a 40%–50% reduction in the biomass yield of silage maize (Raghavan et al., 1979). Studies in Ohio showed that compaction of soil caused a significant increase in soil BD, affected crop growth and decreased in yield by 17%–25% in maize (Lal, 1996) and 9%–21% in soybean (Flowers & Lal, 1998; Lal, 1996). Botta et al. (2010) reported a 0.25–0.45 Mg ha^{-1} soybean yield reduction because of soil compaction resulting from light versus heavy equipment traffic. A recent study on sandy loam soil in North Dakota showed an increase in soil PR from 1.57 to 2.00 MPa and 3.00 MPa (gravimetric water content, θ_m ranged from 10.6% to 11.3%), as a result of different magnitudes of compaction, caused a reduction of maize yield of 7.8% and 33.0%, respectively (Jabro et al., 2021).

Deep tillage (DT) is used in approximately 40% of the Midwestern U.S. farming area (Simmons & Nafziger, 2009) and 29% of Illinois (Zulauf & Brown, 2019). DT helps to alleviate soil compaction; however, undertaking routine field operations without identifying the compacted layer or structural problem may increase the risk of subsoil re-compaction (Godwin et al., 2022; Morris et al., 2010; Soane et al., 1986) and thus site-specific precision deep tillage sometimes recommended (Shaheb et al., 2022; Wells et al., 2005). In comparison to chisel ploughing at 200 mm followed by a disc harrow, no-till (NT) farming possesses several benefits, such as conserving soil and water (Grabski et al., 1995) with higher macro-porosity and saturated hydraulic conductivity (Cavalieria et al., 2009). However, because of increased surface compaction, heavy NT soils were reported to have greater PR with lower macropores and soil water infiltration than conventional tillage systems on sandy clay soils (Martínez et al., 2008) and moldboard ploughing systems on silty clay soil (Blanco-Canqui et al., 2017).

To minimize soil compaction while boosting crop production and maintaining soil physical health, farmers need to consider sustainable management systems. Lower soil contact pressure systems, using rubber tracks or lower inflation pressure tires, can reduce ground contact stress transmitted during field operations (Ansorge & Godwin, 2007, 2008; Chamen, 2011). High flexion tires (e.g. ultraflex), which are operated at lower tire inflation pressures for a given load with larger footprint areas, are claimed to reduce soil compaction and improve crop yield (Michelin, 2017) and farm profitability (Shaheb et al., 2023). However, apart from studies in the UK (Godwin et al., 2015, 2022; Smith, Misiewicz, Chaney, et al., 2014; Smith, Misiewicz, Girardello, et al., 2014), results of replicated experiments on the effects of high flexion tires could not be identified. Therefore, field-scale studies were undertaken to determine the effects of tire-induced ground pressure, by comparing tires at both the standard tire inflation pressure (STP) for conventional radial tires and low tire inflation pressure (LTP) systems, on soil structure, growth, and yield of maize and soybean for deep tillage (DT), shallow tillage (ST) and no-till (NT) systems in a silty clay loam soil in Central Illinois.

2 | MATERIALS AND METHODS

The experimental program was established at the Agricultural Engineering Research Farm of the University of Illinois at Urbana-Champaign, USA (lat/lon: 40.070965, −88.217538) from November 2015 to October 2018. The farm is representative of a typical maize (*Zea mays* L.) and soybean (*Glycine max* L.) rotation in a Midwest farming system. As shown in Figure 1, two adjacent near-square fields of near-identical size 3.24 ha were selected, where both fields were used for alternative rotations of these two crops. Maize was grown in the North field (2016), South field (2017) and North field (2018) in a rotation with soybean grown in the South field (2016), North field (2017) and South field (2018).

2.1 | Site descriptions

Figure 1 shows that the soil of the experimental site consisted of a Drummer series soil (152A, characterized as a silty clay loam) with a Thorp series silt loam soil (205A) being present at the north-eastern corner of the North field (USDA NRCS, 2015). The Drummer series consists of soils that are comprised 1–1.5 m of loess or other silty materials over an underlying stratified, loamy glacial drift. Both soil series have 0%–2% slope and are poorly drained. The electrical conductivity (EC) data in Figure 1 shows that the boundary between Thorp and Drummer series soils lie westward of the boundary suggested by the classical soil survey, hence a greater proportion of the field area is Thorp series (206A) than first expected, with some intrusion of Thorp series into the South field. The EC data in the North field ranged from 13.2 to 46 mS/m, with higher values in the Drummer soil series (the majority in between 29 and 46 mS/m) than in the Thorp soil series (13–29 mS/m), the range of the initial EC values of the soil in the South field was similar (13.24–46.00 mS/m) with a majority of values between 26 and 36 mS/m. A preliminary assessment showed that the chemical properties of the soil of the North and South fields were similar (Shaheb, 2020).

The daily maximum (max.) and minimum (min.) temperatures (°C), rainfall and snowfall (mm) from January 2016 to December 2018, collected from a weather station located at 500 m from the experimental site, are shown in Figure 2. The weather data show that the temperatures of all 3 years were similar in range except in 2018, when in May, the mean maximum temperature was highest at 28°C. The maximum total annual rainfall in 2016 was 1168 mm, followed by 1024 mm in 2018, with the lowest of 883 mm in 2017. The rainfall distribution tended to peak in the spring/early summer and again in the fall.

2.2 | Details of experimental design and treatments

The experiment comprised a 2 × 3 factorial randomized complete block design ($n = 5$) with standard (STP) and low tire inflation pressure (LTP) systems (Table 1) and three tillage systems: deep (DT, 450 mm), shallow (ST, 100 mm) and no-till (NT). Following the initial deep loosening in the fall of 2015, to remove any underlying compaction from previous field operations, only the effect of tire inflation pressure was investigated in 2016. The individual plot area was 180 m × 6 m = 1080 m^2 with 10 m headlands with eight crop rows/plot. The plots were orientated in the East–West direction. The plot configuration is shown in Figure 3.

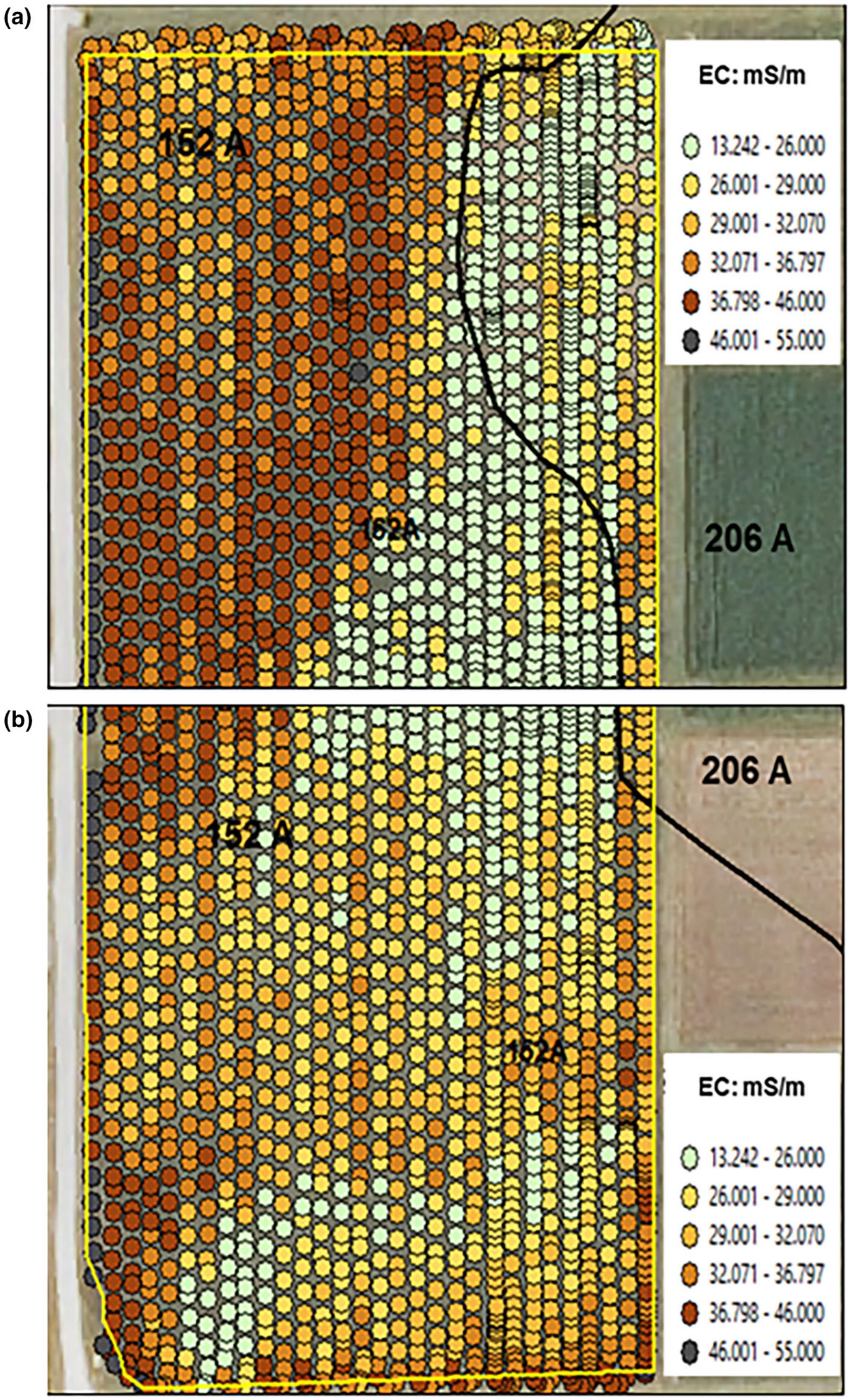

FIGURE 1 Electrical conductivity of soil in April 2016 overlaid onto the USDA NRCS soil survey map of the North field (a) and the South field (b). 152A indicates a Drummer soil and 206A a Thorp soil series.

2.3 | Farm equipment and agricultural tires

The equipment consisted of tractors for tillage (John Deere, JD 7930) and planting operations (JD 7700), a combine harvester (JD 9410), spring tine tillage tools for shallow tillage (Sunflower/AGCO 6221–20″), a disc ripper with five deep tines for deep tillage (Case/IH Ecolo-Tiger 527B) and an 8-row planter (JD 7200 Max Emerge 2, with 0.75 m row spacing). A self-propelled 36.5 m wide sprayer (JD 4930) was used for pre- and post-emergence chemical application and operated perpendicular (North–South) to the crop rows to minimize any potential variation in application rate among the treatments. High flexion tires were fitted to the tractors and combine harvester and tire pressures were adjusted for either STP or LTP for the appropriate treatment (Table 1). Raising and lowering tire pressures for these tires saved the requirement to change tires during the experimental

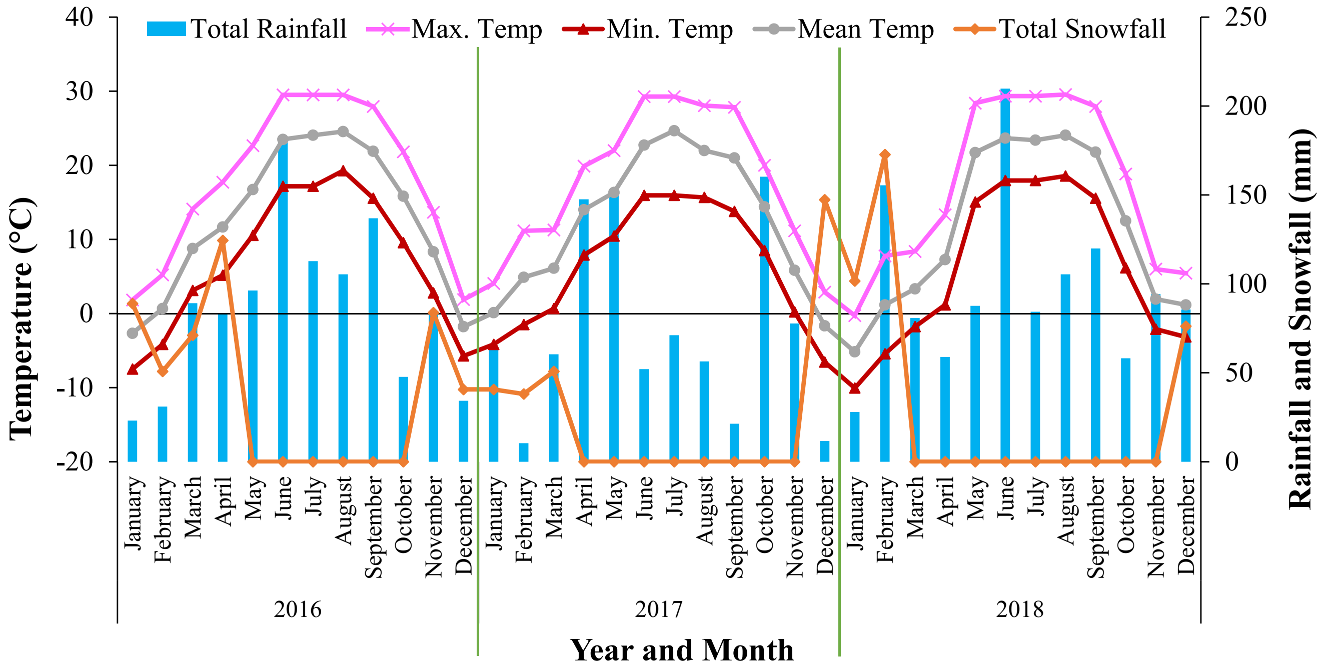

FIGURE 2 Monthly mean, maximum and minimum temperatures (°C) and combined monthly rain and snowfall (mm) at the experimental site during the years 2016–2018.

TABLE 1 Recommended tire inflation pressures for the tractors and combine harvester (Michelin, 2017).

Equipment	Axle, mass (Mg)	Front tires	Rear tires	Pressure mode	Tire inflation pressure (MPa) Front/rear tires 2016	Tire inflation pressure (MPa) Front and rear tires 2017–2018
Tillage tractor	10.30	Yieldbib VF 380/85 R34	Yieldbib VF 480/80 R46	STP	0.12/0.14	0.14
				LTP	0.06/0.06	0.07
Planting tractor	8.60	Yieldbib VF 380/85 R34	Yieldbib VF 480/80 R46	STP	0.12/0.12	0.12
				LTP	0.06/0.06	0.05
Combine harvester	18.14	Cerexbib IF 800/65 R32	Cerexbib 14.9 R24	STP	0.20/0.16	0.21
				LTP	0.15/0.16	0.14

program. This followed the recommendations from Smith, Misiewicz, Girardello, et al. (2014), who showed that there was no significant difference in the subsoil pressure between standard radial and high flexion tires when inflated to the same pressure.

2.4 | Field operations and crop production technology

All field equipment was operated using a real-time kinematic tractor guidance system combined with auto-steer technology (Model: JD StarFire™ 6000 system). DT (fall tillage—a typical tillage practice in Illinois) was conducted in October and ST at the end of April. To simulate grain cart chase-bins, extra compaction after ST using the planting tractor was applied on crop rows 1 and 3 for all plots at the end of April 2017 and 2018. The pre-emergence spray was applied with 32% UAN @ 563 L ha^{-1} fertilizer with Harness Xtra @ 5.27 L ha^{-1} for maize and Authority Assist 250 GL @ 0.42 kg ha^{-1} for soybeans. All plots in 2016 and DT and ST plots in 2017 and 2018 were levelled using the spring tillage tool attached to the tillage tractor in mid-May. Maize (variety P1221AMXT, Pioneer seed @ 86,076 seeds ha^{-1}) and soybean (variety P35T58R, seed @ 307,406 ha^{-1}) were planted in mid-May, maintaining the row-to-row distance of 0.75 m using the eight rows planter. In line with local practice, a 2% increase in seed rate was applied to the NT plots in order to achieve the uniform plant establishment equivalent to conventional tillage culture (Oplinger & Philbrook, 1992). The post-emergence spray was applied with the herbicides Calisto 4SC 0.14 kg ha^{-1} and Round-up @ 2.24 kg ha^{-1} for maize and Cobra @ 0.70 kg ha^{-1} Select Max @ 0.42 kg ha^{-1} and

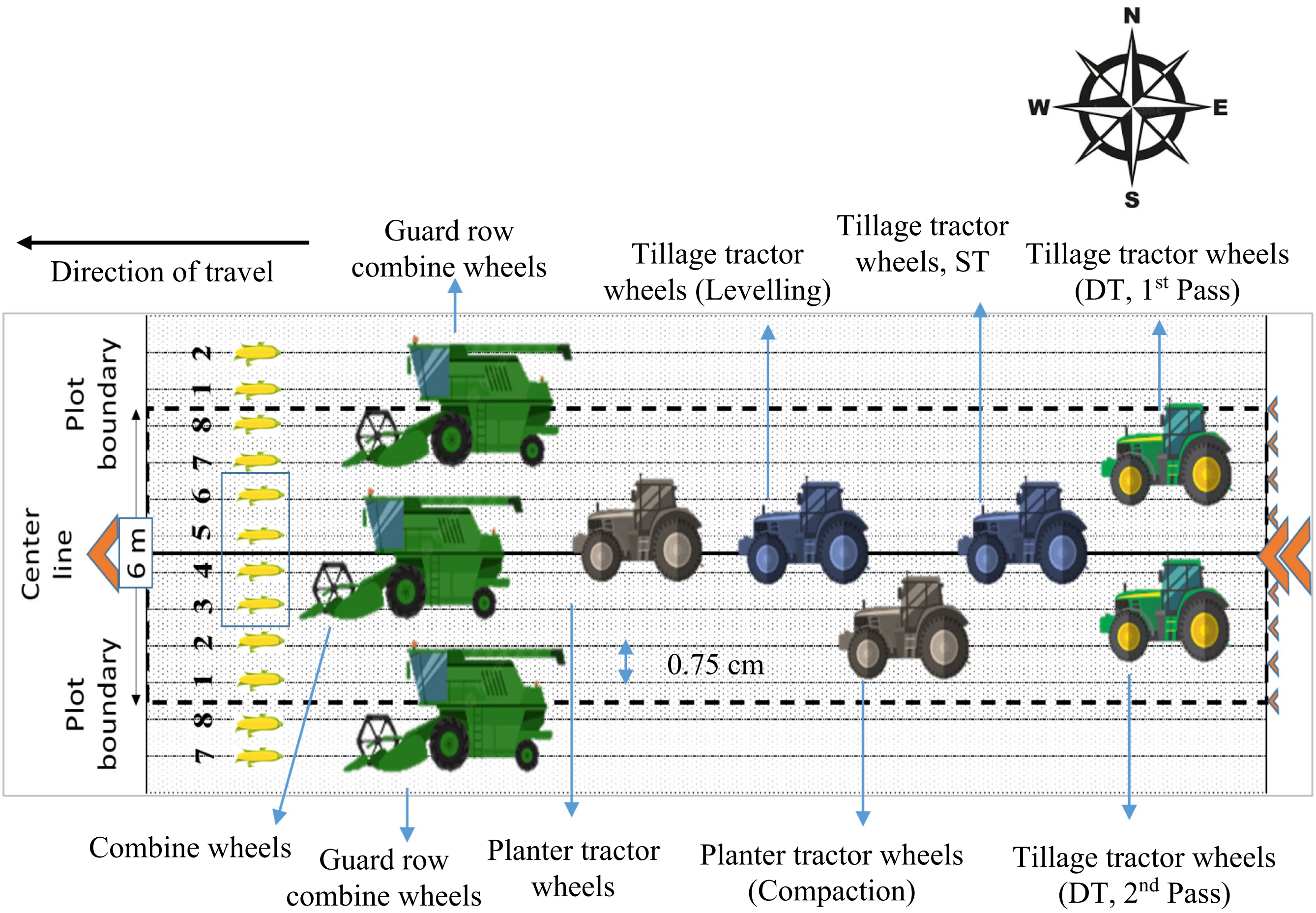

FIGURE 3 Plot configurations showing crop row position (e.g. maize ears, 1–8), tractors and combine harvester wheel positions (solid rectangles) and tillage tine positions (chevrons). Adapted from Shaheb (2020). The DT plots received DT, ST, levelling and planting tractor's wheel traffic sequentially; ST plots received ST, levelling and planting tractor's wheel traffic sequentially and NT plots only received planting tractor's wheel traffic.

Warrant @ 0.21 kg ha^{-1} for soybean at 30 days after planting (DAP). Maize and soybean were harvested at 135–150 DAP using a combination with a 6-row header for maize and an 8-row header for soybean. This implied that the outer rows (1 and 8) of maize remained unharvested during the first pass, to be harvested as a secondary operation; hence, their yield was not considered.

2.5 | Soil sampling, soil and crop data recording

In early April 2016, 50 soil core samples per field were collected by an automatic sampler installed on a light-weight utility terrain vehicle (UTV, 0.67 Mg) in 300 mm × 58 mm PVC tubes following a grid sampling method at the spacing of 25 m. Each sample out of 25 was separated into three depth ranges of 0–100 mm, 101–200 mm and 201–300 mm. Initial soil properties data included EC, soil nutrients, penetrometer resistance (PR), moisture content (MC), particle density (PD), dry basis BD and total porosity (%).

EC data shown in Figure 1 were collected using an EM38 sensor drawn behind a light-weight UTV on 28 April 2016 at a sampling rate of 1 Hz (one sample per 3.6 m). Soil PR data were recorded in April 2016 from the above 50 sampling points (3 readings/point) of both fields and at approximately 35–40 DAP in 2016 and 2017 and after harvest of maize in 2017, and 95–100 DAP for maize and 55–60 DAP for soybean in 2018 when the field was at field capacity. PR data were collected from between rows 3 and 4 ('highly trafficked', HT) and between rows 4 and 5 ('un-trafficked', UT) in 2016 (3 readings per row) and after the harvest of maize in 2017, and crop row 1–8 and inter-row of 4 and 5 (5 readings per row) in 2017 and 2018 (see Figure 3). Soil PR values were measured in 25 mm increments to 450 mm soil depth using a Soil Compaction Meter (Model: Field Scout SC 900 Spectrum Technologies Inc.) with a cone angle of 30° and a base area of 130 mm^2 (ASABE, 2013; ASABE Standards, 2018). Further, 60 soil cores (replication 5× tire inflation pressure 2×tillage system 3 × traffick location 2) were collected after the harvest of maize in 2017 from the HT and UT locations, and soils were separated into five depths in 60 mm increments. Soil PD using the Graduated Cylinder Method and soil MC, BD and total porosity using the Gravimetric Method (Hallett & Bengough, 2013; USDA NRCS, 2019) were measured. The volumetric soil MC to a depth of 200 mm was also measured for each soil PR data recording time in 2017 and 2018, using the TDR 300 soil moisture meter (Model: Spectrum Field Scout).

Data on plant establishment (%) and the number of plants per hectare were recorded at 15–18 DAS and 30–35 DAP, respectively, and plant height (m) was recorded at 40–45 DAP in 2016 and at 130–135 DAP in 2017 and 2018. Ear height (m) of maize was recorded at 130–135 DAP in 2018. Hand harvest maize samples of five ears per row and 0.5 m linear soybean plants/row were collected prior to the combined harvest. Ear length (m) of maize, grain MC (%), 1000-grain weight of both crops and soybean biomass yield in 2018 were recorded. The yields (Mg ha^{-1}) of maize and soybean were recorded using a weigh wagon (Model: Par-Kan GW 200A) and were adjusted to 15.5% and 13% MC, respectively.

2.6 | Data analysis

The experimental data were analysed using a two-way analysis of variance (ANOVA) for the effect of tire inflation pressure and tillage system on the grain yield and General ANOVA for soil MC, crop growth and yield parameters using Genstat 18th Edition (VSN International, 2015). The soil PR data were analysed using a repeated measure ANOVA (VSN International, 2015). Before conducting the ANOVA, the examination of the histogram of residuals revealed that all data of the experiment were normally distributed. Tukey multiple range tests were conducted to determine which treatments were significantly different at $p \leq .05$.

3 | RESULTS

The preliminary assessment of soil of both North and South fields is presented in the supplementary file (Table S1 and Figures S1 and S2). The detailed experimental results during the years 2017 through 2018 are described in the following:

TABLE 2 Effect of tire inflation pressure, tillage system and their interaction on bulk density of soil after harvest of maize in South field in 2017.

	Bulk density (Mg m^{-3})					
Treatments[a]	**0–60 mm**	**60–120 mm**	**120–180 mm**	**180–240 mm**	**240–300 mm**	**Mean**
Tire inflation pressure						
STP	1.49b	1.51b	1.51b	1.48b	1.49b	1.50b
LTP	1.39a	1.41a	1.41a	1.40a	1.40a	1.40a
p Value	<.001	<.001	<.001	<.001	<.001	<.001
Tillage system						
DT	1.43a	1.45b	1.43b	1.45b	1.45a	1.44a
ST	1.43a	1.46b	1.46b	1.43a	1.43a	1.44a
NT	1.46a	1.48b	1.48b	1.46b	1.46a	1.47b
p Value	.14	.38	.08	.02	.20	.046
Tire inflation pressure × tillage system						
STP × DT	1.45bc	1.49a	1.48a	1.49a	1.49a	1.48a
STP × ST	1.52d	1.51a	1.51a	1.46a	1.49a	1.50a
STP × NT	1.50c	1.53a	1.54a	1.49a	1.49a	1.51a
LTP × DT	1.41ab	1.40a	1.38a	1.41a	1.40a	1.40a
LTP × ST	1.34a	1.40a	1.41a	1.39a	1.37a	1.38a
LTP × NT	1.42b	1.43a	1.42a	1.42a	1.42a	1.42a
p Value	<.001	.41	.90	.74	.90	.31

[a]STP, LTP, DT, ST and NT represent standard tire inflation pressure, low tire inflation pressure, deep tillage, shallow tillage and no-till, respectively. Means in a column with the same letters are not significantly different at $p < .05$.

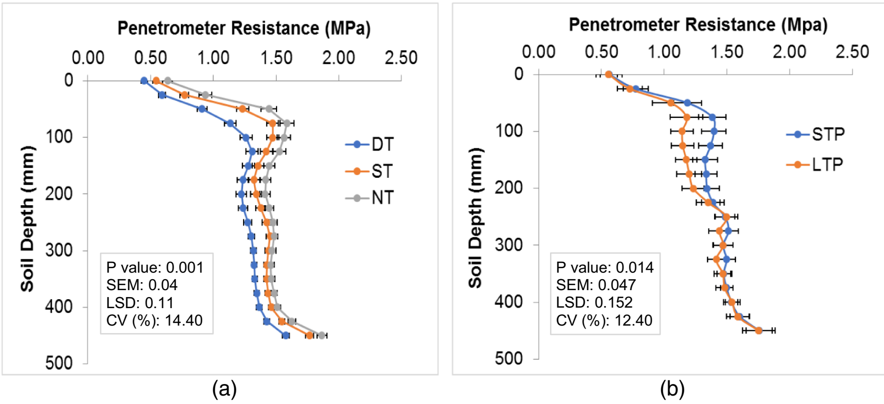

FIGURE 4 Effect of (a) tillage system at 35–40 DAP of maize and (b) tire inflation pressure after harvest of maize on the penetrometer resistance of soil in the South field, 2017. Error bars indicate the standard error of the mean. STP, LTP, DT, ST and NT represent standard tire inflation pressure, low tire inflation pressure, deep tillage, shallow tillage and no-till, respectively.

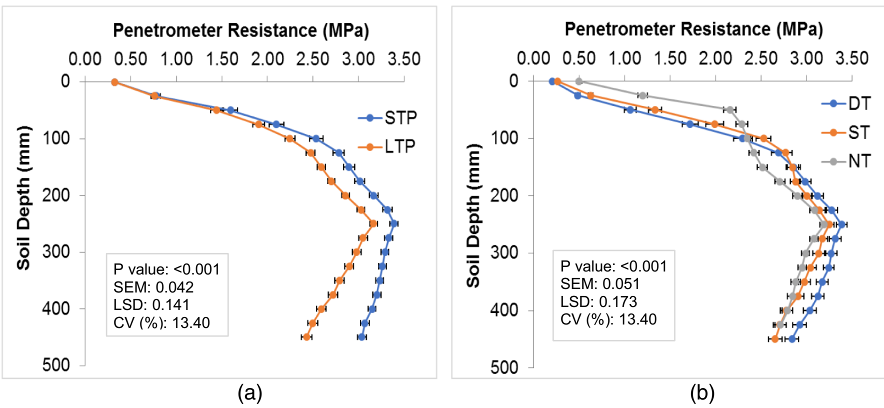

FIGURE 5 Effect of (a) tire inflation pressure and (b) tillage system on the penetrometer resistance of soil at 95–100 DAP of maize in North field, 2018. Error bars indicate the standard error of the mean. STP, LTP, DT, ST and NT represent standard tire inflation pressure, low tire inflation pressure, deep tillage, shallow tillage and no-till, respectively.

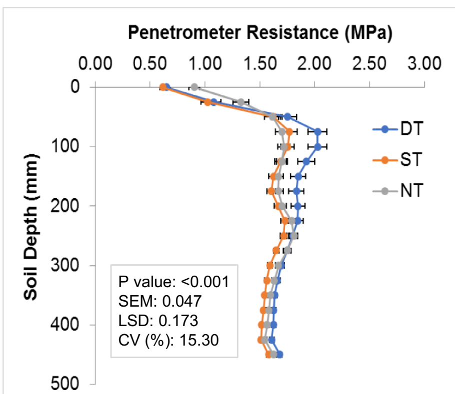

FIGURE 6 Effect of the tillage system on the penetration resistance of soil 35–40 DAP of soybean in the North field, 2017. Error bars indicate the standard error of the mean. DT, ST and NT represent deep tillage, shallow tillage and no-till, respectively.

3.1 | Effect of tire inflation pressure and tillage systems on soil properties

The 2016 soil PR data reveal that the tire inflation pressure had a significant effect on the PR of soil at 35–40 DAP of maize in the North field ($*p \leq .05$) but had no significant difference in soybean in the South field (Figure S2). The PR values in the STP treatment was significantly higher at soil depths of 100 mm and >275 mm in 2016 ($*p \leq .05$) than the LTP treatment, with peak PR at depths of 300 mm (3.48 MPa) and 275 mm (3.35 MPa), respectively. The results of the effect of tire inflation pressure and tillage systems on soil properties during the maize and soybean growing periods in North and South fields (2 crops × 2 seasons) are presented in Table 2 and Figures 4–7.

3.1.1 | Soil properties in the maize field

In 2017, there was no significant difference between the three tillage systems on soil MC, tire inflation pressure and their interaction with the tillage system on MC and PR of soil, with the mean soil MC of 31.2%. Figure 4a shows that the tillage system had a significant influence on the PR of soil at 35–40 DAP of maize ($**p \leq .01$ and DF = 36). The PR of soil was higher in the NT compared to both the DT and ST treatments, with a trend of NT > ST > DT throughout the soil profile and the differences were substantially greater at depths between 75 and 125 mm. The data showed that the PR of soil was lower in DT compared with others throughout the 450 mm soil depths, with a maximum PR of soil in NT of 1.87 MPa, which was significantly different from DT (1.58 MPa). Figure 4b shows that tire inflation pressure had a significant effect on the PR of

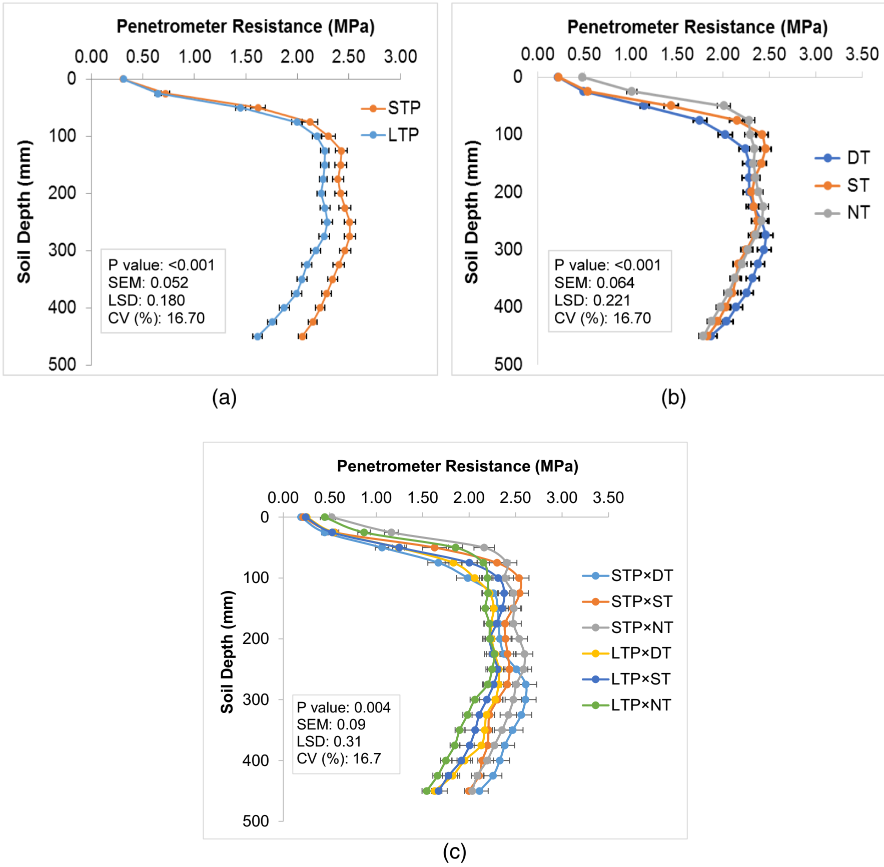

FIGURE 7 Effect of (a) tire inflation pressure, (b) tillage system, (c) the interaction effect of tire inflation pressure and tillage system on the penetration resistance of soil 55–60 DAP of soybean in the South Field, 2018. Error bars indicate the standard error of the mean. STP, LTP, DT, ST and NT represent standard tire inflation pressure, low tire inflation pressure, deep tillage, shallow tillage and no-till, respectively.

soil after the harvest of maize in the South field in 2017 ($*p \leq .05$ and DF = 18). The PR values in the STP treatment were significantly higher from the depths of 50 to 225 mm compared with the LTP.

Table 2 shows that the dry BD of soil varied significantly among tire inflation pressures ($***p \leq .001$ and DF = 2, Residual DF = 20) and tillage systems ($*p \leq .05$ and DF = 2, Residual DF = 20). The BD of soil was significantly higher in all five different depths in the STP (1.49–1.51 $Mg\,m^{-3}$) with the profile soil BD of 1.50 $Mg\,m^{-3}$ compared with LTP (1.39–1.41 $Mg\,m^{-3}$) with profile mean BD of 1.40 $Mg\,m^{-3}$ (CV = 1.70%). Among the tillage systems, the BD of soil was recorded to be highest in NT at depths of 180–240 mm (1.46 $Mg\,m^{-3}$) was significantly different from DT (1.43 $Mg\,m^{-3}$) with profile soil BD (1.47 $Mg\,m^{-3}$) and significantly varied at greater depths (1.44 $Mg\,m^{-3}$, CV = 1.70%). Based on the above soil BD data, the total porosity of soil at the five different depths was higher in the LTP treatment (46.1%–46.7%) compared with STP treatments (42.1%–43.1%). As expected, because of higher BD, the NT treatment showed slightly lower total porosity (43.8%) compared with both DT and ST (44.9%).

The 2018 results show that there was no significant effect of tire inflation pressure, tillage system and their interaction on soil MC with the mean soil MC of 33.8%. The PR data in Figure 5a,b show that the effect of tire inflation pressure ($**p \leq .01$ and DF = 18) and tillage system was significant at 90–95 DAP in 2018 ($**p \leq .01$ and DF = 36), with no significant interaction between them. The PR values were significantly lower in the LTP compared with the STP treatment at soil depths greater than 75 mm, with the maximum PR values of 3.16 and 3.39 MPa at a depth of 250 mm (Figure 5a). Among the tillage systems, the NT treatment had a significantly higher PR at depths 25–75 mm than the ST and DT; at depths below 150–325 mm, there were no significant differences (Figure 5b). Below 325 mm, the PR of soil was higher in the DT compared with both the ST and NT treatments, with a trend of DT > ST > NT down to a soil depth of 425 mm.

3.1.2 | Soil properties in the soybean field

In 2017, there was no significant effect of tire inflation pressure, tillage system and their interaction on soil MC in North field, with the mean soil MC of 34.3%. Figure 6 shows that the tillage system had a significant effect on the PR of soil ($**p \leq .01$ and DF = 36), but there was no significant effect of tire inflation pressure and its interaction with the tillage system on soil PR. Among the tillage systems, initially, NT had higher PR values to depths of 25 mm than DT and ST. After that, the PR values were significantly higher in DT from the soil depths of 75–175 mm than NT and ST with a trend in the order of DT > NT > ST to the depth of 450 mm, with a few exceptions at depths from 250 to 300 mm. The peak soil PR was recorded higher in DT (2.03 MPa) at soil depths of 100–125 mm was followed by ST (1.77 MPa) and NT (1.72 MPa) at depths of 75 and 100 mm, respectively.

In 2018, there was no significant effect of tire inflation pressure, tillage system and their interaction on soil MC with the mean soil MC of 34.1%. Figure 7 shows that tire inflation pressure (**$p \leq .01$ and DF = 18), tillage system (**$p \leq .01$ and DF = 36) and their effect of interaction (*$p \leq .05$ and DF = 36) were significant on the PR of soil. The soil PR in the STP was higher compared with that of the LTP treatment throughout the soil profile depth with an exception from the topsoil of 0–125 mm depth, where both treatments were not significant (Figure 7a). The maximum PR values of STP and LTP were 2.51 and 2.29 MPa, respectively, at 250 mm soil depth. The PR values among the tillage systems were initially higher in NT up to 250 mm depth with a peak PR of 2.43 MPa with an exception between the depths 100–150 mm, where ST had higher PR values with a peak PR of 2.46 MPa at a depth of 125 mm in comparison with other tillage treatments (Figure 7b). The PR values after that were recorded higher in DT to a depth of 450 mm with a peak PR of 2.46 MPa at a soil depth of 275 mm. Figure 7c shows that the interaction between STP × NT had a significantly higher PR of soil from depths 0 to 75 mm with a peak PR of 2.60 MPa at a depth of 225 mm compared with STP × DT, LTP × NT and LTP × DT. However, the PR soil was recorded to be higher in STP × DT soils from a depth of 275 mm down to 450 mm with a peak PR of 2.61 MPa at depths 275 and 300 mm compared with LTP for all three tillage systems.

3.2 | Effect of tire inflation pressure and tillage systems on the growth and yield of maize

The data on the growth and yield parameters and grain yield of maize during the years 2016 through 2018 are presented in Table 3 and Figure 8.

3.2.1 | Growth parameters of maize

The data in Table 3 show that LTP had a small (0.76%) but significant effect on both plant establishment (**$p \leq .01$ and CV = 0.30%) and the number of plants per hectare (**$p \leq .01$ and CV = 1.60%) in 2016. However, there was no significant effect of tire inflation pressure on plant height (CV = 2.70%). In 2017, tire inflation pressure had no significant effect on the number of plants ha^{-1}, with tillage having a small (1%) but significant effect (***$p \leq .001$ and CV = 0.40%). Similarly, there was a small (1%) but significantly greater plant height in the LTP treatment (2.15 m) compared to the STP treatment (2.13 m) (*$p \leq .05$ and CV = 1.20%). In 2018, LTP had a small but significant effect on maize plant establishment (+1%) (**$p \leq .01$ and CV = 0.90%), plants per hectare (+0.6%) (**$p \leq .01$ and CV = 0.50%) and plant height (+2%) (**$p \leq .01$ and CV = 1.40%). The effect of tillage system on the plant height was significant (*$p \leq .05$), with plant height (2.56 m) being marginally higher in the DT plots compared to ST and NT plots.

3.2.2 | Yield parameters and grain yield of maize

Table 3 shows that the effect of the tillage system was significant only in 2018, with the highest 1000 grain weight (+8.2%) recorded for the DT treatment that was significantly different from the ST and NT treatments (**$p \leq .01$ and CV = 5.50%). There was no significant effect between the two tire inflation pressure treatments and their interaction with the tillage system on 1000 grain weight in any of the 3 years. On the contrary, the LTP treatment had a significantly higher ear length (+6.29%) compared to the STP treatment (***$p \leq .001$ and CV = 4.20%) in 2018.

Tire inflation pressure had no significant effect on the grain yield in 2016, with the mean grain yield for the STP and LTP treatments being 14.28 and 14.38 Mg ha^{-1}, respectively (CV = 1.70%). Figure 8 shows that LTP systems significantly increased the grain yield by 4.31% in 2017 (**$p \leq .01$ and CV = 3.70%) and 2.70% in 2018 (*$p \leq .05$ and CV = 2.90%) in comparison with the STP systems. Tillage system had a significant influence on the grain yield of maize in 2018 with DT yield being significantly higher than ST, which, in turn, was significantly higher than that of the NT treatment (***$p \leq .001$ and CV = 2.90%). There was no significant effect of the tillage system on maize yield in 2017 and any interaction with tire inflation pressure on the grain yield of maize in 2017 and 2018.

3.3 | Effect of tire inflation pressure and tillage systems on the growth parameters of soybean

The detailed data on the growth, yield parameters and grain yield of soybean for the years 2016 through 2018 are presented in Table 4 and Figure 9.

TABLE 3 Effect of tire inflation pressure, tillage system and their interaction on growth and yield parameters of maize during the years 2016 through 2018.

	Plant establishment (%)			Number of plants (1000 ha^{-1})			Plant height (m)			Maize 1000 grain weight (g)			Ear length (m)
Treatments[a]	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**	**2018**
Tire inflation pressure													
STP	95.0a	97.6a	90.4a	88.4a	91.3a	84.3a	1.26a	2.13a	2.52a	295a	336a	292a	0.175a
LTP	95.8b	97.4a	91.2b	89.0b	91.1a	84.7b	1.27a	2.15b	2.57b	298a	339a	296a	0.186b
p Value	.01	.34	.007	.01	.09	.005	.08	.04	.004	.47	.25	.47	<.001
LSD	0.46	2.15	0.59	4.27	2.94	3.28	0.02	0.019	0.019	12.8	6.47	12.3	0.006
Tillage system													
DT	—	97.2a	90.5a	—	90.7a	84.5a	—	2.14a	2.56b	—	340a	309b	0.183a
ST	—	97.5a	91.1a	—	91.2b	84.4a	—	2.15a	2.52a	—	335a	286a	0.182a
NT	—	97.7a	90.9a	—	91.6c	84.6a	—	2.13a	2.55a	—	337a	285a	0.179a
p Value		.11	.26		<.001	.47		.44	.04		.18	.005	.44
LSD		2.59	0.73		3.61	4.03		0.023	0.03		7.92	15.1	0.007
Tire inflation pressure × Tillage system													
STP × DT	—	97.4a	90.1a	—	90.9a	84.5a	—	2.13a	2.53a	—	335a	305a	0.177a
STP × ST	—	97.5a	90.6a	—	91.2a	83.9a	—	2.15a	2.49a	—	335a	287a	0.178a
STP × NT	—	97.9a	90.2a	—	91.8a	84.3a	—	2.11a	2.55a	—	337a	283a	0.171a
LTP × DT	—	97.0a	91.0a	—	90.5a	84.5a	—	2.15a	2.59a	—	345a	314a	0.189a
LTP × ST	—	97.6a	91.6a	—	91.3a	84.8a	—	2.15a	2.55a	—	335a	285a	0.183a
LTP × NT	—	97.6a	91.3a	—	91.5a	84.9a	—	2.15a	2.56a	—	338a	288a	0.186a
p Value		.50	.95		.28	.08		.18	.33		.27	.18	.37
LSD		3.48	1.03		5.10	5.69		0.033	0.05		11.2	21.3	0.01

Note: Degree of freedom (DF) in 2017 and 2018: Tire inflation pressure—1, tillage systems—2, their interaction—2 and residual DF—20.

[a]STP, LTP, DT, ST and NT represent the standard tire inflation pressure, low tire inflation pressure, deep tillage, shallow tillage and no-till, respectively. Means in a column with the same letters are not significantly different at $p \leq .05$.

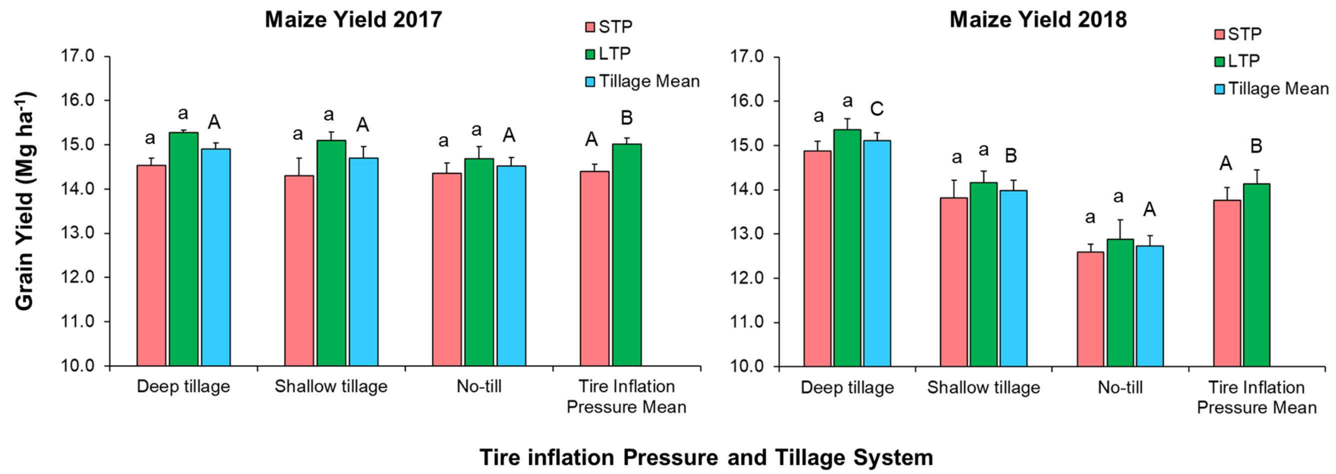

FIGURE 8 Effect of tire inflation pressure, tillage system and their interaction on the yield of maize in 2017 and 2018. Means in a column with the same letters are not significantly different at $p \leq .05$. The error bar indicates the standard error of the mean. The degree of freedom (DF) of tire inflation pressure, tillage systems and their interaction were 1, 2 and 2, respectively, whereas the residual DF was 20.

3.3.1 | Growth parameters of soybean

Table 4 shows that tire inflation pressure had no significant effect on the growth of soybean in 2016, with the exception of plant height, where the LTP had a 3.21% higher plant height (0.354 m) compared with STP (0.343 m) (**$p \leq .01$ and CV = 0.80%). The 2017 results showed that the tillage system had a significant effect on plant establishment, the number of plants ha^{-1} and plant height of soybean, but had no significant difference between tire inflation pressures and its interaction with tillage systems on these parameters. Plant establishment was higher in NT (89.8%), which was significantly different from the ST treatment (85.1%) (**$p \leq .01$ and CV = 3.60%). However, the number of plants ha^{-1} was significantly greater in DT (+6.16%) than in the ST (*$p \leq .05$) and CV = 4.10% and greater plant height (+4.04%) was obtained in the DT treatment (1.03 m) compared to the NT treatment (0.988 m) (***$p \leq .001$ and CV = 2.20%).

The 2018 results show that plant establishment and the number of plants ha^{-1} of soybean in LTP were significantly increased by 2.45% (***$p \leq .001$ and CV = 1.40%) and 2.13% (***$p \leq .001$ and CV = 1.50%), respectively, in comparison with the STP treatment. Likewise, the LTP treatment had a 5.98% higher plant height (0.833 m) compared with that of the STP treatment (0.786 m, ***$p \leq .001$ and CV = 2.70%). Among the tillage systems, there was a small but significantly greater plant establishment (+1.11%) and plant height (+3.53%) recorded in the DT treatment (91.8% and 0.822 m), which was significantly different from the NT treatment (90.1% and 0.794 m) (CV = 1.40% and 2.70%). The interaction between LTP and DT treatments had a +5.45% higher plant establishment (92.9%) that resulted in 4.99% increase in the number of plants ha^{-1} (292,031) in comparison with the STP × NT treatment with the lowest plant establishment of 88.1% (**$p \leq .01$) and the number of plants ha^{-1} of 278,154 (*$p \leq .05$). Similarly, the plant height was recorded to be 10.44% higher in the LTP × DT combination (0.857 m) compared with the STP × NT combination (0.776 m) (*$p \leq .05$ and CV = 2.70%). However, there was no significant effect of the tillage system on the number of plants ha^{-1} of soybean in 2018.

3.3.2 | Yield parameters and grain yield of soybean

Table 4 shows that tire inflation pressure had no significant effect on 1000 grain weight of soybean during any of the 3 years. Similarly, there was no significant effect of the tillage system and its interaction with tire inflation pressure on 1000 grain weight in 2017 and 2018. The biomass yield of soybean in LTP treatment was significantly increased by 8.41% (8.64 Mg ha^{-1}) compared with the STP treatment (7.97 Mg ha^{-1}) in 2018 (***$p \leq .001$ and CV = 5.80%).

Yield data in Figure 9 show that the grain yield of soybean was significantly influenced by tire inflation pressure in 2018 (*$p \leq .05$ and CV = 3.90%), tillage system in 2017 (***$p \leq .001$ and CV = 2.30%) and the interaction between tire inflation pressure and tillage system in 2018 (*$p \leq .05$ and CV = 3.90%). A significantly 3.70% higher grain yield of soybean was obtained in the LTP treatment (4.25 Mg ha^{-1}) compared with the STP treatment (4.10 Mg ha^{-1}) in 2018. In 2016, the mean grain yield of soybean for the STP and LTP treatments was 4.93 and 4.91 Mg ha^{-1}, respectively, while in 2017, it was 4.76 and 4.73 Mg ha^{-1}, respectively

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TABLE 4 Effect of tire inflation pressure, tillage system and their interaction on growth and yield parameters of soybean during the years 2016 through 2018.

	Plant establishment (%)			Number of plants (1000 ha^{-1})			Plant height (m)			1000 grain weight (g)			Biomass yield (Mg ha^{-1})
Treatments[a]	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**	**2018**
Tire inflation pressure													
STP	92.84a	88.3a	89.9a	294.1a	258a	284a	0.343a	1.01a	0.79a	159.5a	179.9a	151.4a	7.97a
LTP	92.45a	87.4a	92.1b	292.6a	254a	289b	0.354b	1.02a	0.83b	160.7a	179.2a	152.3a	8.64b
p Value	.52	.26	<.001	.53	.28	.001	.003	.24	<.001	.61	.50	.33	.001
LSD	1.57	2.81	0.99	4.99	8.03	3.31	0.005	0.017	0.017	2.17	2.34	1.98	0.36
Tillage system													
DT	—	88.6b	91.8b	—	264b	289a	—	1.03b	0.82b	—	178.8a	152.2a	8.46a
ST	—	85.1a	91.3ab	—	248a	287a	—	1.01ab	0.81ab	—	178.9a	151.5a	8.35a
NT	—	89.8b	90.1a	—	257ab	284a	—	0.99a	0.79a	—	181.1a	151.9a	8.10a
p Value		.009	.03		.01	.07		.001	.03		.18	.80	.24
LSD		2.94	1.21		9.83	4.05		0.021	0.02		2.87	2.43	0.45
Tire inflation pressure × Tillage system													
STP × DT	—	89.4a	90.6ab	—	266a	286ab	—	1.01a	0.79ab	—	178.6a	152.1a	8.06a
STP × ST	—	85.5a	91.3b	—	248a	286ab	—	1.01a	0.79ab	—	179.7a	149.6a	8.03a
STP × NT	—	89.9a	88.1a	—	261a	278a	—	0.99a	0.77a	—	181.6a	152.4a	7.82a
LTP × DT	—	87.8a	92.9b	—	261a	292b	—	1.05a	0.86c	—	179.1a	152.3a	8.86a
LTP × ST	—	84.7a	91.3b	—	249a	287ab	—	1.02a	0.83bc	—	178.1a	153.3a	8.67a
LTP × NT	—	89.7a	92.1b	—	253a	289b	—	0.98a	0.81ab	—	180.6a	151.4a	8.37a
p Value		.63	.008		.64	.02		.07	.05		.76	.13	.84
LSD		6.28	1.71		13.9	5.72		0.02	0.02		4.05	3.44	0.63

Note: Degree of freedom (DF) in 2017 and 2018: Tire inflation pressure—1, tillage systems—2, their interaction—2 and residual DF—20.

[a]STP, LTP, DT, ST and NT represent the standard tire inflation pressure, low tire inflation pressure, deep tillage, shallow tillage and no-till, respectively. Means in a column with the same letters are not significantly different at $p \leq .05$.

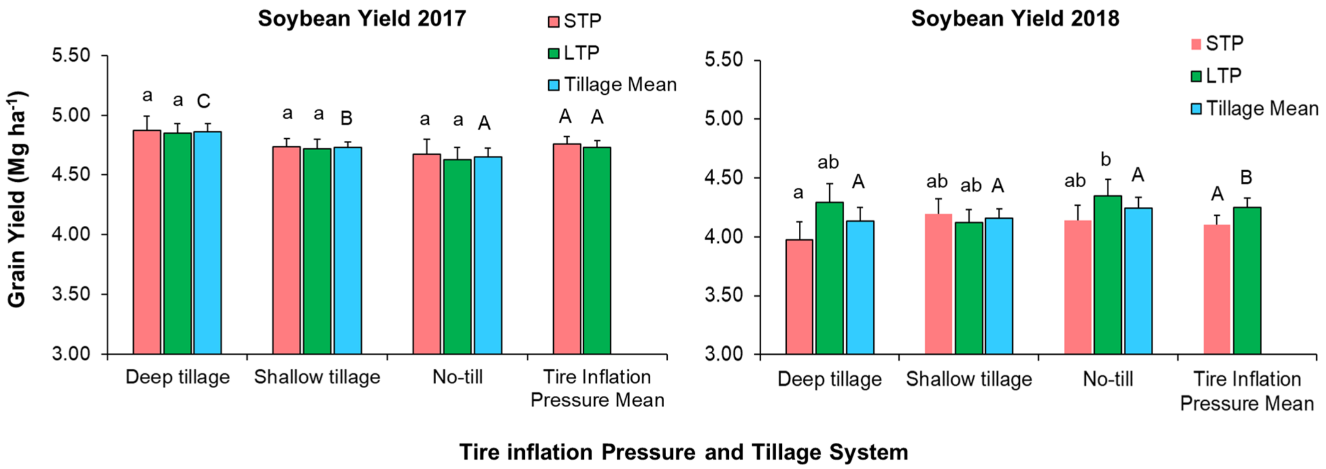

FIGURE 9 Effect of tire inflation pressure, tillage system and their interaction on the grain yield of soybean in 2017 and 2018. Means in a column with the same letters are not significantly different at $p \leq .05$. The error bar indicates the standard error of the mean. The degree of freedom (DF) of tire inflation pressure, tillage systems and their interaction were 1, 2 and 2, respectively, whereas the residual DF was 20.

(CV = 2.30%). Among the tillage systems, the grain yield of soybean in DT and ST was significantly increased by 4.52% (4.86 Mg ha^{-1}) and 1.72% (4.73 Mg ha^{-1}), respectively, compared with the NT (4.65 Mg ha^{-1}) in 2017. The highest grain yield of soybean in 2018 was recorded in the treatment combination of LTP × NT (4.35 Mg ha^{-1}) which was significantly different from the STP × DT treatment combination (3.97 Mg ha^{-1}). However, tire inflation pressure in 2016 and 2017, tillage system in 2018 and the interaction between tire inflation pressure and tillage system in 2017 had no significant influence on the grain yield of soybean at $p \leq .05$. Overall, the data show that the yield benefit of low tire inflation pressure systems for soybean production was consistent among the three tillage systems in 2018.

4 | DISCUSSION

The present study demonstrated that tire inflation pressure and tillage system had significant effects on soil properties, growth and the yield of maize and soybean; however, these varied between years. The increased PR in STP-treated soils in the maize fields at soil depths of 100 and > 275 mm in 2016 (*$p \leq .05$), from 50 to 225 mm in 2017 (*$p \leq .05$), and > 75 mm in 2018 (**$p \leq .01$) and the soybean field at depth > 125 mm in 2018 (**$p \leq .01$) provided evidence of additional soil compaction compared with the LTP. This indicated that soil PR was sensitive to tire inflation pressure and tillage systems when the volumetric MC of the soil at 200 mm depth in both experimental fields was similar. These findings generally agree with others (Hamza et al., 2011; Hula et al., 2009; Raper & Kirby, 2006; Soane et al., 1981), who found that soil compaction caused by field traffic with high inflation pressure tires increased both the PR and the BD of soil. Further, the LTP systems demonstrated benefits in managing soil physical condition by maintaining lower soil BD, and hence greater porosity (measured in 2017 in the maize field) and lower PR of the soil. The results are in agreement with the findings of Hamza and Anderson (2005), Batey (2009), Hula et al. (2009), Keller et al. (2017) and Shaheb and Shearer (2021), who reported that compaction damages soil structure and increases soil strength while reducing the porosity of soils. Further, the increased soil PR in STP can be because of the modification of the pore structure and volume of the soils, which agrees with Soane et al. (1980), who described that when soil compaction occurs, the size and number of macropores are reduced, and shape and continuity of pores are changed. The results are also aligned with Whalley et al. (2008) and Keller et al. (2019), particularly Shaheb et al. (2020), who used computed tomography (CT) scanning of undisturbed soil cores and reported that the CT-derived macro-porosity (%) and the number of macropores of the soil were higher in LTP systems than that of the STP. The greater benefits, however, are that the LTP systems can lower stress, distribute uniform contact stresses on soils and generate a greater surface imprint and traction while minimizing soil compaction, fuel use and increasing return (Boguzas & Hakansson, 2001; Koolen et al., 1992; Michelin, 2017). Schjønning et al. (2012) reported that high inflation pressure and the small contact area were the reasons for the highest values of vertical stress (0.55 MPa) in the centerline 200 mm below under the narrow tire than the wider tire.

It has been seen that the soil PR increase with the trend of STP > LTP was generally in topsoil between ≥50 and

≤300 mm depths but slightly decreased at greater depths, except in the maize field in 2017, where the PR values were relatively constant (between 1.50 and 1.85 MPa). The topsoil compaction because of the STP partially agreed with the findings of (Duiker, 2004; Van den Akker et al., 1994). One possible reason for lower PR values ≤50 mm soil depth could be the surface effect resulting from shearing action caused by tillage and planting tools at the point of soil contact breaking apart soil aggregates. While for a significant increase in PR in STP than LTP at greater soil depths (but decreasing in trend >300 mm depths) can be because of greater vertical stress throughout the soil layers (Figures 5a and 7a). It may also relate to the fact that the relatively large subangular blocky structure and firm soils at depths of 350–480 mm of the experimental soils (USDA NRCS, 1999) can resist penetration (i.e. increase PR) and also the movement of water than in granular and friable structured soil in the top layers (0–178 mm depths). The results are well agreed with the findings of (Keller & Arvidsson, 2004), who reported that tire inflation pressure significantly influenced the vertical soil stress in the topsoil (100 and 300 mm depths) and subsoil (700 mm depth, possibly owing to axle load effect) with the stress lower in low tire pressure than high tire pressure treated soils. This is because soil stress is a function of the soil conditions, tire properties, load and tire inflation pressure (Arvidsson & Keller, 2007). The result is also in agreement with Söhne (1953), where tire inflation pressure and the wheel load accounted for the variation of vertical stresses in the upper subsoil and lower parts of the subsoil, respectively. Another reason could be higher soil water content in the deeper soil, as Jones et al. (2003) suggested susceptibility of soil compaction owing to packing density and vulnerability likely owing to soil water content increases the risk of soil compaction.

Plant establishment and the number of plants per hectare are the determining factors of crop yield (Van Roekel & Purcell, 2016). The agronomic results show the increased plant establishment and the number of plants ha^{-1} of maize (2016 and 2018) and soybean (2018), and plant height of maize (2017 and 2018) and soybean (2018) were associated with the decrease in soil PR in the LTP-treated soils. Soil penetrometer resistance is a function of the soil conditions and tire inflation pressure and thus has an effect on crop growth and yield. This indicates that LTP-treated soils allow greater root development and penetration in deeper soil layers and higher plant establishment and growth compared with STP. This is in agreement with Flowers and Lal (1998), Nawaz et al. (2013) and Shah et al. (2017), who reported that increased soil PR owing to compaction reduced root access to nutrients and water, hence impeding root growth and crop establishment, which, in turn, leads to losses in yield.

Thus, it is evident that increased crop growth of the crops grown under LTP treatment compared with STP treatment, did not affect the grain weight, yet:

(i) increased the ear length of maize in 2018 with the LTP system leading to significant yield benefits of +4.51% and +2.70% in 2007 and 2018, respectively, and
(ii) increased the soybean biomass and yield by 8.41% and +3.70%, respectively, in 2018.

Smith, Misiewicz, Girardello, et al. (2014) and Godwin et al. (2015) reported similar findings in traffic and tillage research using LTP systems in sandy loam soil. The results are similar to the results reported by Godwin et al. (2022) of an average 3.90% greater yield of using LTP tires (0.07 and 0.08 MPa) for DT over the STP tire system (0.10–0.15 MPa) in the U.K. soil. The results also agree with earlier studies where the reduction of yield of various crops because of soil compaction resulting from different machine-soil–plant systems ranged from 9% to 50% (Flowers & Lal, 1998; Lal, 1996; Raghavan et al., 1979). Subsoiling during the fall of 2015 to remove any underlying soil compaction and increased rainfall during later growth stages of crops in 2016 resulted in uniform crop growth and yield between both tire inflation pressure treatments. The increase in PR in both STP and LTP (LTP < STP) at greater soil depths (but decreasing in trend >300 mm depths) as described above (Figures 5a and 7a) resulted in a slight decrease in yield in both crops in 2018 compared to the year 2017 (Figures 8 and 9). A reason for the lack of response of soybean yield to LTP in 2017 is hypothesized to be owing to the lower rainfall and increased temperatures at the later growth stages compared to that in 2016 and 2018 (Figure 2) (Buttery et al., 1998; Yang et al., 2003). Furthermore, soybean plants are more tolerant to soil compaction than maize (Schwab et al., 2004).

Similarly, among the three tillage systems, the increased soil PR values in the NT treatment in both maize and soybean fields can be caused by topsoil compaction compared with the ST and DT treatments. Rearrangement of soil structure owing to soil compaction and lack of diverse crop rotation could also be reasons for a higher soil PR in the NT treatment (Munkholm et al., 2013). Lower PR and BD (measured only in the maize field, 2017) of soils can be linked to the deep tilling process of soils with increased porosity, which is confirmed by the results of Jabro et al. (2021) for maize and soybean. The results also agree with Etana et al. (2020), where PR values of soil were reported to be lower in the DT (depth, 150–200 mm) and ST (depth, 50–100 mm) than in the NT. Thus, increased pore space in the DT treatment, as indicated by lower soil PR in the upper soil layers, helped enhance plants ha^{-1} of soybean in 2017 and plant and ear heights and ear length of maize in 2018 (Shaheb, 2020), as the topsoil structure has the most significant influence on crop growth and yield (Munkholm et al., 2013; Seehusen et al., 2014). As a consequence, this increased the soybean yield in the DT treatment in 2017. While for maize, a higher plant height and ear length and 1000 grain/kernel weight in DT in 2018 contributed to an increased grain yield in 2018 compared with ST and NT treatments.

Since in maize, crop yield is a function of ear length (resulting in more kernel rows and number of kernels) and grain/kernel weight of maize (Iowa State University, 2020; Subedi & Ma, 2005), the maize yield advantage was increased in LTP systems. Husnjak et al. (2002), assessing differences between NT and DT treatments in clay soil in a soybean/wheat rotation, showed that crop yield reduction was linked with higher deterioration of soil properties in NT soils; however, the effect was obtained only in 1 year out of three. In contrast, the results of the present study are partially consistent for both soybean and maize, albeit there were increased PR values of soil in the lower layers of the DT treatment plots in the maize field in 2018 and soybean fields in 2017 and 2018. This indicates that possible re-compaction can occur in the deeper soil layers owing to multiple machinery traffic in the DT system (Millington, 2019; Soane et al., 1986). The results agree with the findings of Etana et al. (2020) and Jabro et al. (2021), who reported that the NT treatment reduced crop development and yield and partially agreed with (Soane et al., 2012), who reported that the NT soil may cause topsoil compaction and lower plant establishment; however, crop yield in the NT treatment plots may often result being equal or even exceed those obtained after ploughing. Overall, the benefit of LTP systems was more evident when associated with deep tillage and, in particular, for maize in 2018 and soybean in 2017, which is also in agreement with the findings of Shaheb et al. (2023), who highlighted that the farm profitability of using LTP tire systems was US$ 42/ha and 45/ha for 200 and 800 ha farms with higher economic advantage observed in the deep tillage system. Nonetheless, the lack of significant interaction between tire inflation pressure and tillage systems in both crops in 2017 and maize in 2018 demonstrates that the effect of LTP systems was consistent among all tillage treatments.

5 | CONCLUSIONS

This study for a typical maize and soybean rotation demonstrates that, following a pilot season with uniform deep tillage, to remove any underlying compaction, the use of low tire inflation pressure systems had a positive effect on soil physical conditions. This has been achieved by maintaining greater total soil porosity following tillage, together with lower soil penetrometer resistance in maize fields in 2017 and 2018 and soybean fields in 2018. Compared with the STP, the LTP systems increased the maize grain yield by 4.31% in 2017 and 2.70% in 2018, and the soybean grain yield by 3.70% in 2018. The penetration resistance in the upper soil layers in the two experimental fields in 2017 and 2018 were in the order of NT > ST > DT. DT and ST systems showed significant yield advantages over the NT system of 4.52% and 1.72%, respectively, for soybean in 2017 and 18.70% and 9.82%, respectively, for maize in 2018. While the use of reduced tire inflation pressures has been recommended for several decades, this is the first major field experiment to quantify these benefits for high flexion tires by linking the resulting soil conditions to crop yield. Hence, the present experiment confirms the hypothesis that reduced tire inflation pressure traffic systems improve crop development and yield by reducing soil compaction in maize and soybean rotation in silty clay loam soils in Central Illinois.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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