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An economic appraisal of the effect of tire inflation pressure for alternative tillage systems on a silty clay loam soil

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Abstract

Compacting soil has an adverse effect on soil properties, decreases crop productivity, and subsequently reduces farm income. Low tire inflation pressure (LTP) help in managing soil compaction and protecting the soil environment; however, there is scant economic data available on LTP in US Midwest farming systems. Hence, a 3-year study investigated the effects of LTP, compared to tires inflated to the standard tire inflation pressure systems, on crop yield and farm economy for a typical maize/soybean rotation. The effect of the two tire inflation pressure systems was factorialized with three tillage systems: deep tillage (DT, 450 mm), shallow tillage (ST, 100 mm), and no-till systems. The results showed that LTP systems increased maize (*Zea mays*) yield by 4.51% (2017) and 2.70% (2018) and soybean (*Glycine max*) by 3.70% in 2018. Annual earnings for both 200- and 800-ha farms increased for all tillage systems with LTP tires based on a partial budget analysis. The payback periods for LTP tires were very short, ranging from 0.32 years for DT on an 800-ha farm to 1.18 years for ST on a 200-ha farm. The net present value of the higher returns with LTP tires was substantial, especially for the DT system. This study shows a strong

Abbreviations: AE, annual earnings ($); DT, deep tillage (depth, 450 mm); GVC or TR, gross value of crops or total returns ($); LSD, least significant difference; LTP, low tire inflation pressure; NPV, net present value ($); NT, no-till; PBA, partial budget analysis; PI, profitability index; ST, shallow tillage (depth, 100 mm); STP, standard tire inflation pressure; ΔFC, change in fixed costs ($); ΔNI or ΔAE, changes in net income or annual earnings ($); ΔTR, change in total returns ($); ΔVC, change in variable costs ($).

economic benefit from investments in LTP tires on silty clay loam soils in the US Midwest.

1 | INTRODUCTION

Soil compaction alters soil physical, chemical, and biological properties and negatively impacts crop performance (Botta et al., 2010; Horn et al., 2003; Keller et al., 2019; Shaheb, Klopfenstein, et al., 2021). It disrupts soil structure, increases water run-off, accelerates erosion, and damages the soil's ecological balance (Houšková & Montanarella, 2008). It decreases productivity, crop growth, and yield, which in turn causes economic losses (Hakansson, 2005; Hula et al., 2009). The reasons for compaction are many, but heavy machinery with high axle loads and high tire inflation pressures are a major factor (Ansorge & Godwin, 2007; Botta et al., 2016; Chamen et al., 2015; Hamza & Anderson, 2005; Schjønning et al., 2016; Soehne, 1958). In conventional tillage systems, the soil is trafficked several times with heavy machinery (Kroulík et al., 2009), which poses a risk of severe soil structural damage due to the destruction of aggregates (Pulido-Moncada et al., 2019). It is worth noting that in one cropping cycle, the percentage of trafficked areas is likely to exceed 60% for 2–3 passes under minimum tillage and almost 100% for multiple passes under conventional tillage (Soane et al., 1982). Repeated field traffic and tillage systems enhance soil erosion and degradation processes, decreasing crop growth and yield (Koch et al., 2008; Tullberg et al., 2007).

However, research has reported higher crop yields from deep-tilled soil due to improved porosity, compared to no-till (NT) and reduced tillage systems (Bogunovic et al., 2018; Botta et al., 2010; Jabro et al., 2021). In 8-years of study, Godwin et al. (2022) reported that deep tillage (DT) and shallow (ST) tillage had greater yield than NT in 4 out of 8-years. They also highlighted that the interaction between tire pressure systems and tillage was substantial, with greater yield in the low tire inflation pressure (LTP) systems and standard tire inflation pressure (STP) with the DT system. However, tire pressure did not impact yield in the ST and NT treatments. In temperate climates, the yields of winter-sown crops in NT or reduced tillage systems after a number of years were reported to be similar to and then higher than those of conventional tillage (Carter, 1994; Kaczorowska-Dolowy, 2021), while for spring crops, yields were often decreased (Soane et al., 2012). Conservation tillage, including no-till, mulch, and strip tillage, however, has gained acceptance in the United States, with approximately 70% of soybean and 65% of maize in 2012 and 2016, respectively (Claassen et al., 2018), as a result of faster operations, reduced costs, and environmental factors (Godwin, 2014; Soane et al., 2012).

Maize (*Zea mays* L.) and soybean (*Glycine max* L.) are the major grain crops grown in rotation in the Midwestern United States (Illinois Department of Agriculture, 2019). The production of maize in the United States in 2018 was 370 million Mg (14,400 million bushels) from an area of 33.1 million hectares and soybean was 121 million Mg (4430 million bushels) from an area of 35.6 million hectares (USDA NASS, 2019). Earlier reports suggest that compaction of soil caused soil degradation in many areas in the United States (Flowers & Lal, 1998), if not in all regions of the United States (DeJong-Hughes, 2018; USDA NRCS, 2004), and is a widespread problem in soils in the heavily mechanized NT agriculture specially in the US Corn Belt region (Blanco-Canqui & Lal, 2007). The consequences of soil compaction include (1) damaged soil structure, (2) an increase in the need for DT and associated energy utilization for soil treatment, (3) reduced crop growth and yield, and (4) poor germination of subsequent crops (Defossez & Richard, 2002; Gelder et al., 2007; Hula et al., 2009; Shaheb, Klopfenstein, et al., 2021). A multi-year study in Ohio showed that soil compaction due to vehicle traffic with 10 and 20 Mg axle loads (harvest loads created by grain carts) caused a reduction in maize yield by about 17% and 25% and soybean yield by about 9% and 21%, respectively, as compared to the control (Lal, 1996). Further severe reductions in yield were reported due to compaction on poorly drained heavy textured soils (Flowers & Lal, 1998). Thus, the crop yield loss due to soil compaction leads to a substantial reduction in overall farm returns (Godwin et al., 2022; Hula et al., 2009; Nawaz et al., 2013; Shaheb, Klopfenstein, et al., 2021).

Sustainable soil management for improved crop yields and the economic profitability of cropping systems is crucial. Farmers decide and adopt new technology based on both short- and long-term profitability while striving to protect the environment and achieve other goals. Mitigation of soil compaction often leads to negative returns; however, avoiding soil compaction is more cost-effective (Hallett et al., 2012). Reducing and restricting field traffic to 20%–30% of the field area by controlled traffic farming or a combination of approaches, including judicious loosening and the use of low tire inflation pressure systems, was found to be beneficial to topsoil quality and crop yield (Chamen et al., 2015; Kaczorowska-Dolowy, 2021). High-flexion tires inflated to a rated LTP generate a greater surface imprint while minimizing soil compaction (Michelin, 2017; ten Damme et al., 2019). Studies during the 1990s showed an economic advantage of low over high tire pressure systems. The benefits of the use of low tire inflation pressure systems obtained from these studies were mostly concentrated on cereal silage production (Godwin et al., 1992) and root crops (Tijink et al., 1995; Vermeulen & Klooster, 1992), yet little information exists concerning the economic evaluation for whole-farm situations, especially in relation to crop production for various tillage practices. Shaheb (2020) reported that LTP reduced soil compaction and increased maize and soybean yields for three tillage systems. While the benefit of low tire inflation pressure systems has been reported in recent studies in the United Kingdom (Godwin et al., 2015, 2017, 2022; Smith, Misiewicz, Chaney, et al., 2014), a farm-scale economic analysis of the reduced tire inflation pressure system is yet to be conducted. Thus, a partial budget analysis (PBA), including robust methods such as net present value (NPV), payback period (PBP), and sensitivity testing, was utilized. The hypothesis therefore was that low tire inflation pressure systems increase the economic profitability for a maize/soybean rotation for three tillage systems. The objectives of the study were to determine the costs and potential economic benefits of high-flexion tires operating at the rated LTP, compared to STP, for a maize/soybean rotation for deep, shallow, and NT tillage regimes in the US Midwest.

2 | MATERIALS AND METHODS

A field experiment was conducted at the Agricultural Engineering Research Farm of the University of Illinois at Urbana-Champaign, IL, USA, from November 2015 to October 2018 (40°04′15.5″N; 88°13′03.1″W). The main crops of this region are maize and soybean, and therefore the study location was well-fitted to compare the benefits of different tire inflation pressure systems for alternate tillage systems for maize/ soybean rotation on silty clay loam soil (USDA NASS, 2019; https://croplandcros.scinet.usda.gov/). The soils of the experimental site were predominately silty clay loam Drummer soil series (152A) with small areas of similar silt loam Thorp series soil (206A). The agronomic management and economic evaluation of the present study are described below:

2.1 | Agronomic study

The experiment was established in two adjacent fields (North and South, each of 3.24 ha), which were planted in rotation with maize and soybean in alternate years. The varieties were P1221AMXT (Pioneer seed) and P35T58R for maize and soybean, respectively, which were planted in a maize–soybean–maize rotation in the North field and soybean–maize–soybean rotation in the South field from 2016 through 2018. A detailed description of the experiment and the effect on soil properties and crop development is given in Shaheb et al. (unpublished data, 2023). The present study demonstrated the economic performance of the farming systems by several robust methods, including sensitivity testing of the cost-effectiveness of alternative soil management practices, to increase crop productivity and farm profitability while maintaining environmental sustainability.

Core Ideas

- Low tire inflation pressure (LTP) increased crop yield and farm income.
- Per hectare annual earnings in LTP tires increased by \$42/ha and \$45/ha for 200- and 800-ha farms for maize/soybean cropping systems.
- The benefit of LTP tires was more consistent when associated with the deep tillage system.
- The payback period for LTP tires at the current grain and tire prices is less than 2-years.
- The LTP tires are profitable even if grain prices are much lower than the current level.

2.1.1 | Experimental design and treatments

The experiment was designed as a 2 × 3 factorial randomized complete block design, with five blocks. The treatments comprised (i) two tire inflation pressures: standard (STP, 0.14, 0.12, and 0.21 MPa) and low tire inflation pressures (LTP, 0.07, 0.05, and 0.14 MPa) for the tillage tractor, planter tractor, and combine harvester, respectively, and (ii) three tillage systems: DT (450 mm), ST (100 mm), and NT. The unit plot area was 180 × 6 m = 1080 m^2 with 10 m headlands with eight crop rows per plot, and the plots were oriented in an East-West direction. In the fall of 2015, prior to the two experimental years, the fields were deep loosened to a depth of 0.45 m to remove any underlying compaction, and the crops were established in the spring of 2016. Thus, the effect of three tillage systems for two tire inflation pressure systems was investigated in the subsequent 2-years. However, the year 2016 was considered a normalization year and provided data concerning the variability of the experimental sites with coefficients of variation (CVs) of soil penetrometer resistance (450 mm depth) of 13.7% and 15.6% for the North and South fields, respectively (Shaheb, 2020). The tractors and combine harvester (Table 1) were fitted with high-flexion radial tires manufactured by Michelin. To save the need to

TABLE 1 Specifications of equipment and high-flexion radial tires.

Equipment	Make—model	Power (kW)	Mass (Mg)		High-flexion tires	
			Front axle	Rear axle	Front	Rear
Tillage tractor	John Deere–7930	164	3.81	6.49	Yieldbib VF380/85R34	Yieldbib VF480/80R46
Planting tractor	John Deere–7700	94	3.12	5.51	Yieldbib VF380/85R34	Yieldbib VF480/80R46
Combine harvester[a]	John Deere–9410	306	12.7	5.44	Cerexbib 800/65/R32	Cerexbib 14.9R24

[a]The weight ratio of the front and rear axle loads of the combine was assumed 70%:30% (Ansorge & Godwin, 2007).

change the tires during the field experimental phase, following the results from (Smith, Misiewicz, Girardello, et al., 2014), the high-flexion tires were inflated to both low and standard (conventional) tire pressures.

2.1.2 | Field operations

DT was conducted using a Case/IH Ecolo-Tiger 527B attached to the John Deere–7930 tractor in October 2015; this was followed by shallow tillage (ST; Sunflower/AGCO 6221-20) using the same tillage tractor and planting (John Deere–7200 Max Emerge 2) using John Deere–7700 tractor in the spring of 2016. The DT operation was conducted only in DT plots in the autumn of 2016 and 2017 and ST in the spring to both the DT and ST plots in 2017 and 2018. Pre- and post-emergence herbicides were applied perpendicular to the direction of the plots in May and 30 days after planting using a 36.6-m boom-width self-propelled sprayer. After spraying the pre-emergence herbicides, a shallow spring tillage tool (Sunflower/AGCO 6221-20) was used to level the soil and incorporate herbicides in the deep- and shallow-tilled plots. Maize and soybean crops were planted in mid-May with 0.75-m row spacing, using the John Deere–7200 Max Emerge 2 eight rows planter for the tilled and NT treatments. The center six maize rows and all soybean rows of each plot were harvested using the combine harvester with header widths of 4.5 and 6 m for maize and soybean, respectively, and the plot yields were measured using a weigh wagon with a resolution of 0.05 kg. The yield of maize and soybean were adjusted to seed moisture contents of 15.5% and 13% for maize and soybean, respectively.

2.2 | Economic study

The economic analysis of the use of alternate tire technologies, that is, LTP systems or high-flexion tires, compared with STP systems in the cropping system, was evaluated by mainly using PBA, NPV, PBP, and profitability index (PI). A sensitivity test was also conducted for different output/grain prices, tire prices, and discount rates scenarios to see whether purchasing LTP tires would still be breakeven for the present cropping systems for two sizes of farms.

2.2.1 | Economic assumptions

The economic analysis was based on the following assumptions:

1. Farm sizes of 200 and 800 ha were considered. The first is one-third larger than the official quoted size of an average Illinois farm (c.150 ha, Illinois Department of Agriculture, 2019), and the second is that of frequently found commercial farming operations (Mike Pantaleo, personal communication, March 23, 2019).
2. The retail prices for the standard and high-flexion tires (baseline level price) for the equipment required for the two farm sizes were provided by Michelin, North America Inc. (Mike Pantaleo, personal communication, March 23, 2019) and Michelin Tire Company Ltd., UK (Gordon Brookes, personal communication, March 31, 2019). The equipment specification, the number of tires, and their costs for the 200- and 800-ha farm sizes are given in the Supplementary Material (Tables S1 and S2). The cost differences between standard and high-flexion tires for the 200- and 800-ha farms were $8,200 and $17,000, respectively.
3. Tire life expectancy was considered to be 8-years or 4,000 h (Mike Pantaleo, personal communication, March 23, 2019), assuming a usage of 500 ha/year, which is similar to the average usage of a tractor of approximately 400–500 ha/year in the US Midwest (Edwards, 2015; Jacobs, 2020). A recent report in the United Kingdom, however, showed that the longevity of Michelin high-flexion tires was 9,500 h (Tillage & Soils, 2020) indicating that a tire life of 8-years could be conservative for tractors of 135 kW (Gordon Brookes, personal communication, March 31, 2019).
4. The annual mean price of maize and soybean in Illinois in 2018 was \$142.00 Mg^{-1} (\$3.60 bu^{-1}) and \$323 Mg^{-1} (\$8.80 bu^{-1}), respectively (Schnitkey & Swanson, 2019), and are considered the baseline level prices of both crops.

5. Seed, fertilizer, herbicides, labor, tillage, repair, and overhead costs were assumed equal for both tire inflation pressure treatments as these were applied equally to both tire systems for each type of tillage.
6. The straight-line method was used to estimate the depreciation cost for the tire systems as described in Bochtis et al. (2019).
7. The discount rate of 5.0% was considered reasonable (Langemeier, 2021) for a US farm and as a baseline level rate to determine the NPV for the investment of high-flexion tires over standard tires. The "discount rate" estimates the present value of future costs and benefits. It also is labeled the "opportunity cost of capital" because the rate is usually related to potential earnings on alternative investments.
8. The fuel consumption was assumed to be equal for both STP and LTP systems (Arslan et al., 2014). Although the fuel cost varies between tillage systems, however, fuel costs were assumed to be the same or do not vary between both tire systems/technologies, they drop out of the change in net income.
9. Equal areas of maize and soybean were grown on commercial farms in each year of the rotation (Stewart Melvin, personal communication, December 22, 2018).

2.2.2 | Economic analysis

The PBA was used to assess the impact of a technological change (LTP tires over STP tires) on farm costs and returns (Kay et al., 2019; Roth & Hyde, 2002). It is a planning and decision-making framework that quantifies changes in income and expenditure resulting from the adoption of LTP tires in the farming system over STP tires. The PBA comprised (i) the total difference in tire expenditure (standard vs. high-flexion tires), (ii) the annual value of crops, (iii) the yield increase or decrease, and (iv) the annual earnings (AE) increase or decrease for the life of the tire. The PBA for both farms was estimated by determining the net income (NI) and change in NI (ΔNI; Roth & Hyde, 2002). The NI is the difference between the total returns (TR) or gross value of crops (GVC) and the total costs (TC) of individual farms featuring fixed costs (FC) and variable costs (VC). However, the PBA only considers the VCs that change or vary between the technologies (here, costs of LTP and STP tires) being evaluated. As FCs were assumed to be the same or do not vary between both treatments or tire technologies, they dropped out of the change in NI. The ΔNI or AE increase of an individual farm is the difference between the change in TR (ΔTR) and the change in FC (ΔFC) and change in VC (ΔVC, i.e., additional investment for LTP tires). As FC are assumed to be the same for both tire technologies, ΔFC was also dropped out. The ΔNI helps in deciding whether or not to adopt a new technology that will potentially increase the farm's NI (Roth & Hyde, 2002). In addition, the PBP was estimated to provide the time required for the cash flows generated by the investment to repay the cost of the NPV of the original investment (Barnard & Nix, 1979), where the NPV is the value of a series of cash flows over the life of the project discounted to the present value (Barnard & Nix, 1979). The cash flow budget is a plan of how cash will be coming into (cash inflows) and out of the operations (cash outflows). The cash flows in the NPV calculation were the generated income from the farm over the tire life using LTP tire systems.

The PI is calculated by dividing the present value of all the future cash flows of the project by the initial additional investment in the project. The cost and benefits of production per hectare were determined based on the market price of production inputs and crop values in 2018. The production cost includes total direct (seed, fertilizer, and pesticides), equipment, and overhead (Schnitkey, 2020). Government payments on US maize and soybean farms were considered to be the same regardless of tire technology or other production practices. The economic components were calculated using the following Equations (1)–(7):

$$\begin{aligned}\text{Difference in tire expenditure } \left(\text{US\$ ha}^{-1}\right) \\ = \text{Cost of high} - \text{flexion tires} \\ - \text{Cost of standard tires,}\end{aligned} \tag{1}$$

$$\text{GVC (US\$)} = \frac{(\text{Farm size} \times \text{maize yield} \times \text{price}) + (\text{Farm size} \times \text{soybean yield} \times \text{price})}{2}, \tag{2}$$

$$\begin{aligned}&\text{AE increase/decrease } (\text{US\$}) \\ &= [\text{GVC in STP} \times \text{percent yield } (\pm) \text{ from LTP}] \\ &- \left[\frac{\text{Difference in tire expense } (\text{US\$})}{\text{Tire life } (\text{years})}\right],\end{aligned} \tag{3}$$

$$\begin{aligned}\text{Total income over the tire life } (\text{US\$}) \\ = \text{AE increases} \times \text{tire life } (\text{years}),\end{aligned} \tag{4}$$

$$\text{PBP (years)} = \frac{\text{Differences in tire expense } (\text{US\$})}{\text{Difference in GVC between LTP and STP } (\text{US\$})}, \tag{5}$$

$$\text{NPV(US\$)} = \sum_{i=1}^{n} \frac{\text{cash flow}_i}{\left(1 + r_2\right)^i} - \text{initial additional investment}, \tag{6}$$

$$\mathrm{PI} = \frac{\text{Present value of all future cash flows}}{\text{Initial cash outflows or additional investment (I)}} = 1 + \left(\frac{\mathrm{NPV}}{\mathrm{I}}\right), \quad (7)$$

where GVC is the gross value of crop, AE is the annual earnings, PBP is the payback period, NPV is the net present value, PI is the profitability index, r is the discount rate (5.0%), n is the number of time periods, and i is the cash flow period.

Sensitivity testing of the additional investment of the high-flexion/LTP tires was conducted for three scenarios: (a) using the five different prices of output products or grains of crops, (b) three different tire prices, and (c) three different discount rates. The grain prices were (i) baseline level price @ maize \$142 Mg^{-1} (\$3.60 bu^{-1}) and soybean \$323 Mg^{-1} (\$8.80 bu^{-1}); (ii) half the baseline level price; (iii) the lowest Illinois farm grain price during 2016–2020, that is, summer/June 2020 @ maize \$124 Mg^{-1} (\$3.16 bu^{-1}) and soybean \$306 Mg^{-1} (\$8.34 bu^{-1}); (iv) 2016–2020, 5-years average grain price, @ maize \$138 Mg^{-1} (\$3.51 bu^{-1}) and soybean \$333 Mg^{-1} (\$9.07 bu^{-1}); and (v) the highest price on June 30, 2022, after Russia and Ukraine war started @ maize \$290 Mg^{-1} (\$7.37 bu^{-1}) and soybean \$602 Mg^{-1} (\$16.4 bu^{-1}; USDA NASS, 2022). The tire prices were (i) baseline level price (Supplementary Material, Tables S1 and S2), (ii) double the baseline level price, and (iii) triple the baseline level price, considering a view that if the tire manufacturers ran into logistics problems and could not get raw materials or those raw materials were much higher priced, particularly affected the low-pressure tires, then how high would the tire price be and purchasing LTP would still be breakeven. The discount rate of 5% was the baseline rate, with 10% and 20% as sensitivity tests. Five percent was a reasonable choice for the 2018 period. Interest rates were very low then, as were returns to equity in general. A 10% opportunity cost of capital was used for agricultural investments prior to the 2007–2008 financial crisis. It was often justified by the average returns to capital in the equity markets. A 20% opportunity cost of capital would seem extreme to most US farmers, but the interest rate reached that neighborhood in the late 1970s and early 1980s when the Federal Reserve was trying to combat inflation. Also, 20% is frequently reached in developing country financial markets. With current US interest rates of 7%–8%, the opportunity cost of capital must be at least that just to stay even.

The statistical analysis of crop yield data used a two-way analysis of variance with Genstat 18th edition (VSN International, 2015) and Tukey multiple range tests ($P < 0.05$). The economic components were calculated using Microsoft Excel spreadsheets based on crop values, tire costs, and the number of tires required for the 200- and 800-ha farms in Illinois. The economic data (total return, NPV, and sensitivity testing) were analyzed using the R software environment (R Development Core Team, 2022).

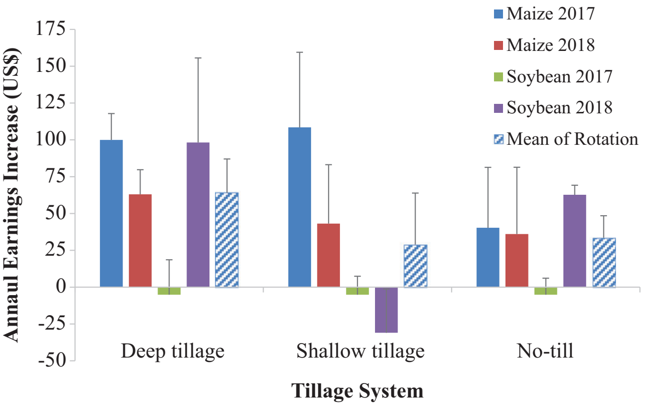

FIGURE 1 Per hectare annual earnings (AE) increase for the low tire inflation pressure (LTP) systems, compared to standard inflation pressure (STP) tires for a 200-ha farm (grain price at baseline level). Error bar indicates the standard error of mean ($n = 5$).

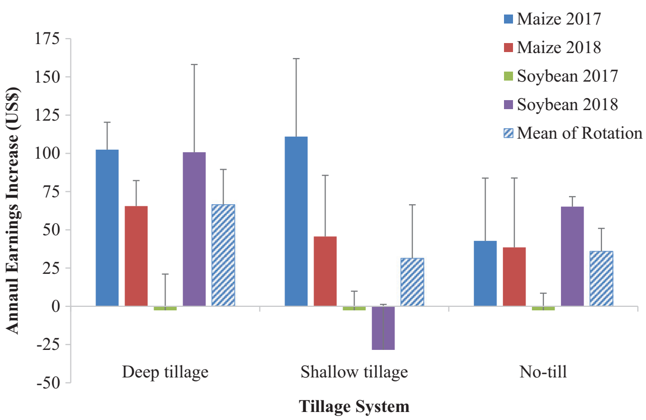

FIGURE 2 Per hectare annual earnings (AE) increase for low tire inflation pressures (LTP) compared to standard inflation pressures (STP) tires for an 800-ha farm (grain price at baseline level). Error bar indicates the standard error of mean ($n = 5$).

3 | RESULTS

The effect of LTP systems on the grain yield and economic value, tire costs, AE, PBP, NPV, and PI of maize and soybean cropping systems are presented in Tables 2–7 and Figures 1–4. The per-hectare cost of production, GVC, and net returns are presented in Table 8.

3.1 | Effect of LTP system on the yield and economic value of maize and soybean

The detailed crop yield and economic value of crops given in Table 2 indicate that the LTP systems increased the yield of maize in both years (**$P < 0.01$ and *$P < 0.05$) and soybean in 2018 (*$P < 0.05$). The maize yield increased by 4.31% and 2.70% in 2017 and 2018 and the soybean yield by 3.70% in 2018. There was no significant effect of tire inflation

TABLE 2 Grain yield and economic value of crops in the maize–soybean and soybean–maize crop rotations from 2017 through 2018.

	Crop yield (Mg ha^{-1})						Mean economic value ($ ha^{-1})		
	2017		2018		Mean				
Treatments	Maize	Soybean	Maize	Soybean	Maize	Soybean	Maize	Soybean	2-year rotation
Tire inflation pressure									
STP	14.40a	4.76a	13.76a	4.10a	14.08	4.43	1999	1431	1715a
LTP	15.02b	4.73a	14.13b	4.25b	14.57	4.49	2069	1450	1760b
Increase (LTP-STP)	0.62	−0.03	0.37	0.15	0.50	0.06	70	19	45
% increase	4.31	−0.56	2.69	3.70	3.52	1.39	3.52	1.39	2.63
Tillage system									
DT	14.90a	4.86c	15.11c	4.13a	15.01	4.50	2131	1454	1792c
ST	14.70a	4.73b	13.98b	4.16a	14.34	4.45	2036	1437	1736b
NT	14.52a	4.65a	12.73a	4.24a	13.63	4.45	1935	1437	1686a
% increase in DT over ST	1.36	2.75	8.08	−0.72	4.67	1.12	4.67	1.12	3.23
% increase in DT over NT	2.62	4.52	18.70	−2.59	10.12	1.12	10.12	1.12	6.29
Tire inflation pressure × tillage system									
STP × DT (1)	14.53a	4.87a	14.87a	3.97a	14.70	4.42	2087	1428	1758c
STP × ST (2)	14.30a	4.74a	13.81a	4.20ab	14.06	4.47	1997	1444	1720bcd
STP × NT (3)	14.36a	4.67a	12.59a	4.14ab	13.48	4.41	1914	1424	1668d
LTP × DT (4)	15.27a	4.85a	15.35a	4.29ab	15.31	4.57	2174	1476	1825a
LTP × ST (5)	15.10a	4.72a	14.15a	4.12ab	14.63	4.42	2077	1428	1752bc
LTP × NT (6)	14.68a	4.63a	12.88a	4.35b	13.78	4.49	1957	1450	1704ab
% increase in 4 over 1	5.09	−0.41	3.23	8.06	4.15	3.39	4.15	3.39	3.81
% increase in 5 over 2	5.59	−0.42	2.46	−1.90	4.05	−1.12	4.05	−1.12	1.86
% increase in 6 over 3	2.23	−0.86	2.30	5.07	2.23	1.81	2.23	1.81	2.16

Note: Crop value: maize—$142 Mg^{-1} and soybean—$323 Mg^{-1}. Means with the same letters in a column are not significantly different at $p < 0.05$.
Abbreviations: DT, deep tillage; LTP, low tire inflation pressure; NT, no-till; ST, shallow tillage; STP standard tire inflation pressure.

TABLE 3 Costs of standard (STP) and low (high flexion, LTP) tires for 200- and 800-ha farms (baseline level tire price).

	Tire costs		
		Annual cost ($)	
Treatments	Total cost ($/8-years)	Farm/year	ha/year
200-ha farm			
STP	34,400	4,300	21.5
LTP	42,600	5,325	26.6
Difference/additional investment	8,200	1,025	5.13
% cost increase in LTP over STP	23.8	23.8	23.8
800-ha farm			
STP	84,600	10,575	13.2
LTP	101,600	12,700	15.9
Difference/additional investment	17,000	2,125	2.66
% cost increase in LTP over STP	20.1	20.1	20.1

Abbreviations: LTP, low tire inflation pressure; STP, standard tire inflation pressure.

TABLE 4 Significance level (*p*-value) and LSD values of economic performance (ha per farm) and NPV/farm for maize/soybean rotation.

	Economic value/ha/farm										NPV/farm					
	Maize				Soybean				2-year rotation mean		5% DR		10% DR		20% DR	
	2017		2018		2017		2018									
Treatments	*p*-value	LSD	*p*-value	LSD	*p*-value	LSD	*p*-value	LSD	*p*-value	LSD	*p*-value	LSD	*p*-value	LSD	*p*-value	LSD
200-ha farm																
TIP	0.015	66.3	0.08	55.2	0.31	55.2	0.05	43.7	0.014	31.1	0.017	40,285	0.021	33,276	0.033	23,979
TS	0.40	81.3	0.001	67.6	0.002	67.6	0.35	53.5	0.001	38.1	0.000	49,339	0.000	40,755	0.000	29,369
TIP × TS	0.65	114.9	0.91	95.6	0.96	95.6	0.05	75.7	0.59	53.8	0.59	69,777	0.59	57,636	0.60	41,534
800-ha farm																
TIP	0.013	66.4	0.07	55.3	0.40	28.8	0.042	43.6	0.009	31.1	0.010	161,144	0.013	112,056	0.015	95,919
TS	0.40	81.3	0.001	67.7	0.002	35.2	0.34	53.4	0.000	38.1	0.000	197,361	0.000	137,241	0.000	117,477
TIP × TS	0.65	115.1	0.91	95.8	0.96	49.9	0.058	75.6	0.58	53.9	0.59	279,110	0.59	194,088	0.60	166,137

Abbreviations: DR, discount rate; LSD, least significant difference; NPV, net present value; TIP, tire inflation pressure; TS, tillage systems.

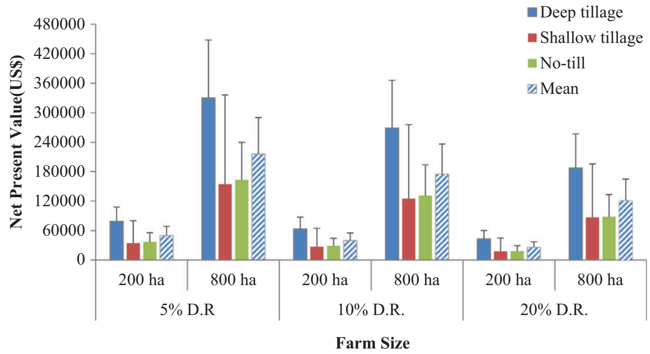

FIGURE 3 Net present value of the use of low tire inflation pressure (LTP) systems for 8-year periods at discount rates of 5.0%, 10%, and 20% and grain price at baseline level. Error bar indicates the standard error of mean ($n = 5$). D.R. denotes discount rate.

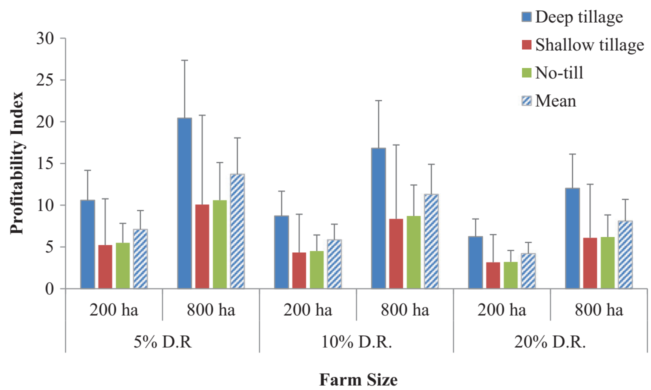

FIGURE 4 Profitability index of the use of low tire inflation pressure systems at discount rates of 5.0%, 10%, and 20% and grain price at baseline level. Error bar indicates the standard error of mean ($n = 5$). D.R. denotes discount rate.

pressure on soybean yield in 2017. Tillage had a significant effect on the yield of soybean in 2017 (***$P < 0.001$) and maize in 2018 (***$P < 0.001$), with the highest yield recorded in DT, compared to ST and NT systems. In comparison to STP, the 2-years mean crop yield in LTP was increased by 0.50 and 0.06 Mg ha^{-1} for maize and soybean, respectively. While maize yield response was more consistent in both years, the decreased rainfalls and increased temperatures at later growth stages could be a reason for the lack of response in soybean yield, compared to that in 2018 (Shaheb, 2020). Irrespective of tillage systems, the 2-years rotation mean crop value per hectare in LTP was increased by $45 (+2.63%) as compared to STP. The mean economic value for 2-years of crop rotation in DT was increased by 3.23% and 6.29%, compared to the ST and NT, respectively. When averaging over tillage systems, the economic value in LTP was higher and more consistent for all three tillage systems than the STP systems.

TABLE 5 Sensitivity analysis of additional investment in low tire inflation pressure (LTP) tires and per hectare annual earnings in different output products (grain) and tire prices scenarios.

	Per ha annual earnings ($) increase in LTP									
	Grain price scenarios									
	A. 50% less the baseline		B. Baseline level (2018)[a]		C. Summer/June 2020[b]		D. 2016–2020 average[b]		E. June 30, 2022[b]	
Tillage systems	**200-ha**	**800-ha**	**200-ha**	**800-ha**	**200-ha**	**800-ha**	**200-ha**	**800-ha**	**200-ha**	**800-ha**
(A) Baseline tire price										
Deep tillage	29.5	31.9	64.0	66.5	55.3	57.7	62.1	64.5	136.1	138.6
Shallow tillage	11.9	14.3	28.9	31.4	24.6	27.0	27.9	30.4	64.3	66.8
No-till	14.2	16.7	33.5	36.0	28.6	31.1	32.4	34.9	73.7	76.2
Mean	18.5	21.0	42.1	44.6	36.1	38.6	40.8	43.3	91.4	93.9
(B) Double the tire price										
Deep tillage	24.3	29.3	58.9	63.8	50.1	55.1	57.0	61.9	131.0	135.9
Shallow tillage	6.8	11.7	23.8	28.7	19.4	24.4	22.8	27.7	59.2	64.1
No-till	9.1	14.0	28.4	33.3	23.5	28.4	27.3	32.2	68.6	73.5
Mean	13.4	18.3	37.0	41.9	31.0	36.0	35.7	40.6	86.3	91.2
(C) Triple the tire price										
Deep tillage	19.2	26.6	53.8	61.2	45.0	52.4	51.8	59.2	125.8	133.3
Shallow tillage	1.6	9.0	18.6	26.0	14.3	21.7	17.7	25.1	54.1	61.5
No-till	3.9	11.3	23.2	30.6	18.3	25.7	22.1	29.6	63.5	70.9
Mean	8.3	15.7	31.9	39.3	25.9	33.3	30.6	38.0	81.1	88.5

[a]Schnitkey and Swanson (2019).
[b]USDA NASS (2022).

TABLE 6 Significance level (*p*-value) and least significant difference (LSD) values for sensitivity tests for different tire and grain prices scenarios for maize/soybean rotation.

Treatments	Tire price	Sensitivity tests (economic value/ha/farm)									
		Grain price									
		Baseline level (2018)		50% less the baseline		Summer/June 2020		2016–2020 average		June 30, 2022	
		p-value	LSD	*p*-value	LSD	*p*-value	LSD	*p*-value	LSD	*p*-value	LSD
200-ha farm											
TIP	Baseline	0.014	31.1	0.029	15.5	0.015	27.2	0.014	30.3	0.009	63.7
	Double	0.029	31.1	0.11	15.5	0.038	27.2	0.031	30.3	0.014	63.6
	Triple	0.06	31.1	0.35	15.6	0.06	30.2	0.06	30.2	0.020	63.6
TS	Baseline	0.000	38.1	0.000	19.1	0.000	33.3	0.000	37.1	0.000	77.9
	Double	0.000	38.2	0.000	19.0	0.000	33.3	0.000	37.1	0.000	77.9
	Triple	0.000	38.1	0.000	19.1	0.000	37.0	0.000	37.0	0.000	78.0
TIP × TS	Baseline	0.59	53.8	0.59	26.9	0.58	47.1	0.58	52.4	0.58	110.2
	Double	0.58	54.0	0.59	26.9	0.58	47.1	0.58	52.5	0.59	110.1
	Triple	0.59	53.9	0.57	27.0	0.58	52.3	0.58	52.3	0.58	110.3
800-ha farm											
TIP	Baseline	0.009	31.1	0.014	15.6	0.010	27.2	0.010	30.3	0.007	63.5
	Double	0.014	31.1	0.032	15.6	0.015	27.1	0.015	30.2	0.009	63.7
	Triple	0.02	31.2	0.06	15.6	0.02	30.2	0.021	30.2	0.011	63.6
TS	Baseline	0.000	38.1	0.000	19.1	0.000	33.4	0.000	37.2	0.000	77.8
	Double	0.000	38.1	0.000	19.1	0.000	33.2	0.000	37.0	0.000	78.03
	Triple	0.000	38.2	0.000	19.2	0.000	37.0	0.000	37.0	0.000	77.9
TIP × TS	Baseline	0.58	53.9	0.57	27.0	0.59	47.2	0.58	52.5	0.58	110.2
	Double	0.59	53.8	0.57	27.0	0.59	47.0	0.58	52.5	0.58	110.4
	Triple	0.59	53.9	0.60	27.1	0.59	52.3	0.59	52.4	0.58	110.2

Abbreviations: LSD, least significant difference; TIP, tire inflation pressure; TS, tillage systems.

TABLE 7 Partial budget analysis for the use of low tire inflation pressure (LTP) tires in maize/soybean rotation for two sizes of farms (based on baseline level grain and tire prices).

	Total returns, TR ($)					
Tillage systems	STP	LTP	Tillage mean	Difference, ΔTR ($)	Additional tire investment, ΔVC ($)	Payback period (year)
200-ha farm						
Deep tillage	351,553b	365,008a	358,280a	13,830	8,200	0.59
Shallow tillage	343,872bcd	350,471bc	347,171b	6,802	8,200	1.21
No-till	333,680d	340,676 cd	337,178c	7,723	8,200	1.06
Mean	343,035b	352,051a		9,452	8,200	0.87
800-ha farm						
Deep tillage	1,406,213b	1,460,033a	1,433,123a	55,320	17,000	0.31
Shallow tillage	1,375,489bcd	1,401,884bc	1,388,686b	27,208	17,000	0.62
No-till	1,334,721d	1,362,705 cd	1,348,713c	30,890	17,000	0.55
Mean	1,372,141b	1,408,207a		37,806	17,000	0.45

Note: Means with the same letters in a column are not significantly different at $P < 0.05$.
Abbreviation: LTP, low tire inflation pressure system; STP, standard tire inflation pressure; ΔTR—change in total return; ΔVC—change in variable costs.

3.2 | Economic evaluation of the effect of low tire inflation pressure for maize/soybean rotation

The detailed results of the effect of LTP systems on tire costs, AE, PBA, PBP, NPV, and PI of maize and soybean cropping systems are presented in Tables 3–7 and Figures 1–4. The per hectare cost of production and returns ($ ha^{-1}) for maize/soybean crop rotations is given in Table 8.

3.2.1 | Annual cost of different tire systems for two typical farms in Illinois

The total 8-year and annual costs of LTP and STP tires for the 200- and 800-ha farms are given in Table 3 and show that the total cost of purchasing LTP tires ($42,600) for a 200-ha farm was 23.8% higher than that of the STP ($34,400). Likewise, for an 800-ha farm, the total tire cost using LTP ($101,600) increased by 20.1%, compared to the cost of an STP tire system ($84,600). The annual tire costs (e.g., cash outflow) per hectare assuming an 8-year tire life for LTP and STP tire systems are, therefore, $26.6 and $21.5, respectively, for the 200-ha farm and $15.9 and $13.2, respectively, for the 800-ha farm. However, the additional investment or cash outflows for purchasing LTP tires over STP were $8200 and $17,000 for the 200- and 800-ha farms, respectively. For sensitivity testing, double and triple baseline prices of both the standard and low-pressure tires have the effect of doubling and tripling the difference between STP and LTP tires.

3.2.2 | Per hectare AE increase of different tire systems for two farm sizes

The AE increase was calculated as the difference between the GVC in STP and LTP treatments and the cost of the LTP and STP tires. The use of LTP systems had significantly higher AE for 200- and 800-ha farms over STP (significance level and least significant difference (LSD) values are shown in Table 4), with a higher per hectare AE for the DT for both farms (Figures 1 and 2 and Table 4). The per hectare AE of maize and soybean rotation for 200-ha farm in the DT ($64) was increased by 120.7% and 93.9% as compared to that of the ST ($29) and NT ($33). The per hectare AE increase for an 800-ha farm followed a similar trend to that of a 200-ha farm. The per hectare AE of a maize and soybean rotation for an 800-ha farm was found to be 112.9% and 83.3% higher in the DT ($66), compared to ST ($31) and NT ($36). The per hectare AE in the DT, ST, and NT for the 800-ha farm was 3.13%, 6.89%, and 9.09%, respectively, higher, compared to that of the DT, ST, and NT for the 200-ha farm. The overall per hectare average AE varied with farm size. However, the benefit of LTP tires was larger and more consistent when associated with DT than ST and NT for both farms. When averaging over tillage systems, the mean changes in per hectare NI or AE increase of using LTP tires were $42.1 and $44.6 for the 200- and 800-ha farms, respectively.

The sensitivity testing results indicate that the per hectare AE increase due to the investment of LTP tires for both farms was proportional to the grain prices of crops and inversely proportional to the increase in tire prices (Tables 5 and 6). Interestingly, the results showed that even if the grain prices

TABLE 8 Cost of production and returns for maize/soybean crop rotations for standard and low tire inflation pressure systems during 2017–2018 (mean of 2-years).

	STP/standard tires		LTP/high-flexion tires	
Items	**Maize**	**Soybean**	**Maize**	**Soybean**
Two years mean yield (Mg ha^{-1})	14.08a	4.43a	14.57b	4.51b
Price per Mg ($)	142	323	142	323
Crop revenue ($)	1,999.36a	1,430.89a	2,068.94b	1,456.73b
Gross revenue ($) (A)	1,999.36a	1,430.89a	2,068.94b	1,456.73b
Gross revenue, mean ($) (B)	1,715.13		1,762.84	
Fertilizer ($)	323.57	103.74	323.57	103.74
Pesticides ($)	187.72	113.62	187.72	113.62
Seed ($)	284.05	180.31	284.05	180.31
Storage ($)	37.05	19.76	37.05	19.76
Crop insurance ($)	54.34	34.58	54.34	34.58
Total direct costs ($) ($C_1$)	886.73	452.01	886.73	452.01
Tractor/machine hire/lease ($)	34.58	24.70	34.58	24.70
Tire costs ($)	21.50 (13.22)	21.50 (13.22)	26.63 (15.88)	26.63 (15.88)
Fuel/oil ($)	44.46	32.11	44.46	32.11
Utilities ($)	4.94	9.88	4.94	9.88
Machine repair and maintenance ($)	61.75	44.46	61.75	44.46
Machinery depreciation ($)	158.08	138.32	158.08	138.32
Total power costs ($) ($C_2$)	325.31 (317.03)	270.97 (262.69)	330.44 (319.69)	276.10 (265.35)
Hired labor ($)	56.81	44.46	56.81	44.46
Taxes and insurance ($)	24.70	24.70	24.70	24.70
Miscellaneous ($)	22.23	24.70	22.23	24.70
Interest (non-land, $)	64.22	37.05	64.22	37.05
Total overhead costs ($) ($C_3$)	167.96	130.91	167.96	130.91
Total costs (TC; $) ($C = C_1 + C_2 + C_3$)	1,380.00 (1371.72)	853.89 (845.61)	1,385.13 (1374.38)	859.02 (848.27)
% Cost for tire over total cost	1.64 (0.96)	2.64 (1.56)	2.02 (1.16)	3.25 (1.87)
TC, mean ($) (D)	1,116.95 (1108.66)		1,122.07 (1111.32)	
% Cost for tire over total cost, mean	1.92 (1.19		2.37 (1.43)	
Net return ($) (E = A – C)	619.36 (627.64)	577.00 (585.28)	683.82 (694.57)	597.72 (608.47)
Net return, mean ($) (F)	598.18 (606.46)		640.77 (651.52)	
Return in LTP over STP ($)				+42 (+45)
% of change in LTP over STP				7.12 (7.43)

Note: Economic value ($ ha^{-1}) is represented for 200-ha farms and in the parenthesis for 800-ha farms, respectively. Means with the same letters in a column are not significantly different at $P < 0.05$.

Abbreviations: STP and LTP represent standard and low tire inflation pressure systems, respectively.

(a) Costs of items were based on the unit price of inputs and outputs per hectare in the year 2018 (Schnitkey, 2020).

(b) Per hectare cost of tires for 200- and 800-ha farms were calculated as per Michelin North America Inc. (Gordon Brookes, personal communication, March 31, 2019; Mike Pantaleo, personal communication, March 23, 2019).

(c) Per hectare cost of production for both tire systems was assumed to be equal except for the costs of tires required for two sizes of farms.

(d) Government payments would be the same regardless of LTP and STP tires, and thus, it was not considered in the above calculation.

(e) Land cost was assumed to be equal for both treatments and thus these were not considered for determining the cost of production and return.

of crops having the lowest (June 2020) or half of the baseline level and tire prices were triple the baseline level, farmers would still receive profit using LTP tires. However, per hectare AE increase for the lowest grain price ($25.9) and half the baseline level price ($8.30) with a tire price triple the baseline level would be dropped by 38.5% and 80.3%, respectively, for a 200-ha farm when compared with per hectare AE obtained for baseline level prices of grains and tire ($42.1). Similarly, for an 800-ha farm, per hectare AE increase for the lowest grain price ($33.3) and half of the baseline level price ($15.7) with a triple the baseline level tire prices would be dropped by 25.3% and 64.8%, respectively, compared to AE obtained for baseline level prices of grains and tire ($44.6 ha^{-1}).

Further, when the grain prices are the highest on June 30, 2022, the per hectare AE would be increased for baseline level, double and triple the baseline level tire prices by 117.1% ($91.4), 104.9% ($86.3), and 92.6% ($81.1) for a 200-ha farm, compared to the AE at baseline level grain and tire prices. While for an 800-ha farm, the AE for these three tire prices would be increased by 110.5% ($93.9), 104.5% ($91.2), and 98.4% ($88.5), compared to the AE recorded for baseline level grains and tires prices.

3.2.3 | PBA and PBP of the use of the LTP tire system

The PBA for both farms presented in Table 7 shows that the ΔTR due to the investment of LTP tires for DT, ST, and NT were $13,820, $6925, and $7637, respectively, for the 200-ha farm and $55,820, $26,396, and $27,984, respectively, for the 800-ha farm. The PBP for the investment of LTP tires was the ratio of the difference in expenditure between LTP and STP tires and the difference between the GVC (ΔTR) in STP and LTP. The PBPs of the use of LTP tires for the 200- and 800-ha farms are shown in Table 7. These results show that the PBP for the three tillage systems and two farm sizes using the LTP tires was less than 2-years and less than 1-year for the 200- and 800-ha farms, respectively. The PBPs ranged from 0.32 years for the DT system on the large farm to 1.18 years for the ST system on the small farm. Both farm sizes had a similar trend for the different tillage systems, with the PBP for the 800-ha farm being approximately half that of the 200-ha farm.

3.2.4 | NPV and PI of the use of LTP tire system

The mean NPV for the additional investment or cash outflows of LTP tires ($8200 and $17,000 for the 200- and 800-ha farms, respectively), assuming a discount rate of 5% (baseline) and over the tire life, is shown in Figure 3. The average of the 2-years (2017 and 2018) of crop rotation cash inflows for the DT, ST, and NT systems for 200- and 800-ha farms was considered as average cash inflows for years 3 to 8. Although it shows a bit of extrapolating yield effects over the duration of the experiment, these average cash inflows for different tillage systems helped to calculate the NPV for additional cash outflow/investment over the tire life and provided a better understanding of whether the farmers' additional investment in the alternate tire technology would be more profitable than standard tires. Results show that the mean NPVs for 200- and 800-ha farms due to additional investment in LTP tires at a 5% discount rate and 8-years of tire life were $50,028 and $215,913, respectively (Figure 3). The NPVs for DT, ST and NT were $78,596, $34,643 and 36,847, respectively, for a 200-ha farm and $330,183, $154,371 and $163,186, respectively, for an 800-ha farm. The NPV values were found profitable for all tillage systems following the trend of DT > NT > ST for both sizes of farms. However, the NPV of DT, ST, and NT for the 800-ha farm was in excess of four times greater than the values for the 200-ha farm due to the greater economic scale. The positive NPV values across three tillage systems indicate that the additional investment in LTP tires in maize and soybean cropping systems was economically viable and profitable. The significance level and LSD values for NPV for two tire pressure systems for two sizes farms are shown in Table 4. The sensitivity test shows that the NPV of the project decreased with the increase in discount rates. This indicates that if the discount rates increased from 5% to 10% and 20%, the mean NPVs would be dropped by 20.4% and 47.5% for the 200-ha farm and 18.9% and 44.1% for the 800-ha farm, respectively (Figure 3).

The PI shown in Figure 4 revealed that the ratio between the present value of all future cash flows and the additional investment for LTP systems at a 5.0% discount rate was higher than 5.00, ranging from 5.20 (ST for 200-ha farm) to 20.4 (DT for 800-ha farm) with a mean PI of 7.10 and 13.7 for 200- and 800-ha farms, respectively. The PI of the present investment was found to have a similar trend to that of the NPV (DT > NT > ST). The comparatively lower yield and, thus, the net cash flows in the ST system led to a small decrease in PI in ST for both sizes of farms. It is speculated to state that the increase in the discount rates resulted in a decrease in NPV and PI of an alternative tire technology investment. However, farmers would still be benefited from the investment in LTP tires even though the discount rates and tire prices were increased from baseline levels.

3.2.5 | Cost of production ($ ha^{-1}) and returns for maize/soybean crop rotation

Table 8 shows that irrespective of the tillage system, the rotation-mean gross revenue per hectare of maize and soybean cropping systems increased by $47.7 using high-flexion (LTP) tires ($1,762.84) as compared to the STP ($1,715.13). The mean annual TC for the rotation for the STP and LTP tires for the 200-ha farm were $1,117 and $1,122, respectively. For the 800-ha farm, these values (shown in parentheses) were $1,109 and $1,111, respectively. The percentage of STP and LTP tire costs from the TC of production were 1.92 and 2.37, respectively, for the 200-ha farm and 1.19 and 1.43, respectively, for 800-ha farm. The per hectare mean net returns under LTP systems were 7.12% higher ($641) than STP ($598) for small farm and 7.43% higher ($652) than STP ($606) for large farm, respectively. However, the net return in the LTP system was increased by $42 ha^{-1} for the small farm and $45 ha^{-1} for the large farm, compared to the STP system for a maize/soybean cropping system.

4 | DISCUSSION

The economic analysis aims to determine whether improved technology can increase net farm income (Kay et al., 2019; Roth & Hyde, 2002). The present study demonstrated that the use of low tire inflation pressure systems increased crop yield, compared to standard tire inflation pressure systems (Table 2), which led to higher AE for both farm sizes in maize/soybean cropping systems (Figures 1 and 2). The results agree with Smith, Misiewicz, Chaney, et al. (2014) and Godwin et al. (2015), who highlighted that field traffic with low tire inflation pressures was less detrimental to soil structure, with improved crop growth and yield, when compared to high tire inflation pressure systems. Godwin et al. (2017) summarized a long-term traffic and tillage study on sandy soil in the United Kingdom and reported that the use of LTP tires showed an increased benefit of 0.10 Mg ha^{-1} crop yield (worth $19 ha^{-1}) over standard tire pressure systems. Several researchers reported that LTP (high flexion) tires can generate a greater footprint and contact area (Michelin, 2017; Schjønning et al., 2008; Shaheb, Venkatesh, & Shearer, 2021; Vermeulen & Perdok, 1994b) that help to uniformly distribute contact pressure on soil (Alakukku et al., 2003; Vermeulen & Klooster, 1992) and maintained greater macroporosity of soil (Shaheb et al., 2020). As a result, LTP-treated soils had improved soil physical conditions, enhancing crop growth and yield while offering higher economic potential due to less compacted soil (Shaheb et al., unpublished data, 2023; Smith, Misiewicz, Chaney, et al., 2014; Stranks, 2006; Tijink et al., 1995). The results of the present study are also in agreement with the findings of Godwin et al. (2022) who highlighted that LTP tires (0.07 and 0.08 MPa) for the DT (depth, 250 mm) had worth $53 ha^{-1} (£39 ha^{-1}) benefit (average 3.9% greater yield over the experimental periods) than the STP systems (0.10 to 0.15 MPa) in sandy loam soil in the United Kingdom. Even though there was a significant interaction between tire inflation pressure and tillage systems only in maize in 2018, the effect of the LTP system was consistent in all tillage treatments.

The market price of LTP tires is higher, with a working life equal to or greater than standard tires of equivalent size and load specification, causing an increase in the total cost required for the two farm sizes (Gordon Brookes, personal communication, March 31, 2019; Mike Pantaleo, personal communication, March 23, 2019). The total cost of tires and their benefit varied depending on the farm size as larger farms require more equipment and tires and, therefore, higher capital investment. These results are consistent with the findings of Godwin et al. (1992), who reported that the benefit of LTP tires is farm size-dependent, indicating that the per hectare additional expenditure for low ground pressure tires for a larger farm (300 ha) was less than that of a smaller farm (100 ha). In previous studies, the benefits of increasing yield, gross margin, and farm profitability using lower tire inflation pressure systems in comparison with higher tire inflation pressure systems were reported by Vermeulen and Klooster (1992) and Tijink et al. (1995). However, these benefits were in regard to cereal silage (Godwin et al., 1992) and the production of root crops (Tijink et al., 1995; Vermeulen & Klooster, 1992).

The PBP for the LTP tires was less than 2-years for the three tillage systems and two farm sizes. This is a very short PBP for investments in LTP tires on US grain farms. The PBPs of additional investment in LTP tires will vary when the costs of tires and gross values of crops are changed. This indicates that at higher prices and opportunity costs involved, farmers will require more extended periods for a return on their investment (Purola & Lehtonen, 2020). The sensitivity test demonstrated that if the grain were half the baseline level and tire prices triple the baseline level, per hectare AE increase would be dropped, compared to the mean AE obtained in baseline level prices of grains and tires; however, farmers would still receive profit using LTP tires. This indicates that purchasing LTP tires would still be breakeven for the present cropping systems for two sizes of farms due to its higher productivity benefits, compared to STP tire systems.

The positive NPV for all tillage systems revealed that the additional investment in the LTP systems in the maize/soybean crop rotation is economically viable as positive NPV of any investment of a project indicates the proposed project would be beneficial as described by Barnard and Nix (1979) and Kay et al. (2019). However, the NPVs of the present investment would decrease with the increase of the discount rate. For example, a discount rate of 20% from the baseline level (5%) would drop the mean NPV by 47.5% and 44.1% for 200- and 800-ha farms, respectively (Figure 3). The higher NPV value in DT, compared with other tillage systems is due to improved soil condition and aeration (Bogunovic et al., 2018; Jabro et al., 2021), which significantly impacts crop growth and grain yield. The observation also agrees with the results of Godwin et al. (1992), who reported that irrespective of farm size, the net economic benefit of the use of low ground pressure tires was increased (\$30 ha^{-1}) while avoiding remedial subsoiling. The value of \$30 ha^{-1} reported in 1992 is approximately \$45 ha^{-1} in 2019, according to the Producer Price Index for maize (U.S. Bureau of Labor Statistics, 2021). Purola and Lehtonen (2020) showed that an investment in soil management measures, such as subsoiling, adding wood fiber, and green manuring to mitigate soil compaction at a 5.0% discount rate, increased the NPV value. This indicates that the substantial increase in grain yield and, thus, gross income attributed to the use of low tire inflation pressure systems resulted in an increase in NPV and PI of the additional investment. The results for both 200- and 800-ha farms show that the use of LTP tire systems was an economically viable traffic management system for sustainable land use for maize and soybean crop production on silty clay loam soil in the Midwestern United States.

5 | CONCLUSION

This farm-scale 2-year economic analysis study for a typical maize/soybean rotation demonstrates that, by reducing soil compaction, low tire inflation pressure systems had a positive effect on maintaining soil structure. This resulted in a measurable impact on crop yield and profitability in a maize and soybean rotation on silty clay loam soil in the Midwestern United States. The per hectare annual benefit of using LTP systems for the DT, ST, and NT was \$64, \$29, and \$33, respectively, for a 200-ha farm and \$66, \$31, and \$36, respectively, for an 800-ha farm.

The sensitivity test demonstrated that the per hectare AE was reported to be increased due to investment in LTP tires for all output product/grain and tire price scenarios. This indicates that the investment of LTP tires would still be breakeven for the present cropping systems for both farms even with tire prices triple the baseline level and output product prices half the baseline level. The PBP for the investment in LTP systems was less than 2-years with higher NPV if even the discount rates are increased from 5.0% to 10% and 20%. The increased crop yields linked to lower soil compaction, that is, greater soil porosity that led to more significant crop growth, are the main reason for the economic benefits. The DT treatment has the most field traffic and thus benefits most from reducing compaction with LTP. The long-term effect of LTP systems could extend the beneficial effect reported in the manuscript, and therefore it is recommended that this kind of study be carried out longer in different soil–machine–plant systems.

AUTHOR CONTRIBUTIONS

Md Rayhan Shaheb: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; validation; visualization; writing—original draft; writing—review and editing. **Paula A. Misiewicz**: Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing. **Richard J. Godwin**: Conceptualization; funding acquisition; methodology; project administration; supervision; validation; visualization; writing—review and editing. **Edward Dickin**: Conceptualization; investigation; methodology; supervision; writing—review and editing. **David R. White**: Conceptualization; methodology; project administration; supervision; writing—review and editing. **James Lowenberg-DeBoer**: Data curation; formal analysis; methodology; validation; visualization; writing—review and editing. **Scott A. Shearer**: Data curation; methodology; validation; visualization; writing—review and editing. **Tony E. Grift**: Conceptualization; data curation; investigation; methodology; project administration; resources; supervision; validation; writing—review and editing.

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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.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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