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Effect of moldboard plow share age and tillage depth on slippage and fuel consumption of Tractor (MF399) in Varamin region

Efecto de la edad del arado de vertedera y la profundidad de labranza sobre el deslizamiento y el consumo de combustible del tractor (MF399) en la región de Varamin

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ABSTRACT

The abrasion of tillage implements, such as moldboard plows that consume more energy than others, dramatically affects tillage quality and compacts soil, reduces tillage depth, increases fuel consumption, wears out engine components, and reduces traction efficiency. Therefore, the effect of tillage depth (10, 20, and 30 cm) and share age (in hectares of operation in 20 two-hectare plots for each depth) on the MF399 tractor's fuel consumption and drive wheel slippage was evaluated. The split-plot design based on a randomized complete block design was used for data analysis, and Duncan's multiple range test conducted the mean comparison at $\alpha = 1\%$. The results show that tillage depth and share age significantly affected tractor fuel consumption and drive wheel slippage. Maximum (68.67 lit/ha) and minimum (44.73 lit/ha) average fuel consumption and maximum (21.32%) and minimum (11.84%) average drive wheel slippage percentages were measured in 30 and 10 cm tillage depths. Moreover, increasing tillage depth from 10 to 20 cm and from 10 to 30 cm respectively increased fuel consumption by 18.90 and 53.52% and increased slippage from 32.68% and 80.06%. Meanwhile, slippage exceeded 15% after respectively 30, 20, and 12 hectares of tillage in 10, 20, and 30 cm depths, and fuel consumption significantly increased after 14, 12, and 10 hectares relative to using new shares.

Keywords: moldboard plow, tractor (MF399), fuel consumption, slippage, share, tillage depth.

RESUMEN

El desgaste o erosión de los implementos de labranza, como por ejemplo los arados de vertedera que consumen más energía que otros, afecta en gran medida la calidad de esta labor y compactación del suelo, reduce la profundidad de labranza, aumenta el consumo de combustible, desgasta los componentes del motor y reduce la eficiencia de la tracción. Por lo tanto, se evaluó el efecto de la profundidad de labranza (10, 20 y 30 cm) y edad (en hectáreas de operación en 20 parcelas de dos hectáreas para cada profundidad) sobre el consumo de combustible y el patinaje de las ruedas motrices del tractor MF399. El diseño de parcelas divididas basado en un diseño de bloques completos al azar se utilizó para el análisis de datos y la comparación de medias se realizó mediante la prueba de rango múltiple de Duncan a $\alpha = 1\%$*. Los resultados muestran que la profundidad de labranza y la edad de la repartición afectaron significativamente el consumo de combustible del tractor y el deslizamiento de las ruedas motrices. El consumo medio de combustible máximo (68,67 lit/ha) y mínimo (44,73 lit/ha) y los porcentajes de patinaje medio máximo (21,32%) y mínimo (11,84%) de las ruedas motrices se midieron respectivamente en profundidades de laboreo de 30 y 10 cm. Además, al aumentar la profundidad de labranza de 10 a 20 cm y de 10 a 30 cm, respectivamente, aumentó el consumo de combustible en un 18,90 y un 53,52% y aumentó el deslizamiento en un 32,68% y un 80,06%. Mientras tanto, el deslizamiento superó el 15% después de 30, 20 y 12 hectáreas respectivamente de labranza en profundidades de 10, 20 y 30 cm, y el consumo de combustible aumentó significativamente después de 14, 12 y 10 hectáreas en relación con el uso de nuevas rejas.*

Palabras clave: *arado de vertedera, tractor (MF399), consumo de combustible, deslizamiento, distribución, profundidad de labranza.*

Introduction

Although fossil fuels are an important energy source for the world, their growing prices and depletion make securing the energy required for agricultural operations an important problem for agricultural machinery designers and manufacturers; energy consumption, energy generation cost,

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and energy efficiency guide farmers in selecting economical methods for producing various agricultural products.

In recent years, there has been a growing interest in finding solutions to the energy supply problem, such as saving and optimizing energy consumption, using alternative energy resources such as nuclear and solar, and precision agriculture. Meanwhile, excessively burning fossil fuels releases carbon dioxide and methane into the atmosphere, and the accumulation of greenhouse gases has increased the earth's temperature and negatively affected its climate, a crucial ecological and political problem of our time (Tabatabaeefar *et al.,* 2009; Alluvione *et al.,* 2011; Behnke *et al.,* 2018). In farming activities, tillage operations account for a significant amount (20 to 40%) of energy for producing various products, and the moldboard plow is the most energy-intensive tillage implement (Samiei Far *et al.,* 2015; Askari *et al.,* 2017). Tillage energy consumption depends on soil type and structure, moisture, tillage depth, tractor type (two-wheel or four-wheel drive), operation speed, and how implements are attached to the tractor. The literature on product performance for some crops under specific conditions shows no specific advantage to using moldboard plow. The moldboard plow is widely-used for primary tillage operations (Sessiz *et al.,* 2008). At the same time, drawing implements in the soil create shear and compressive stress to cut and break soil mass, which abrades all tillage implement components that contact the soil. A study reported about 350-1250 grams of steel degradation due to carbon steel plowshare abrasion for plowing one hectare of farmland (Stolk, 1970).

A tillage implement's lifespan is projected according to its abrasion resistance, and more abrasion reduces operational efficiency. Tillage implemented abrasion increases drag, leads to inadequate clod breaking, reduces effective operating width and depth, lifts the plow from the soil, reduces product, destroys soil structure, stops work, induces costs of repairing or replacing abraded components, compacts the soil, especially at plow bottom groove, increases draft forces and fuel consumption, and wears out the engine and tires (Godwin, 2007; Li *et al.,* 2015).

The share is nearly-a trapezoidal steel or cast-iron surface that cuts the soil along its sharp edge and pushes the plow into the soil, increases the plow layer's horizontal cut, and creates a vertical gap with the moldboard front plate. The cut soil layer moves up on the shared surface and is transferred to the moldboard plate. Thus, the share starts returning to the soil. During tillage, the share's constant contact with soil rapidly abrades and blunts the edge, making cutting more difficult. Share abrasion problems are related to the surface since abrasion at the back leads has the desirable self-sharpening effect. More complex cutting blade surfaces will suffer abrasion slowly but are easily broken after hitting rocks or other obstacles.

A blunt share will struggle to penetrate the soil and fail to reach the intended depth even after shortening the top link since it is forced to tear the soil instead of cutting it. This requires greater draft force, which raises fuel consumption, roughens the plowshare groove, and raises the share's bottom from the soil, raising the last bottom relative to the first bottom.

Therefore, share bluntness is technically and economically damaging. The literature has shown that maintaining the tillage implement share's sharpness requires increasing draft force by 30%, an important factor in increasing fuel consumption (Hunt, 1973). Although various studies have investigated the effect of tillage depth and soil moisture, and texture on tractor fuel consumption, few studies have investigated the effect of plowshare bluntness on tractor energy consumption (Godwin, 2007; Sessiz *et al.,* 2008; Stajnko *et al.,* 2009; Ibrahmi *et al.,* 2015; Li *et al.,* 2015; Krauss *et al.,* 2017; Uegul *et al.,* 2017; Sarikhani Khorami *et al.,* 2018). A study evaluated the draft force and vertical force of blunt and new shares 35 cm deep into dry sandy loam, and the results showed that share bluntness has a minor effect on draft force but a significant effect on vertical force or bottom penetration. If excessive abrasion turns aggregate vertical force negative (upward), the plow will inadequately penetrate the soil and be kept inside only by its weight. Stolk (1970) evaluated tillage implements and discovered that shares could operate at high speeds, create less movement resistance, and reduce slippage and fuel consumption by up to 55%.

As mentioned, mechanized agriculture is very dependent on energy, especially fossil fuels, and it is very costly to supply the required power. Due to limited energy resources, especially fossil fuels, and since energy efficiency is a measure of technological progress, it is necessary to conduct a basic analysis of energy resources, optimize energy consumption, and select the most profitable agricultural implements. Since farmers in developing countries are not willing to replace shares and attempt inadequate repairs when they fail, the effect of share age on tractor fuel consumption was investigated in three tillage depths in the Varamin region.

Materials and Methods

This study was conducted in 2019 in the semi-arid Varamin region located at longitudinal 51° 39" and latitudinal 35' 19" and 1000 meters above sea level. Down to the 30 cm depth, the test region's soil texture was silty clay (45% clay, 25% sand, and 30% silt), and moisture at 0-10, 10-20, and 20-30 cm depths were respectively 11.25, 12.86, and 13.68%. As mentioned, soil texture and moisture varied at different points due to the vast tillage area, but tested lands were as consistent as possible.

Specifications of Implements

The two-wheel-drive Massey Ferguson 399 (MF399) made by Iran Tractor Manufacturing Company produces maximum power at 2200 RPM, maximum torque at 1200 RPM, and maximum power take-off of 83.08 kW, 430 Nm, and 70.89 kW. The tractor's mass is 3300 kg with eight 34 kg tractor weights in the front and 480 liters of water in each rear wheel. The three-bottom plow weighed 300 kg and had a 35 cm per bottom operating width. Khorasan Ironworks Parts Co made the steel shares.

Soil Moisture Measurement

Tillage operations were conducted in 10, 20, and 30 cm depths. Forty hectares of land were considered and divided into 20 two-hectare plots for tillage operations. In each plot, moisture was measured at three sampling points, and the mean 20-plot moisture was obtained as the average moisture of 40 hectares. Moisture was measured using special cylindrical containers with 5 cm diameter and 98.17 cm^3 volume, which were weighed when empty and after sampling and then placed in a 105 ºC oven for 24 hours and weighed again. Moisture was calculated according to Eqn. 1 (Ahmadi Chenarbon and Movahhed, 2021).

$$M = \frac{A - B}{B - C} \times 100 \qquad (1)$$

Where: -moisture (%), -container weight with moist soil (g), -container weight with dry soil (g), -empty container weight.

Drive Wheel Slippage Measurement

Tractor movement speed and actual drive wheel slippage were measured using two E50S8-500-3-T-1 shaft encoders from Autonic, South Korea, installed on the fifth wheel and the tractor's real drive wheel. Next, drive wheel slippage was automatically calculated by the difference of shaft encoder data installed on the fifth wheel and the rear driver wheel using the data acquisition system. The system's preliminary data used the tire air pressure of 1.1 bars and a contact plane of 5 cm.

Fuel Consumption Measurement

Fuel consumption was measured using two turbine flowmeters. Since diesel engines return surplus fuel from the injection pump back to the tank, another flowmeter was placed at the fuel return line in addition to the sensor placed along the fuel line to the injection pump, and the engine's fuel consumption flow was calculated according to the difference of flow through the two sensors.

Test Methodology

The split-plot design used three replications based on a randomized complete block design. In this analysis, the main factor was tillage depth (A), and 10, 20, and 30 cm depths were considered according to the region's dominant plants (wheat, corn, alfalfa, cotton). The secondary factor was share age (B), chosen for operation in 20 two-hectare surfaces (for each depth). Therefore, there will be three main plots in three replications. The main plots were 40 hectares (800m x 500m), and each was divided into 20 two-hectare subplots (500m x 40m). Then, tillage started at the specific depth in each plot, the tractor's fuel consumption and drive wheel slippage were measured, and Duncan's multiple range test conducted the mean comparison at $\alpha = 1\%$ by SPSS software version 14. The tractor and the three-bottom plow were transferred to the block and configured for the specified depth to measure fuel consumption and drive wheel slippage. New shares were attached to the plow before tillage operations in each 40-hectare plot. Next, fuel consumption and slippage were measured after tillage operation in each two-hectare plot. Moreover, the tractor's travel speed during tillage operations in various depths was kept constant at 4 km/h.

Theoretical Tractor Fuel Consumption During Tillage in 10, 20, and 30 cm Depths of Clay-Silt Soil

The necessary drawbar power for pulling the moldboard plow was calculated using Eqns. 2, 3, and 4 (Hunt, 1973).

$$P_{db} = \frac{F.V}{3.6} \qquad (2)$$

Where: - drawbar power (kW), - draft force (kN), - forward speed (km/h).

$$F = D.W.h \qquad (3)$$

Where: - unit draft (N/cm^2), - operating width of plow (cm), - tillage depth (cm).

$$D = C_1 + C_2V^2 \qquad (4)$$

Where: and - coefficients depending on soil type. This study set = 0.024 and = 4.8.

According to these equations, respective drawbar powers () of 6.048, 12.096, and 18.144 kW were calculated for pulling the plow in 10, 20, and 30 cm depths.

Next, the force required to move the tractor was calculated according to Eqn. 5 (Hunt, 1973).

$$F = \sum r_i W_i \qquad (5)$$

Where: - tractor movement force (N), - rolling resistance, and - tractor weight (N).

In the following, the required tractor movement power of 7.51 kW was calculated according to Eqn. 2. Also, total tractor and moldboard plow drive power during tillage in 10, 20, and 30 cm depths were calculated at 13.56, 19.61, and 25.65 kilowatts, according to Eqn. 6. Moreover, axle power was obtained from Eqn. 7 (Hunt, 1973).

$$P_{Total} = P_{db} + P_{Tractor} \qquad (6)$$

$$P_{axle} = \frac{P_{Total}}{(1-slip)TE} \qquad (7)$$

Axle power during tillage in 10, 20, and 30 cm depths were respectively 21.52, 31.13, and 40.71 kW. In this equation, slippage was 12% and traction efficiency (TE) was 0.72 (Hunt, 1973).

$$P_b = \frac{P_{axle}}{0.8} \qquad (8)$$

$$P_{PTO} = 0.9P_b \qquad (9)$$

$$L = \frac{P_{PTO}}{P_{MAX-PTO}} \times 100 \qquad (10)$$

Where: - crankshaft power (kW), - loading rate (%).

According to Eqns. 8, 9, and 10, the equivalent power take-off and loading rate for tillage operating in 10, 20, and 30 cm depths were 24.21, 35.021, and 45.80 kW and 34.15, 49.40, and 64.61 (%). On the other hand, fuel efficiency can be obtained according to the calculated loading rate and Table 1. In 34.15, 49.40, and 64.61% loading rate, fuel efficiency was respectively 1.97, 2.37, and 2.66 kWh/lit.

According to Eqn. 11, tillage fuel consumption in 10, 20, and 30 cm depths were respectively 12.29, 14.78, and 17.22 lit/h.

$$FC = \frac{P_{PTO}}{e_{fule}} \qquad (11)$$

Where: - fuel consumption (lit/h), - total tractor power (PTO equivalent) (kW),- fuel efficiency (kW-h/lit).

Meanwhile, the field capacity of 0.31 ha/h was calculated according to Eqn. 12, where S=4 km/h and = 0.74.

$$C_a = \frac{sw_\eta}{10} \qquad (12)$$

Where: - field capacity (ha/h), - travel speed (km/h), - field efficiency (%), and - operating width (m).

According to Eqns. 11 and 12, tillage fuel consumption in 10, 20, and 30 cm depths were respectively 39.64, 47.68, and 55.54 lit/h.

Results and Discussion

The Effect of Share Age and Tillage Depth on Fuel Consumption and Slippage

Table 2 shows that the effect of tillage depth (A), share age (B), and their interaction (AB) on

Table 1. Fuel efficiency (kW-h/lit) (Hunt, 1973).

Diesel engine			Gas	Petrol	Total load (%)
Turbo cooling	Turbo	General			
3.09	3.07	2.90	1.78	2.17	100
2.86	2.82	2.84	1.68	1.96	80
2.59	2.55	2.60	1.47	1.63	60
2.15	2.10	2.13	1.17	1.28	40
1.42	1.36	1.38	0.83	0.83	20

Table 2. Variance analysis of data obtained from the effect of share age, tillage depth and their interaction on fuel consumption and slippage of tractor (MF399).

S.O.V	Fuel consumption (lit/ha)			Slip (%)		
	df	MS	F	df	MS	F
Main factor (A)	2	84.25	38.23**	2	42.12	28.12**
Sub factor (B)	19	104.12	29.41**	19	20.41	21.52**
A×B	38	67.12	12.10**	38	15.32	12.14**

A- Tillage depth, B- Share age, *Significant difference at α = 1%.

fuel consumption and drive wheel slippage was significant ($p \leq 0.01$).

According to Figures 1 and 2, maximum (68.67 lit/ha) and minimum (44.73 lit/ha) fuel consumption and maximum (21.32%) and minimum (11.84%) slippage were measured in 10 and 30 cm tillage depths. Moreover, increasing tillage depth from 10 to 20 cm and from 10 to 30 cm increased fuel consumption by 18.90 and 53.52% and drive wheel slippage by 32.68% and 80.06% due to increased soil volume and weight in higher tillage depths requiring more cutting force.

The weight of heavy and compacted soil on the moldboard will increase lateral pressure on the plow and increase each bottom's landside friction with the plowed groove, increasing the tractor's draft force and the plow's drag (Abbaspour-Gilandeh *et al.,* 2016). In other words, overcoming increased plow drag at higher tillage depth requires more power, which increases fuel consumption and slippage. Also, higher tillage depth increases special resistance, which can be attributed to the soil's apparent density, which is another contributor to increased fuel consumption

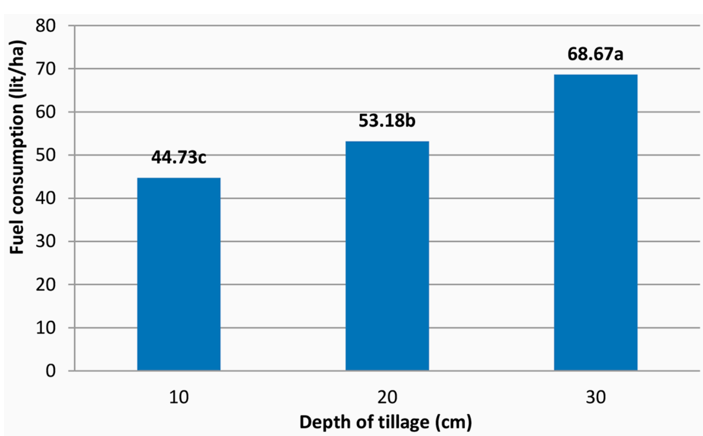

Figure 1. Effect of tillage depth on fuel consumption of tractor (MF399) Means with at least one common letter have no significant difference (p ≤ 0.01).

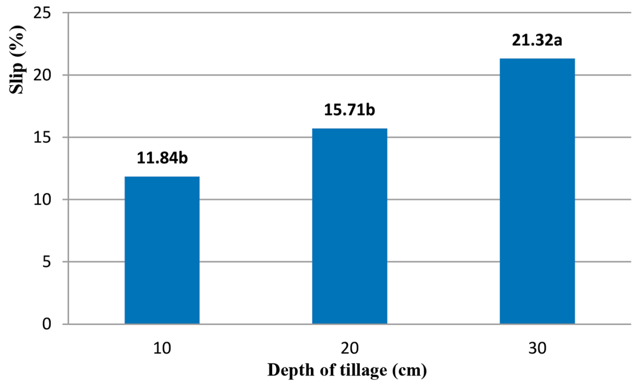

Figure 2. Effect of tillage depth on slippage of tractor (MF399) Means with at least one common letter have no significant difference (p ≤ 0.01).

and drives wheel slippage (Hunt, 1973). Al-Suhaibani & Ghaly (2010) showed that all implements require higher drawbar power under higher forward speeds and tillage depths, and moldboard and chisel plows have the highest and lowest special tractive force.

In another study, increasing the moldboard plow's tillage depth from 15 to 20 and 15 to 25 cm respectively increased fuel consumption by 8.64 and 16.05% (Askari *et al.,* 2017). Godwin (2007) showed that reducing tillage depth to tillage implement width of share increases energy efficiency. Fathollahzadeh *et al.* (2010) studied the effects of changing the three-bottom moldboard plow's tillage depth on the average fuel consumption of the John Deere 3140 tractor with 72.3 kW of power. The results suggested that tillage in 15, 25, and 35 cm depths results in tractor fuel consumption of 27.446, 30.096, and 34.06 lit/ha. Increasing tillage depth from 15 to 25 cm and from 15 to 35 cm respectively increased fuel consumption by 9.66 and 24.1%.

As mentioned, draft force is the power required by tillage implements and an important parameter in dynamic soil analysis. The most important tractor performance factors are drag or drawbar power and traction efficiency. Rolling resistance and wheel slippage should be minimized to obtain maximum traction efficiency, and the maximum tractive efficiency occurs in 8 to 15% slippage (Abbaspour-Gilandeh *et al.,* 2016). It is noteworthy that horizontal factors of shear and drag are directly related to tillage implements pulling power. Therefore, tillage depth and share sharpness and shape are important factors for tillage implement drag (Al-Suhaibani and Ghaly, 2010; Abbaspour-Gilandeh *et al.,* 2016). Figures 3 to 8 and Table 3 show that increasing tillage surface for each tillage depth significantly

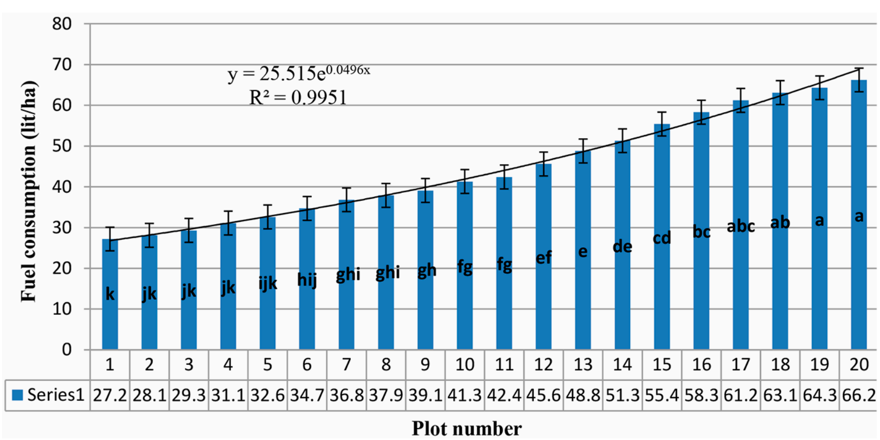

Figure 3. Comparing the effect of share age on fuel consumption during tillage in 10 cm depth Means with at least one common letter have no significant difference (p ≤ 0.01).

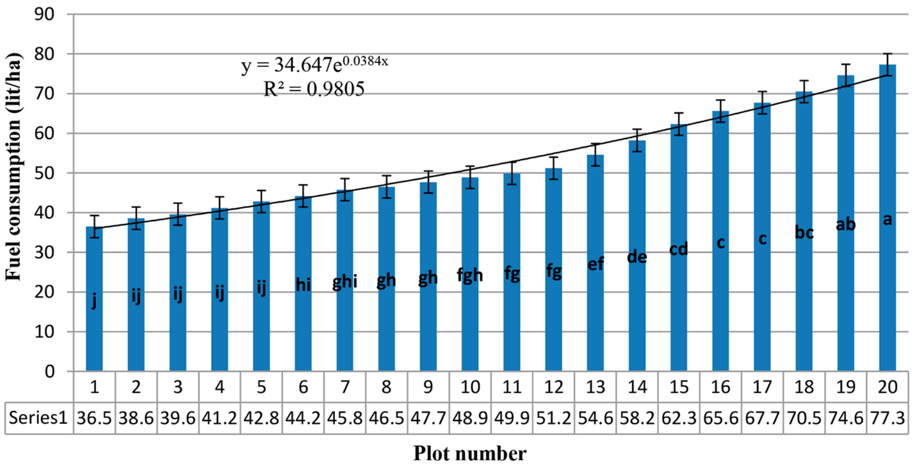

Figure 4. Comparing the effect of share age on fuel consumption during tillage in 20 cm depth Means with at least one common letter have no significant difference (p ≤ 0.01).

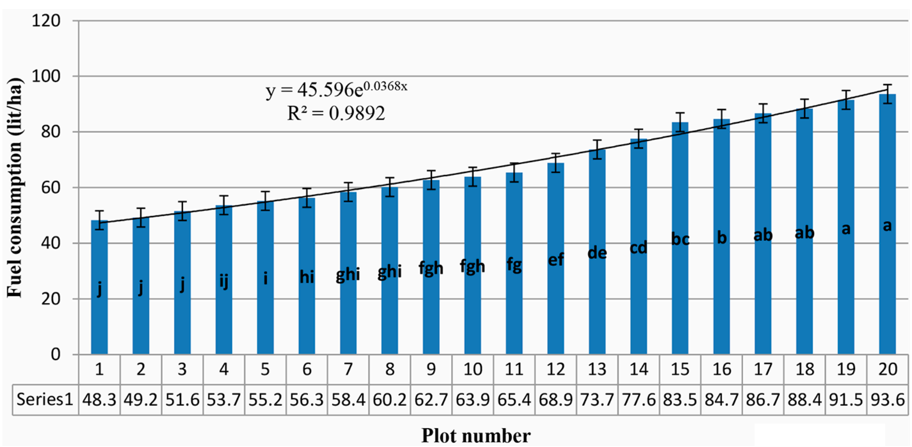

Figure 5. Comparing the effect of share age on fuel consumption during tillage in 30 cm depth Means with at least one common letter have no significant difference (p ≤ 0.01).

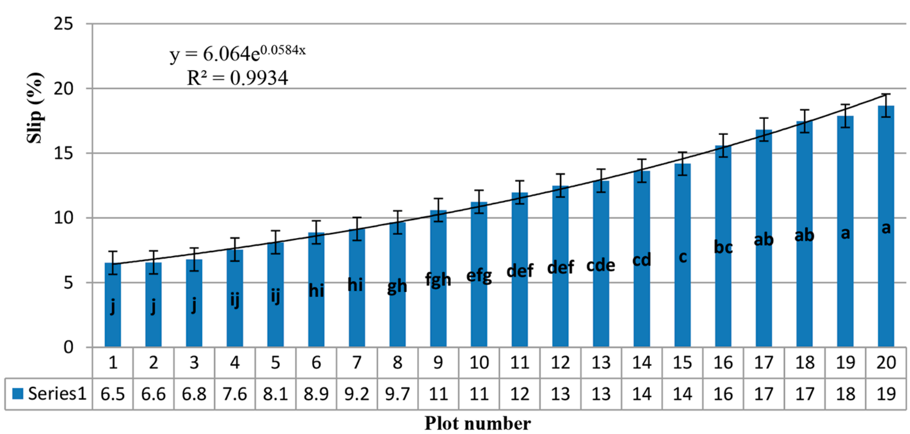

Figure 6. Comparing the effect of share age on slippage during tillage in 10 cm depth Means with at least one common letter have no significant difference (*p* ≤ 0.01).

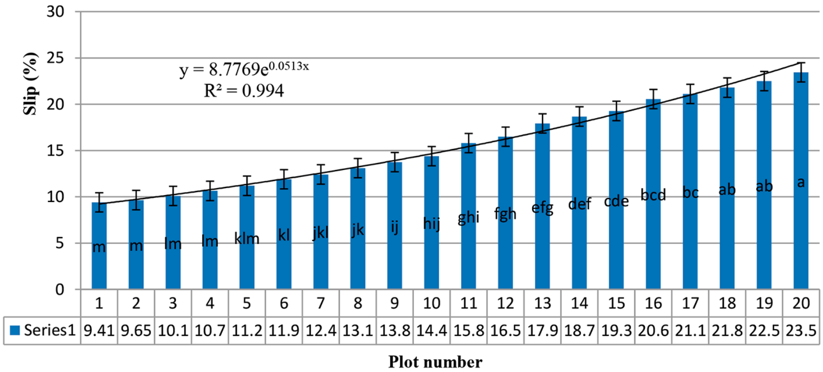

Figure 7. Comparing the effect of share age on slippage during tillage in 20 cm depth Means with at least one common letter have no significant difference ($p \leq 0.01$).

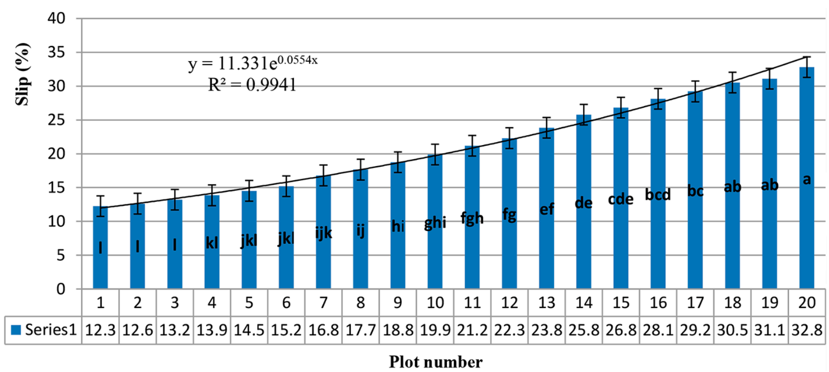

Figure 8. Comparing the effect of share age on slippage during tillage in 30 cm depth Means with at least one common letter have no significant difference ($p \leq 0.01$).

Table 3. Mean comparison of interaction between share age and tillage depth on fuel consumption and slippage of tractor (MF399)

	Fuel consumption(lit/ha)			Slip (%)		
	Depth of tillage (cm)			Depth of tillage (cm)		
Plot number	10	20	30	10	20	30
1	27.2^{r}	36.5^{p}	48.3^{l}	6.54^{i}	9.41^{hi}	12.27^{h}
2	28.1^{r}	38.6^{op}	49.2^{l}	6.57^{i}	9.65^{hi}	12.62^{h}
3	29.3^{r}	39.6^{o}	51.6^{kl}	6.80^{i}	10.10^{hi}	13.22^{gh}
4	31.1^{qr}	41.2^{no}	53.7^{kl}	7.56^{i}	10.65^{h}	13.86^{gh}
5	32.6^{qr}	42.8^{no}	55.2^{jk}	8.12^{hi}	11.20^{h}	14.52^{fgh}
6	34.7^{pq}	44.2^{mn}	56.3^{j}	8.89^{hi}	11.91^{h}	15.21^{fg}
7	36.8^{p}	45.8^{mn}	58.4^{ij}	9.15^{hi}	12.42^{h}	16.80^{fg}
8	37.9^{op}	46.5^{m}	60.2^{hi}	9.67^{hi}	13.10^{gh}	17.66^{fg}
9	39.1^{o}	47.7^{lm}	62.7^{hi}	10.61^{hi}	13.75^{gh}	18.75^{ef}
10	41.3^{no}	48.9^{l}	63.9^{h}	11.25^{h}	14.40^{fgh}	19.88^{def}
11	42.4^{no}	49.9^{l}	65.4^{gh}	11.98^{h}	15.81^{fg}	21.18^{de}
12	45.6^{mn}	51.2^{kl}	68.9^{fg}	12.50^{h}	16.50^{fg}	22.31^{de}
13	48.8^{l}	54.6^{jk}	73.7^{e}	12.88^{h}	17.93^{fg}	23.84^{cd}
14	51.3^{kl}	58.2^{ij}	77.6^{d}	13.65^{gh}	18.68^{ef}	25.77^{bc}
15	55.4^{jk}	62.3^{hi}	83.5^{cd}	14.20^{fgh}	19.28^{def}	26.82^{bc}
16	58.3^{ij}	65.6^{gh}	84.7^{c}	15.60^{fg}	20.56^{de}	28.12^{b}
17	61.2^{hi}	67.7^{fg}	86.7^{bc}	16.83^{fg}	21.12^{de}	29.22^{ab}
18	63.1^{h}	70.5^{ef}	88.4^{ab}	17.48^{f}	21.80^{de}	30.52^{a}
19	64.3^{gh}	74.6^{e}	91.5^{a}	17.89^{f}	22.50^{de}	31.10^{a}
20	66.2^{fg}	77.3^{de}	93.6^{a}	18.68^{ef}	23.45^{d}	32.80^{a}

increases tractor fuel consumption and drive wheel slippage ($p \leq 0.01$) due to the gradual loss in share sharpness during tillage and its inability to cut soil, increasing soil drag and contributing to increased tractor fuel consumption and slippage.

Higher tillage depths accelerate the share's loss of sharpness. Various studies have investigated share features such as shape, size, rake angle, and operating width on tillage implement drag and tractor fuel consumption (Karparvarfard and Rahmanian-Koushkaki, 2015; Al-Janobi *et al.,* 2002; Jalali *et al.,* 2015). Also, the regression equations between tractor fuel consumption and slippage with the tillage surface were considered plowshare aging factors and shown in Eqns. 13 to 17 for each tillage depth.

$$FC_{10} = 25.515e^{0.0496x} \quad R^2 = 0.9951 \quad (13)$$

$$FC_{20} = 34.647e^{0.0384x} \quad R^2 = 0.9805 \quad (14)$$

$$FC_{30} = 45.596e^{0.0368x} \quad R^2 = 0.9892 \quad (15)$$

$$Slip_{10} = 6.064e^{0.0584x} \quad R^2 = 0.9934 \quad (16)$$

$$Slip_{20} = 8.7769e^{0.0513x} \quad R^2 = 0.9941 \quad (17)$$

$$Slip_{30} = 11.331e^{0.0554x} \quad R^2 = 0.9941 \quad (18)$$

Where: - Fuel consumption (lit/ha), e - the Napier number, and - plot number.

Conclusions

Tillage operations consume a significant amount of energy to produce various products, and the moldboard plow consumes more energy than other implements, demonstrating the need to optimize fuel consumption and reduce production costs. Hence, the effect of share age and tillage depth on tractor fuel consumption and drive wheel slippage was studied in the Varamin region's clay-silt soil. The results suggest that share age and tillage depth significantly affected the MF399 tractor's fuel consumption and drive wheel slippage. According to the literature, maximum tractive efficiency occurs in 8 to 15% slippage, which in this study exceeded 15% in 10, 20, and 30 cm tillage depths after respectively 30, 20, and 12 hectares. During tillage operations in 10, 20, and 30 cm depths, fuel consumption after 14, 12, and 10 hectares increased significantly relative to new shares, which stresses the need to sharpen shares (repeatedly over a farming season) or use high-quality and cheap shares and incentivize farmers for timely replacement. Developing countries can adequately manage farming equipment by applying these results and replacing or repairing shares on time. From a macro perspective, government subsidies to manufacturers to produce high-quality and inexpensive shares is an effective and promising step to reduce fuel consumption, production cost, and environmental pollution.

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