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Effect of Plowing Depth of Tillage and Forward Speed on the Performance of a Medium Size Chisel Plow Operating in a Sandy Soil

S.A. Al-Suhaibani and A.E. Ghaly
Department of Agricultural Engineering, College of Food Science and Agriculture,
King Saud University, P.O. Box 2460, Riyadh 11451 Kingdom of Saudi Arabia

Abstract: Problem statement: Tillage is a process of creating a desirable soil condition for seed germination and growth. The tillage of soil is considered to be one of the biggest farm operations as the tillage operation requires the most energy on the farm. Chisel plow is widely used by farmers as a primary tillage tool. Performance data for chisel plow operation is essential in order to reduce the cost of tillage operation. **Approach:** Field experiments were conducted using a fully instrumented MS 3090 tractor to measure the draft of a heavy duty chisel plow in a sandy soil over wide ranges of plowing depths and forward speeds. The data were measured and recorded using an instrumentation system and data logger. **Results:** The effects of plowing depth and forward speeds on draft, unit draft, vertical specific draft, horizontal specific draft and coefficient of pull were evaluated. The results indicated that increasing the plowing depth and/or the forward speed increased the draft, unit draft and vertical specific draft. Also, increasing the plowing depth increased the horizontal specific draft and the coefficient of pull, while increasing the forward speed decreased the horizontal specific draft and the coefficient of pull. **Conclusion:** About 16.6% of the draft force was directed towards cutting the soil and 83.4% was consumed in pulverization of soil particles. The values of the vertical specific draft were much higher than those of the horizontal specific draft for all plowing depths and forward speeds. The plowing depth had more pronounced effect on the draft, unit draft, specific draft and coefficient of pull than the forward speed. The optimum forward speed was 1.75 m sec^{-1}. The recommended plowing depth should be based on the type of crop (depth of the root system).

Key words: Tillage, draft, unit draft, specific draft, coefficient of pull, sandy soil, instrumentation, chisel plow

INTRODUCTION

The tillage of soil is considered to be one of the biggest farm operations (Finner and Straub, 1985). Gill and Vanden Berg (1968) defined tillage as a process aimed at creating a desired final soil condition for seeds from some undesirable initial soil condition through manipulation of soil with the purpose of increasing crop yield. Several tillage implements are used by farmers to prepare seedbed. However, the selection of tillage implements for seedbed preparation and weed control depends on soil type and condition, type of crop, previous soil treatments, crop residues and weed type (Upadhyaya *et al*., 2009). One of the tillage implements widely used by farmers is the chisel plow which is considered to be a primary tillage implement because it is mainly used for the initial soil working operations. Chisel plows function most effectively when the soil is dry and firm (Srivastava *et al*., 1993).

The ability of tillage implements to maintain surface residue coverage is largely dependent on the main active component of implement. Raper (2002) compared two categories of tillage implements to determine their ability to maintain grain sorghum surface residue coverage when operating at two different tillage depths for fall and spring tillage. Chisel-type implements were found to bury substantially less crop residue than disk-type implements. Disk-type implements were found to bury increased amounts of crop residue when operating at deeper tillage depths.

The tillage operation requires the most energy and power spent on farms. Therefore, draft and power requirements are important in order to determine the size of the tractor that could be used for a specific implement. The draft required for a given implement will also be affected by the soil conditions and the geometry of the tillage implement (Taniguchi *et al*., 1999; Naderloo *et al*., 2009; Olatunji *et al*., 2009).

Corresponding Author: S.A. Al-Suhaibani, Department of Agricultural Engineering, College of Food Science and Agriculture, King Saud University, P.O. Box 2460, Riyadh 11451 Kingdom of Saudi Arabia

The effects of soil conditions, tillage depth and forward speed on soil translocation by chisel plow were studied by Van Muysen *et al*. (2000). The specific draft (force per cross sectional area of worked soil), energy use for moldboard plow, chisel plow and disc harrow at different soil conditions were investigated by Arvidsson *et al*. (2004). They found that the specific draft was generally the highest for the chisel plow and the lowest for the moldboard plow and the disc harrow and referred that to the differences in implement geometry and mode of soil break-up.

Several models were developed to predict draft for tillage tools based on soil condition, soil properties and implement width (Sahu and Raheman, 2006). Owen (1989) studied the force-depth relationship of a chisel plow tine with three different wing types in a compacted clay loam soil and found the vertical force on the tine to increase linearly with the operating depth while the horizontal force, moment and total force to increase quadratically with operating depth. He also noticed that the wing width had a significant effect on the vertical force and no interaction existed between the wing width and the depth. The relationship between depth of cut and the increase in the weight of disc plow and the draft was investigated by Olatunji *et al*. (2004). The model derived from the field work showed that the draft for disc plow increase with speed and soil moisture content and the depth of cut varied with changes in the weight of the implement. Mamman and Qui (2005) studied the draft performance of a chisel plow model using a soil bin. The design parameters considered were: nose angle, slide angle, depth and speed. The draft increased with increases in tillage depth and the levels of nose and slide angles and the cutting edge height.

Brown *et al*. (1989) stated that manufacturers of tillage implements tend to overdesign their products due to a lack of the proper design and analysis of tools and the technical expertise required to optimize the strength of an implement. Gill and Vanden Berg (1968) stated that the efficiency and economy of the tillage operation could be evaluated from the mechanics of tillage tools/soil interaction which would provide a method by which the performance of the tillage implements could be predicted and controlled by the design of a tillage tool or by the use of a sequence of tillage tools. In studying the strength and forces for the chisel plow, Brown *et al*. (1989) evaluated the stress on the chisel plow using the finite element analysis and reduced the weight by 23% without causing excessive stress on the plow.

The main objectives of this study was to evaluate the performance of a medium size (weight = 380 kg, width = 190 cm) chisel plow with three rows of fully curved thin (5 cm) shanks (7) in a sandy soil. The specific objectives were to study the effects of plowing depth and forward speed on: (a) draft, (b) unit draft, (c) specific draft and coefficient of pull.

MATERIALS AND METHODS

Tractors and instrumentation system: A fully instrumented Massy Ferguson (MF) 3090 tractor (Fig. 1) was used in the study. The specification of the tractor are presented in Table 1. The instrumentation system consisted of: (a) a drawbar dynamometer, to measure drawbar pull (b) two wheel torque transducers, to measure wheel forces (c) a three-point linkage-implement force and depth transducer, to measure the three-point linkage forces and depth, (d) other transducers, to monitor ground speed, fluid temperatures (engine oil, transmission oil, front axle oil, engine coolant and engine fuel), Power Take Off (PTO) torque, right and left position of front wheel steering and angular position and indication of the lifting position of the three-point linkage, (e) a data logger, to monitor and record data from various parameters and (f) a computer, for processing and analyzing data (Al-Suhaibani *et al*., 1994).

The draft was measured using a drawbar dynamometer (Fig. 2) consisting of two load sensing clevis bolts and the force exerted by the plow was measured by a strain gauge bridge within the clevis bolts.

Fig. 1: The fully instrumented tractor

Table 1: Tractor specifications

Parameter	Value
Power	75 kW
Weight	47.35 kN
Weight on front wheels	18.50 kN
Weight on rear wheels	28.85 kN
Distance between front and rear wheels	269.90 cm
Distance between front wheels	187.00 cm
Distance between rear wheels	163.00 cm
Front wheels size	31.60 R 28
Rear wheels size	18.40 R 38
Height of drawbar	58.30 cm
Height of center of gravity	174.00 cm

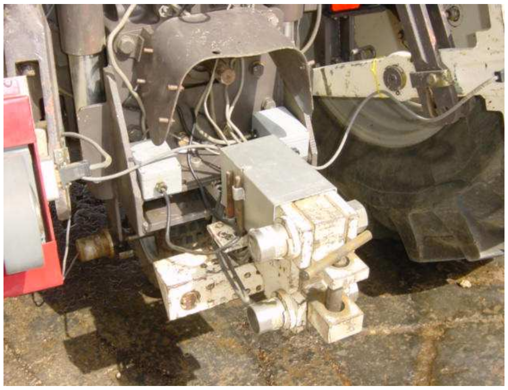

Fig. 2: The draw bar dynamometer used for measuring draft

Fig. 3: The fifth wheel used for measuring the forward speed

The tractor ground speed was measured using a fifth wheel attached to a suitable position underneath the tractor as shown in Fig. 3. An RS shaft encoder (360 pulses/revolution) was mounted on the fifth wheel and used to measure the distance traveled and hence the actual ground speed.

The depth was measured using the three point linkage-implement force and depth transducer (Fig. 4) which was developed specifically for use with mounted implement of categories II (40-100 hp) and III (80-225 hp) as specified by the ASAE Standards (1985).

A data logger mounted on a platform to the left of the tractor operator was used to scan and record the output signals from the transducers. The strain gauge transducers in the instrumentation system were connected to the data logger through amplifier boxes, which also provided a regulated power supply to give excitation to the transducer. The activity unit was used to provide excitation to both the data logger and transducers with input supply from the tractor battery (12 V). It was, also, used to indicate the activity performed during field tests.

Fig. 4: The system used for measuring forces and determination of tillage depth

Fig. 5: A medium size chisel plow

Chisel plow: A medium size (Fig. 5) Massy Ferguson (Denmark) chisel plow (model MF 38, serial No. L4078) was used in the study. The plow weighed 380 Kg (3.73 kN) and had a width of 190 cm. It had 7 shanks distributed in 3 rows. The specifications of the plow are shown in Table 2.

Field experiments: Experiments were conducted using the fully instrumented MF 3090 tractor to measure the draft requirement of a medium size chisel plow in a sandy loam soil over wide ranges of speeds and depths at the Agricultural Research and Experimental Farm of the King Saud University in Dirab. Four speeds and three depths were tested as shown in Table 3. This resulted in 12 treatment combinations. Ten measurements were taken for each treatment combinations at 5 min intervals. The data logger monitored and recorded the data for depth, speed and draft during the field experiment. The laptop displayed the values of the measured parameters and analyzed the data.

Table 2: Chisel plow specifications

Parameter	Volume
Type of plow	Heavy duty
Model	1-1 (Serial No. 603)
Manufacture	IH Company England
Total weight	380 Kg (3.73 kN)
Total width of tillage	210 cm
Number of shanks	7
Width of shank	5 cm
Thickness of shank	2.5 cm
Shank stem angle	50°
Number of rows	3
Number of shanks in first row	2
Distance between shanks in first row	120 cm
Number of shanks in second row	2
Distance between shanks in second row	60 cm
Number of shanks in third row	3
Distance between shanks in third row	85 cm
Width of chisel tool	5 cm

Table 3: Experimental parameters

Parameter	Values
Depth (mm)	115, 160, 230
Speed (m sec^{-1})	0.75, 1.20, 1.75, 2.30

RESULTS

Figure 6 shows the distribution of shanks on plow frame while Fig. 7 shows the distance between the paths of shanks and the width of worked soil (plowed strip). The width of the plow was 190 cm and the total width of plowed strip was 210 cm. The total width of cut (35 cm) was calculated by multiplying the width of shank (5 cm) by the number of shanks (7). The remaining part of the width of plowed strip (175 cm) was considered to be the width of pulverization. Accordingly, the plow shanks were able to cut 16.6% of the total plowed width and the movement of the soil (pulverization) resulted in the breakage of soil particles and preparation of the seedbed.

Table 4 shows the measured draft force (kN) and the calculated unit draft (kN m^{-1}) at various plowing depths and forward speeds. The unit draft is defined in this study as the draft per unit width of the worked soil (width of plowed strip).

Table 5 shows the calculated vertical specific draft (kN m^{-2}) which is defined in this study as the draft per project unit area of vertical cut (vertical cross sectional area of worked soil). The cross sectional area of the worked soil was calculated by multiplying the plowing depth by the width of plowed strip. The portions of the vertical specific draft used for cutting the soil and moving the soil particles (pulverization) were, also, calculated as shown in Table 5.

Table 6 shows the calculated horizontal specific draft. The horizontal specific draft is defined in this study as the draft divided by horizontal plowed area per unit time.

Table 4: Draft and unit draft

Depth (mm)	Speed (m sec^{-1})	Draft (kN)	Unit draft (kN m^{-1})
115	0.75	3.14 (0.52)	1.50
	1.20	3.76 (0.14)	1.79
	1.75	4.11 (0.24)	1.96
	2.30	4.59 (0.25)	2.19
160	0.75	5.54 (0.38)	2.64
	1.20	6.56 (0.38)	3.12
	1.75	7.41 (0.14)	3.53
	2.30	8.01 (0.68)	3.81
230	0.75	8.33 (0.62)	3.97
	1.20	9.60 (0.84)	4.57
	1.75	10.58 (0.10)	5.04
	2.30	11.92 (1.92)	5.68

( ) The values represent standard deviation; Plow width = 190 cm; Width of plowed strip = 210 cm; Unit draft = Draft/width of plowed strip

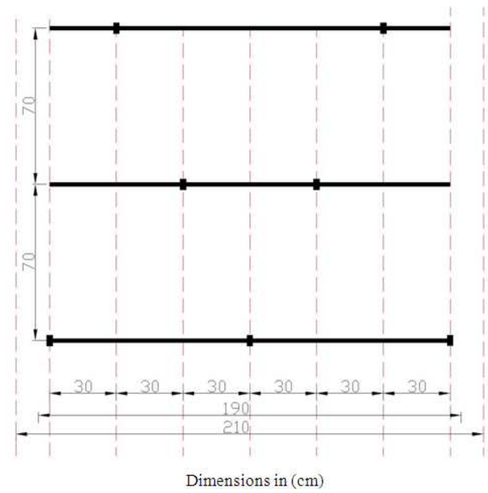

Fig. 6: Distribution of shanks on the plow frame (Plow with = 190 cm; with of tillage = 210 cm; distance between the paths of shanks = 30 cm)

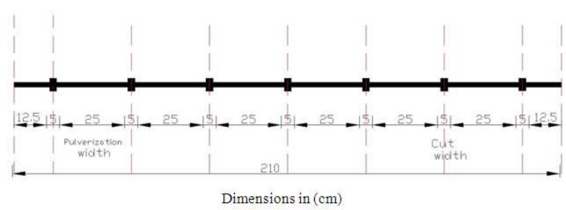

Fig. 7: Distance between the paths of shanks (total width of tillage = 210 cm; Number of shanks = 7; width of chisel tool = 5 cm; total width of cut = 35 cm; % of cut = 16.6%; Width of pulverization = 175 cm; percentage of pulverization = 83.4%)

The horizontal plowed area per unit time (sec) was calculated by multiplying the forward speed by the width of plowed strip. The results of the vertical specific draft are shown in Table 6.

Table 7 shows the total weight of the plow and the worked soil (cut/moved) by the plow) at various plowing depths and forward speeds. The weight of worked soil was calculated from the volume of soil created by the plowing depth and the forward movement of the plow in a unit time (sec) and the width of plowed strip. The coefficient of pull (kN kN^{-1}) was calculated by dividing the draft by the total weight of plow and the worked soil. The results are, also, presented in Table 7.

Table 5: Vertical specific draft

Depth (mm)	Speed (m sec^{-1})	Draft (kN)	Vertical specific draft (kN m^{-2}) Total	Cutting	Pulverization
115	0.75	3.14	13.00	2.17	10.84
	1.20	3.76	15.57	2.59	12.97
	1.75	4.11	17.02	2.84	14.18
	2.30	4.59	19.01	3.17	15.84
160	0.75	5.54	16.49	2.75	13.74
	1.20	6.56	19.52	3.25	16.27
	1.75	7.41	22.05	3.68	18.38
	2.30	8.01	23.84	3.97	19.87
230	0.75	8.33	17.25	2.87	14.37
	1.20	9.60	19.88	3.31	16.56
	1.75	10.58	21.90	3.65	18.25
	2.30	11.92	24.68	4.11	20.57

Vertical tilled area = Depth of tillage × width of plowed strip; for a depth of 115 mm = 0.115×2.1 = 0.2415 m^2; for a depth of 160 mm = 0.160×2.1 = 0.3360 m^2; for a depth of 230 mm = 0.230×2.1 = 0.4830 m^2; % Width of plow strip = 16.6%

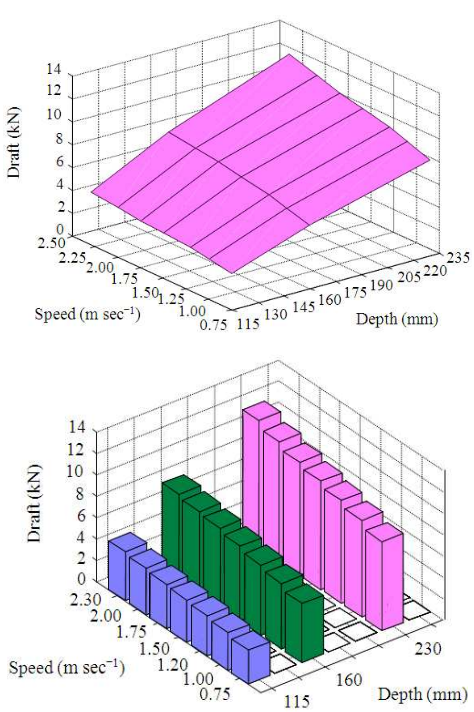

Fig. 8: Effects of plowing depth and forward speed on the measured draft

Figure 8-12 show the effects of plowing depth and forward speed on the draft, unit draft, vertical specific draft, horizontal specific draft and coefficient of pull.

Table 6: Horizontal specific draft

Depth (mm)	Speed (m sec^{-1})	Draft (kN)	Horizontal specific draft (kN m^{-2}) Total	Cutting	Pulverization
115	0.75	3.14	1.99	0.32	1.67
	1.2	3.76	1.49	0.24	1.25
	1.75	4.11	1.12	0.19	0.93
	2.3	4.59	0.95	0.16	0.79
160	0.75	5.54	3.52	0.58	2.94
	1.2	6.56	2.6	0.43	2.17
	1.75	7.41	2.02	0.33	1.69
	2.3	8.01	1.65	0.28	1.37
230	0.75	8.33	5.29	0.88	4.41
	1.2	9.6	3.81	0.63	3.18
	1.75	10.58	2.88	0.48	2.4
	2.3	11.92	2.47	0.41	2.06

Horizontal tilled area = Width of tillage × forward speed; Width of plowed strip = 210 cm; % Width of cut = 16.6%

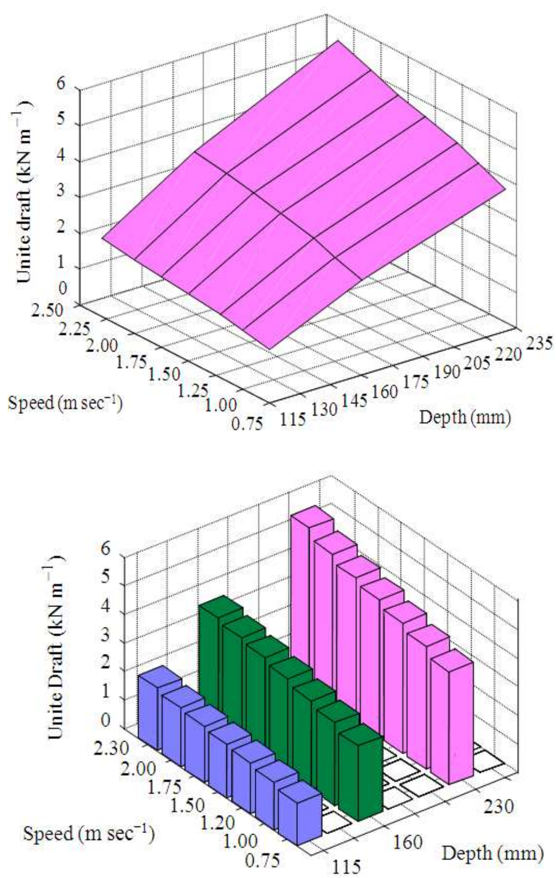

Fig. 9: Effects of plowing depth and forward speed on the unit draft

Table 7: Coefficient of pull

Depth (mm)	Speed (m sec^{-1})	Draft (kN)	Volume of worked Soil (m^3)	Weigh of plow and worked soil (kN)	Coefficient of pull (kN kN^{-1})
115	0.75	3.14	0.18	6.13	0.51
	1.20	3.76	0.29	7.57	0.50
	1.75	4.11	0.42	9.33	0.44
	2.30	4.59	0.56	11.09	0.41
160	0.75	5.54	0.25	7.07	0.78
	1.20	6.56	0.40	9.07	0.72
	1.75	7.41	0.59	11.52	0.64
	2.30	8.01	0.77	13.96	0.57
230	0.75	8.33	0.36	8.53	0.98
	1.20	9.60	0.58	11.41	0.84
	1.75	10.58	0.84	14.92	0.71
	2.30	11.92	1.11	18.44	0.65

Plow weight = 380 kg = 3.73 kN; Volume of worked soil = Plowed depth × width of plowed strip × forward speed; Soil density = 1350 kg m^{-3} = 13.24 kN m^{-3}

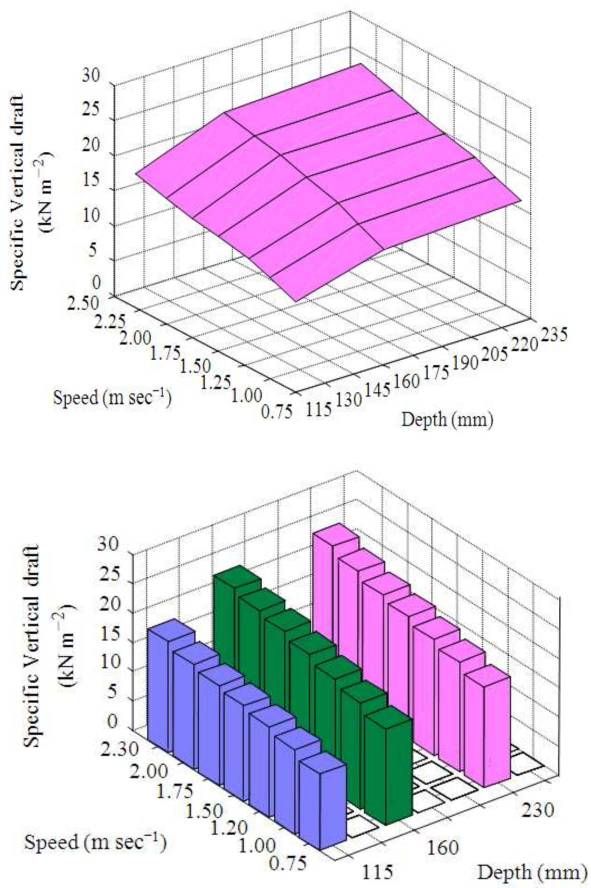

Fig. 10: Effects of plowing depth and forward speed on the specific vertical draft

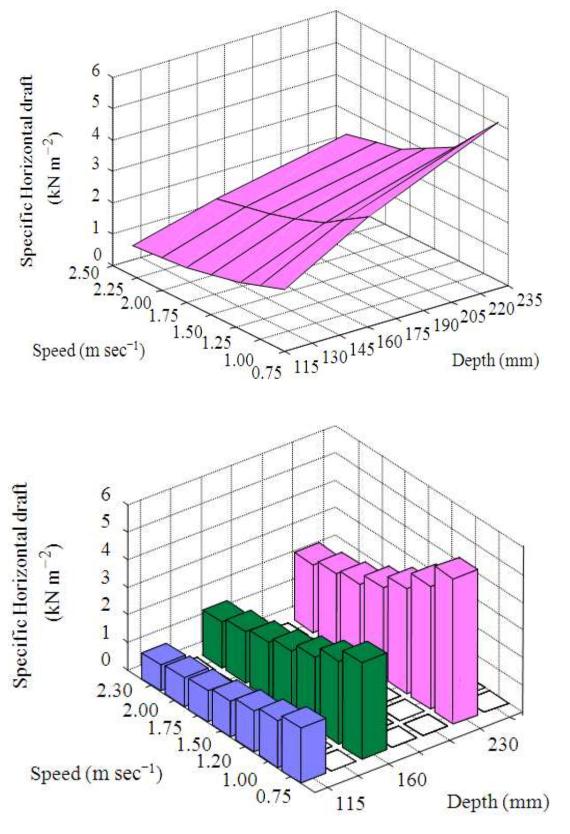

Fig. 11: Effects of plowing depth and forward speed on the specific horizontal draft

DISCUSSION

Draft and unit draft: The force required to work (cut and move) the soil varied with both the plowing depth and the forward speed as shown in Table 4 and Fig. 8. However, the increase in draft with the plowing depth or the forward speed did not appear to be linear as shown in Table 7-9. For all plowing depths, the observed increase in draft when the forward speed was increased from 0.75-1.20 m sec^{-1} was higher than the observed increases in draft when the forward speed was increased from 1.20-1.75 m sec^{-1} and from 1.75-2.30 m sec^{-1}.

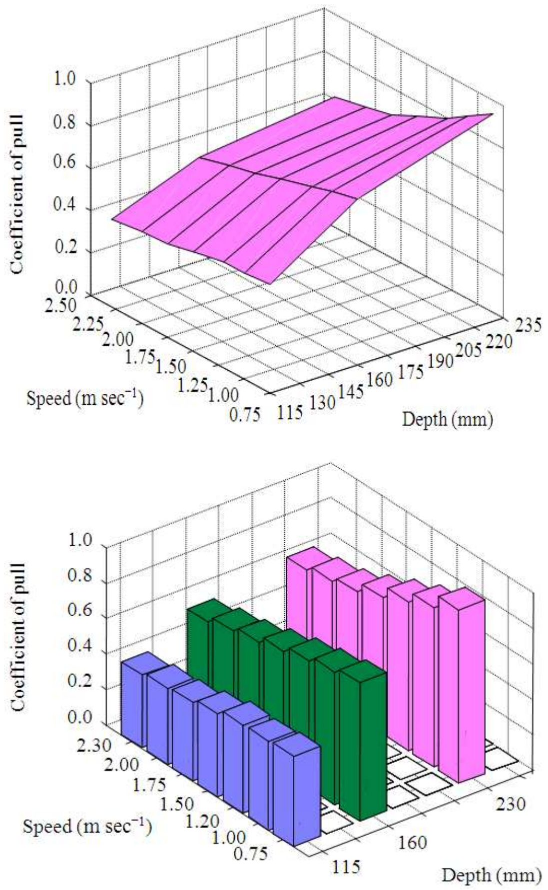

Fig. 12: Effects of plowing depth and forward speed on the coefficient of pull

Table 8: The incremental increase in draft with increases in forward speed at various depths

Depth (mm)	Forward speed interval (m sec^{-1})	Increase in draft (kN/m sec^{-1})
115	0.75-1.20	1.38
	1.20-1.75	0.64
	1.75-2.30	0.87
160	0.75-1.20	2.22
	1.20-1.75	1.54
	1.75-2.30	1.99
230	0.75-1.20	2.82
	1.20-1.75	1.78
	1.75-2.30	2.97

However, the increase in the draft observed when the forward speed was increased from 1.20-1.75 m sec^{-1} was lower than the increase in the draft observed when the forward speed was increased from 1.75-2.30 m sec^{-1}. This may indicate that the forward speed of 1.75 m sec^{-1} is the optimum speed. It was, also, observed that the increase in draft when the depth was increased from 115-160 mm was higher than the increase in the draft when the depth was increased from 160-230 mm.

Table 9: The incremental increase in draft with increases in depth at various speeds

Speed (m sec^{-1})	Depth intervals (mm)	Increase in draft (kN/m)
0.75	115-160	53.3
	160-230	39.9
1.2	115-160	62.2
	160-230	57.7
1.75	115-160	73.3
	160-230	45.3
2.3	115-160	76.0
	160-230	55.8

Table 10: Length of roots of common agricultural crops

Crop	Root length (mm)
Egg plant	50-60
Clover	40-50
Corn	30-40
Fava beans	30-40
Wheat (all cereals)	30-40
Cucumber	40
Beans	30
Tomatoes	25
Lutes	20

The unit draft was defined in this study as the draft divided by the width of worked soil (width of plowed strip). The results followed the same trend as the draft as shown in Table 4 and Fig. 9. It appears, also, that the plowing depth had more effect on the unit draft than the forward speed. Increasing the depth from 115-230 mm (100%) increased the unit draft by 164.6, 158.3, 157.1 and 159.4% for the forward speeds of 0.75, 1.20, 1.75 and 2.30 m sec^{-1}, respectively. On the other hand, increasing the forward speed from 0.75-2.30 m (206.6%) increased the unit draft by 46.0, 44.3 and 43.1% for the plowing depths of 115, 160 and 230 mm, respectively. On the average, doubling the plowing depth increased the unit draft by about 159% while doubling the forward speed increased the unit draft by 21.5%.

Mamman and Qui (2005) studied the performance of a chisel plow and found the speed and tillage depth to have more influence on the draft than the plow design. Sahu and Raheman (2006) found that the effect of speed on the draft was less than that of the depth. Owen (1989) found the vertical force to increase linearly with the plowing depth while the horizontal force to increase quadratically with the plowing depth.

Shallow seed placement (less than 25 mm) is recommended for most crops that are directly seeded (Collins and Fowler, 1996). However, the depth of the crop roots will be a deterministic factor of plowing depth, while the availability of time and implement width will determine the speed required to finish the work on time (Mustafa and Turgut, 2007). The results obtained from this study indicated that the depth has more effect on the draft than the forward speed.

Therefore, the depth of plowing should be determined based on the root length shown in Table 10. Increasing the forward speed will improve the quality of the seedbed and will not increase the draft proportionally.

Specific draft: The vertical specific draft is defined in this study as the draft per worked vertical cross sectional area. The results presented in Table 5 and Fig. 10 shows that increasing the plowing depth and/or the forward speed increased the vertical specific draft. Increasing the plowing depth from 115-230 mm (100%) increased the vertical specific draft by 32.7, 27.7, 28.7 and 29.8% for the speeds of 0.75, 1.20, 1.75 and 2.30 m/s, respectively. On the other hand, increasing the forward speed from 0.75-2.30 m sec^{-1} (206.6%) increased the vertical specific draft by 46.2, 43.4 and 43.1% for the plowing depths of 115, 160 and 230 mm, respectively. On the average, doubling the plowing depth increased the vertical specific draft by 44.2% while doubling the forward speed increased the specific draft by 14.4%.

The horizontal specific draft is defined in this study as the draft per worked horizontal area per unit time. The results are presented in Table 6 and Fig. 11 show that increasing the plowing depths of the forward speed increased the horizontal specific draft. Increasing the plowing depth from 115-230 mm (100%) increased the horizontal specific draft by 165.8, 155.7, 157.1 and 166.0% for the forward speed of 0.75, 1.20, 1.75 and 2.30 m sec^{-1}, respectively. On the other hand, increasing the forward speed from 0.75-2.30 m sec^{-1} (206.6%) reduced the horizontal specific draft by 52.3, 53.1 and 53.3% for the plowing depths of 115, 160 and 230 mm, respectively. On the average, doubling the plowing depth increased the horizontal specific draft by 161.15%, while doubling the forward speed reduced the horizontal specific draft by 25.6%.

It must be noted that the vertical specific draft has much higher values than those of the horizontal specific draft, indicating that the depth of plowing has significantly more effect on the specific draft than the forward speed. Increasing the depth increased both the vertical specific draft and horizontal specific draft while increasing the forward speed increased the vertical specific draft and reduced the horizontal specific draft. This could have a significant impact on the economical tillage. Van Muysen *at al*. (2000) stated that the specific draft is affected by the tool geometry.

Coefficient of pull: The coefficient of pull is defined in this study as the draft divided by the total weight of the plow and the worked soil. The weight of the worked soil was determined by multiplying the soil density by the volume of the worked soil. The volume of the worked soil was determined by multiplying the plowed depth by the width of plowed strip by the forward speed. The results presented in Table 7 and Fig. 12 show that increasing the depth of plowing increased the coefficient of pull for all forward speeds. Increasing the plow depth from 115-230 mm (100%) increased the coefficient of pull by 92.1, 68.0, 61.3 and 58.5% for the forward speeds of o.75, 1.20, 1.75 and 2.30 m sec^{-1}, respectively. On the other hand, increasing the forward speed from 0.75-2.30 m sec^{-1} (206.6%) reduced the coefficient of pull by 19.6, 26.9 and 33.7% for the plowing depths of 115, 160 and 230 mm, respectively.

CONCLUSION

The effects of plowing depth and forward speeds on draft, unit draft, vertical draft, horizontal draft and coefficient of pull were evaluated. The results indicated that increasing the plowing depth and/or the forward speed increased the draft, unit draft and vertical specific draft. Also, increasing the plowing depth increased the horizontal specific draft and the coefficient of pull, while increasing the speed decreased the horizontal specific draft and the coefficient of pull.

About 16.6% of the draft force was directed towards cutting the soil and 83.4% was consumed in pulverization of soil particles. The values of the vertical specific draft were much higher than those of the horizontal specific draft for all plowing depths and forward speeds. The plowing depth had more pronounced effect on the draft, unit draft, specific draft and coefficient of pull than the forward speed. The optimum forward speed was 1.75 m sec^{-1}. The recommended plowing depth should be based on the type of crop (depth of the root system).

Shallow seed placement (less than 25 mm) is recommended for most crops that are directly seeded. However, the depth of the crop roots to be raised is a deterministic factor of plowing depth, while the availability of time and implement width will determine the speed required to finish the work on time. The results obtained from this study indicated that the depth has more effect on the draft. Therefore, the depth of plowing should be determined based on the root length.

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