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Determination of Draught Requirement of Single-furrow Mouldboard Plough in Sandy Loam Soil in Yola, Northeastern Nigeria

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HIGHLIGHTS

- This study used two oxen (White-Fulani) with a draught capability of 633.33 N.
- A spring-loaded dynamometer (5000 N) was used to measure the pull force at a tractive angle of 20°.
- The draught force increases with an increase in depth and speed of operation.
- The draught force depended on the depth and width of cut, speed, type of soil, agronomic requirement, and animal.

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ABSTRACT

The draught requirement of a single-furrow animal-drawn mouldboard plough implement was determined on sandy loam soils from June to July 2021 at Modibbo Adama University, Yola. The effect of speeds (0.65, 0.83, and 1.05 ms-1) and depths (8, 13, and 18 cm) upon the draught was investigated. Soil analysis, animal specification, and results of tillage experiments are reported. A pair of oxen weighing 538 kg was used as a power source. A 1 x 3 x 3 factorial experimental design was arranged in a Randomized Complete Design (RCD) for the study on a test plot of 50 m long x 25 m wide and replicated three times. The highest mean draught values of 458.43 N and the lowest mean draught values of 456.03 N were obtained at a speed and depth combination of 1.05 ms-1 and 0.183 m and 0.65 ms-1 and 0.083 m, respectively, with a unit draught of 11.07 kpa. Analysis of Variance (ANOVA) between speed and depth had a significant effect at a 1% level of probability ($P \leq 0.01$) on draught requirement. Linear regression equations showed an increase in draught with an increase in tillage depth and speed. The high coefficient of determination r^2 values show that the plough is operated more economically at a mean speed of 0.83 m/s and a depth of 0.135 m. These regression equations can predict draught during the design of animal-drawn tillage implementation. Substantial energy savings can be obtained with proper animal-tillage implements combination.

1. Introduction

Tackling the challenges of increasing agricultural production and labour saving facing the agricultural policymakers in developing countries will provide motive power in various proportions for crop production. This involves finding appropriate ways and means to develop, introduce, and utilize the available and appropriate power source and implement combinations in our agricultural production system [1]. For example, in any country, tractors, commonly used as primary tillage implements, have been observed to have limitations such as high cost of implements and inefficient methods for utilization on small farms. However, most farmers are still operating the traditional method of tillage operation with local hand tools and human muscles, which places a premium on the farm size that a family can effectively maintain [2]. Under these conditions, significant improvements in the hand and animal-operated farm implement remain the main, reliable, affordable, and one of the most important energy sources for agriculture to raise crop yield and farmers' income [3].

The draught animal tillage system is complex by various interacting factors at different levels (the animal, tillage implement, harness, operator, and soil) of operations [4]. Animal-drawn mouldboard plough has been and is still the basic and the most widely employed primary tillage implement on the farm in developing countries due to its low cost and the availability of work animals [3,5]. In Nigeria, particularly in Adamawa state, the ridger mouldboard plough is often the most commonly used animal traction implement for primary cultivation, weeding, and earthen up [6]. However, this ridger plough creates furrows between the ridges, which may not be suitable for some crops such as rice, sugar beet, groundnut, Bambara nut, and tiger nuts are grown in the arid semi-arid regions. However, animal-drawn mouldboard tillage implements hold immense potential for reducing the ridger plow's perceived limitation. Practically, this can be accomplished by carrying out studies on the soil-tool interaction system that can be used to study its performance [7].

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Due to the limitations of the ridger plough in relation to agronomic crop requirements, an animal-drawn single furrow mouldboard plough was developed in Modibbo Adama University Yola in 2007 with its performance in terms of field capacity, efficiency, and work time demonstrated for farmers [6]. However, the performance of the mouldboard plough in terms of draught force was not determined. Therefore, the performance or suitability of tillage implements for soil manipulation is determined by their specific draught force required in pulling the tool through the soil and energy requirement, which are considered essential parameters to match tillage implement to any source of power [3].

Many studies on draught and power requirements under various soil conditions showed that draught output varies with variations in soil conditions, tool design, and operational parameters [3, 8]. However, presently, very few published data are available on draught requirements of agricultural implements operating on soils of Nigeria. All the draught data presented in the ASAE Standards (1994) were based mostly on USA soils [8]. This data constraint hinders farmers and extension workers from selecting the appropriate size of animals and implements for a particular farm operation [9,10].

The present assessment of draught force of animals/implements combination will help in developing/matching implements for utilizing power without over-stressing the animals. It also provides decision support system data for agricultural planners, consultants, and agencies interested in designing and constructing animal-drawn tillage implements, especially in Nigeria.

2. Materials and Methods

2.1 Study Area and Experimental Procedure

The field study was conducted between June-July 2020 cropping season at Modibbo Adama University, Yola, within the Savannah region, Yola area (9^0 14'N and 12^0 32'E) of Adamawa State – Nigeria. The area is 200 m above sea level and falls within Nigeria's Eastern Sudan Savanna ecological zone. The area is an agrarian tropical environment marked by a dry season (November-April) and wet season (May-October), with mean annual rainfall usually ranging from 700 mm to 1,050 mm [11], [12]. The soil type in the area is predominantly sandy loam textures [10,11]. Two white Fulani bulls (Zebu) aged between five and six years with two years of tillage experience and a total weight of 538 kg (5277.78) live weights as draught animals Plate 1. The animal-drawn mouldboard plough developed in the University Plate 2 was used. The tractive capability of the oxen is 633.33 N (12% live weight) [13].

Plate1: Draught Animals Used for Field Operation

Plate2 : Single-furrow mouldboard plough

2.2 Treatment and Experimental Design

A 1x3×3 factorial experiment in completely randomized design (CRD) was arranged on a test plot of 1250 m^2 involving three-speed levels S_1, S_2, S_3 (0.65, 0.83, and 1.05 ms^{-1}) and three depth levels (d_1, d_2, d_3) 8, 12, and 15 cm for the study [8,13]. The experimental plot with 1250 m^2 was divided into nine sub-plots of size 16.7 m long x 8.3 m wide each. This plot was replicated three times. The combination of the implements, speed, and depth resulted in nine treatments applied to each plot of 1250 m^2. The experimental arrangement is as presented below.

$T_1 = I_1S_1d_1$	$T_2 = I_1S_1d_2$	$T_3 = I_1S_1d_3$
$T_4 = I_1S_2d_1$	$T_5 = I_1S_2d_2$	$T_6 = I_1S_2d_3$
$T_7 = I_1S_3d_1$	$T_8 = I_1S_3d_2$	$T_9 = I_1S_3d_3$

Common soil analysis, data collection, and analysis methodology were applied to all the experimental treatment plots.

2.3 Experimental Instrumentation

The major instrument used in the research work was a spring-type dynamometer (500 kg) used to measure the pull exerted on the mouldboard plough implement by the draught oxen at various speeds (0.65, 0.83, and 1.05 ms^{-1}) and depths (8, 12, and 15 cm) of operation. Other pieces of equipment used included stopping watches used to measure and record the time taken to cover each run in seconds for each treatment during operation, measuring tape, a 100 m fiber tape graduated both in meters and feet used to measure the field layout, meter rule used for measuring the depth and width of operation, electronic and spring weighing machine used to measure the weight of soil samples both before and after operation for moisture content and bulk density determination, soil moisture meter(MD760), AMS soil samplers, and graduated measuring cylinders.

2.4 Field Measurements

2.4.1 Determination of soil properties

Soil samples of the top soil (0 – 15 and 15 – 30 cm) were obtained from the field before and after tillage using an auger, core samplers, cutting blade, and nylon bags for the laboratory determination of particle size analysis, bulk density and soil moisture content.

Soil texture classification was determined using the equation given by [14]

$$S_p = \frac{(R - R_L \pm r)}{w} \times 100 \tag{1}$$

S_p is the percentage of particles on suspension (%). R is the sample reading for the hydrometer. R_L is the blank reading for hydrometer. r is the temperature correction factor (0.36); w is the weight of the sample used (g).

The average soil moisture content was determined before and after each treatment using an electronic soil moisture meter (MD760). First, the soil bulk density was determined by the core sample method described by [14]. This involved taking three soil samples randomly in a container from each test plot on the surface of 0-25 cm at 5 cm depth increment using a core sampler (4.35 cm diameter, 9.90 cm depth, and 143.77 cm^3 of volume) before and after ploughing. Next, the bulk density was determined using the relationship given by [14]:

$$B_d = 4\frac{W_d}{\pi D^2 h} \tag{2}$$

Where: B_d = Soil bulk density (g/cm^3); W_d = Weight of dry soil (g); D = Internal diameter of core sampler (cm); h = Height of core sampler (cm)

2.4.2 Draught measurement

The field trials measured draught force using a dynamometer, spring type (5000 N) capacity on 50 m long x 25 m wide plots. The dynamometer was attached between the plough and the chain. The chain was connected to the center of the yoke of the oxen to measure the tractive pull forces. Readings were taken every 15 seconds and averaged to get the mean for each treatment. The pulling force (Pf) was measured at the hitch point on the implement and represented the amount of draught force developed by the pair of oxen to pull the implement on a continuous working through the soil. The working height of the yoke and the beam length was measured to determine the angle α the beam makes with the ground. Furrow depth, width, cross-section area, and the time taken to cover a run and the whole plot were measured during the test. The actual draught was calculated using the equation by; [15];

$$D_R = P_f \times cos\alpha \tag{3}$$

Where: D_R = Actual Draught (N); P_f = Tractive pull, (N); α – the angle of inclination of the chain to the horizontal (20^0).Eighty-nine passes were recorded for every plot measured 50 m long by 25 m in width. The theoretical and effective time to complete each pass length was taken using stopwatches. The implement was operated targeting each of the three working speeds (S_1 = 0.65 m/s, S_2= 0.83 m/s and S_3 = 1.05 m/s) and depths (d_1 = 8.27 cm; d_2 = 12.77 cm and d_3 = 18.35) as recommended by [10] while ploughing with animal-drawn implement respectively. The depth of soil cut was measured with a plastic ruler at various points along the furrow, while the width of cut was taken at a distance between successive furrow edges to ascertain the average width for each plot. It was further confirmed by using the relation described by [15].

$$W_{wd} = \frac{W_l}{N_p} \tag{4}$$

Where: W_{wd} = working width (m); W_l = width of land (m); N_p = number of plough passes

The specific draught was calculated using the equation [15];

$$SD_R = {}^{D_R}/_{A} \tag{5}$$

Where: SD_R = Specific (unit) Draught (N/m^2); D_R = Actual Draught (N); A = cross-Sectional Area of the Furrow (m^2)

Other parameters computed from the field performance are; The working speed [16].

$$W_{SP} = \frac{D_w}{T_h} \tag{6}$$

Where: WSP = working speed (m/s); Dw = Distance covered per run (m); Th = theoretical time (min)

$$\text{Theoretical field capacity:} \quad C_{th} = \frac{A_C}{T_h} \tag{7}$$

Where: C_{th} = theoretical field capacity (ha/hr); A_c = area cultivated (ha); T_h = total time (min)

Effective field capacity:

$$C_{eff} = \frac{A_C}{T_e} \tag{8}$$

Where: T_e = effective (actual) time taken to cover the area (hr)Field efficiency:

$$F_{eff} = \frac{C_{eff}}{C_{th}} \times 100 \tag{9}$$

3. Results and Discussion

3.1 Textural Classification

Table 1 shows the mean value of the soil textural classification results within the top 30 cm with about 65% sand, 18% silt, and 17% clay. Using the USDA soil classification texture triangle, the soil at the experimental site is sandy loam with the sand fraction (62.8 – 67.8%) in the constituent.

Table 1: Average Soil Texture of the Trial Site

Soil depth (cm)	0-15 (cm)	16-30 (cm)	Texture class
% Sand 200-2000 µm	64.03	65.93	Sandy loam
% Silt 2 – 20 µm	18.35	18.03	
% Clay < 2 µm	17.23	16.03	

3.2 Soil Physical Properties

Table 2 shows the average values of the soil water content and soil bulk density at the experimental site. Soil water holding capacity values were obtained both from laboratory experiments and in-situ for better results. The result showed an average soil moisture content (SMC) value of 8.84%, standard deviation (St. dev.) of 0.27 and coefficient of variation, CV of 3.05% on a dry weight basis before and after tillage operation. The average soil bulk density (SBD) in g/cm^3 was 1.62 g/cm^3, std. dev. of 0.02 and CV of 1.03% on a dry weight basis. The result conforms to [10,15], which stated that lower bulk density was found at a depth of 15 – 30 cm than 30 – 50 cm with mould board plough.

Table 2: Soil moisture content (% d.b.) and Bulk density on a dry weight basis

		Soil moisture content (% d.b)	Bulk density (g/cm^3)
Mean		8.84	1.62
Standard deviation		0.27	0.02
Standard error		0.13	0.01
Coefficient of variation (%)		3.05	1.03
95% Confidence Intervals (CI)	LL	8.51	1.60
	UL	9.26	1.64

3.3 Determination of Maximum Draught Requirement

Table 3 shows the result of the implement draught requirement obtained from a combination of speed and depth of operation used in the experiment. The statistical analysis of the draught requirements of the animal-drawn single-furrow implement showed that the highest draught means, a value of 458.43 N, was obtained in treatments T_9, the combination (S_3d_3) of speed 1.05 ms^{-1} and 0.183 m depth. Conversely, the lowest mean value of 456.03 N was obtained in T_1 (S_1d_1) speed of 0.65 ms^{-1} and 0.083 m depth, respectively, for the single-furrow mouldboard plough.

Table 3: Maximum Draught Requirement Means of the Animal Drawn mouldboard ridger with Speed and depth of operation

Sn	Treatment	Draught (N)	Speed (m/s)	Depth (m)
1	S_1d_1	456.03	0.65	0.083
2	S_1d_2	457.97	0.83	0.135
3	S_1d_3	458.34	1.05	0.183
4	S_2d_1	457.33	0.65	0.083
5	S_2d_2	458.07	0.83	0.135
6	S_2d_3	458.41	1.05	0.183
7	S_3d_1	457.98	0.65	0.083
8	S_3d_2	458.03	0.83	0.135
9	S_3d_3	458.43	1.05	0.183
	Mean	457.84		
	Minimum	456.03		
	Maximum	458.43		
	Cv (%)	0.16		
	Stdev	0.71		

It showed that the lower the depth of operation, the lower the draught of implement used and vice versa. This shows that the more soil is cut and turned over by the implement operating at a deeper range, the higher the draught values. Similar trend were reported by [9,10,15,17,19].

3.4 Determination of Specific Draught and Field Performance of Mouldboard Plough

Table 4 shows the field performance of oxen-drawn single-furrow mouldboard plough obtained from the field experiment. From the Table, the mean value of specific draught forces was 11.07 kpa, with the average depth and width of operation of 0.135 m and 0.275 m, respectively. The experimental specific draught force, as shown in Table 4, agrees with those reported by [15,17,18], with a 1.75% difference in actual draught force.

These differences in implement draught forces are in agreement with [1,18] that the draught requirement of different implement must be related to the volume of soil tilled (specific draught) and other agronomic and soil data to be selected for a particular soil and climatic region. The effective field capacity was found to be 0.41 ha/hr with a field efficiency of 72.5%, which is in line with efficiencies (66.7 – 83.8%) established by [6] and [19].

Animal-drawn implements could not achieve high efficiencies because of the variation in the performance of animals and the alertness of the operator. This is in agreement with [3] and [19], who stated that the performance of an implement sometimes depends on the operator's skill and soil conditions.

Table 4: Specific draught and Field Performance of a Single-furrow mouldboard plough

S/N		Mean	Standard dev	Coeff. of Variation (%)	Confidence Interval 95%	
					Upper limit	Lower limit
1	Length of the run (m)	50	-	-	-	-
2	Width of field (m)	25	-	-	-	-
3	No of passes	89	-	-	-	-
4	Pull (N)	484	0.75	0.16	485	483
5	Actual draught (N)	458	0.71	0.16	456	458
6	Depth of cut (m)	0.140	0.001	0.69	0.152	0.128
7	Width of cut (m)	0.275	0.004	0.16	0.276	0.275
8	Cross-sectional area of furrow (m^2)	0.0413	0.0003	0.72	0.0417	0.0410
9	Specific draught (kPa)	11.07	0.082	0.74	11.18	10.97
10	Effective time for operation (min)	18.50	0.32	1.74	-	-
11	Total operating time (min)	25.52	0.16	1.26	-	-
12	Effective field capacity (ha/hr)	0.41	0.01	1.73	-	-
13	Field efficiency (%)	72.5	0.35	0.48	-	-

3.5 Influence of Speed and Depth of Operations on Draught

Figures 1a and 1b illustrate the effect of tillage depth on draught at different levels of forwarding speed and the effect of forwarding speed on draught at different levels of tillage depth for the single-furrow mouldboard plough. From these Figures, it was observed that draught increased with forwarding speed and tillage depth. Figure 1a shows that draught force increases with an increase in working depth at 0.65 m/s, 0.83 m/s, and 1.05 m/s speeds of operation. Equations of best fit lines show a good correlation of values of r^2 very close to 1, with the best fit obtained at a speed of 0.83 m/s, which can be used to estimate the expected draught data. Figure 1b showed that draught force increased with an increase in working speed at 0.083 m, 0.135 m, and 0.183 m depths of operation. Equations of best-fit lines in all the Figures show a good correlation of values of r^2 very close to 1, with the best fit obtained at a depth of 0.135 m and 0.83 m/s speed of operation. Although both approaches gave a very close correlation of draught data to each other, the equation of fit due to speed show higher r^2 values for the relationship between the corresponding data points. These results showed that draught force increased in all implements with an increase in tillage depth and implement speed which is in agreement with earlier studies reported by [1,8,10,16].

The result of the analysis of variance (ANOVA) for the test of speed and tillage depth effect on draught for the mouldboard plough is presented in Table 5.

Table 5: Analysis of Variance (ANOVA) for speed and depth on Draught force for single-furrow mouldboard plough

	Sources of variation	Df	SS	MSS	F_{cal}	Ft	
1	Replication	2	0.00	0.00	0.16	6.23	**
2	D	2	7.99	3.99	44474.79	,,	**
3	S	2	2.27	1.14	12650.52	,,	**
4	SD	4	3.56	0.89	9897.08	4.77	**
5	Error	16	0.00	0.00			
6	Total	26	13.82				

**significant at 0.01 level

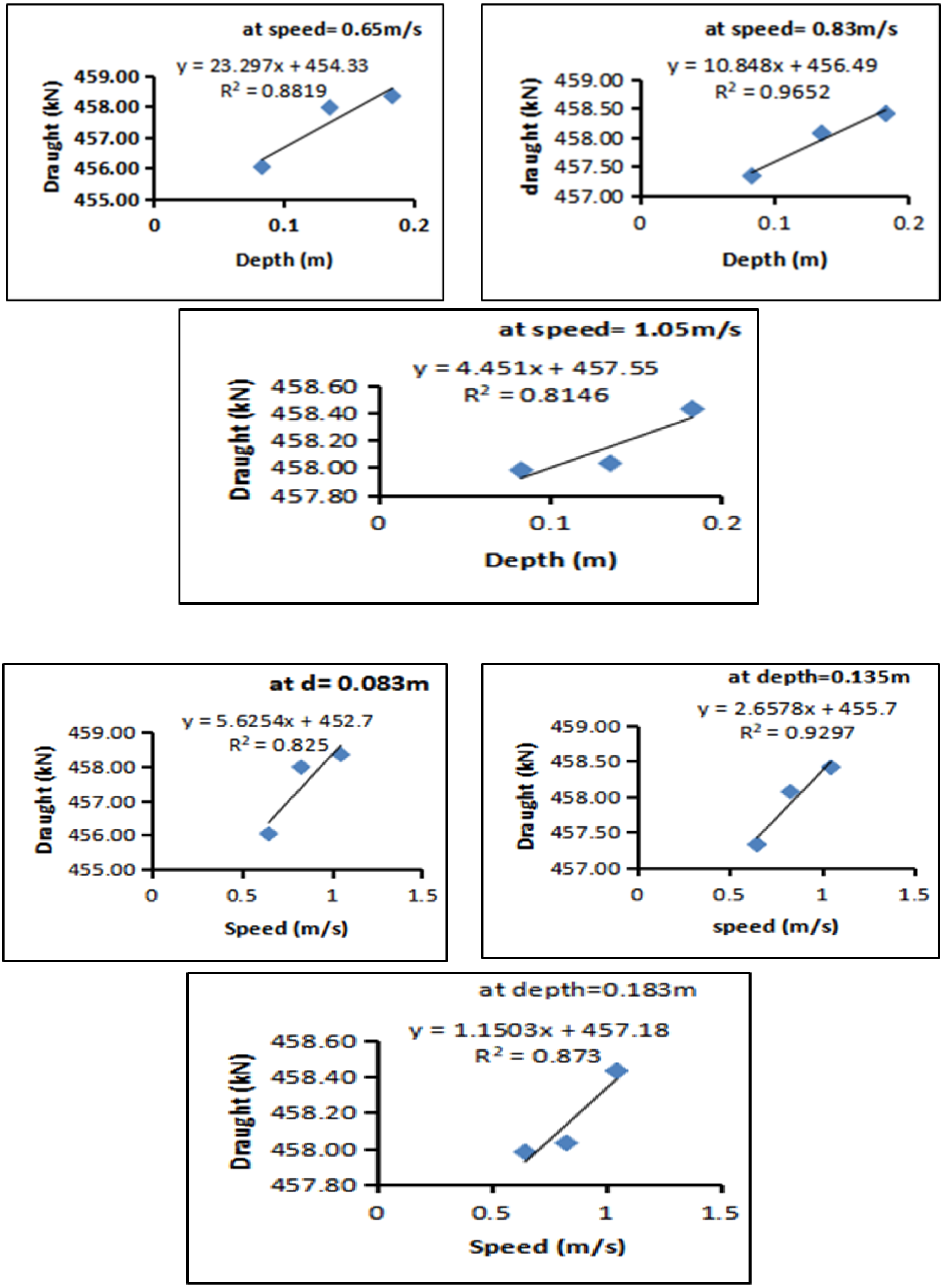

Figure 1: (A) The effect of depth on experimental draught at three different speed of operation
(B) The effect of speed on experimental draught at three different depth of operation

The result showed that forward speed and tillage depth affected the draught of the implement significantly at a 1% level of probability (P≤0.01). Furthermore, the interaction between the two factors (forward speed and tillage depth) was also statistically significant at a 1% level of probability (P≤0.01). Similar results were reported by [1,8,9], and [10], which showed that the draught of animal-drawn tillage implement is significantly affected by tillage depth (P≤0.01).

The results of the regression equations obtained from the analysis of the single-furrow plough are presented in Table 6. From this Table 6, it was observed that the coefficient of determination r^2 values from all the equations was very high.

The highest r^2 values show that the plough is operated more economically at a mean speed of 0.83 m/s and a mean depth of 0.135 m which is in agreement with earlier reported by [1,7,11]. Therefore, the equations can be suitable for predictive purposes for researchers and extension workers during the design of animal-drawn tillage implements.

Table 6: Linear Equations for Draught-Depth and Draught-Speed Relationship

Treatment	Draught-Depth/Draught-Speed Relationship	R^2
Speed 1 (0.65 m/s)	D = 23.297*d + 454.33	0.8819
2 (0.83 m/s)	D = 10.848*d + 456.49	0.9652
3 (1.05 m/s)	D = 4.451*d + 457.55	0.8146
Depth 1 (0.083 m)	D = 5.6254*S + 452.7	0.825
2 (0.135 m)	D = 2.6578*S + 455.7	0.9297
3 (0.183 m)	D = 1.1503*S + 457.18	0.873

4. Conclusion

Field tests were performed to determine the draught requirement of a developed single-furrow animal-drawn mouldboard plough and the effects of forwarding speed and tillage depth on the draught during tillage operation in sandy loam soil. A significant increase in draught requirement was observed in all the treatments, with an increase in forwarding speed and tillage depth. The highest draught mean value of a 458.43 N was obtained in speed-depth combination (S_3d_3) of 1.05 ms^{-1} and 0.183 m, and the lowest mean value of 456.03 N was obtained in speed-depth combination (S_1d_1) 0.65 ms^{-1} and 0.083 m respectively for the single-furrow mouldboard plough. The mean draught force of 458 N was obtained with a specific draught force of 11.07 Kpa at an average ploughing speed of 0.83 m/s (2.88 km/h), soil moisture content of 8.84%, and soil bulk density of 1.62 g/cm^2. Analysis of Variance (ANOVA) showed that forward speed and tillage depth had a significant effect at a 1% level of probability ($P \leq 0.01$) on draught requirement. Similarly, the interaction between forwarding speed and tillage depth was statistically significant at a 1% level of probability ($P \leq 0.01$). However, the very high coefficient of determination (r^2) values would make the equations suitable for predictive purposes for agricultural planers, extension workers, researchers, and designers of animal-drawn tillage implements. Hence, substantial energy savings can be obtained with developed single-furrow animal-drawn tillage implemented by proper animal-tillage implements.

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Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study can be obtained on a request from the corresponding author.

Conflicts of interest

“The authors declare no conflict of interest.”

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