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Original Research Article

Development of a Mathematical Predicting Model for Bullock-Drawn Mouldboard Plough in Sandy Loam Soil in Yola, Nigeria

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Abstract

The prediction model equation of a draught force of animal-drawn Mouldboard plough has several advantages in improving tillage performance in smallholder farming systems. These include fully utilizing input data for implement designers and extension workers, proper usage of draught animals, and minimizing operator tragedy. A 1 x 3 x 3 factorial experimental design was arranged in a Randomized Complete Design (RCD) on three blocks of test plots each measuring 25 m x 80 m to generate input parameters for predicting the draught of animal-drawn mouldboard plough on the sandy loam soils at Yola. The model input parameters include implement mass, operation speed, operation depth, soil moisture content, and bulk density. A pair of oxen weighing 560 kg was used as a power source. The highest mean draught values of 436.40 N and the lowest of 381.47 N were obtained at a speed and depth combination of 1.25 m/s and 0.183 m and 0.69 m/s and 0.083 m respectively. A mathematical model with a correlation between the measured and predicted r2 value of 0.9683 was developed using the concept of Buckingham's Pi theorem. The model developed effectively predicted draught for animal implements by 96.83 %. A paired t-test revealed no significant difference between the measured and the predicted values at 0.05 significant levels. The result showed that a developed mathematical equation can effectively predict the draught force of mouldboard plough in sandy loam soil.

Keywords: Mathematical model, mouldboard plough, Draught, Dimensional analysis, Bullock, Sandy loam soil.

1. INTRODUCTION

Utilization of the available power sources and correct implement selection in the agricultural production system will provide the motive power in various proportions for crop production and processing [1-3]. Draught animal technology in Africa and Nigeria in particular is still an appropriate, affordable, and sustainable technology dominantly applied by smallholder farmers due to the limitations of tractor affordability commonly used as primary tillage operation. These limitations include high costs to purchase or rent tractors and implements and inefficient methods for utilization on small farms [3-6]. Draught animals and implements are used as prime movers for the tillage operation due to their affordability and availability, ease of maintenance, and environmental suitability to tilt on areas where tractors cannot [3, 6]. Proper handling and matching of draught animals and implements will play a fundamental role in reducing the tragedy of work and increasing the productivity of draught animals. The operator skill controls the operation by minimizing the risk of stones and roots, and resisting draught force due to the operator's side movement which caused alteration of the depth of the soil tillage [9].

Animal-drawn tillage implements hold immense potential for reducing the cost of production of crops especially if methods for reducing its perceived excessive power requirements in tillage operation can be found. Practically, this can be accomplished by conducting studies on the soil-tool interaction system that can be used to study its performance [7, 8]. Several researchers [4-6, 8, 10-12] have examined various factors that affect the draught force of the tillage tool and reported draught force as a function of working depth, operating speed, implement width, length of the tool, soil moisture content, bulk density, and cone penetration resistance [10, 13] reported that travelling speed, acceleration of gravity, working depth, cutting angle, angle of internal soil friction, angle of soil-metal friction, soil cohesion, soil adhesion, and bulk density were used to develop equations of the draught force. The complexity of the soil texture varies with the required amount of penetrating and cutting soil. An appropriate number of draught animals that are related to the resistance force of a particular soil can be assigned. Otherwise, the excessive load or underload may be applied and cause fatigue and inconvenience for draught animals, tillage tools, and operators. A simple, accurate, consistence, and sensitive, yet most powerful model tool that can be used to overcome the complexity of animal-implement-soil interaction is the dimensional analysis [14]. Dimensional analysis is critical in developing a mathematical model with several parameters for prediction [15]. It is broadly used to derive theoretical relationships and offers a method for simplifying the correlation between the variables with maximum accuracy of prediction and it reduces the parameters vital to running the system by recognizing how physical amounts are related to one another [5, 6, 8, 14-16]. The model dependencies can be illustrated by the equation of the model as defined by the groups, which enables simple realization. Dimensionless parameters with more than a 90 % correlation coefficient can be valid for predicting force and the model explains good precision with less average error in predicting force [17].

Several mathematical models have been developed on animal-implement interaction to compensate for some shortcomings of the models that are either complicated or ignoring some basic aspects that affect the results [18, 5, 19-22]. Currently, there are very few published data available on animal draught force requirements operating on soils of Nigeria. All the draught data presented in the ASAE Standards (1994) were based mostly on USA soils [23, 1, 24]. This data constraint hinders designers, farmers, and extension workers from selecting the appropriate size of animals and implements for a particular farm operation [25, 1, 24]. This study aimed to develop and validate a mathematical model that could predict the draught force of an animal-drawn mouldboard plough and provide sufficient data input for the design and utilization of mouldboard plough in sandy loam soil of the savannah region.

2. MATERIALS AND METHODS

In this study, modeling the effects of several pertinent factors such as soil moisture content, bulk density, speed and depth of operation, and implement mass that affects implement draught was carried out using both theoretical and experimental fieldwork. The theoretical work involves the formulation of a prediction equation using the Buckingham Pi theorem, while the field experiment involves the collection of data on-farm for the development and validation of the mathematical model.

2.1. Theoretical Model Development

The model development was based on certain assumptions to reduce the number of parameters involved to a manageable level. This assumption includes: Soil in the test plots is assumed to be of the homogenous type, the tillage treatments considered are economical with minimum labour requirements, the animals and operators used are well experienced in carrying out field operations, and the yoking system is efficient.

2.1.1. Formulation of the prediction equations

The output draught requirement of the model was developed by dimensional analysis using the Buckingham-Pi theorem to derive a relationship between various physical quantities [26]. Considering some pertinent factors affecting draught, a mathematical model of the implement draught force can be represented as a function of the dependent variable. The 'effect' (draught) could be hypothesized as a function of the 'cause' (draught characteristics) such as the mass of the implement, depth of operation, speed of operation, soil bulk density, and moisture content [5, 21, 27]. The 'cause-effect' function could be expressed as:

$$f(D, M, \rho, d, S, I_m) = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where:

D = Draught, N
I_m = Implement mass, kg;
S = Speed of operation, m/s;
d = Depth of operation, m;
M = Soil moisture content, %;
ρ = Soil bulk density, kg/m^{-3};
f = functional relationship between the variables.

The general relationship between the dependent and the independent variables may be expressed as:

$$D = f(M, \rho, d, S, I_m) \text{ or } f(D, M, \rho, d, S, I_m) = 0 \quad \ldots. 2$$

Using the three basic dimension systems of mass (M), length (L) and time (T), the variables and their corresponding dimensions used in the model development are given in Table 1. The dimension matrix is presented in Table 2. The procedure for applying Buckingham's Pi Theorem to identify the dimensionless group to be formed is as follows: Total number of quantities involved (n) = 6, Number of basic dimensions involved (b) = 3, the number of dimensionless (Pi terms) to be formed (Np) is given as 6-3=3.

Table 1: Variables and their Corresponding Dimensions

Variables	Symbol	Unit	Dimensional symbol (M,L,T)
Draught	D	N	MLT^{-2}
Soil moisture content	M	%	$M^0L^0T^0$
Soil bulk density	ρ	Kg/m^3	ML^{-3}
Depth of operation	d	m	L
Operating speed	S	m/s	LT^{-1}
Mass of the implement	I_m	Kg	M

Table 2: Dimensional Matrix of Variables

	D	M	P	D	S	I_m
M	1	0	1	0	0	1
T	-2	0	0	0	-1	0
L	1	0	-3	1	1	0

Considering S, ρ, and d as repeating quantities

$\pi_1 = f(S, \rho, d, D) = f[S]^a[d]^b[\rho]^c[D]$

Equating the dimensions and solving for the exponents:

$M^0L^0T^0 = [LT^{-1}]^a[L]^b[ML^{-3}]^c[MLT^{-2}]$ This is dimensionless

$$\pi_1 = k_1[S^{-2}\rho^{-1}d^{-2}D] \quad \ldots\ldots 3$$

$$\pi_2 = f(S, \rho, d, I_m) = f[S]^a[\rho]^b[d]^c[I_m]$$

Equating the dimensions and solving for the exponents:

$M^0L^0T^0 = [LT^{-1}]^a[ML^{-3}]^b[L]^c[M]$. This is also dimensionless

$$\pi_2 = k_2[S^0\rho^{-1}d^{-3}I_m] = k_2\frac{I_m}{\rho d^3} \quad \ldots\ldots 4$$

$$\pi_3 = k_3M = M^0L^0T^0 \quad \ldots\ldots 5$$

$\pi_3 = k_3M$. Another dimensionless term

k_1, k_2, k_3, represent an unknown function.

The three Pi terms required and the equation can be written as:

$$\pi_1 = f(\pi_2, \pi_3) \quad \ldots\ldots 6$$

Where:

$$\pi_1 = \frac{D}{s^2d^2\rho}, \pi_2 = \frac{I_m}{\rho d^3}, \pi_3 = M \quad \ldots\ldots 7$$

The general solution can therefore be written from the dimensional analysis including three dimensionless groups (π_1, π_2 and π_3) as:

$$\frac{D}{S^2d^2\rho} = f\left(\frac{I_m}{\rho d^3}, M\right) \quad \ldots\ldots 8$$

This involved an unknown function f. The formulation of the prediction equations involves the determination of the function for the general equation. Considering all parameters and determining the accurate equations of draught force desires, would require experimental data. The component equations are formed from the plots of π_1 against π_2 and π_1 against π_3 generated from experimental data.

2.2. Field Experimental Study

The field studies were conducted at the Engineering Research Farm of the Modibbo Adama University, Yola (90 14'N and 120 32'E) of Adamawa State – Nigeria. The area is at an elevation of 200m above sea level within the Eastern Sudan Savanna ecological zone of Nigeria with mean annual rainfall usually ranging from 700mm to 1,050mm [28, 29]. The soil is predominantly of sandy loam textures [30]. A light-weighed (57kg) animal-drawn mouldboard plough and a pair of oxen (white Fulani) weighing 560kg with a tractive capability of 659.23 N (12% live weight) were used for the field study. A 1 x 3 x 3 factorial experiment design involving three-speed levels (0.69m/s, 0.97 m/s, 1.25 m/s) and three depth levels (0.083 m, 0.135 m, 0.183 m) in a Completely Randomized Design (CRD) was used for the study. The experimental test plot measured 25 m x 80 m with a total area of 2000 m2 (0.2ha). The plot was divided into nine sub-plots of size 20 m long x 5 m wide (900m2)with 10m and 5m intervals along the length and width respectively and replicated three times. The variables measured include the weight of animals (kg), Pulling force (N), angle of pull (o), distance travelled (m), working time (s), working speed (m/s), implement working depth (m), implement working width (m) and soil gravimetric water content (%). These values were used as input data for the development and validation of the model for the prediction of draught force.

2.2.1 Determination of Soil Properties

The soil moisture content was determined before and after each treatment using an electronic soil moisture meter (MD760). The soil bulk density was determined by the core sample method described by [18]. 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 cm3 of volume) before and after ploughing. Next, the bulk density was determined using the relationship given by [18]:

$$B_d = 4\frac{W_d}{\pi d^2 h} \quad \ldots\ldots 9$$

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)

2.2.2. Draught measurement

The field draught force was measured using a dynamometer, spring type (5000 N) capacity. The dynamometer was attached between the plough and the chain. 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. Readings were taken every 30 seconds and averaged to get the mean for each treatment. The angle (α) the beam makes with the ground was determined by measuring the height of the yoke and the beam length. Furrow depth, width, cross-section area, and the time taken to cover a run and the whole plot were measured. The experimental draught was calculated using the equation by; [15];

$$D_R = P_F \times cos\alpha \quad \ldots\ldots 10$$

Where: D_R = Actual Draught (N); P_f = Tractive pull, (N); α – the angle of inclination of the chain to the horizontal (20^0).

The depth of the soil cut was measured with a plastic ruler at various points along the furrow, while the width of the 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 [8].

$$W_{wd} = \frac{W_l}{N_p} \quad \ldots\ldots 11$$

Where: W_{wd} = working width (m); W_l = width of land (m); Np = number of plough passes
Other parameters computed from the field performance are; the working speed [16].

$$W_{SP} = \frac{D_w}{T_h} \quad \ldots\ldots 12$$

Where: W_{SP} = working speed (m/s); D_w = Distance covered per run (m); T_h = theoretical time (min)

2.3. Statistical Analysis

Descriptive statistics and an Excel spreadsheet were used to analyze the data obtained while the least-square linear regression technique was used to determine the relationship among variables and to draw conclusions and interactions among variables.

3.0. RESULTS AND DISCUSSIONS

Table 3 shows the field experimental data collected using the animal-drawn mouldboard plough within the study area. These values were used as input data for the development and validation of the predictive draught force model developed. The highest draught mean of 436.40 N was obtained in a speed-depth combination of 1.25 m/s and 0.183 m and the lowest mean value of 381.47 N was obtained in a speed-depth combination of 0.69 m/s and 0.083 m respectively. These results show that the deeper soil is cut and turned over by the implement resulting in a high draught value. Draught force increased with an increase in working depth and bulk density with a decrease in moisture content at various working speeds. Similar trends were reported by [6, 8, 14, 18, 24].

Table 3: Field Experimental Data

Treatment		Draught (D) N	Depth of Cut (d) m	Speed of operation (m/s)	Bulk Density(ρ) g/cm^3	Moisture Content (MC) %	Implement Weight (I_m) kg
1	s_1d_1	381.47	0.083	0.69	1.18	6.08	57
2	s_1d_2	388.03	0.135	0.69	1.43	5.78	
3	s_1d_3	400.01	0.183	0.69	1.59	5.50	
4	s_2d_1	394.13	0.083	0.97	1.26	4.88	
5	s_2d_2	417.07	0.135	0.97	1.58	4.17	
6	s_2d_3	426.34	0.183	0.97	1.78	4.69	
7	s_3d_1	403.22	0.083	1.25	1.45	4.37	
8	s_3d_2	422.02	0.135	1.25	1.65	4.43	
9	s_3d_3	436.40	0.183	1.25	1.86	5.11	

3.1. Determination of the Component Equations

The component equations are formed from the plots of π_1 against π_2 and π_1 against π_3 (Table 4) generated from experimental parameters measured on the field. Using equation 7 above, the component equations may be combined by either summation or multiplication to form the general prediction equation, the selection of which depends on the criteria a set of component equations satisfies [8, 24]. The plot of the π –terms (Figures 1 & 2) showed that each of the component equations formed a plane surface in linear space. These regression equations, being linear, favoured combination by summation.

Table 4: Computed π-terms from Experimental Data

Treatment		$\pi_1 =(\frac{D}{S^2 d^2 \rho})$	$\pi_2 = \left(\frac{I_m}{\rho d^3}\right)$	$\pi_3 = M$
1	s_1d_1	98565.29	84480.91	5.65
2	s_1d_2	31272.57	16200.84	4.48
3	s_1d_3	15778.78	5849.58	4.13
4	s_2d_1	48258.00	79117.04	5.27
5	s_2d_2	15393.62	14662.78	4.35
6	s_2d_3	7601.34	5225.18	3.29
7	s_3d_1	25834.37	68749.98	3.53
8	s_3d_2	8981.762	14040.73	3.26
9	s_3d_3	4483.835	5000.44	3.43

The general condition for summation with respect to the three π –terms is given as:

$$\pi_1 = f(\pi_2, \bar{\pi}_3) + f(\bar{\pi}_2, \pi_3) - f(\bar{\pi}_2, \bar{\pi}_3) \quad \text{............} \; 13$$

Where,
$f(\bar{\pi}_2, \bar{\pi}_3)$ = constant of summation (C).

The bar denotes constant values that could be established Equation (8) shows that if the component equations are to be combined by addition to form the general prediction equation, a constant, C must be subtracted from the sum of the component equations.

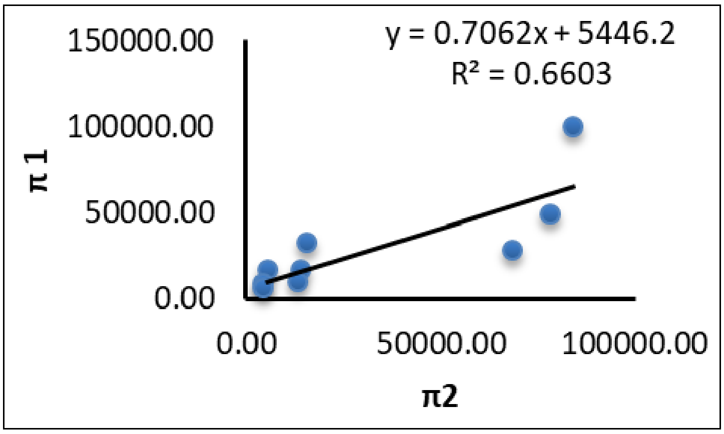

Figure 1: Plot of π_1 against π_2

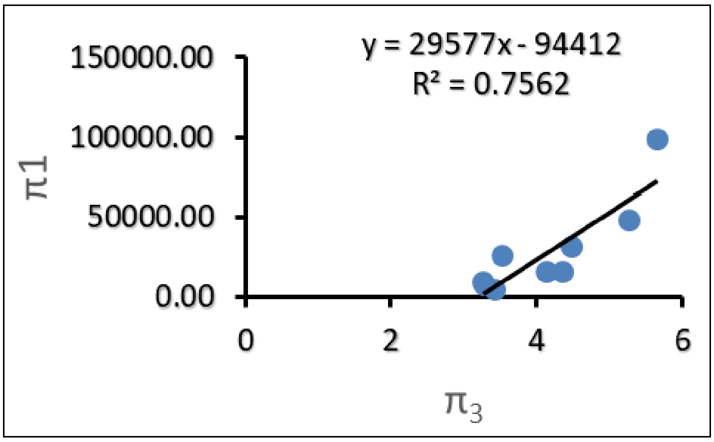

Figure 2: Plot of π_1 against π_3

The regression equations representing the component equations (Fig 1 and 2) are:

$\pi_1 = 0.7062\pi_2 + 5446.2 = f(\bar{\pi}_2, \bar{\pi}_3)$ ………… 14

$\pi_1 = 29577\pi_3 - 94412 = f(\bar{\pi}_2, \bar{\pi}_3)$……..……. 15

3.1.1. Determination of the Constant of Summation (C)

The constant of summation (C) for the three π-terms is:

$C = f(\bar{\pi}_2, \bar{\pi}_3)$ ………………………. 16

The constant C can be evaluated from any of the component equations (14 or 15)

$C = 0.7062\pi_2 + 5446.2$ ……………..…. 17

Or

$C = 29577\pi_3 - 94412$ …………………. 18

Taking π_2= 79117.04 and π_3 =5.27 (from Table 4)
C = 61318.65 or 61458.78

Since the constants calculated from the component equations (17) and (18) are approximately equal to each other; therefore, the component equations are correct to be used for predicting the general equation for the system as reported by [3, 12, 15-17].

3.1.2. Determination of Prediction Equation

The general prediction equation for the system involving the three π-terms as indicated in equation (8) was formed by adding the component equations as:

$\pi_1 = F(\pi_2, \bar{\pi}_3) + F(\bar{\pi}_2, \pi_3) - C$ ……….…. 19

Substituting equations 14 and 15 into equation 19

$$\pi_1 = (0.7062\,\pi_2 + 5446.2) + (29577\pi_3 - 94412) - 61318.65$$

$\pi_1 = 0.7062\,\pi_2 + 29577\,\pi_3 - 150284$ ….….. 20

Therefore, from equation (8):

$$\frac{D}{s^2 d^2 \rho} = 0.7062\,\frac{I_m}{\rho d^3} + 29577\,M - 150284$$

$$D = s^2 d^2 (0.7062\,I_m d^{-3} + 29577\,\rho\,M - 150284\rho)$$

$D = 0.7062\,I_m s^2 d^{-1} + 29577\,s^2 d^2 \rho\,M - 150284\,s^2 d^2 \rho$ ………………………..………. 21

Equation (21) gives the required model for predicting the draught requirement of animal-drawn mouldboard tillage tools at different operating conditions. It can be used to determine the contribution of each factor to the total draught or energy requirement of an animal-drawn mouldboard plough at different soil and operating conditions.

3.2. Validation of the Model Equation

Table 5 shows the results of the predicted draught and the experimental draught measured on the field. The model was validated with field experimental data of Table 3 by comparing the results of the predicted draught and measured field draught under farmers' field conditions. The regression equation obtained from the least square analysis for the predicted and measured results is:

$D_p = 0.8509D_m + 60.326$……………. 22

The result showed a very good agreement between the predicted and field experimental data with R^2 = 0.9683 as shown in Figure 3 with the value of the slope and intercept (regression coefficient) as 0.8509 and 60.33 respectively. This result is in agreement with [17, 21] who reported that Dimensionless parameters with more than a 90 % correlation coefficient can be valid for predicting force and the model explains good precision with less average error in predicting force.

Table 5: Experimental and Predicted draught Force of animal-drawn mouldboard plough

SN	Treatment	Measured draught (N)	Predicted draught (N)
1	s_1d_1	381.40	379.15
2	s_1d_2	388.03	392.97
3	s_1d_3	400.01	400.98
4	s_2d_1	394.13	398.54
5	s_2d_2	417.07	414.97
6	s_2d_3	426.34	421.06
7	s_3d_1	403.22	406.87
8	s_3d_2	420.02	417.86
9	s_3d_3	435.40	432.22
	Mean	407.29	407.18
	Stdv	5.77	5.09
	SE	1.11	0.98
	CV	0.21	0.19

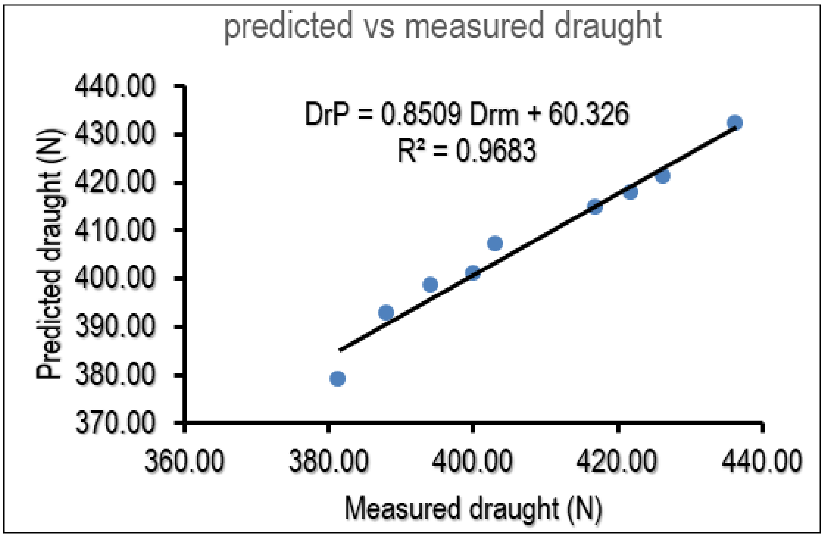

Figure 3: Predicted Draught against the Measured Draught for mouldboard plough

A paired t-test conducted for the means value of the predicted and measured data at 0.05 significant levels (Table 6) showed that the calculated t-value (0.2357) is less than the t-critical value (2.306). Hence, there is no significant difference between the predicted and the measured draught values for the mouldboard plough draught requirement (Table 5). The model has a high correlation with the measured data (Table 6). This result is in agreement with that reported by [8, 12, 24]. The measured output data was 0.03% greater than the predicted output. The likely discrepancies noted in the measured draught requirement values could be due to the assumptions regarding the homogeneity of the soil and strength parameters used in the model; and the unsteady interaction between the soil-tool interface arising from tool-frame instability and the soil movement over the mouldboard during the tillage operations.

Table 6: t-Test: Paired Two Sample for Means of Measured and Predicted Draught Data

	Measured Variable 1	*Predicted Variable 2*
Mean	407.29	407.18
Variance	36963.37	36920.70
Observations	9	9
Pearson Correlation	0.98384	
Hypothesized Mean Difference	0	
Df	8	
t Stat	0.23571	
P(T<=t) one-tail	0.40979	
t Critical one-tail	1.85955	
P(T<=t) two-tail	0.81958	
t Critical two-tail	2.306	

The results showed that the ploughing depth had a more pronounced effect on draught than the forward speed and other parameters. Increasing the ploughing depth increased the volume of soil to be cut, moved and pulverized which required more force. Similar results were reported by [5, 6, 8].

4.0. CONCLUSIONS

Field tillage operations were performed to generate input parameters for developing a model for draught force of a mouldboard plough. The highest draught means of 436.40 N was obtained in speed-depth combination of 1.25 m/s and 0.183 m and the lowest mean value of 381.47 N was obtained in speed-depth combination 0.69 m/s and 0.083 m respectively. The mathematical model equation $D = 0.7062\, I_m s^2 d^{-1} + 29577\, s^2 d^2 \rho\, M - 150284\, s^2 d^2 \rho$ has been developed to predict the relationship between the input parameters and draught force requirement of animal-drawn mouldboard plough tillage implement. The model input parameters include implement mass, operation speed, operation depth, soil moisture content, and bulk density. The least-squares linear statistical technique method is used for establishing the best relationship between variables. The differences between the means of the predicted and measured draught output are not statistically significant at a 5 % level of significance showing a high correlation with the measured data. The developed model can be used as a tool for strategic planning in tillage operations to improve the efficiency of draught animal power in crop production. Generally, this research solved the problem of lack of sufficient data input in the literature on the appropriate draught force for the design and utilization of animal-drawn mouldboard plough in the sandy loam soil of the savannah region.

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