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MODELING AND OPTIMIZATION OF DRAWBAR POWER NECESSITIES OF DISC PLOUGH IN SANDY–CLAY SOIL IN SOUTH–EAST NIGERIA

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Abstract: The incongruities between agro–ecological soil states demand statistical records of the performance of tillage equipment under various soil classifications for proper choice of implements to lessen cost, curtail energy loss, and upsurge agricultural output. This study was conducted to model and optimize the drawbar power requirements of disc plough on sandy–clay soil in South – East Nigeria that will help farmers predict the power requirements and detect the optimum value of power demand of the plough in order to select apposite plough subject to the soil type for proficient and bravura productions. Results showed that the highest drawbar power of 5.42kW was achieved when the plough was engaged at full working width of 180 cm, at tillage depth of 15 cm and least operational speed of 6km/hr. The statistical analyses carried out, revealed that tillage depth and operational speed has significant effect ($p < 0.05$) on the drawbar power of the disc plough as compared to the effective working width of the plough. The quadratic model was statistically significant for the response ($P < 0.05$). Results also pointed out that the coefficient of determination; R^2 was 0.9759 for drawbar power, which indicated high correlations amid the factors. The adequacy Precision of 19.912 obtained indicated decorous indicator and that the models could navigate the design space. The optimum drawbar power of 4.95kW was achieved with the desirability of 1.000 at optimal effective working width of 119.06 cm, ploughing depth of 13.71 cm and operational speed of 7.74kmh^{-1}. Farmers can henceforth, appraise and select the disc plough implements with the developed model equation.
Keywords: Agriculturists, drawbar power, disc plough, modeling, soil tillage

1. INTRODUCTION

Ploughing is an aspect of soil tillage carefully considered as a major farm operation intended to influence the soil to produce a seemly environment for plant growth and development. It is an exercise premeditated to fashioning a favorite soil environment for seeds from some adversarial original soil state by manipulating the soil with the purpose of increasing crop yield (Al–Suhaibani and Ghaly, 2010). Several tillage apparatuses are used by farmers to formulate seedbed. Upadhyaya *et al.* (2009) noted that the choice of tillage implements for seedbed preparation and weed control hinged on soil type and condition, type of crop, crop residues and weed type. One of the most tillage implements widely used by farmers in South–east Nigeria is the disc plough. Olatunji (2011) defined soil tillage as the mechanical influence of the soil aimed at improving soil environments for crop production; and added that it characterizes the most costly single item in the financial plan of an arable farmer. According to the researcher, tillage offers good weed control with minimum herbicide cost; permits the control of disease and insects by eliminating them through burying of crop residues.

The vigorous response of soil to tillage implements is a foremost factor in assessing their performance (Kareem and Sven (2019). The collaboration between tillage tools and soil is of a principal attention to the design and utilization of these tools for soil manipulation (Almaliki et al., 2016). Tillage process involves the most power and energy consumed on farms. Thus, draft and Power requirements are imperative in order to select the size of the tractor that could be used for a specific implement. Naderloo et al. (2009) noted that the draft required for a given contrivance is also affected by the soil conditions. Van Muysen *et al.* (2000) studied the effects of soil conditions, ploughing depth and speed of operation on soil translocation by chisel plow while Arvidsson *et al.* (2004) investigated the specific draft, energy requirement for moldboard plow, chisel plow and disc harrow under different soil conditions. They noticed that the specific draft was mostly the uppermost for the chisel plow and the least for the moldboard plow and the disc harrow and denoted that to the variances in contrivance geometry and manner of soil break–up. A good measure used to consider the fitness of an implement for tillage operation is the force required in drawing the contrivance to pulverize through the soil (Olatunji et al., 2009; McLaughlin et al., 2008).

One of the elementary thoughts in choosing farm tillage machinery is its size. The width of cut and operational speed is frequently enough records to appositely match the size of the device to the farming enterprise, similarly imperative in the selection is the consideration of the power requirements of the tools in order to match the agriculturalist's power unit. For the reason that the power necessities of tillage equipment are large, the suitability is typically critical. The greatest challenging use of the power unit will be achieved simply once the contrivance is matched appropriately to the tractor's obtainable power. The power requirements of tillage equipment are principally reliant on the operational speed and the tillage

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depth. Other features that affect the power requirements are soil bulk density, moisture content, texture, superficial trash situations, weed growth, compression and shear strength of the soil (McLaughlin et al., 2008). Moitzi et al. (2013) noted that, the overall drawbar power needed in soil tillage is reliant largely on the working depth. According to Boxberger et al. (2008), about 150 t/ha (soil density: 1.5 kg dm^{-3}) must be moved if 1 cm soil is tilled. Moenifar et al. (2014) noted that, tillage process requires the most energy and power used up on farms. Hence, draft and power requirements are essential in order to select the size of the tractor that might be used for a particular implement. The power and draft requisite for a specific device is also influenced by the soil environments and the geometry of the implement (Naderloo et al., 2009; Olatunji et al., 2009).

Study on the modeling and optimization of drawbar power necessities of disc plough is vital and a means of helping farmers in assessing and predicting the credible capabilities of ploughing equipment for suitable selection of the implement in view of the soil environment before acquiring and engaging the mechanism to work. The aim of this study is to model and optimize the drawbar power requirements of disc plough on sandy–clay soil in South – East Nigeria that will help farmers predict the power requirements and detect the optimum value of power demand of the plough in order to select apposite plough subject to the soil type for proficient and bravura productions in the region and other areas with similar soil type/conditions in assessing and selecting the tillage implement to reduce cost and lessen energy loss.

2. STUDY MATERIALS AND METHODS

Research Site

The research was carried out at the research farm of Michael Okpara University of Agriculture, Umudike (05° 25'N/ 7° 34'E), Abia State, Nigeria. The climatic state in the farm is categorized by a mean temperature of 27°C, yearly rainfall varying from 2250 to 2500mm and mean relative humidity of 75%, typical of tropical rain forest areas (Amanze et al., 2020). Sandy–clay is appropriate for arable farming.

The experimental area has average soil bulk density of 1.68 g/cm^3, porosity of 37.40%, moisture content varying from 12.35% to 18.90% (w.b) and granular in structure.

Tractor and plough used for the research

A Massey Ferguson tractor of model MF430E and capacity measuring 55.2kw with 3– point hitch device and a disc plough obtained from Works Department, Michael Okpara University of Agriculture was used for the research.

Field Test process

The tillage operation was conducted at selected effective working widths of 60, 120 and 180 cm and tillage depths of 10, 15 and 20 cm at selected forward speeds of 6, 7 and 8 km/hr using disc plough. The area worked and the equivalent time taken to till the area was recorded according to Oduma et al (2021).

Determination of Drawbar Power Requirement

Drawbar power is the power transmitted through the drive wheels or tracks to move the tractor and implement. It was evaluated from Equation 1 conferring to Rangapara et al. (2017)

$$\text{Drawbar power (kW)} = \frac{\textbf{Total Draft} \times \textbf{operating speed (km/hr)}}{\textbf{3.6}} \quad (1)$$

Experimental design

The experimental design adopted in the research work was a three level – three factor full factorial design. The experiment consists of three factors which were varied at three levels of tillage depths which include 10, 15, 20 cm, three levels of effective working widths of 60, 120 and 180 cm and three levels forward speeds (6, 7, and 8 km/hr). Central Composite Response Design which gives 17 test runs was performed for each sample using Equation 2 (Umani et al., 2019).

$$N = 2^k + 2k + n_c \quad (2)$$

where, N = number of test runs, k = experimental factors and n_c = Centre point

Table 1. Actual values, codes and levels of the test variables for design of experiments

Factors	Symbols	Codes and levels		
		–1	0	1
Working width (m)	A	60	120	180
Tillage Depth (cm)	B	10	15	20
Operational speed (km/hr)	C	6	7	8

In order to obtain the desired data, the range of values of every one of the 3 factors (k) was evaluated (Table 1). Working width, operational speed and tillage depth were adopted as independent factors for the

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drawbar power requirement of the plough. The response selected was the drawbar power, kW. Four repetitions of the center points were adopted in order to predict a well and concise approximation of errors; and the field experiments were conducted in randomized form.

Response Surface Methodology (RSM)

The Design Expert of version 11.0 was employed to design the experiment, analyze data obtained, optimize the practical factors and produce models for the estimation of the draft force and drawbar power of the disc plough. The quadratic, cubic, linear and two factorial interaction (2F1) models were designated to analyze the draft force and drawbar power of the implement; and the models were fixed to the generated experimental data.

Data obtained were analyzed using the Response Surface Methodology (RSM) to fit the quadratic polynomial equation gotten from the Design Expert Software as expressed in Equation (3) according to Chih et al. (2012).

$$Y = \beta_0 + \sum_{i=1}^{2} \beta i X i + \sum_{i=1}^{2} \beta ii X i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{2} \beta ij X i X j \qquad (3)$$

where: **Y** = Response; β_0 = constant term; $\sum_{i=1}^{2} \beta i$ = Summation of coefficient of linear terms; $\sum_{i=1}^{2} \beta ii$ = Summation of quadratic terms; $\sum_{i=1}^{2} \sum_{j=i+1}^{2} \beta ij$ = summation of coefficient of interaction terms; $XiXj$ = independent variables.

Also, the multiple regressions were adopted to fit the coefficient of the polynomial model to enable the response variables be correlated with the independent variables. The reliability of fit of the model, the discrete and interaction effect of the tillage parameters (effective working width, operational speed and depth of tillage) on the response (drawbar power) of the implement were evaluated using analysis of variance (ANOVA). Data attained were also subjected to statistical analysis to obtain the effects of the effective working width, operational speed and tilling depth and their interactions on the drawbar power of the implement at $\propto = 0.05$ using Minitab 17.0.

3. RESULTS AND DISCUSSION

Tillage maneuver

The Tillage process was accomplished at selected ploughing width (60, 120 and 180 cm) with designated speeds (6, 7 and 8 cm) and tillage depths (10, 15 and 20 cm), at soil moisture content varying from 12.35% to 18.90% (w.b) and the results of the drawbar power requirements of the disc plough was shown in Table 2. Results showed that the values of the drawbar power recorded during the ploughing operation ranged from 2.90 – 5.42kW for the range of working width (60 – 180 cm), operational speed (6 – 8 km/hr) and ploughing depth varying from 10 to 20cm.

Table 2. Randomized design layout of three levels –three factors full factorial composite design of experiment with actual and predicted values of draft force and power requirements of disc plough

Run order	Coded factors			Actual factors			Drawbar Power Requirements (kW)	
	A	B	C	Working Width (m)	Tillage depth (cm)	Operational speed (km/hr)	Actual values of Drawbar Power	Predicted values of Drawbar Power
1	0	0	0	120	15	7	4.71	5.489
2	0	0	0	120	15	7	4.71	5.489
3	0	0	0	120	15	7	4.71	5.489
4	0	0	0	120	15	7	4.71	5.489
5	0	0	0	120	15	7	4.71	5.489
6	1	0	1	180	15	8	5.21	5.299
7	1	0	–1	180	15	6	5.42	5.507
8	–1	0	1	60	15	8	2.90	5.355
9	–1	0	–1	60	15	6	3.79	5.523
10	1	1	0	180	20	7	5.31	5.474
11	1	–1	0	180	10	7	5.20	5.459
12	–1	1	0	60	20	7	3.50	5.453
13	–1	–1	0	60	10	7	3.47	5.443
14	0	1	1	120	20	8	5.31	5.383
15	0	–1	1	120	10	8	5.06	5.376
16	0	1	–1	120	20	6	4.06	5.522
17	0	–1	–1	120	10	6	3.95	5.506

Results revealed that the highest drawbar power of 5.42kW was achieved when the plough was operated at full working width of 180 cm, tillage depth of 15 cm and operational speed of 6km/hr. While the lowest drawbar power of 2.90 kW was recorded at operational speed of 8 km/hr, effective working width of 60

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cm and ploughing depth of 15 cm. The highest drawbar power recorded at least operational speed of the plough was in line with the observation of Oduma et al. (2021) in their study of the effect of soil type and operational speed on performance of some selected agricultural field machinery in south east Nigeria, where they noticed that plough recorded the highest field efficiency of 88.11% at least operational speed of 6 km h^{-1} in clay – loam soil as compared to other tillage implements and they propounded that at lower operational speed, the plough generates higher tractive and draft force required in its operation to initially break the compacted soil in order to create an enabling environment for the germination and proper growth of crops.

It was broadly noted that at different ploughing width and operational speed, the drawbar power increases with the increase in ploughing depth and increased to maximum of 70% at ploughing depth of 15 cm, speed of 6 km/hr and effective working depth of 180 cm. This result is reliable with the opinion of Ajav and Adewoyin (2012) in their research on the effect of depth and speed on tractor energy demand in sandy–loam soil of Oyo State, Nigeria, in which they observed that energy demand increases with tillage depth (31% rise from 20 to 25cm and 48% rise from 25 to 30cm depths). Nonetheless, the trivial variance in their results and the present research might be ascribed to the differences in soil situations amid dissimilar agro–ecological regions as indicated by Saeed et al. (2017).

Figure 1 shows the response surface plot of effective working width, speeds and tilling depths against the drawbar power requirement of the disc plough indicating the correlation between the factors and the response. Results of this figure revealed that the highest drawbar power of 5.42kW was achieved when the plough was engaged at full working width of 180 cm, at tillage depth of 15 cm and least operational speed of 6km/hr. The highest drawbar power attained at lowest operational speed of 6km/hr is in agreement with the observations of Olatunji (2011) and was accredited to the high tractive and draft force allied with low operational speed facilitating the device to penetrate deep and breakdown the resisting force and /or strength of the firmed soil thus producing a suitable ecological condition for root penetration and development as professed by Sale *et al.* (2013).

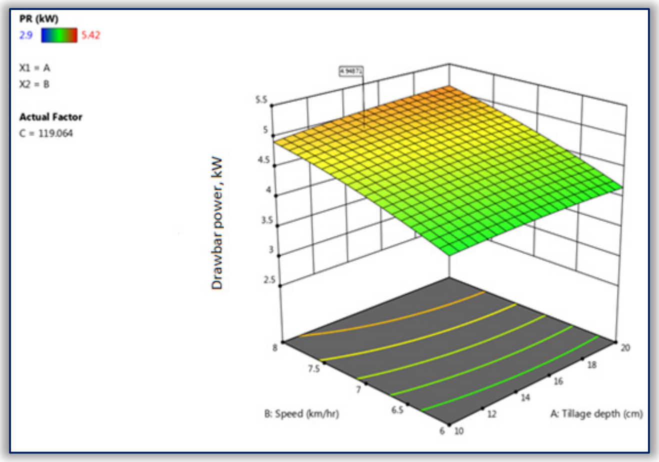

Figure 1. Response surface plot of working width, cutting depth and operational speed against power requirement of the disc plough in sandy–clay soil

Statistical analysis of results

The statistical analysis of the effects of tillage factors (effective working width, operational speed and tillage depth) on the drawbar power requirement of the disc plough is presented in the ANOVA results for drawbar power requirement in Table 3. This result indicated that the effect of tillage depth and operational speed on the drawbar power requirement are statistically significant ($P < 0.05$) which is in tandem with the findings of Kareem and Sven (2019). In broader sense it therefore implies that the mean drawbar power requirement vary for the different tillage depth and operational speeds. Inversely, the effect of the effective working width on drawbar power requirement of the plough is not statistically significant ($P > 0.05$) which is also an indication that the mean drawbar power requirement is not different for the effective working width of the plough.

Table 3. Analysis of variance for drawbar power requirement of disc plough

Source	Sum of Squares	df	Mean Square	F–value	p–value
A– Width	0.0312	1	0.0312	0.9744	0.3565
B– Tillage depth	1.50	1	1.50	46.66	0.0002
C–Speed	6.99	1	6.99	218.07	< 0.0001
Pure Error	0.0000	4	0.0000		
Total	9.30	16			

Model Equation of drawbar power requirements of disc plough

The drawbar power requirement of the disc plough in sandy–clay soil is dependent on the results illuminating the significant variation for combination of the operational speed, working width and tillage depth. The model coefficient, effect, contribution, test of lack of–fit and the significance of the factors and

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their interactions on the drawbar power were evaluated according to Fakayode *et al.* (2016) and Umani *et al.* (2019). Both linear and quadratic models were statistically significant for the response ($P < 0.05$) and therefore were suggested (Table 4). This implies that the significant model term was identified at 95% significance level. The quadratic model with the highest order polynomial ($R^2 = 0.9759$) and with significant additional terms as revealed in table 4 is designated. The quadratic model equation produced to estimate the drawbar power requirement relating to the independent variables (working width, operational speed and tillage depth) is as presented in Equation 4.

$$D_{PR} = 4.71 + 0.063A + 0.433B + 0.935C + 0.035AB + 0.020AC - 0.170BC - 0.038A^2 - 0.078B^2 - 0.303C^2 \quad (6)$$

Where D_{PR} = drawbar power, kW; A = effective working width, cm; B = tillage depth, cm; and C = operational speed, km/hr

Table 4. ANOVA of model summery statistics for drawbar power

Source	Sequential p–value	Lack of Fit p–value	Adjusted R^2	Predicted R^2	
Linear	< 0.0001		0.8964	0.8438	Suggested
2FI	0.6204		0.8863	0.7181	
Quadratic	0.0455		0.9449	0.6140	Suggested
Cubic			1.0000		Aliased

The model p–value of 0.0001 recorded in Table 5 is lower than the selected α– level of 0.05 indicating that the model is statistically significant. Therefore, the tillage depth and operational speed except the effective working width with p–value of (0.3565) have significant effects on the drawbar power of the plough. Thus, the model term p–values of 0.0002, 0.0001 and 0.0105 which are less than the selected α – level of 0.05 stipulate that the model expressions are statistically significant. As a result, B–tillage depth, C–operational speed and C^2 are significant model terms according to Table 5 which is in line with the findings of Oduma et al. (2022) and Ajav and Adewoyin (2012).

Table 5: ANOVA of response surface quadratic model for drawbar power requirement

Source	Sum of Squares	df	Mean Square	F–value	p–value
Model	9.08	9	1.01	31.46	< 0.0001
A– Width	0.0312	1	0.0312	0.9744	0.3565
B–Tillage depth	1.50	1	1.50	46.66	0.0002
C– speed	6.99	1	6.99	218.07	< 0.0001
AB	0.0049	1	0.0049	0.1528	0.7075
AC	0.0016	1	0.0016	0.0499	0.8296
BC	0.1156	1	0.1156	3.60	0.0994
A^2	0.0059	1	0.0059	0.1846	0.6803
B^2	0.0253	1	0.0253	0.7885	0.4040
C^2	0.3853	1	0.3853	12.01	0.0105
Residual	0.2245	7	0.0321		
Lack of Fit	0.2245	3	0.0748		
Pure Error	0.0000	4	0.0000		
Cor Total	9.30	16			

Model validation of the drawbar power requirement of disc plough

The results of validation of the generated model for the drawbar power of the disc plough are displayed in Table 6. According to this result, the model is significant with coefficient of determination, R^2 of 0.9759 and 0.9158 for quadratic and linear models which were respectively suggested. However, the quadratic model with the highest order polynomial ($R^2 = 0.9759$) and with significant additional terms is selected. The R^2 of the quadratic model (0.9759) shows remarkable relationships amid the independent variables and it specifies that the response model can elucidate 97.6% of the entire erraticism in the response. The simulation of the model equation achieved indicated that the drawbar power requirements of the plough fall within the trial range. The Predicted R^2 of 0.6140 was reliable with the Adjusted R^2 of 0.9449 according to Kothari (2014).The adjusted R^2 attained is also compatible with the R^2 of 0.9615 obtained by Almaliki et al. (2016). The adequacy Precision of 19.912 ratio reached is greater than 4 is suitable, establishing an allowable signal and that the model may possibly be espoused to navigate the design space.

Table 6. ANOVA of validation of model term for drawbar power

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	0.2455	0.9158	0.8964	0.8438	1.45	Suggested
2FI	0.2571	0.9289	0.8863	0.7181	2.62	
Quadratic	0.1791	0.9759	0.9449	0.6140	3.59	Suggested
Cubic	0.0000	1.0000	1.0000		*	Aliased

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Optimization of the drawbar power requirement of disc plough

The optimization of the drawbar power requirement of disc plough was conducted using design expert in response surface methodology. Figure 2 presents the response plot of the optimization process with the optimum functional factors of effective working width of 119.06 cm, operational speed of 7.74kmh^{-1} and ploughing depth of 13.71 cm. Correspondingly, the optimum drawbar power requirement of 4.95kW was obtained and the desirability of 1.00 was obtained for the response. The optimum speed and depth which gave the optimum drawbar power in this study fall within the values (optimum depth of 15cm and 7km/hr) obtained by Kareem and Sven (2019) in their study of effect of ploughing depth, tractor forward speed, and plough types on the fuel consumption and tractor performance. However the slight difference may be ascribed to the variation in ecological soil conditions.

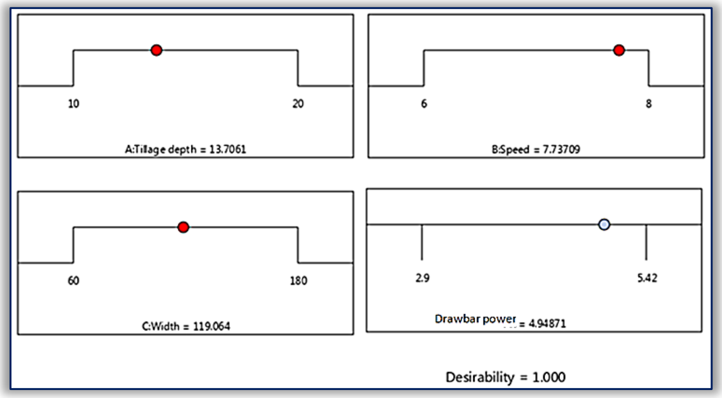

Figure 2. Optimization plot of effective working width, operational speed, tillage depth and drawbar power requirement of disc plough

4. CONCLUSIONS

The modeling of the drawbar power requirement of disc plough on sandy–clay soil in South–East Nigeria was meritoriously carried out. In the course of the ploughing process, it was noticed that the highest drawbar power of 5.42kW was achieved when the plough was engaged at full working width of 180 cm, at tillage depth of 15 cm and least operational speed of 6km/hr. The statistical analyses carried out, showed that the quadratic model was recommended for the prediction of the drawbar power requirement of the disc plough.

The developed models and the coefficients were statistically significant. The predicted and adjusted R^2 values were determinedly consistent. Hence, the investigational values were apposite with the coefficient of determination ($R^2 = 0.9759$), proposing excellent correlations amid the independent variables.

Tillage depth and operational speed has significant effect ($p < 0.05$) on drawbar power of the disc plough as compared to the effective working width of the plough.

The obtained models will help farmers in evaluating the enactment of the disc plough for proper selection and engagement to work.

The optimum drawbar power of 4.95kW was achieved with the desirability of 1.000 at optimal effective working width of 119.06 cm, ploughing depth of 13.71 cm and operational speed of 7.74kmh^{-1}.

Disparities emanates in soil situations as well as characteristics between various ecological areas; it is henceforth recommended that further investigations need to be conducted in different regions to obtain records and model equations which can estimate and/or optimize the drawbar power requirement of disc plough task and other tillage implements on diverse soil categories for apposite selection of tools for soil preparation, in order to increase agricultural productivities, minimize expenses, subside energy consumption and unnecessary failures and breakdown during field operations.

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