Development of empirical regression equations for predicting the performances of disc plough and harrow in clay-loam soil

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Abstract: A research was conducted to develop some empirical regression equations that could be used to predict the performances of disc plough and harrow on clay – loam soil in South – East agro – ecological region of Nigeria, and then to enable farmers, and users of these farm machinery assess and select appropriate implements based on soil type and conditions for their agricultural operations. It will be used to avoid unnecessary breakdown/failures, energy wastage and to optimize production at reduced cost. Performance indicators studied include field efficiency, effective field capacity, theoretical field capacity and material capacity of the implements. Results showed that, for plough operated in clay – loam soil, the regression equations could be used to predict its various performance indicators, including: $Y = 0.067x^2 – 0.7733x + 89.283$, respectively for field efficiency; $Y = 0.0864x^2 – 1.4406x + 6.8173$ for effective field capacity; $Y = 0.0026x^2 – 0.0877x +1.7641$ for theoretical field capacity and $Y = 0.0888x^2 – 1.6513x + 49.11$ for material efficiency. While for harrow operated on the same soil, the regression equations were $Y = –0.3745x^2 + 7.4659x + 50.757$; $Y = –0.0056x^2 + 0.1486x + 0.3631$; $Y = 0.0041x^2 + 0.0885x + 0.9156$, $Y = 0.1952x^2 – 0.6095x + 84.343$ for field efficiency, effective field capacity, theoretical field capacity, and material capacity. The coefficient of determination, R^2 obtained for the regression equations ranged from 0.71 to 0.9838. This showed that the performance indicators and the operational speeds were highly correlated and that the developed equations and the predicted values were adequate. Furthermore, the error root mean square (ERMS) obtained in the comparison of the experimental result and the developed regression equation results ranged from 4.30% to 6.80% for plough operation and 2.80% to 4.10% for harrow operation. The comparison revealed that the equations broadly did not over or under- predict the experimental results, thus, the prediction errors (i.e. ERMS) were within allowable range of ±5%. However, the little deviation in the prediction of some performance indicators in ploughing operation was attributed to variations in soil conditions/characteristics.

Keywords: empirical, harrow, plough, performances, regression equations, soil type

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1 Introduction

Today’s competitive agricultural market demands better utilization/management of resources and minimization of operating costs in order to maximize profits. One of the major costs of every agricultural production system is machinery cost. Increasing the performance efficiency of farm machinery will lead to cost reduction. Farmers like other business ventures strive to cover up their expenditures in addition to the cost of the machinery. This is why Yohanna and Ifem (2000) noted that an intelligent and well experienced farmer tried to make proper use of farm inputs (seeds, fertilizers, herbicides or insecticides, irrigation water and farm equipment) So as to reduce cost. In Nigeria farm

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mechanization technology has continually been import-oriented. Agricultural machines and equipment are imported into the country to aid the various governments' mechanization policies (Oluka, 2000). Presently, the cost of importation of agricultural machinery has been sky rocketed due to the devaluation of the local currency and to operate within such a bad economic condition. Machinery managers, owners and/or users must be careful in selecting and purchasing new machinery. It is therefore necessary that the users should know how a machine performs a given task and the rate at which it does the work without failure or breakdown and at minimal loss of energy and time.

Efficient machinery utilization and/ or management needs accurate performance data on the capabilities of the individual machines to achieve a given work schedule and to obtain a balanced mechanization system by matching the performance of different farm equipment. The variation in agro-ecological soil condition also requires the knowledge of the field efficiencies or capabilities of the coupled implements. However, producers of those machines do not make the data available for the farmers in Nigeria. It should have been a better guide in the selection of the implements based on the soil differences applicable in various agricultural regions in Nigeria.

Oduma et al. (2015) noted that farmers are prudent and much concerned about the quality and quantity of the performances of their machines during operation to ensure that they were able to recover the expenses incurred either in hiring/purchase or maintenance of such machinery. Sale et al. (2013) maintained that agricultural operation was highly sensitive to time and weather conditions, and much money are involved in the investment, thus, it was wise to assess the capacitive performance of farm machines for better selection, optimization of production and proper farm scheduling. Oluka (1998) also noted that it was necessary to consider the various indicators associated with the cost of owning and operating tractors, to enable a farmer know if he/she was making profit or loss in the farm business by using a tractor.

Development of empirical model is an essential and simple way of assisting the farmers, farm managers and other users of agricultural machinery both at subsistence and commercial level in assessing and predicting the possible performance capabilities of farm machinery in order to make proper selection of the equipment based on soil type/conditions and season of operation before purchasing and/or engaging any machine to work. This will go a long way to reduce failures, unnecessary break down, mismatching of implement to prime movers, minimize fuel consumption (energy loss), reduce cost and generally maximize production and profit.

The objective of this work is to develop empirical model equation that will be used to predict the field performances of tractor hitched plough and harrow implement in clay-loam soil in South-east agro ecological region of Nigeria.

2 Materials and method

2.1 Materials

2.1.1 Description of the experimental site

The experimental sites have average area of 8100 m^2 (0.81 ha) each. The land area was divided into four units of 45×45 m^2 each for random observations. Each unit was separated by a distance of 2.5 m from the other to avoid interaction between the plot borders and to be equally used as head lands for the commencement of the experimental operations.

The tests were conducted in May, through June, July, August, September and October, 2016. These months were coincide with planting season of the year, and also offered the tractor and the hitched implements an exposure to wide range of soil conditions.

2.1.2 Description of Machine used and its operation

A Massey Ferguson tractor with 3- point hitch systems and age of five months from date of first-hand purchase was hired with the hitched implements and used for the study. The same operator was used to operate the machine throughout the test to ensure minimal variation in the operation skill and style throughout the study. Each field operation (test) starts in the morning (9:00 am) and lasts for 2.5 hrs to ensure that the operator did not get weary during the operation and the machines are properly checked for faults before being engaged to work. This is to minimize delays or unnecessary failures and to ensure optimum production time during operation.

2.2 Methods

2.2.1 Determination of soil physical properties

Some soil physical properties such as moisture contents, bulk density, soil structure, texture, porosity, which affect implement performances, were examined by using the method adopted by Oduma and Oluka (2017) before conducting the test.

2.2.2 Field Performance Characteristics Test

The field operations were generally performed longitudinally at selected forward speeds, the distance travelled and the corresponding time taken to complete the working distance noted. The total productive and delay time were recorded (Afzalina et al., 2006). The speed selections were made within the speed range recommended by Hunt (2013) for tillage. The implement performance indicators such as field efficiency, effective field capacity, theoretical field capacity and material efficiency were evaluated.

2.2.3 Measurement of Productive and Delay (Idle) Time

The total time spent on the entire row length operation and the delay or idle time encountered in the operation which include, time for refilling the tank, time for repair of breakdown/adjustments, turning time, and any other idle time observed were noted and the actual time (productive time) used in the operation was evaluated from equation (1) according to Oduma et al. (2015);

$$T_e = T_t - T_d \quad (1)$$

where, T_e = actual (productive) time, hr; T_t = total time spent on the entire row length operation, hr; T_d = delay (idle) time, hr.

Three replications were taken as the working time.

2.2.4 Determination Field Efficiency

The field efficiency was determined from the expression suggested by Kepner et al. (1982)

$$\varepsilon = \frac{100T_e}{T_t} \quad (2)$$

where, ε field efficiency, %; T_e = actual working (productive) time, hr; T_t = total working time = (T_e + T_d), hr; T_d = delay or idle time.

2.2.5 Determination of the Effective Field Capacity

The effective field capacity was determined by noting the speed of operation, implements working width and the field efficiency of the machine; and then was evaluated from the expression suggested by Hunt (2013)

$$Ce = \frac{SWe}{c} \quad (3)$$

where, Ce = effective field capacity, hahr^{-1} [ahr^{-1}]; S = speed, kmh^{-1} [mihr^{-1}]; W = rated width of implement, m [ft]; e = field efficiency as a decimal; c = constant, 10 [8.25].

2.2.6 Determination of Theoretical Field Capacity

The Theoretical Field Capacity was determined by rearranging the expression suggested by Gbadamosi and Magaji (2004) for field efficiency and obtained a new relationship for theoretical field capacity as follows: (Gbadamosi and Magaji, 2004).

$$\varepsilon = \frac{Ce}{C_t} \quad (4)$$

By rearrangement,

$$C_t = \frac{Ce}{\varepsilon} \quad (5)$$

where, C_t = theoretical field capacity, ha hr^{-1}; Ce = effective field capacity, ha hr^{-1}; ε = field efficiency, decimal.

2.2.7 Determination of the Material Capacity

The machine material capacity was determined by noting the speed of operation, implement working width, the field efficiency of the machine and the weight of soil scooped (for tillage implements). But for the planter, the quantity/weight of seeds loaded in the hopper was obtained from the Equation (6) (Hunt, 2013).

$$M = \frac{Swey}{c} \quad (6)$$

where, M = material capacity, kg hr^{-1}; y = yield/mass of material handled, kg m^{-2}; s = implement/machine speed, km hr^{-1}; w = implement working width, cm; e = implement field efficiency, %; c = constant = 10.

2.10 Regression Equation Development

The data obtained from the study were subjected to regression analysis and empirical regression equations for predicting the implement performances at different operation speeds were developed.

2.11 Determination of the adequacy of the equations

The adequacy of the equations developed from the study were determined by comparing the results obtained from the experiment with the model results using percentage error (Equation (7)) suggested by Onwualu et al. (1998).

$$Error = \frac{\text{Regression Result} - \text{Experimental Result}}{\text{Experimental Result}} \quad (7)$$

Thereafter, the root mean square (RMS) of the error was evaluated to determine the accuracy of the predicted results. The predictions were considered accurate if the RMS errors of the prediction were within the tolerable limit of ±5%. Moreover, the coefficient of determination (R^2) indicates the adequacy of the model if it is within the limit of 0 and 1 (Kothari, 2014).

3 Results and Discussion

3.1 Soil physical characteristics before and after tillage

Table 1 showed the physical properties of the soil under the study before and after the field operation. Before the field test the soil had average moisture content of 17.6% (w.b), bulk density of 1.68 kg m^{-3} and average porosity of 34.40%. Then after the operation, the ploughed soil recorded average moisture content of 16.3%, bulk density of 1.54 kg/cm^3 and porosity of 45.22%. While harrowed soil recorded 15.5% (w.b), 1.49 kg cm^{-3}, and 48.18% for moisture content, bulk density and porosity respectively. The lower moisture contents and bulk density with higher porosity were observed in this study as compared to the initial values which were an indication of soil improvement resulting from tillage operations. That was why Eje and Oluka (1999) maintained that the primary aim of tillage operation was to change the physical conditions of the soil such as the soil moisture contents, structure, bulk density etc. and create a good environment for crop growth, development and better yield. These changes implied a change of soil air, water distribution characteristics, resistant to root penetration, weed and erosion control through proper tillage operation.

Table 1 Physical characteristics of the soil in the area studied.

		Percentage of soil content/type				Average Moisture content (%) w.b	Average Bulk density (g cm^{-3})	Average Porosity (%)	Structure type
		Sand (%)	Silt (%)	Clay (%)	Textural class				
Before tillage		34.9	35	68	Clay-loam	17.6	1.68	37.40	Granular
After tillage	Ploughing	34.9	35	68	Clay –	16.3	1.54	45.22	Granular
	Harrowing	34.9	35	68	loam	15.5	1.49	48.18	Granular

3.2 Implement performances on clay-loam soil

Table 2 presents the field performance of the implements studied in clay – loam soil. Results of this table indicated that the disc plough had field efficiency range of 85.74% to 87.91%; effective and theoretical field capacities range of 0.846 to 1.031 ha hr^{-1} and 0.987 to 1.184 ha hr^{-1} respectively; and material efficiency of 35.67 to 43.46 kg m^{-2} at speed range of 5.48 to 6.58 km hr^{-1} and average moisture content of 16.3% (w.b) with the bulk density varying from the initial value of 1.68 to 1.54 kg cm^{-3} after plouhing. The disc plough had its optimum field efficiency of 87.91% at the operation speed of 6 km hr^{-1} and at cutting depth of 25.2 cm.

On the other hand, results (Table 2) also revealed that harrow recorded efficiency range of 87.17% to 87.98% with effective and theoretically field capacities of 0.931 to 1.458 ha hr^{-1} and 1.151 to 1. 667 ha hr^{-1} respectively and material efficiency range of 86.89 to 105.36 kg m^{-2} at tractor speed range of 5.72 to 6.22 km hr^{-1} and average moisture content of 15.5% with the bulk density varying from initial value of 1.68 to 1.49 kg m^{-3} after harrowing. The harrow recorded optimum field efficiency of harrow was 87.98% at working speed of 9 $kmhr^{-1}$ and at cutting depth of 21.3 cm. The field efficiencies obtained for tillage implements in the study are within the typical ranges of field efficiencies of implement recorded by Yohanna (1998). The efficiencies also fall within the ranges obtained by Sale et al. (2013), and Oduma et al. (2015); but was slightly higher than the efficiencies obtained by Kaul and Egbo (1985) for tillage implements. The variations in the efficiencies may be due to the differences in field conditions/physical characteristics, frequent breakdown/down times, skill of operation etc encountered in different agricultural/ ecological zones as observed by Oduma and Oluka (2017).

3.3 Developed empirical regression equations

Table 3 shows the results of the empirical regression equations developed from the experimental results for predicting the performances of the implements in clay – loam soil. Results showed that for plough operated in clay

– loam soil, the regression equations that can predict its various performance indicators are: field efficiency, $Y = 0.067x^2 - 0.7733x + 89.283$; effective field capacity, $Y = 0.0864x^2 - 1.4406x + 6.8173$; theoretical field capacity, $Y = 0.0026x^2 - 0.0877x + 1.7641$ and material efficiency, $Y = 0.0888x^2 - 1.6513x + 49.11$. Where X in the models represents trial number corresponding to the speed of field operation and Y represent the implement performance indicators.

Furthermore, results of Table 3 also showed the model equations developed for predicting the field performances of the harrow implement in clay - loam soil under different soil conditions. For field efficiency the equation is $Y = 0.067x^2 - 0.7733x + 89.283$; effective field capacity, $Y = 0.0864x^2 - 1.4406x + 6.8173$; theoretical, $Y = 0.0026x^2 - 0.0877x + 1.7641$ and material efficiency, $Y = 0.0888x^2 - 1.6513x + 49.11$. The values of X and Y are as earlier defined.

Table 2 Field performance of plough and harrow in clay-loam soil under different conditions.

Implements	Operation speed, km/hr	Working width (cm)	Av. speed (km/hr)	Plowing Depth (cm)	Operation time (mins)			Mass of soil handled (kg)	Field efficiency (%)	Effective field capacity (ha/hr)	Theoretical field capacity (ha/hr)	Material efficiency (kg/m^2)
					Delay time	Productive time	Total working time					
Plough	5	180	6.58	24.5	20.22	136.28	156.50	42.15	87.08	1.031	1.184	43.46
	6	180	6.24	25.2	18.12	134.26	152.38	42.15	87.91	0.990	1.123	41.73
	7	180	6.24	26.0	20.12	135.19	155.31	42.15	87.05	0.978	1.124	41.22
	8	180	6.55	24.5	21.09	134.50	155.31	42.15	86.45	1.019	1.179	42.95
	9	180	5.48	24.2	23.21	139.53	162.74	42.15	85.74	0.846	0.987	35.67
	10	180	6.38	25.5	20.00	136.58	156.56	42.15	87.24	1.002	1.149	42.23
	mean	**180**	**6.34**	**25.1**	**21.16**	**134.56**	**87.15**	**42.15**	**86.91**	**0.990**	**1.140**	**41.93**
Harrow	6	225	5.72	20.5	25.33	120.14	145.47	81.74	82.59	1.063	1.287	86.89
	7	225	6.00	22.0	24.26	122.16	146.38	81.74	83.42	1.126	1.350	92.04
	8	225	6.08	21.5	25.16	128.27	153.43	81.74	87.17	1.097	1.368	89.67
	9	225	6.51	20.5	17.22	126.10	143.32	81.74	87.98	1.289	1.465	105.36
	10	225	6.13	20.5	19.40	128.23	147.63	81.74	86.70	1.196	1.379	97.76
	11	225	6.22	21.3	16.24	125.72	141.96	81.74	88.56	1.239	1.399	101.28
	mean	**225**	**6.57**	**21.7**	**18.67**	**124.21**	**145.56**	**81.74**	**85.78**	**1.248**	**1.444**	**103.04**

Table 3 Empirical regression equations for predicting performance indicators of the implement in different in clay loam soil in south-east Nigeria

Field operations	Performance indicators	Regression equations	Coefficient of determination, R^2
Ploughing	Field efficiency ($\mathcal{E}$)	$Y = 0.067x^2 - 0.7733x + 89.283$	0.9838
	Effective capacity (Ce)	$Y = 0.0864x^2 - 1.4406x + 6.8173$	0.8081
	Theoretical field capacity (Te)	$Y = 0.0026x^2 - 0.0877x + 1.7641$	0.909
	Material efficiency (Me)	$Y = 0.0888x^2 - 1.6513x + 49.11$	0.71
Harrowing	Field efficiency ($\mathcal{E}$)	$Y = -0.3745x^2 + 7.4659x + 50.757$	0.9149
	Effective capacity (Ce)	$Y = -0.0056x^2 + 0.1486x + 0.3631$	0.9007
	Theoretical field capacity (Te)	$Y = 0.0041x^2 + 0.0885x + 0.9156$	0.8894
	Material efficiency (Me)	$Y = 0.1952x^2 - 0.6095x + 84.343$	0.9144

3.4 Validation result of the regression equations

The results of validation of the developed empirical regression equations is presented in Table 4. Results as recorded in this table indicate that in ploughing operation, the prediction error for field efficiency range from 0.94% to 4.48% with error root mean square (ERMS) of ±4.48%, while the effective and the theoretical capacity recorded 0.01% to 13.5% (±ERMS of 6.32%) and 1.86% to 2.14% (ERMS of ±5.01%), respectively and material efficiency recorded 1.46% to 12.8% with error root mean square of ±6.81%.

Additionally, in harrowing, the prediction error in field efficiency range from 0.25% to 7.77% ERMS of ±3.62% while the effective and theoretical field capacity had prediction errors of 1.15% to 4.83% (ERMS of ±2.82%) and 0.22% to 3.26% (ERMS of ±4.11%, respectively and material efficiency of 1.12% to 4.83% with ERMS of ±4.12%.

The comparison of the predicted results with the experimental results of the study revealed that the models broadly did not over or under- predict the experimental results, thus, the prediction errors were within the allowable range. Moreover, from the root mean square error analysis, the errors were within acceptable limitation of ±5%. However, the little deviation in the prediction of some performance indicators in ploughing operation was attributed to variations in soil conditions/characteristics.

Table 4 Validation or Comparison of the field experiment and model equation results for ploughing operation

Implement	Operation Speed, (km/hr)	Field efficiency (%)			Effective field capacity (ha/hr)			Theoretical field capacity (ha/hr)			Material efficiency (kg/m^2)		
		Exp.	Mod	Error (%)	Exp.	M od	Error (%)	Exp.	Mod	Error (%)	Exp	Mod	Error (%)
Plough	5	87.08	87.47	4.48	1.031	1.016	–1.45	1.844	1.162	–1.86	43.46	42.82	–1.46
	6	88.11	87.26	–0.96	0.99	1.002	1.21	1.123	1.147	2.14	41.73	42.18	1.08
	7	87.05	87.08	0.03	1.978	0.988	–0.01	1.124	1.132	0.71	41.22	40.53	–1.67
	8	86.45	86.84	–4.51	1.019	0.974	–4.42	1.179	1.117	–5.3	42.95	40.89	–4.8
	9	85.74	77.18	–9.77	0.847	0.960	13.5	0.981	0.912	–7.6	35.67	40.24	12.8
	10	87.24	86.42	–0.94	1.002	0.946	–5.6	1.149	1.059	–7.83	42.23	38.35	–9.19
	ERMS			**4.48**			**6.3**			**5.0**			**6.8**
Harrow	6	82.59	83.68	1.32	1.063	1.076	1.22	1.287	1.329	3.26	86.899	88.01	1.29
	7	83.42	85.04	1.94	1.126	1.113	–1.15	1.350	1.347	–0.22	2.04	91.01	–1.12
	8	80.17	86.40	7.77	1.097	1.150	4.83	1.368	1.365	–0.22	89.67	94.00	4.83
	9	87.98	87.76	–0.25	1.289	1.187	–7.91	1.465	1.387	–5.60	105.8	97.00	–8.28
	10	86.70	89.12	2.79	1.196	1.224	2.34	1.379	1.401	1.60	97.76	99.99	2.28
	11	88.56	90.48	2.17	1.239	1.261	2.73	1.399	1.419	1.43	101.3	102.9	1.68
	ERMS			**3.6**			**4.1**			**2.8**			**4.1**

Note: ERMS = Error root mean square.

3.5 Effect of speed on the implement speed

Figure 1 showed the curves of the plough performance plotted against the speeds of operation on clay-loam soil of the study area. The curves revealed that maximum performance of the plough was recorded within the forward speeds of 6 km hr^{-1}. The higher the speed, the higher the field efficiency and the lower the theoretical and effective field capacities of the plough. This was consistence with the observations of Hunt (2013). The theoretical and effective field capacities maintained very small values and did not vary much with the speeds of the plough operation (i.e. they maintained almost constant values with the speed of operation). The curves finally, revealed that the field efficiency was higher than the material efficiency of the plough. The coefficient of determination, R^2 with values varying from 0.7 to 0.9 indicated that the performance indicators were highly correlated with the speeds of implement operation.

Furthermore, the curves of harrow performances against its working speeds (Figure 2) indicated that maximum performance of the harrow was recorded within the speed range of 9 km hr^{-1}. Like the ploughing operation, the higher the speed, the higher the field efficiency and the lower the theoretical and effective field capacities of the harrow. The material efficiency was higher than the field efficiency, and could be attributed to higher soil-implement interaction observed in harrow operation than ploughing operations; and as evidence, the harrow recorded the best soil performance indicators as compared to plough. The coefficient of determination, R^2 with values varying from o.8 to o.9 indicated that the performance indicators were highly correlated with the speeds of implement operation which showed that the developed regression equation were consistent.

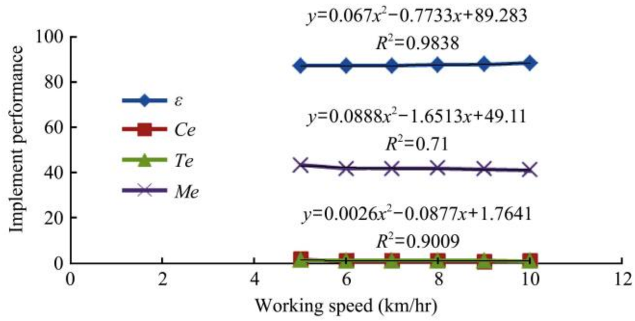

Figure 1 Performance versus speed of disc plough in Clay-loam soil

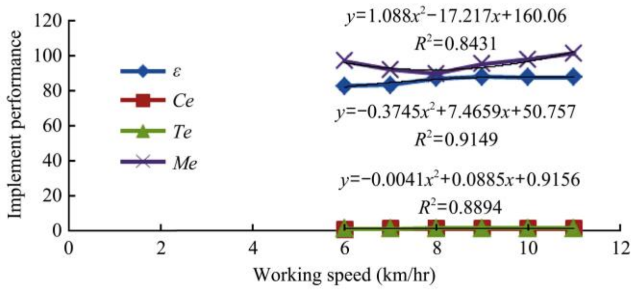

Figure 2 Performance versus speed of disc harrow in clay-loam soil

3.6 Comparison of results of field experiment and the regression equations

The plots of the model confirmatory tests (comparison of results of field experiment and the developed empirical regression equations) presented in Figures 3 and 4 indicated that the fitted functions for the prediction of the implements performances were good fits for the machine efficiency responses and could be used for predicting performances of the implements with the predicted values having a percentage error of ±5%.

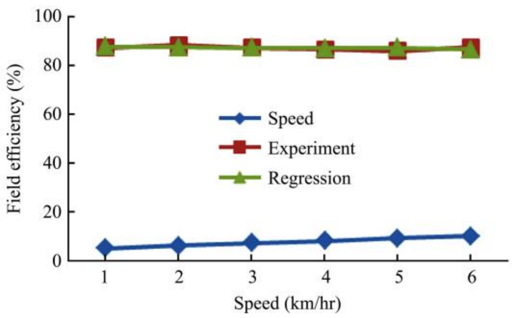

Figure 3 Confirmatory test for field efficiency of plough in clay-loam soil

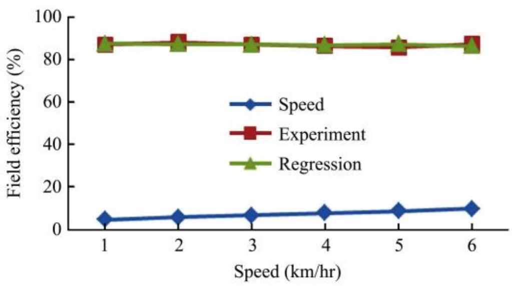

Figure 4 Confirmatory test for field efficiency of plough in clay-loam soil

4 Conclusion

The following conclusions can be made from the present study:

i. Tillage operation generally improved the soil condition for seed germination, growth, proper root penetration in the soil and good yield.

ii. Plough recorded the optimum field efficiency of 88.11% at speed of 6.24 km hr^{-1} and cutting depth of 25.2 cm.

iii. Harrow had the optimum field efficiency of 88.55% at speed of 6.22 km hr^{-1} and cutting depth of 21.3 cm.

iv. Harrow had better soil- machine performance indicators range of 82.59%-98.54% for efficiency than the disc plough with field efficiency range of 85.74%-

87.98%).

v. The comparison between the predicted results and the experimental results revealed that the models did not over or under- predict the experimental results. The prediction errors were within allowable range.

vi. The coefficient of determination R^2 with values differing from 0.7 to 0.9 was an indication that the performance indicators and the speeds of operation were highly correlated and that the model developed were adequate for predicting the performances of the implements.

Recommendations

Differences exist in soil conditions/properties among different agricultural or agro-ecological areas; it is therefore recommended that more studies should be conducted in other areas to provide data and mathematical models that can predict the performances of different tillage machines on other soil types for proper selection of machines for seed bed preparation in other to increased production, minimize production costs, loss/wastage of energy, and unnecessary failures or breakdown during operation.

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