Draft and power requirements for some tillage implements operating in clay loam soil

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Abstract: Draft and power requirement for some tillage implements operating on clay loam soil were determined in the study. The implements included a three-bottom disc plough, a spring tine cultivator and an offset disc harrow. The effects of speed (3.6, 5.4, 7.2, 9.0 and 10.8 km hr^{-1}) and depth (10, 20 and 30 cm) upon the draft and power requirements were investigated. Soil analysis test, tractor and implement specifications and results of tillage experiments are reported. A general regression equation to predict draft and power requirements of these implements on a clay loam soil was developed based on speed and depth parameter. These can be used to predict the required draft and power during the design of tillage implements. A significant increase in draft and power requirements at 0.05 level of significance was observed for all the implements with an increase in depth and speed. At a tillage depth of 10 cm, draft and power requirements for three-bottom disc plough at 0.82 m s^{-1}; spring tine cultivator at 0.74 m s^{-1} and offset disc harrow at 0.79 m s^{-1} were 1.34 kN and 1.10 kW; 0.15 kN and 0.11 kW and 1.22 kN and 0.96 kW. Three-bottom disc plough and spring tine cultivator has the highest and lowest draft and power requirements respectively in clay loam soil.

Keywords: draft, power requirement, moisture content, tillage

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1 Introduction

Tillage of soil is considered to be one of the most difficult farm operations (Finner and Straub, 1985) reported by Al-Suhaibani et al. (2010). Gill and Berg (1968) defined tillage as a process aimed at creating a desired final soil condition from some undesirable initial soil conditions through manipulation of soil for seeds with the purpose of increasing crop yield. Several tillage implements are used by farmers to prepare seed bed. However, the selection of tillage implements for seed bed preparation and weed control depends on soil type and condition, type of crop, previous soil treatments, crops residues and weed type (Upadhyaya et al., 2009). Tillage operation requires the most energy and power spent on farms. Therefore, draft and power requirements are important in order to determine the size of the tractor that could be used for a specific implement. The draft required for a given implement is also be affected by the soil conditions and the geometry of the tillage implement (Taniguchi et al., 1999; Naderloo et al., 2009; Olatunji et al., 2009).

Draft and power requirements are important parameters for measuring and evaluating the performance of tillage implements and therefore are considered as essential data when attempting to correctly match a tillage implement to a tractor. Many studies have been conducted to measure draft and power requirements of tillage implements under various soil conditions. The ASAE Standards (1994) provide mathematical expressions for draft and power requirements for tillage implements in several soil types as part of the ASAE Data D497.

Implement width, operating depth and speed are factors that affect draft of a tillage implement. The effect

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of speed on implement draft depends on the soil type and the type of implement. It has been widely reported that the draft forces on implements increase significantly with speed and the relationship varies from linear to quadratic (Grisso et al., 1994). Depth has an obvious effect on implement draft. Harrigan and Rotz (1994) proposed a simple function for a range of soil conditions to model tillage draft under general conditions, where draft per unit width or cross- sectional area of the tilled zone is a function of soil type and the speed at which the implement is pulled. In the proposed model, the authors categorized soil as fine, medium and coarse. These categories were described as corresponding to clay, loamy and sandy soils, respectively.

Presently, there is a shortage of data on draft and power requirements of agricultural implements operating on different soils in Uyo. This drawback could affect advancement in tillage implements operation in a clay loam soil. Therefore, the objectives of this study were to determine the effects of speed and depth on the draft and power requirements of three commonly used tillage implements on clay loam soil and to develop regression equations for draft and power requirements based on speed and depth.

2 Materials and methods

2.1 Soil preparation and implements selection

Experiments were conducted at the University of Uyo's Agricultural research and experimental farm. The soil at the experimental site is clay loam. Soil from the field was classified by mechanical analysis. Soil samples were collected during the tillage experiments to determine the average moisture contents, soil bulk density, cohesion and adhesion and other soil parameters to determine soil conditions under which the experiments were conducted. The samples were weighed using a balance and the weight of each sample was recorded. Then the samples were placed in an oven maintained at 110°C for 48 hours. The dried soil samples were reweighed and the weight was again recorded. The moisture contents were calculated on a dry weight basis as follows:

$$Moisture\ content = \frac{wet\ weight - dry\ weight}{dry\ weight} \times 100 \quad (1)$$

A set of primary and secondary tillage implements comprising a three-bottom disc plough, and offset disc harrow and a spring tine cultivator were used in this study for evaluating draft and power requirements over a wide range of implement forward speed and tillage depths. These implements are representative of the standard primary and secondary tillage implements most commonly used for seedbed preparation in Akwa–Ibom State and the study location. They were owned by the Department of Agricultural Engineering, University of Uyo. Tractor and implement specifications are given in Tables 1 and 2, respectively.

Table 1 Specifications of tested tractor

Specification parameter	Value
Type/model	Swaraj tractor, model 978 FE
Effective output (hp)	72
Type of Engine	four-cylinder
Type of Fuel	Diesel
Type of steering system	Power assisted
Type of injector pump	In – line injector
Fuel tank capacity (L)	98
Lifting capacity (kg)	1250
Rated engine speed (rpm)	2200
Type of cooling system	Water – cooled
Country of manufacture	China
Front tyres (size)	6.0-16
Inflation pressure (kPa)	360
Rear tyres (size)	14.9-28
Inflation pressure (kPa)	180

Table 2 Specifications of implements used during field test

S/N	Item	Disc Plough	Tine Cultivator	Offset disc harrow
1.	Type	mounted	mounted	mounted
2.	Number of bottoms/discs/share blade	3	14	18
3.	Type of disc blade	Plane concave	-	Plane concave
4.	Diameter of bottom/disc, cm	65.3	7	62
5.	Spacing of discs/share blade, cm	68	10	22.5
6.	Rake angle, degree.	35	49	36
7.	Working width, cm	116	231	144

2.2 Field experimental design and procedure

The parameters investigated for draft and power requirement determinations were speed (3.6, 5.4, 7.2, 9.0 and 10.8 km h^{-1}) and tillage depth (10, 20 and 30 cm). An experimental plot of 100 m long by 20 m wide was used for each implement, making 100 m by 60 m for a location. A plot of 30 m long by 10 m wide was used as a practice area prior to the beginning of the experimental runs to enable the tractor and the implement to reach the required depth. The implement forward speeds were changed using the hand throttle after ploughing for 50 m and the tillage depths were fixed using the tractor depth controller. Ploughing time, ploughing depth, implement type and width of implement cut of each implement were measured and recorded in three replications. There were 15 runs i.e. three levels of tillage depth by five levels of tractor speed for each of the three implements (three-bottom disc plough, spring tine cultivator and offset disc harrow) given a total of 45 runs i.e. in the factorial of 3 × 3 × 5 and replicated three times for each implement resulting in 135 runs. The ploughing depths were measured using a steel measuring tape with the undisturbed surface as a reference. Time taken for each implement to travel a distance of 50 m was taken and recorded. The distance was divided by the time taken to obtain the implement speed (Okoko, 2017).

2.3 Data collection and analysis

Soil cohesion and soil angles of internal friction (soil – soil) were determined using the direct sheer test method as described by Mamman and Oni (2005), while coefficient of friction (soil on soil) was determined using an equation given by Gill and Berg (1968):

$$\mu = \tan\varphi = \frac{F}{N} \tag{2}$$

where, μ is the coefficient of friction (soil on soil); F is the frictional force tangent to the surface (N); N is the normal force (perpendicular to the surface, N); φ is the angle of internal friction, degree.

The strength of the soil in the studied location was determined using an equation given by Gill and Berg (1967).

$$S = c + \delta\tan\varphi \tag{3}$$

where, S is the shear strength of the soil, kPa; c is the soil cohesion, kPa; δ is the normal stress, kPa; and φ is the angle of internal soil friction, degree.

The weight of soil was calculated from the equation according to Srivastava et al. (2006):

$$W = \rho b d^{*}\left(L_o + \frac{L_1 + L_2}{2}\right) \tag{4}$$

where, W is the weight of soil, N; ρ is the bulk density of soil, kg m^{-3}; b is the width of implement, m; d^{*} is the tillage depth, m; $\boldsymbol{L_o}$ is the length of implement, m; L_1 is the length of implement with respect to tillage depth, m; L_2 is the length of implement with respect to the rake angle, m; and δ is the rake angle, deg.

$$d^{*} = \frac{\sin(\delta+\beta)}{\sin\beta} \tag{5}$$

$$L_1 = d^{*}\frac{\cos(\delta+\beta)}{\sin\beta} \tag{6}$$

$$L_2 = d^{*}\tan\delta \tag{7}$$

$$\beta = \frac{90^\circ - \varphi}{2} \tag{8}$$

Draft force of all the tillage implements was determined using the equation as given by Srivastava et al. (2006).

$$D = \frac{W}{Z} + \frac{C\left(\dfrac{bd}{\sin\beta}\right) + \rho b d v_o^2 \sin\delta / \sin(\delta+\beta)}{Z(\sin\beta + \mu\cos\beta)} \tag{9}$$

where, D is the draft of tillage implement, N; W is the weight of soil, N; c is the soil cohesion, kPa; μ is the coefficient of internal soil friction; β is the angle of the forward failure surface, deg.; and $\boldsymbol{V_o}$ is the speed of operation, m s^{-1}.

$$Z = \frac{\cos\delta - \mu'\sin\delta}{\sin\delta + \mu'\cos\delta} + \frac{\cos\beta - \mu\sin\beta}{\sin\beta + \mu\cos\beta} \tag{10}$$

where, μ' is the coefficient of internal soil–metal friction.

The equation below was used for the determination of power requirement

$$P = DV_o \tag{11}$$

where, P is the power requirement, W.

Statistical analysis based on randomized complete block design (RCBD) with a factorial treatment design of 3×3×5 (i.e three implements, three levels of tillage depth and five levels of tractor speed) to investigate the interactions between implement forward speed and tillage depth was carried out in Excel Programme. Analysis of Variance (ANOVA) tests were carried out to investigate the interactions between implement forward speed and tillage depth to study their significant effect.

3 Results and discussion

3.1 Soil analysis test

The results of the soil analysis test conducted during the tillage experiments are presented in Table 3. From this table, it could be seen that the soil conditions of the experimental field were in a good working condition for tillage operations.

Table 3 Soil analysis test on university farm for the tillage implements

Soil Parameter	Treatments		
	Three-Bottom Disc Plough	Spring tine cultivator	Off-set disc harrow
Soil texture	%	%	%
Sand	30	30	30
Silt	12	12	12
Clay	58	58	58
Classification	Clay loam	Clay loam	Clay loam
Average Bulk density at depth of:	g cm^{-3}	g cm^{-3}	g cm^{-3}
0-30 cm	1.70	1.70	1.70
Average Moisture content at depth of:	%	%	%
0-30 cm	13.94	14.26	16.15
Penetration resistance at depth of:	MPa	MPa	MPa
10 cm	0.58	0.32	0.21
20 cm	0.94	0.65	0.25
30 cm	1.09	1.93	1.29
Soil cohesion at depth of:	kPa	kPa	kPa
0-30 cm	22.2	22.2	22.2
Shear stress at depth of:	kPa	kPa	kPa
0-30 cm	28.7	28.7	28.7
Soil strength at depth of:	kPa	kPa	kPa
0-30 cm	24.7	24.7	24.7
Soil adhesion at depth of:	kPa	kPa	kPa
0-30 cm	0.24	0.26	0.37
Weight of soil at depth of:	N	N	N
10 cm	1496.1	160.7	1453.8
20 cm	3762.6	395.8	3467.9
30 cm	6350.1	685.2	5847.1
Angle of internal soil-soil friction at depth of:	(°)	(°)	(°)
0-30 cm	36.1	36.1	36.1
Coefficient of internal soil-soil friction at depth of :			
0-30 cm	0.73	0.73	0.73
Angle of soil/implement friction at depth of:	(°)	(°)	(°)
10 cm	22.4	10.4	20.3
20 cm	26.7	12.8	22.9
30 cm	39.6	14.3	25.2
Coefficient of soil/implement friction at depth of:			
10 cm	0.41	0.18	0.37
20 cm	0.50	0.23	0.42
30 cm	0.83	0.25	0.47

3.2 Influence of speed and depth on draft

Figure 1 to 3 illustrates the effect of forward speed on draft at different levels of tillage depth and the effect of tillage depth on draft at different levels of forward speed for three-bottom disc plough, spring tine cultivator and offset disc harrow on clay loam soil. From these figures, it was observed that draft increased with increase in forward speed and tillage depth.

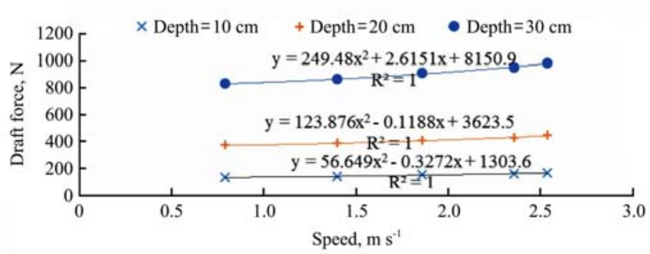

Figure 1 Effect of speed and depth on draft force for three-bottom disc plough at university of Uyo (clay loam soil)

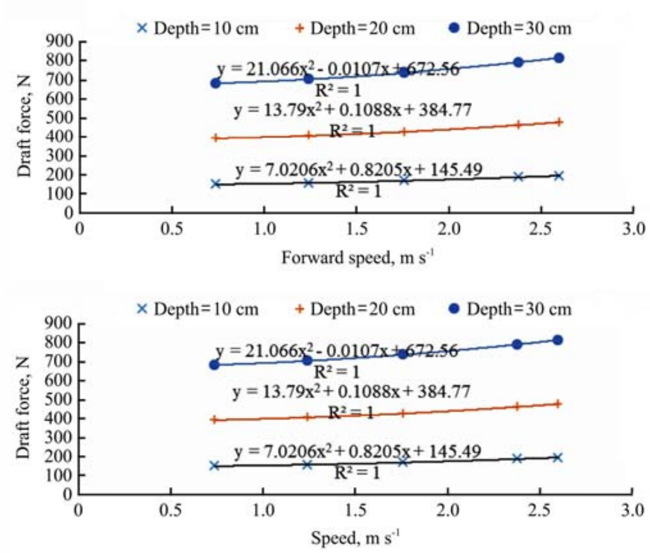

Figure 2 Effect of speed and depth on draft force for spring tine cultivator at university of Uyo (clay loam soil)

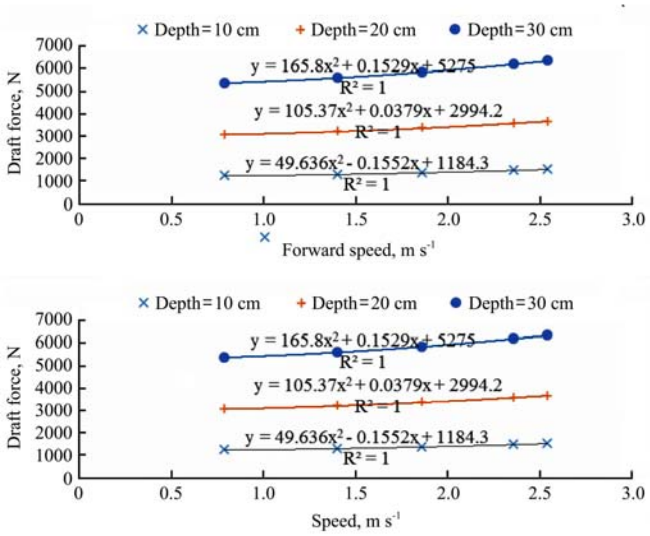

Figure 3 Effect of speed and depth on draft force for offset disc harrow at university of Uyo (clay loam soil)

For a three-bottom disc plough, at a tillage depth of 10 cm, draft force increased from 1341.4 to 1679.8 N at implement speeds of 0.82 and 2.58 m s^{-1}, respectively. Then at a tillage depth of 30 cm, draft force increased from 8320.8 to 9818.5 N at implement speeds of 0.82 and 2.58 m s^{-1}, respectively. At an implement speed of 0.82 m s^{-1}, draft force increased from 1341.4 to 8320.8 N at tillage depths of 10 and 30 cm, respectively. Then at an implement speed of 2.58 m s^{-1}, draft increased from 1679.8 to 9818.5 N at tillage depths of 10 and 30 cm, respectively.

For a spring tine cultivator, at a tillage depth of 10 cm, draft force increased from 149.9 to 195.1 N at implement speeds of 0.74 and 2.60 m s^{-1}, respectively. At a tillage depth of 30 cm, draft force increased from 684.1 to 814.9 N at implement speeds of 0.74 and 2.60 m s^{-1}, respectively. At an implement speed of 0.74 m s^{-1}, draft force increased from 149.9 to 684.1 N at tillage depths of 10 and 30 cm, respectively. Then at an implement speed of 2.60 m s^{-1}, draft increased from 195.1 to 814.9 N at tillage depths of 10 and 30 cm, respectively.

For an offset disc harrow, at a tillage depth of 10 cm, draft force increased from 1215.2 to 1504.2 N at implement speeds of 0.79 and 2.54 m s^{-1}, respectively. At a tillage depth of 30 cm, draft force increased from 5378.6 to 6345.1 N at implement speeds of 0.79 and 2.54 m s^{-1}, respectively. At an implement speed of 0.79 m s^{-1}, draft increased from 1215.2 to 5378.6 N at tillage depths of 10 and 30 cm, respectively. Then, at an implement speed of 2.54 m s^{-1}, draft force increased from 1504.2 to 6345.1 N at tillage depths of 10 and 30 cm, respectively.

These results showed that draft force increased in all implements with increase in tillage depth and implement speed which is in agreement to earlier studies by Al-Suhaibani et al. (2010), Harrigan and Rotz (1994), Nadeloo et al. (2009).

3.3 Influence of speed and depth on power requirement

Figure 4 to 6 illustrates the effect of forward speed on power requirement at different levels of tillage depth and the effect of tillage depth on power requirement at different levels of forward speed for three-bottom disc plough, spring tine cultivator and offset disc harrow on clay loam soil. From these figures, it could be seen that power requirement increased with increase in forward speed and tillage depth.

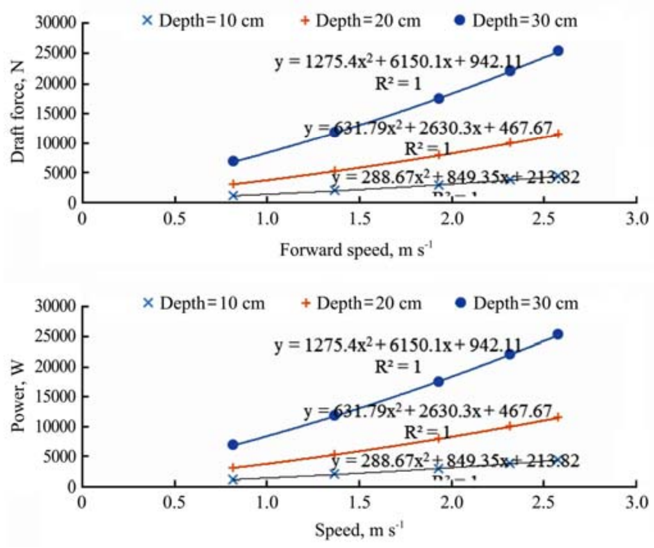

Figure 4 Effect of speed and depth on power requirement on a three-bottom disc plough at university of Uyo farm (clay loam soil)

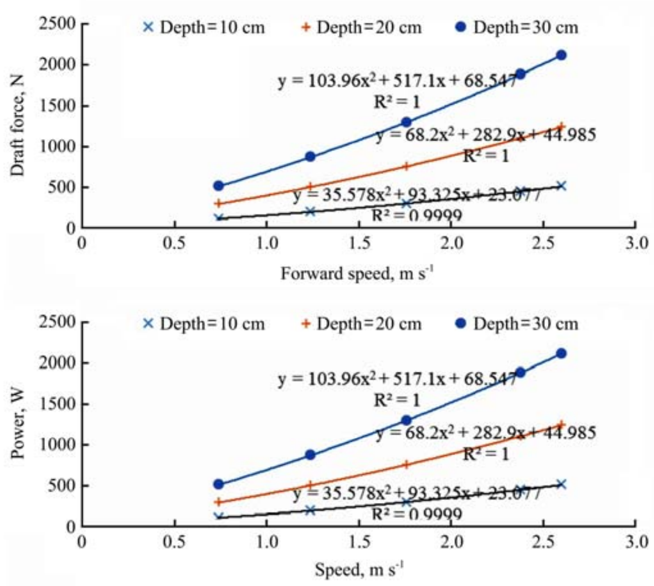

Figure 5 Effect of speed and depth on power requirement on a spring tine cultivator at university of Uyo farm (clay loam soil)

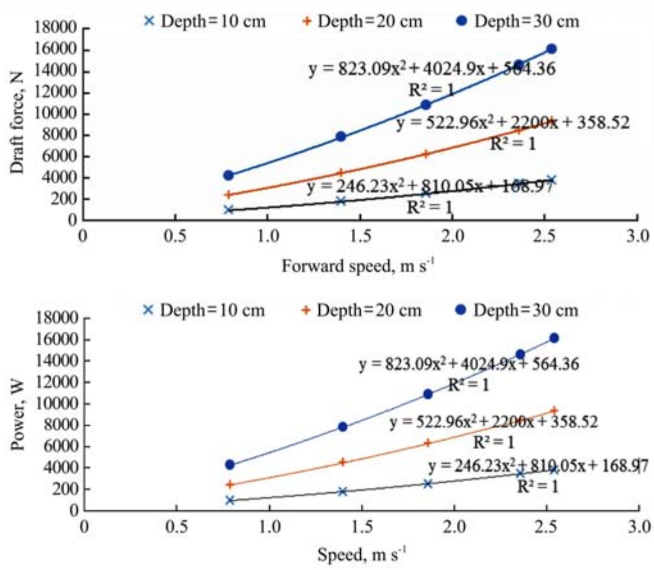

Figure 6 Effect of speed and depth on power requirement on an offset disc harrow at university of Uyo farm (clay loam soil)

For a three-bottom disc plough, at a tillage depth of 10 cm, power requirement increased from 1099.9 to 4333.9 W at implement speeds of 0.82 and 2.58 m s^{-1}, respectively. Then at a tillage depth of 30 cm, power requirement increased from 6823.1 to 25331.7 W at implement speeds of 0.82 and 2.58 m s^{-1}, respectively. At an implement speed of 0.82 m s^{-1}, power requirement increased from 1099.9 to 6823.1 W at tillage depths of 10 and 30 cm, respectively. Then at an implement speed of 2.58 m s^{-1}, power requirement increased from 4333.9 to 25331.7 W at tillage depths of 10 and 30 cm, respectively.

For a spring tine cultivator, at a tillage depth of 10 cm, power requirement increased from 110.9 to 507.3 W at implement speeds of 0.74 and 2.60 m s^{-1}, respectively. At a tillage depth of 30 cm, power requirement increased from 506.2 to 2118.7 W at implement speeds of 0.74 and 2.60 m s^{-1}, respectively. At an implement speed of 0.74 m s^{-1}, power requirement increased from 110.9 to 506.2 W at tillage depths of 10 and 30 cm, respectively. At an implement speed of 2.60 m s^{-1}, power requirement increased from 507.3 to 2118.7 W at tillage depths of 10 and 30 cm, respectively.

For an offset disc harrow, at a tillage depth of 10 cm, power requirement increased from 960.0 to 3820.7 W at implement speeds of 0.79 and 2.54 m s^{-1}, respectively. At a tillage depth of 30 cm, power requirement increased from 4249.1 to 16116.6 W at implement speeds of 0.79 and 2.54 m s^{-1}, respectively. At an implement speed of 0.79 m s^{-1}, power requirement increased from 960.0 to 4249.1 W at tillage depths of 10 and 30 cm, respectively. Then, at an implement speed of 2.54 m s^{-1}, power requirement increased from 3820.7 to 16116.6 W at tillage depths of 10 and 30 cm, respectively.

These results indicated that by increasing the tillage depth and implement speed, more power is needed to cut and transfer soil. This showed that power required from the tractor to pull all the implements considered in this study increased with increase in tillage depth and implement speed. These results confirmed with the findings of other researchers (Al-Suhaibani and Al-Jerobi, 1997; Zwilling and Hummel, 1988).

The result of the analysis of variance (ANOVA) for the test of speed and tillage depth effect on draft for three- bottom disc plough, spring tine cultivator and offset disc harrow on clay loam soil as presented in Table 4-6 respectively. Results from each table showed that forward speed and tillage depth affected the draft of the tillage implements significantly at 5% level of probability (P<0.05). The interaction between the two factors was also statistically significant at 5% level of probability (P<0.05).

Table 4 Analysis of Variance (ANOVA) for speed and depth on draft force for three-bottom disc plough at university of Uyo (clay loam soil)

Source	Type III Sum of Squares	df	Means Square	F	Sig.
Corrected mode	149232477	6	24872079.54	24872079.54	0.0001*
Intercept	358038264.6	1	358038264.6	6157.302	<0.0001*
Speed	1486893.711	4	371723.428	6.393	0.013*
Depth	147745583.6	2	73872791.78	1270.415	<0.0001*
Error	465188.529	8	58148.566		
Total	507735930.4	15			
Corrected total	149697665.8	14			

Note: *Significant at 0.05 level.

Table 5 Analysis of Variance (ANOVA) for speed and depth on draft force for spring tine cultivator at university of Uyo (clay loam soil)

Source	Type III Sum of Squares	df	Means Square	F	Sig.
Corrected mode	845586.764	6	140931.127	421.639	0.0001*
Intercept	3045965.891	1	3045965.891	9112.956	<0.0001*
Speed	16599.463	4	4149.866	12.416	0.002*
Depth	828987.301	2	414493.651	1240.087	<0.0001*
Error	2673.965	8	334.246		
Total	3894226.620	15			
Corrected total	848260.729	14			

Note: * Significant at 0.05 level.

Table 6 Analysis of Variance (ANOVA) for speed and depth on draft force for offset disc harrow university of Uyo (clay loam soil)

Source	Type III Sum of Squares	df	Means Square	F	Sig.
Corrected mode	51878092.9	6	8646348.812	433.940	<0.0001*
Intercept	187715668.8	1	187715668.8	9421.010	<0.0001*
Speed	808836.573	4	202209.143	10.148	0.003*
Depth	51069256.30	2	25534628.15	1281.523	<0.0001*
Error	159401.743	8	19925.218		
Total	239753163.4	15			
Corrected total	52037494.61	14			

Note: *Significant at 0.05 level.

The result of the analysis of variance (ANOVA) for the test of speed and tillage depth on power requirement for three-bottom disc plough, spring tine cultivator and offset disc harrow on clay loam soil are presented in Table 7-9 respectively. Results from each of the tables indicated that forward speed and tillage depth affected the power requirement of the tillage implements significantly at 5% level of probability (P<0.05). The interaction between the two factors was also statistically significant at 5% level of probability (P<0.05).

Table 7 Analysis of Variance (ANOVA) for speed and tillage depth on power requirement for three-bottom disc plough at University of Uyo (clay loam soil)

Source	Type III Sum of Squares	df	Means Square	F	Sig.
Corrected mode	699460074.00	6	116576679	11.766	0.001*
Intercept	1218449445	1	1218449445	122.980	<0.0001*
Speed	199530117.4	4	49882529.36	5.035	0.025*
Depth	499929956.5	2	249964978.3	25.229	<0.0001*
Error	79261663.28	8	9907707.911		
Total	1997171182	15			
Corrected total	778721737.3	14			

Note: * Significant at 0.05 level.

Table 8 Analysis of Variance (ANOVA) for speed and tillage depth on power requirement for spring tine cultivator at University of Uyo (Clay loam soil)

Source	Type III Sum of Squares	df	Means Square	F	Sig.
Corrected mode	4680540.23	6	780090.038	12.063	0.001*
Intercept	9809773.611	1	9809773.611	151.691	<0.0001*
Speed	2045509.249	4	511377.312	7.908	0.007*
Depth	2635030.981	2	1317515.491	20.373	0.001*
Error	517356.479	8	64669.560		
Total	15007670.32	15			
Corrected total	5197896.709	14			

Note: * Significant at 0.05 level.

Table 9 Analysis of variance (ANOVA) for speed and depth on power requirement for offset disc harrow at University of Uyo (clay loam soil)

Source	Type III Sum of Squares	df	Means Square	F	Sig.
Corrected mode	275085859	6	45847643.08	3414156.916	0.001*
Intercept	629683643.8	1	629683643.8	184.433	<0.0001*
Speed	104934458.0	4	26233614.51	7.684	0.008*
Depth	170151400.5	2	85075700.23	24.919	<0.0001*
Error	27313255.33	8	3414156.916		
Total	932082757.6	15			
Corrected total	302399113.8	14			

Note: * Significant at 0.05 level.

The results of the regression equations obtained from the analysis for three–bottom disc plough, spring tine cultivator and offset disc harrow on clay loam soil is presented in Table 10. From this table, it was observed that the coefficient of determination values obtained from all the equations was very high which would make the equations suitable for predictive purposes.

Table 10 Regression analysis for the implements in a clay loam soil

Implement	Regression	Regression equation	R^2
Three-bottom disc plough	Draft Force	$DF = 2031.03 - 657.54s + 3291sd + 143.33s^2 - 1666d + 1213d^2$	0.9998
	Power requirement	$P = 9678.576 - 5444.16s + 4327sd + 732s^2 - 977d + 223d^2$	0.9964
Spring tine cultivator	Draft Force	$DF = -7.23 - 46.36s + 233sd + 13.96s^2 + 1442d + 257d^2$	0.9999
	Power requirement	$P = 313.39 - 357.2s + 3275sd + 69.245s^2 - 2395d + 4526d^2$	0.9995
Offset disc harrow	Draft Force	$DF = 153.02 - 391.05s + 1953sd + 107.12s^2 + 93d + 244d^2$	0.9999
	Power requirement	$P = 2818.63 - 2807.55s + 25763sd + 530.76s^2 - 22534.5d + 44d^2$	0.9994

Note: R^2 = Coefficient of determination.

4 Conclusion

Field tests were performed to determine the effects of forward speed and tillage depth on the three tillage implements used for seed bed preparation in clay loam soil. The soil test from the field indicated that the soil conditions were in good working range for tillage operations. A significant increase in draft and power requirements were observed for all the three tillage implements with an increase in forward speed and tillage depth. Three-bottom disc plough was observed to have the highest draft and power requirements, while the least draft and power requirements were noticed on spring tine cultivator. Analysis of Variance (ANOVA) showed that forward speed and tillage depth had a significant effect (P<0.05) on draft and power requirement. Similarly, the interaction between forward speed and tillage depth was significant (P<0.05). The very high values of coefficient of determination would make the equations suitable for predictive purposes.

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