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Predicting tractor fuel consumption during ridging on a sandy loam soil in a humid tropical climate

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A predictive model for the determination of optimum fuel consumption of a tractor during ridging operation has been developed. The model development involved field experimentations to determine the various parameters affecting tractor fuel consumption, like draught, speed, depth of cut, soil moisture content, cone index and width of cut. The field investigations were carried out at the farm of Rivers State Agricultural Development Programme in Port Harcourt, Nigeria. The field experimental design adopted was the Factorial in Randomized Complete Block Design (RCBD). It consisted of 9 experimental treatments with three replications. The experimental land area was 160 m by 32.5 m (5200 m^2), which was sub-divided into three blocks of 9 plots each, measuring 50 m by 2.5 m, with an inter-plot spacing of 1 m provided for different treatment options. The experimental fuel consumption was determined from measuring the actual amount of fuel used by the tractor per unit time. The model equation was then formulated using the Buckingham pi theorem. The model showed that tractor fuel consumption during ridging is directly proportional to the draught, ridging speed, height of ridge and moisture content; and inversely proportional to the penetration resistance and width of cut. The model was validated by graphical comparison and with root mean square error and paired t-Test. The results obtained showed that there was no significant difference between the measured and predicted values at 95 and 99% confidence limits; and the model can accurately predict tractor fuel consumption during ridging operations using a disc ridger.

Key words: Buckingham pi theorem, disc ridger, fuel consumption, predictive model, ridge height, ridging operation, ridging speed, tractor.

INTRODUCTION

Tillage is a preliminary land preparation operation, which is essential in crop production. Over the years, prior to mechanization of agriculture, tilling the soil to boost production of food in agriculture has been in existence (McKyes, 1985). Ahaneku et al. (2011) state that agricultural tillage involves soil cutting, soil turning and soil pulverization, which are energy-intensive activities in field cultivation, not just due to the large amount of soil mass that must be moved, but also due to inefficient methods of energy transfer to the soil. Mechanized tillage

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has been powered by tractor as the only power source. Tractors are energized by fuel to function and it is one of the parameters considered in the analysis of effective performance of tillage operations. Ahaneku and Ogunjirin (2005) reported that soil strength properties generally decrease with increasing speed, but increase with depth of tillage; and cone index generally increases with soil depth and the speed of operation, whereas dry density generally increases with depth, but decreases with speed of tillage operation within 15 cm of top soil layer.

Tillage operations, such as ploughing, harrowing and ridging, are a very important aspect of agricultural land cultivation activities. The cost of these operations contributes significantly to the overall cost of agricultural production bid; yet their energy utilization efficiency, especially in the amount of fuel consumed by the tractor during the operations, has not been very well established. If this is done, it would help in the determination of optimum levels of their application in field operations.

A predictive model can be deployed in the estimation of fuel consumption by a tractor during tillage and to predict the variation of dependent and independent variables involved in the process. This would considerably enhance the fuel utilization efficiency, reduce operational cost and increase agricultural productivity, with an accompanying increase in profitability in crop production.

Ridging is a reformed tillage operation, which needs conventional tillage to form lasting raised beds or ridges. According to Imonigie (2007), a ridge is a long mound of tilled soil usually between two furrows with specific configuration, the length depending on the size and layout of the field while the width and height of the ridge depend on the implement adjustment and size of the disc used. Nkakini and Fubara-Manuel (2012) defined ridging as tillage operation intended for heaping up tilled soil from two sides to form long stripes of mounds having furrow in between. It is mainly used in an undulating topography, but also applied in flat and low lying flat fields that are prone to being wet and/or any other topographies. The permanently raised ridges are flat and usually 30 to 61 cm (12 to 24 inches) wide and 10 to 16 cm (4 to 6 inches) high and the operation is accomplished with the help of a tillage implement called ridger. Mechanical ridging is always done after ploughing and harrowing operations (Nkakini et al, 2008), at a specified tractor travel speed of 2.22 ms^{-1} (8 kmh^{-1}) in a loamy sand soil (Nkakini and Fubara-Manuel, 2012).

As a result of the continual increase in the cost of fuel, especially in Nigeria, it has become imperative to be more efficient in fuel utilization in agricultural production. This is so because fuel is an important variable in the determination of the cost of using almost all farm machinery for farm operations and its consumption is dependent on the depth of tillage. Asoegwu (1999) reported that the time for seedbed preparation, the fuel consumed per operation, the tillage energy input and the total cost of production for all the tillage methods tested increased with increase in tillage depth.

According to Michalski et al. (2014) fuel consumption is the primary diagnostic parameter in identifying the condition of a vehicle. Moreover, because of the continuous rise in fuel prices, energy consumption has become one of the most important factors in agricultural economy. The factors that fundamentally affect fuel consumption when using tillage equipment are: increased power consumption by increasing the working speed, actual width of cut, soil strength, moisture content and working depth (Cortez et al., 2008; Kichler et al., 2011; Silveira et al., 2013; Moitzi et al., 2014; Leghari et al., 2016; Nasr, 2016). Investigation by Moitzi et al. (2014) revealed that increasing working depth raises the drawbar pull and the slip; and the effect is an increased fuel consumption rate (L ha^{-1}) and area-specific fuel consumption (L ha^{-1}), which is a corroboration of the work of Asoegwu (1999). Cortez et al. (2008), Kichler et al. (2011), and Silveira et al. (2013) posited that within the same operating speed and varying engine speed, there are significant increases in hourly fuel consumption, which also varies directly with the engine speed. Generally, according to Gamero et al. (1986), cited in Correia et al. (2015), in soil tillage operations, fuel consumption is around 30% of the hourly cost of an agricultural tractor. Asoegwu (1999) states that total cost, fuel consumption, time of operation, fuel and tillage energies augmented with tillage depth were higher for combined tillage operations than the single ones.

A number of methods has been adopted for the prediction of fuel consumption. Some of these methods are generally based on power requirements and others are for individual engines, which call for extensive engine testing to verify the amount of fuel consumed (ASAE, 2002a, 2002b; Grisso et al., 2004, 2010, 2011). As a result, it is difficult to properly estimate the amount of fuel needed to perform specific farming operations, especially tillage. There is, therefore, the need to develop a predictive model for fuel consumption that would overcome the constraints of previous attempts. Hence, the objective of this study was to enable agricultural producers determine optimum fuel consumption for tractors during ridging operations, by developing an appropriate predictive model equation for that purpose. The effects of tillage speed and height in ridging operations were also analysed statistical.

MATERIALS AND METHODS

Study area

The experiment was conducted on the farm of the Rivers Agricultural Development Programme in the premises of the Rivers State School to Land Authority, Port Harcourt, Nigeria. It is geographically located on latitude 4° 49′ 27″ N, and longitude 7° 2′ 1″ E. The period of the investigation was when the rains were intense, between August and September, 2018; and the predominant soil type in the farm was loamy sand. The field used

Table 1. Tractor Specifications.

Parameter	Description
Model	Swaraj 978 FE
Drive	2 Wheel drive
Engine horse power	72 hp
Lifting power	2200 kg
Hitch	3 point CAT III
Front tyres	7.5 - 16.8 - ply
Rear tyres	16.9 - 28.12 - ply
Width	2030 mm
Weight	3050 kg
Manufacturer	Swaraj, India

Table 2. Tractor specifications.

Parameter	Ridge
Number of disc	4
Working depth (mm)	330
Frame width (mm)	2525
Width of cut (mm)	1320
Disc diameter (mm)	660
Manufacturer	Baldan Implementos Agricolas

was an uncropped area that had been fallow for upwards of six months, measuring 160 m × 32.5 m (5200 m^2). It was further sub-divided into three blocks of 9 plots each, with dimensions of 50 m × 2 m and inter-plot spacing of 1m provided for different treatment options. A space of 4 m was marked out between the blocks and 1 m at the sides of the outer blocks. All these were to allow for easy movements around the blocks and plots, without altering experimental settings.

Tractor and implement specifications

The specifications of the tractor and implement used for the investigation are presented in Tables 1 and 2, respectively.

Experimental procedure

The experimental design adopted was the factorial in randomized complete block design (RCBD) to evaluate the effects of tillage speed and depth on fuel consumption during ridging operations. Prior to the ridging operation in the field, soil samples were collected randomly at depths of between 0 and 0.3 m, using a soil auger. This was to determine the soil textural classification and moisture content. The composite soil samples were put in well labelled polyethylene bags and immediately taken to the soil/crop science laboratory of the Rivers State University for analysis. The textural classification of the soil was determined by the hydrometer method, where 102 g of air-dried soil was weighed and placed in a 500 ml beaker filled within 5 cm of the top with distilled water. Thus, the temperature reading was taken and the respective percentages of sand, silt and clay in the soil sample were determined. Finally, the textural class was determined using textural triangle. The gravimetric (that is oven dry method) was used to determine the soil moisture content. 100 g of wet soil was weighed and put into an aluminium pan and placed inside an oven at 105°C. The soil was

brought out from the oven intermittently and reweighed each time until a fairly constant weight was achieved. The moisture content was then calculated with the expression:

$$Moisture\ Content\ (MC\%) = \frac{W_2 - W_3}{W_3 - W_1} \times 100 \qquad (1)$$

where W_1-weight of container, W_2-weight of container + wet soil, and W_3-weight of container + dry soil.

Cone index (CI), which is an indication of the soil resistance to penetration of implements, was measured with a cone penetrometer having an enclosed angle of 30°, a base area of 3.23 cm^2 (323 mm^2) and mounted on a shaft of 45.72 cm (457.20 mm). It was measured at three different depths of 0.10, 0.13 and 0.16 m before the ridging operation. During operation, the cone penetrometer was positioned between the operator's two legs and, with his two hands on the handle, pushed into the soil until the marked point on the shaft was reached, then the reading was taken.

For the ridging operation, the ridging heights were fixed by adjustment of the lifting mechanism of the three-point linkage system. Ridging speeds were regulated by the operator with a combination of gear selection and throttling. Ridging heights of 0.10, 0.13 and 0.30 m were attained at different operational speeds of 1.39, 1.94 and 2.50 ms^{-1} respectively. The ridge depth was measured by placing a meter rule from furrow bottom to the surface of the ridge, while the width was measured by placing a steel tape from one side of the furrow to the other across the ridge. The time of operation was determined with a stopwatch.

Draught force was determined using the formula (ASAE, 2002a):

$$D = F_i [A + B(S) + C(S)^2]WT \qquad (2)$$

where D-draught force, N; F-dimensionless soil texture and adjustment parameter (table); i-1 for fine, 2 for medium, 3 for coarse ABC-machine specific parameter; S-speed, m/s; W-machine with or number of rows, m; T-depth, cm.

The fuel consumed by the tractor was measured by the direct method of determining fuel consumption. This process involved filling of the tractor fuel tank to the brim before and after each operation test performed. The measurement of fuel consumption was taken using a 1000 ml graduated cylinder to top-up the fuel level in the tank after each operation test, thereby noting the volume of fuel consumed per time taken for the operation. This method had been successfully used extensively by several researchers, including Abbouda et al. (2001), Udo and Akubuo (2004), Ahaneku et al. (2011), Adewoyin and Ajav (2013), Leghari et al. (2016a), Leghari et al. (2016b), and Shah et al. (2016). After the measurements, the fuel consumption was determined mathematically with Equation 3. Figures 1 and 2 show scenes of the ridging operation and measurement of fuel used respectively

$$FC = \frac{V_{fc}}{T} \qquad (3)$$

where FC-fuel consumption (m^3/s), V_{fc}-volume of fuel consumed, m^3; and T-Time, s.

Development of the model equation

The principle of dimensional analysis using Buckingham pi theorem was used in the formulation of the model equation for the prediction of the tractor fuel consumption during ridging operations. Functional relations were developed to combine various parameters, related to ridging operation and tractor fuel consumption, into groups of dimensionless terms selected as pi terms, which reduce the number

Table 3. Some variables affecting fuel consumption.

Variable	Symbol	Unit	Dimensions
Dependent variable			
Fuel Consumption	Fc	m^3/s	$L^3 T^{-1}$
Independent variable			
Ridging Speed	V	m/s	$LT^{=1}$
Ridge height	h	m	L
Width of cut	W	m	L
Cone index	CI	N/m^2	$ML^{-1}T^{-2}$
Bulk density	ρ_b	Kg/m^3	ML^{-3}
Draught force	D	N	MLT^{-2}
Moisture content	M	%	$M^0L^0T^0$

of variables in a multifaceted phenomenon to a smaller set of dimensionless ratio. This outcome is in considerable savings in both cost and labour during the experimental determination of the function (Srivastava et al., 2006). The dependent and independent variables have been identified and shown in Table 3.

Fuel consumption, Fc is a function of h, W, V, CI, ρ_b, D, S, and M. Mathematically,

$$F_c = f\left(h, W, V, CI, \rho_b, D, M\right) \qquad (4)$$

or

$$F_c = \left(h, W, V, CI, \rho_b, D, M\right) \qquad (5)$$

Total number of variables, n = 8; and total number of fundamental dimensions, m = 3. Therefore, number of π- terms = n − m = 5. Equation 5 can be written as:

$$f_1 = \left(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5\right) \qquad (6)$$

Each π- term contains (m+1) variables, where m=3 and is also equal to repeating variables. Choosing from ρ_b, h, V as repeating variables, we get five π- terms as:

$$\pi_1 = \rho_b^{a_3}.h^{b_3}V^{c_3}.Fc \qquad (7)$$

$$\pi_2 = \rho_b^{a_4}.h^{b_4}V^{c_4}.W \qquad (8)$$

$$\pi_3 = \rho_b^{a_5}.h^{b_5}V^{c_5}.CI \qquad (9)$$

$$\pi_4 = \rho_b^{a_6}.h^{b_6}V^{c_6}.D \qquad (10)$$

$$\pi_5 = M \qquad (11)$$

A resolution of the pi terms results in Equation 12 as the appropriate model for the prediction of fuel consumption by a tractor during ridging in a loamy sand soil. That is:

$$F_c = \varphi\frac{DVhMC}{CIW} + C \qquad (12)$$

or

$$Fc = \varphi Z + C \qquad (13)$$

where   D-draught force, N; W-width of cut, m; V-ridging speed, m/s; h-ridge height, m; CI -cone index, N/m^2; MC-moisture content, %; Z- field test results $\left(\frac{DVhMc}{CIW}\right)$.

Equation validation

The developed equation was validated with regression curve to correlate the measured and predicted values. Also, root mean square error (RMSE) was used to check the error difference as:

$$RMSE = \sqrt{\frac{\frac{1}{N}\Sigma_{i-1}^{i-N}\left(FC_m - FC_p\right)}{N}} \qquad (14)$$

where   N-number of samples, FC$_m$-measured fuel consumption, and FC$_p$-predicted fuel consumption.

Furthermore, the t-Test was used to compare the experimental and predicted data to determine significant differences at 0.05 and 0.01 levels of significance (95 and 99% confidence) as given in Equation 15.

$$t = \frac{\Sigma D/N}{\sqrt{\frac{\Sigma D^2 - \left(\frac{(\Sigma D)^2}{N}\right)}{(N-1)(N)}}} \qquad (15)$$

Where ΣD-summation of the differences, ΣD^2- summation of the squared differences, and $(\Sigma D)^2$-summation of the differences squared.

Statistical analysis

The analysis of variance (ANOVA) was used to analyse the data in this study based on the F-test; and to achieve an appropriate error

term with single probability risk if the means measured are totally different and if the differences are away from what is ascribed to chance or experimental error and considered as significant at $F_{calculated} > F_{tabbular}$ for 5 and 1%, respectively. The Coefficient of Variation (CV) was computed using Equation 16, thus:

$$CV = \frac{\sqrt{Error\ MS}}{Grand\ mean} \times 100 \qquad (16)$$

The means of the treatments were compared using Duncan's Multiple Range Test (DMRT) and considered as significant for all treatment means whose values are less than the computed difference at 0.05 and 0.01 levels of significance (Treatment means < Computed difference). The procedure followed by computing the standard deviation (S_d) and the $(t - 1)$ values of the shortest significant range (R_p) is given thus:

$$S_d = \sqrt{\frac{2S^2}{r}} \qquad (17)$$

where S^2 -Error Mean Square (EMS) and r-number of replications.

$$R_p = \frac{(r_p)(S_d)}{\sqrt{2}} \text{ for } p = 2, 3, \ldots.t \qquad (18)$$

Where t-total number of treatments.

RESULTS

The various results of the experimentation, including field measurements, predicted values and validation results are presented in Tables 4 to 9, while their graphic relationships with one another are shown in Figures 3 to 8.

DISCUSSION

The result of soil textural classification (Table 4) shows the soil as loamy sand (80.40% sand, 5.30% silt and 14.30% clay). The soil bulk density and moisture content were determined as 1.83 g/cm^3 and 18.50% (dried basis), respectively. The model equation developed for tractor fuel consumption during ridging was used to analyse the results from field test. From the plot of fuel consumption (FC, m^3/s) against field test results (Z, m^3/s) (Figure 3), the values for the constants (φ and C) were established for ridging operation and the linear regression equation was fitted into the model equation. This is similar to the work of Nkakini (2013), who used regression curve to established constants in the model equation for tractive force on ploughed soil; and also Kumar and Pandy (2015), where multiple linear regression analysis with excel spread sheet was fitted to the model structure formulae to calculate the coefficient. The result showed acceptable agreement with coefficient of determination, $R^2 = 0.9875$. Also, the established predictive fuel consumption model equation for ridging operations at

speeds of 1.39, 1.94 and 2.50 m/s with depths of 0.1, 0.20 and 0.30 m respectively is:

$$FC = 2.00 \times 10^{-5}Z + 2.00 \times 10^{-6} \qquad (19a)$$

or

$$FC = 2.00 \times 10^{-5}\left(\frac{DVhMc}{CIW}\right) + 2.00 \times 10^{-6} \qquad (19b)$$

The field test is used in the equation to predict the combined effect of soil-implement parameters on tractor fuel consumption performance. For that reason, from Equation 19a or b constants of 2.00×10^{-5} and 2.00×10^{-6} for ridging operation were established.

Effect of ridging speed on fuel consumption

The fuel consumption was affected by ridging speed. Figure 4 shows the relationship between fuel consumption and ridging speed for differing ridge heights. This relationship is given by linear regression equation at different depths (0.10, 0.20 and 0.39 m respectively) as:

$$Y = 5.00 \times 10^{-7}X + 2.00 \times 10^{-6} \quad \text{(0.10 m height)} \qquad (20)$$

$$Y = 2.00 \times 10^{-6}X + 1.00 \times 10^{-6} \quad \text{(0.20 m height)} \qquad (21)$$

$$Y = 2.00 \times 10^{-6}X + 1.00 \times 10^{-6} \quad \text{(0.30 m height)} \qquad (22)$$

with the corresponding coefficients of determination, $R^2 = 0.9499, 0.9112$ and 0.9993, respectively. The ANOVA result for the effect of forward speed on the fuel consumption during ridging operation indicated that there were highly significant differences at 0.05 and 0.01 (95 and 99% confidence) as the forward speed increment (86%) from 1.39 to 2.50 m/s elicited a fuel consumption rise of 18.00, 33.71 and 35.50%, respectively for the three ridge heights used in this study. Also, the DMRT results showed there were highly significant differences among their means. This agreed with the findings of Ahaneku et al. (2011), Adewoyi and Ajav (2013), Balami et al. (2015), Almaliki et al. (2016a and b) and Shafaei et al. (2018).

Effect of ridge height on fuel consumption

Figure 5 shows the effect of ridge height on fuel consumption during ridging. The relationship between the

Table 4. Soil textural class (Particle Size Distribution).

	Percentage by Mass	
Clay	Silt	Sand
14.30	5.30	80.40

Table 5. Mean results of field test performed during ridging operation.

Parameter	Height of Ridge, h_1 (m)			Height of Ridge, h_2 (m)			Height of Ridge, h_3 (m)		
	V_1 (m/s)	V_2 (m/s)	V_3 (m/s)	V_1 (m/s)	V_2 (m/s)	V_3 (m/s)	V_1 (m/s)	V_2 (m/s)	V_3 (m/s)
FC (m^3/s)	2.76E-06	2.92E-06	3.30E-06	3.50E-06	3.90E-06	5.28E-06	4.76E-06	6.00E-06	7.38E-06
W (m)	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
CI (N/m^2)	1900.00	1900.00	1900.00	3100.00	3100.00	3100.00	4000.00	4000.00	4000.00
D (N)	3092.00	3173.51	3256.50	6184.00	6347.02	6513.00	9275.99	9520.50	9769.50
MC (%)	18.52	18.52	18.52	18.52	18.52	18.52	18.52	18.52	18.52

Table 6. Mean values of field test and Z for ridging operation.

Treatment	D (N)	V (m/s)	h (m)	MC (%)	CI (N/m)	W (m)	$Z = \left(\dfrac{DVhMc}{CIW}\right)$
h_1V_1	3092.00	1.39	0.10	18.52	1900.00	1.32	3.17E-02
h_1V_2	3173.51	1.94	0.10	18.52	1900.00	1.32	4.55E-02
h_1V_3	3256.50	2.50	0.10	18.52	1900.00	1.32	6.01E-02
h_2V_1	6184.00	1.39	0.20	18.52	3100.00	1.32	7.78E-02
h_2V_2	6347.02	1.94	0.20	18.52	3100.00	1.32	1.11E-01
h_2V_3	6513.00	2.50	0.20	18.52	3100.00	1.32	1.47E-01
h_3V_1	9275.99	1.39	0.10	18.52	4000.00	1.32	1.36E-01
h_3V_2	9520.52	1.94	0,30	18.52	4000.00	1.32	1.94E-01
h_3V_3	9769.50	2.50	0.30	18.52	4000.00	1.32	2.57E-01

Table 7. Summary of measured FC and field test results, Z (For Ridging), m^3/s.

Ridging (m^3/s)	
Measured	Z
2.76E-06	3.17E-02
2.92E-06	4.55E-02
3.30E-06	6.01E-02
3.50E-06	7.78E-02
3.90E-06	1.11E-01
5.28E-06	1.47E-01
4.76E-06	1.36E-01
6.00E-06	1.94E-01
7.38E-06	2.57E-01

fuel consumption and height is given by linear regression equations at different forward speeds (1.39, 1.94 and 2.50 m respectively) as:

$$Y = 1.00 \times 10^{-5}X + 2.00 \times 10^{-6} \quad \text{(1.39 m/s speed)} \tag{23}$$

$$Y = 2.00 \times 10^{-5}X + 1.00 \times 10^{-6} \quad \text{(1.94 m/s speed)} \tag{24}$$

$$Y = 2.00 \times 10^{-5}X + 1.00 \times 10^{-6} \quad \text{(2.50 m/s speed)} \tag{25}$$

with coefficients of determination, R^2 = 0.978, 0.9578 and 0.9997, respectively. The ANOVA result for the effect of height on the fuel consumption during ridging operation indicated that there were highly significant differences at 0.05 and 0.01 (95 and 99% confidence) as the ridge height percentage increase of 200% from 0.10 to 0.30 m/s led to notable change in the fuel consumption of 42.02, 51.33 and 55.28%, respectively for the three

Table 8. Validation of the model equation for ridging operation.

Treatment	D (N)	V (m/s)	d (m)	Mc (%)	CI (N/m)	W (m)	$FC = 2E\text{-}05\left(\dfrac{DVdMc}{CIW}\right) + 2E\text{-}06$
d_1V_1	3092.00	1.39	0.10	18.52	1900.00	1.32	2.63E-06
d_1V_2	3173.51	1.94	0.10	18.52	1900.00	1.32	2.91E-06
d_1V_3	3256.50	2.50	0.10	18.52	1900.00	1.32	3.02E-06
d_2V_1	6184.00	1.39	0.20	18.52	3100.00	1.32	3.56E-06
d_2V_2	6347.02	1.94	0.20	18.52	3100.00	1.32	4.22E-06
d_2V_3	6513.00	2.50	0.20	18.52	3100.00	1.32	4.94E-06
d_3V_1	9275.99	1.39	0.30	18.52	4000.00	1.32	4.72E-06
d_3V_2	9520.52	1.94	0,30	18.52	4000.00	1.32	5.88E-06
d_3V_3	9769.50	2.50	0.30	18.52	4000.00	1.32	7.14E-06

Table 9. Measured and predicted fuel consumption (m^3/s).

Measured	Predicted
2.45E-06	2.55E-06
2.65E-06	2.79E-06
2.90E-06	3.04E-06
2.81E-06	2.90E-06
3.19E-06	3.29E-06
3.61E-06	3.70E-06
3.31E-06	3.32E-06
3.92E-06	3.88E-06

Figure 2. Measurement of fuel used.

Figure 1. Ridging operation.

heights used in this study. Also, DMRT results showed highly significant differences among their means. This is in line with the findings of Fathollahzadeh et al. (2009, 2010), Gulsoylu et al. (2012), Adewoyin and Ajav (2013), Moitzi et al. (2014) and Shafaei et al. (2018).

Combined effects of ridging speed and height on fuel consumption

The combined effects of ridging speed and height on fuel consumption are shown in Figure 6. From the chart, it is deducible that as the forward speed increased (86%)
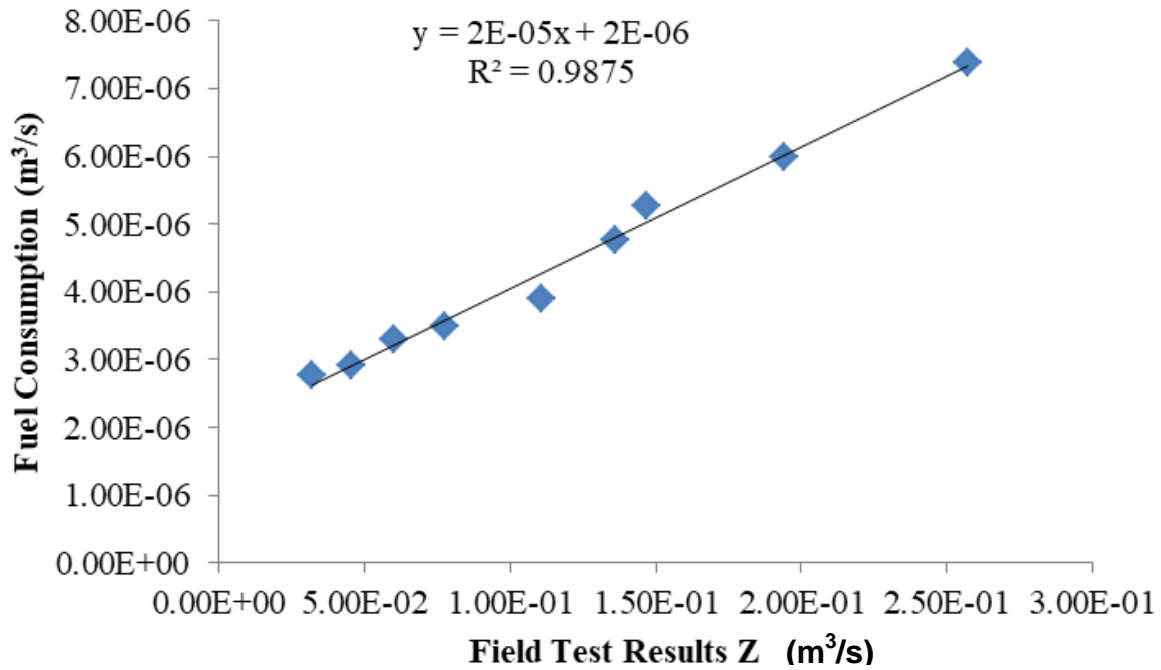
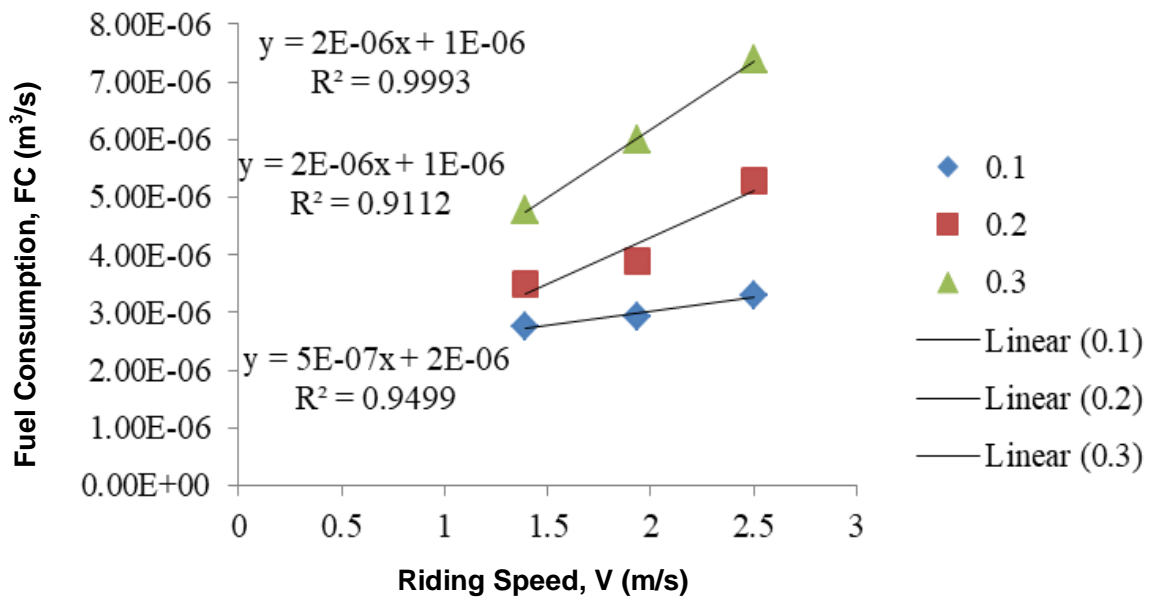**Figure 3.** Relationship between fuel consumption (m³/s) and field test results (m³/s).

Figure 4. Effects of ridging speed (m/s) on fuel consumption.

from 1.39 to 2.50 m/s along with ridging height variations (200%) from the lowest (0.1 m) to the highest level (0.3 m) 62.60% fuel consumption change. The ANOVA result for the combined effects of speed and height on the fuel consumption during ridging operation indicated that there were highly significant differences at 0.05 and 0.01 (95 and 99% confidence); and a CV of 0.24% indicated that the experimental error is low and reliable. Also, the DMRT results showed that there were highly significant differences among their means. This agreed with the findings of Adewoyin and Ajav (2013), and Shafaei et al. (2018).
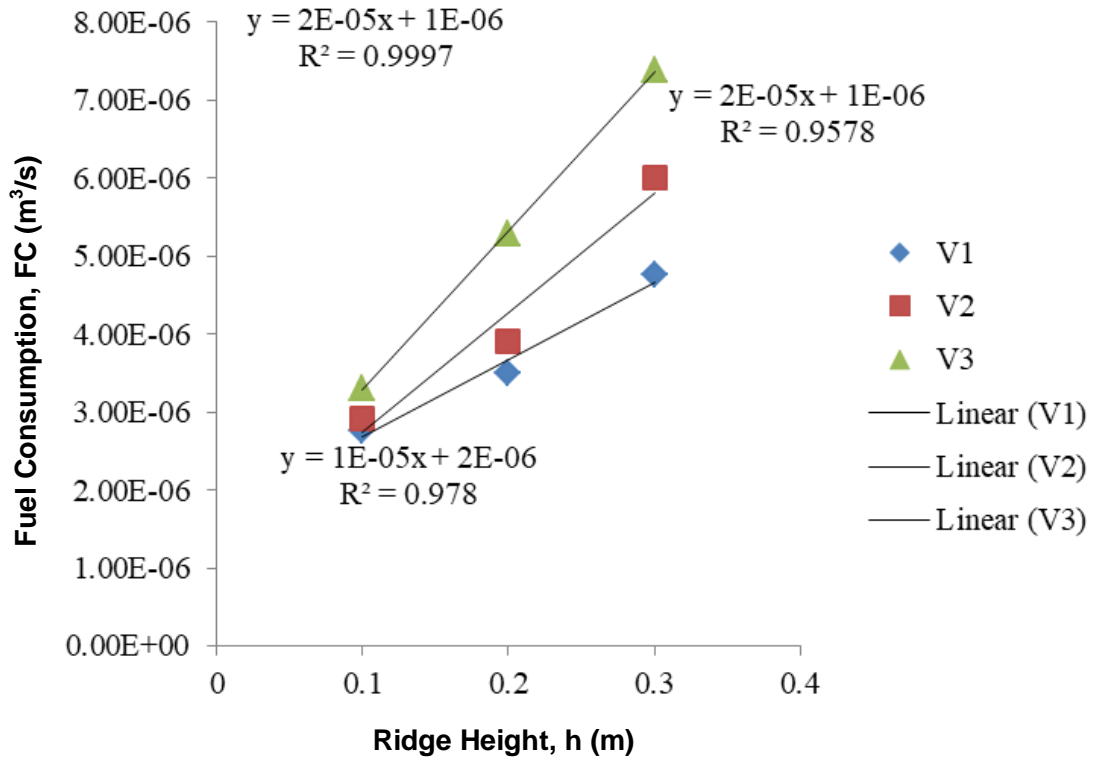
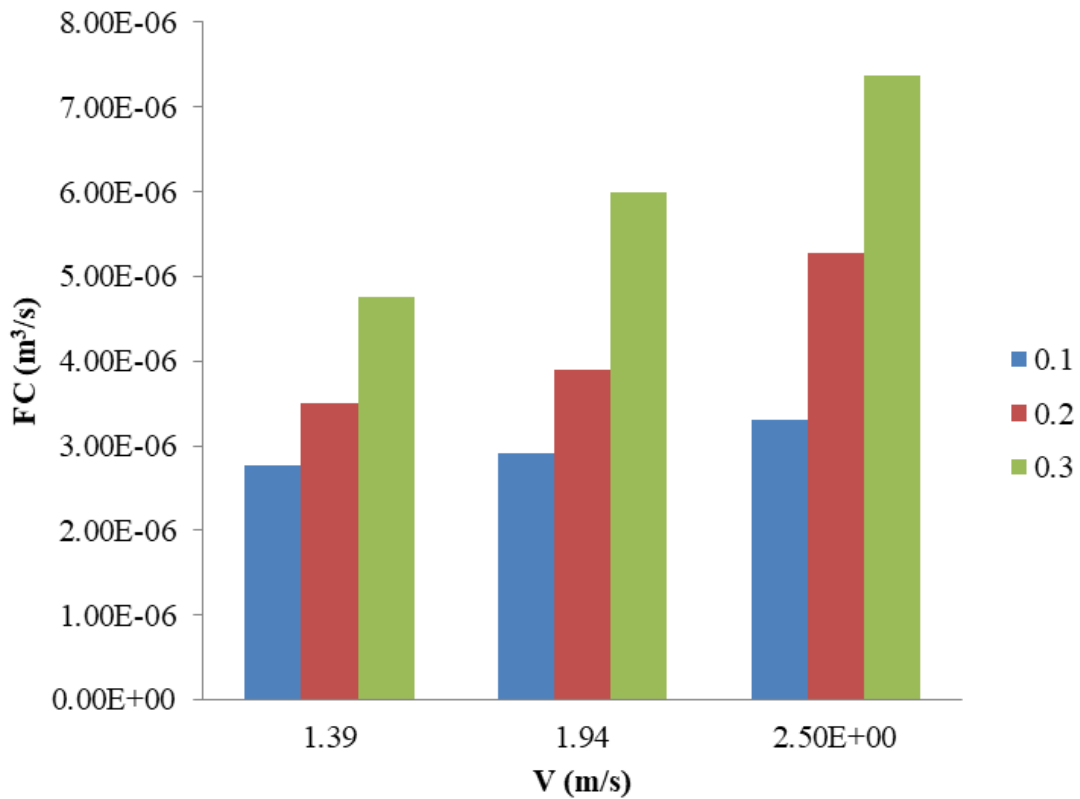**Figure 5.** Effect of ridge height (m) on fuel consumption (m/s).

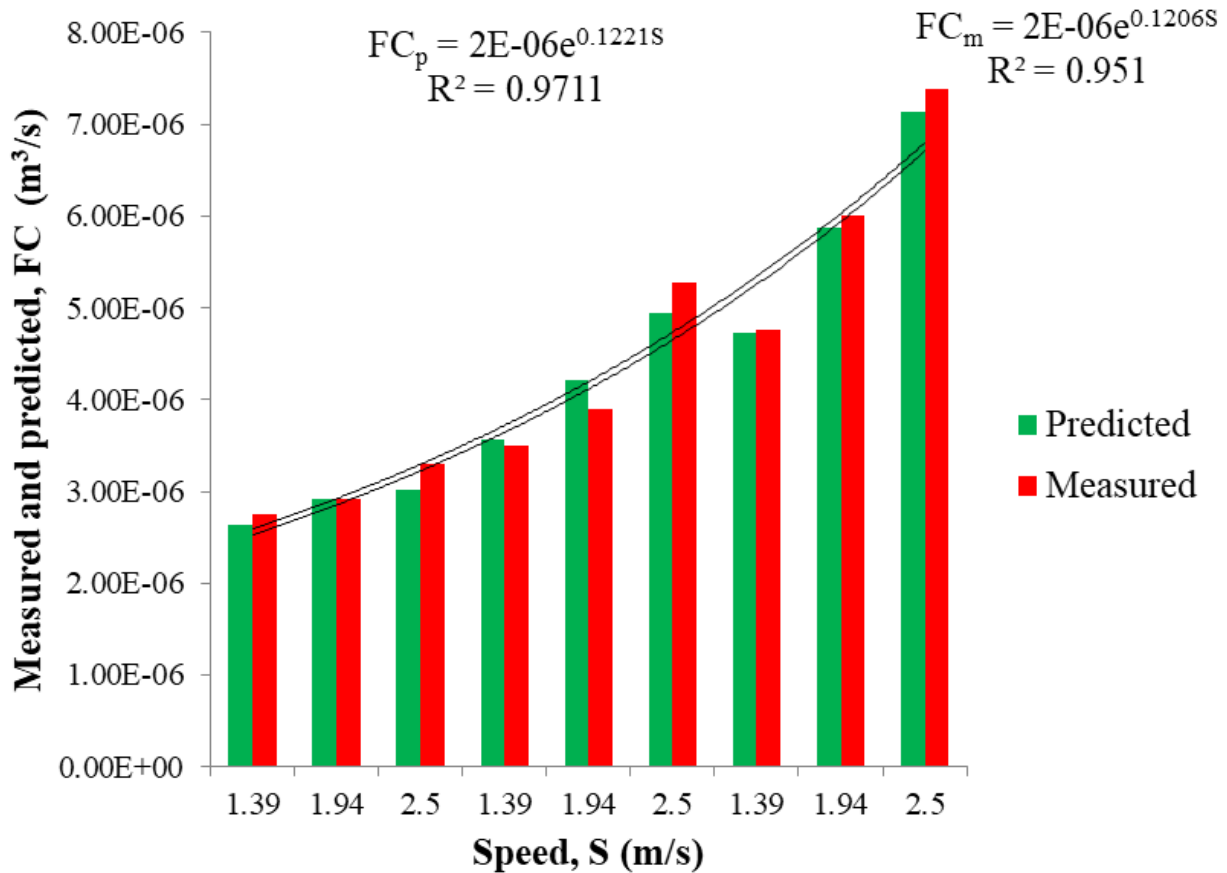**Figure 6.** Combined effects of ridging speed (m/s) and height (m) on fuel consumption (m/s).

Figure 7. Comparison of measured and predicted FC with respect to speed of operation.

Validation of the model

Figure 7 compares the measured and predicted values of the tractor's fuel consumption with respect to the speed of operation. It shows that both the measured and predicted values are exponential functions of the speed of operation, in the order of Equations 26 and 27.

$$FC_p = 2E\text{-}06e^{0.1221S} \qquad (26)$$

$$FC_m = 2E\text{-}06e^{0.1206S} \qquad (27)$$

The correlation coefficients of 0.951 and 0.9711 for the measured and predicted data, respectively, with a marginal 2% deviation, further authenticate the validity of the predictive model so developed. A similar feature is observed in Figure 8 between the measured and predicted fuel consumption data with respect to height of ridge. The characterizing exponential functions are described by Equations 28 and 29.

$$FC_p = 2E\text{-}06e^{0.1221h} \qquad (28)$$

$$FC_m = 2E\text{-}06e^{0.1206h} \qquad (29)$$

The correlation coefficients are the same with those of speed consideration. The indication is that the predicted values compare very well with the measured values and that the predictive model developed in this work can effectively be used in the analysis of tractor fuel consumption for ridging operation in a sandy loam soil in tropical Nigeria.

Furthermore, the error analysis which depicted the differences between the measured and predicted model results ranged between -3.30E-07 and 2.70E-07, while the RMSE was 5.57E-07, which is low. Also, the result of the paired t Test, for the determination of the significant difference between the means of measured and predicted fuel consumption at $t_{calculated} < t_{critical}$ significance (that is, 95 and 99% confidence) levels, showed that 0.12 < 2.306 and 0.12 < 3.355, respectively. This indicated that there were no significant differences between the measured and predicted values. This, indeed is a corroboration of the findings of Karparvarfard and Rahmanian-Koushkaki (2015), who used dimensional analysis in their development of a model for fuel consumption during ploughing with chisel plough. Also ASAE (2002a) referenced ASAE EP496, stating that the fuel consumption equations model developed was 15%
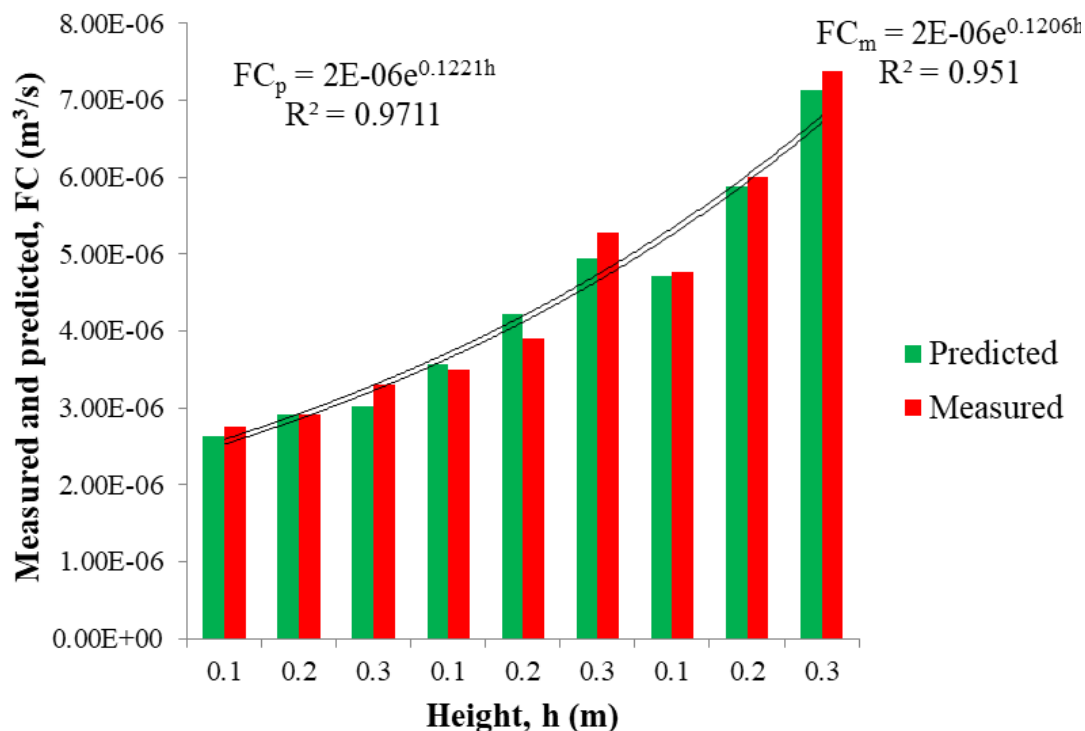
Figure 8. Comparison of measured and predicted FC with respect to height of ridge.

higher than the Nebraska Tractor Test performance under field condition.

Conclusion

From the results of the investigation, this study concludes as follows:

(1) It is possible to use field experimental data to develop a model equation for the prediction of tractor fuel consumption during ridging operation on a loamy sand soil in Port Harcourt, Nigeria, using Buckingham pi theorem.
(2) The model equation developed shows that tractor fuel consumption during ridging is directly proportional to the draught, ridging speed, height of ridge and soil moisture content; and inversely proportional to the penetration resistance and width of cut.
(3) The two constants, φ and C, in the equation were determined as 2.00×10^{-5} and 2.00×10^{-6} respectively.
(4) The coefficient of determination, R^2, for the equation was establised as 0.9488, which is an indication of a proper correlation between measured and predicted data.
(5) The fuel consumption was greatly increased with increasing ridging speed and ridge height, with the latter having greater impact on fuel consumption increase.
(6) The combined effect of increased ridging speed and ridge height was greater on the increasing fuel consumption than their individual effects.

(7) Appropriate combinations of ridging speed and ridge height be selected during ridging, to reduce amount of fuel consumed and the accompanying cost of agricultural production.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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