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DEVELOPMENT AND VALIDATION OF CROP YIELD MODEL

Yusuf, D.D.[1]

Abstract

A 3-year on-farm trial at Samaru (11° 11' N, 07° 38' E) was conducted to develop and validate a new model that can predict maize grain yield from different cultivation practices. An empirical relationship was developed to predict grain yield using soil and management factors. The developed mathematical model was validated using field data. The model was evaluated using statistical indices. Modelling efficiency (*EF*) and root mean square error (*RMSE*) of 0.91 and 0.21 respectively were obtained. Results showed that tillage treatments and planting methods significantly ($P \leq 0.01$) affected the soil shear strength, soil moisture content and maize grain yield. Deep tilled plots showed higher grain yield than shallow tilled plots.

1. Introduction

In Nigeria, there is increasing demand for maize (*Zea mays*) for both human consumption and as raw materials for industrial products. This has encouraged the development of new high yielding varieties and the mechanization of maize production. The yield potential for maize is estimated at between 7.0 and 8.0 tha^{-1} of grain in the northern guinea savanna zone and between 4.0 and 5.0 tha^{-1} in the southern forest zone of Nigeria (Abdul *et al.*, 1990).

In most areas, crops fail to approach their potential yields because of farmer's poor knowledge of soil management skills, and also due to deterioration of soil structure. Even though effects of tillage practices on crop yield have been widely investigated (Gaultney *et al.*, 1980; Wanjura, 1982; Hakanson *et al.*, 1987; Oussible and Crookston, 1987; Yusuf, 1996 and Yusuf and Asota, 1997), they are not well undersatood (Kayombo and Lal, 1986; Thomas and Hakanson, 1994). A crop model for soybean was developed by Sinclair (1986) using crop phonological and physiological framework. This modelling approach was used to examine the yield potential in other crops like sorghum (*Sorghum bicolour*) (Hammer and Muchow, 1991), maize (Muchow *et al.*, 1990) and sunflower (*Helianthus annuus*) (Chapman *et al.*, 1993).

The objectives of this study were to develop a model that predicts maize grain yield response from different soil and management factors and to determine the responses of maize yield to cultivation practices using the developed model.

2. Materials and methods

2.1 Experimental site

Field trials were conducted on sandy loam soil at Samaru (11° 11' N, 07° 38' E and 685 m above sea level) in Kaduna State of Nigeria. The average annual rainfall of the area is 1100 mm and is spread between May and October. Air temperature ranges between 34 and 40 °C during thew cropping seasons of the experimental period. The soil is formed from drift materials and its profile is sandy on the surface overlying clay material. The major crops grown in the area are maize, sorghum, millet and groundnut.

[1]Department of Agric. Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria. Nigeria e-mail: ddyusuf@yahoo.com.

2.2 Field measurements

Five tillage treatments were used as follows: *arara* ploughing followed by zigzag harrowing and *arara* ridging (*TT1*), emcot ploughing followed by zigzag harrowing and emcot ridging (*TT2*), mouldboard ploughing followed by disk harrowing and disk ridging (*TT3*), disk ploughing followed by disk harrowing and disk ridging (*TT4*) and manual ridging (*TT5*). Four nitrogen fertilizer treatments were used, namely 0, 40, 80 and 120 $kgNha^{-1}$ applied in single doses. The maize variety used was TRSR-W and was planted both manually and mechanically. The treatments were randomly assigned in a 4 by 5 by 2 factorial experiment arranged in a strip-split- plot design with tillage treatments as horizontal treatments, fertilizer treatments as vertical treatments and planting methods as sub-plot treatments in four replications. Each plot size was 4 m wide and 4 m long. Moisture contents (θ_g) of the soil samples were determined gravimetrically and calculated using the following equation:

$$\theta_g = \frac{m_m - m_d}{m_d} \tag{1}$$

where, m_m = mass of moist sample taken, kg
m_d = mass of oven-dry sample, kg

Seedbed shear-strength was determined with a 33 mm-diameter, 50 mm-high shear value at 2 and 5 weeks after sowing as described by Ball and O'Sullivan (1987). Maize grain yield was determined after harvesting the crop by hand at a grain moisture of 16%. The maize was shelled and the yield for each plot was weighed and recorded.

2.3 Model development

Mathematical model of crop yield can be represented with an equation relating dependent observable crop response and the pertinent variables influencing the crop yield. The 'effect' could be hypothesized as function of the 'cause' (Lanzer and Paris, 1981).

For a model to improve system understanding, there is the need for detailed representation of the different processes in the system. Some of the pertinent factors affecting crop yield (Figure 1) that have not been considered previously include:

i soil resistance to cone penetrometer pressure (C), MPa;
ii depth of soil cut (D), cm;
iii soil dry bulk density (γ_d), kgm^{-3}
iv time input (I), hha^{-1}

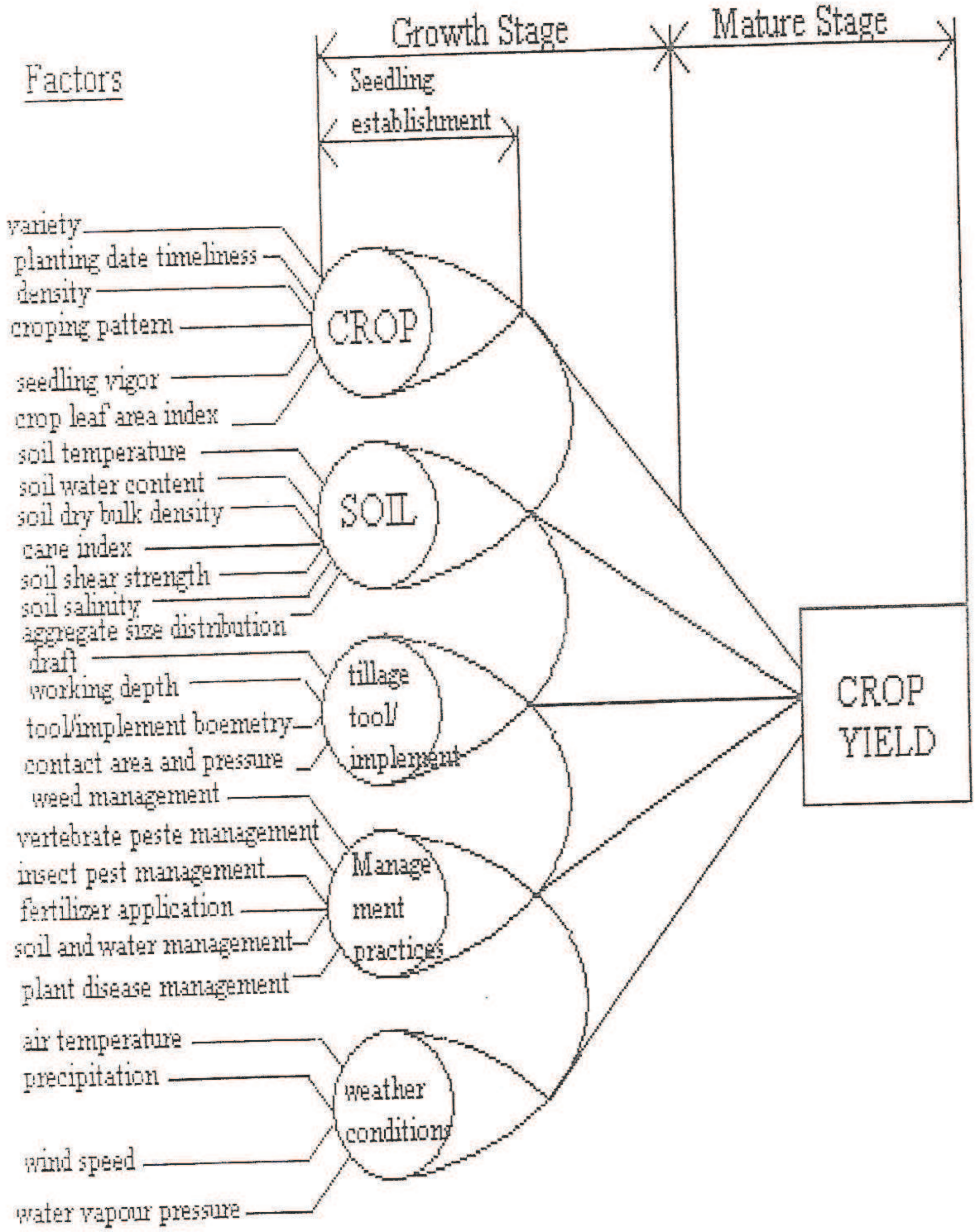

Figure 1: Interrelationship between the main factors that affect crop (maize) yield

A new model that takes all these factors into consideration was developed. The relationship between crop yield (Y) and the above factors can be written as:

$$Y = f(C, D, \gamma_d, N, I) \quad (2)$$

Where N is nitrogen input (kgha^{-1}). Equation (2) represents a multi-variate relationship of the type;

$$K_1 = f(k_2, k_3, j_i) \quad (3)$$

Where K_1 K_2 K_3 are variables and j_i are parameters. Langhaar (1954), Schuring and Emori (1964) and Wang *et al.* (1972) used the same procedure in developing similar models. For fixed parameter ji, Equation (3) can expressed as

$$K_{1j} = f(k_1, k_2) \quad (4)$$

Expanding k_{ij} by Maclaurin's series and substituting k_1, k_2 and k_3 with Y, C and D respectively and j_1, j_2 and j_3 with γ_d, N and I respectively, Equation 5 was obtained.

$$Y = f(C,, \gamma_d, N, I)I + G(C, \gamma_d, N, I)D + H(C,, \gamma_d, N, I)D \quad (5)$$

Where F, G and H are functions dependent upon the given values of j_1, j_2 and j_3.

2.4 Model evaluation

The model was evaluated using both graphical and statistical indices. Measured and predicted values were plotted on 1:1 graph to evaluate the performance of the model. Modelling efficiency (*EF*), root mean square error (*RMSE*) ands coefficient of residual mass (*CRM*) were used to compare the observed and predicted values of the developed model (Equatioins 6, 7 and 8)

$$EF = 1 - \frac{\sum_{N-1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}\left(O_i - \bar{O}_i\right)^2} \quad (6)$$

$$RMS = \frac{1}{N}\sum_{i=1}^{N}(P_i - O_i)^2 \quad (7)$$

$$CRM = \frac{\left(\sum_{i=1}^{N} O_i - \sum_{i=1}^{N} P_i\right)}{\sum_{i=1}^{N} O_i} \quad (8)$$

3. Results and discussion

From Figure 2, it can be seen that there was higher moisture content in 1998 and 1999 than in 1997. The seedbeds of *TT3, TT4* and *TT5* had high soil moisture contents and low soil shear strength (Figure 2) while plots of *TT1* and *TT2* had low soil moisture contents and high soil shear strengths two weeks after sowing. Similar trend was observed at two weeks after sowing. The effect of nitrogen rate was not significant ($P \leq 0.05$) on soil shear strength two weeks after sowing. Analysis of variance showed that tillage treatment, planting method and the interaction of year and tillage treatment significantly ($P \leq 0.05$) affected the soil shear strength. Tillage treatments and planting methods significantly ($P \leq 0.05$) affected the soil moisture content (Table 1).

A reduction of the overall vegetative cover as a result of deep tillage was probably the major cause of high soil water content in plots of *TT3, TT4* and *TT5*. Tillage treatments had significant ($P \leq 0.05$) effect on maize grain yield. Increase in maize grain yield of 45.6 and 78.5% were shown by *TT3* and *TT4* respectively over the control (*TT5*) using mechanical planting method. Similarly, increases of 35.2 and 67.8% in yield were recorded in *TT3* and *TT4* respectively over the control by manual planting method.

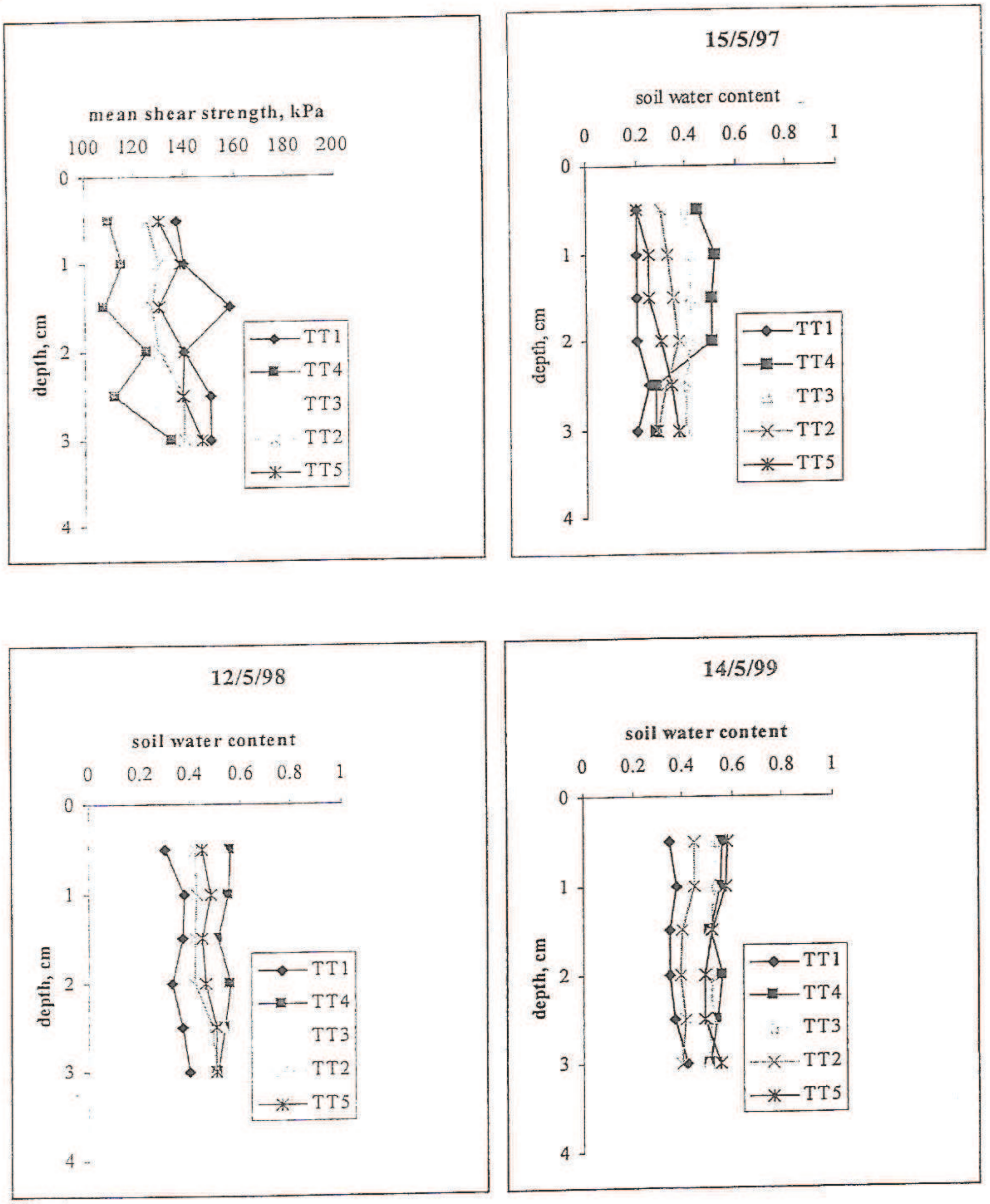

Figure 2:Mean soil shear strength at field capacity moisture content and profile soil water contents at the seedling emergence stage

Table 1: Combined analysis of variance of soil shear strength, soil moisture content and maize grain yield over a 3-year (1997 – 1999) period at Samaru, Nigeria

Source of variation	df	Soil shear strength at 0-30 cm depth		Soil moisture content	Maize grain yield
		2 WAS	5WAS		
Replication	3	246.662	242.043	141.317	10.942
Years (Y)	2	6.804**	22.135**	9.107**	14.637**
Reps (Y)	6	23.034	93.672	87.074	1.376
Vertical factor (A)	3	64.040**	2.185ns	35.096**	0.256ns
Y x A	6	8.962**	1.449ns	13.950**	0.031ns
Rep (Y x A)	27	5.951	0.919	5.620	0.017
Horizontal factor (B)	4	5870.479**	4242.799**	353.746**	37.038**
A x B	12	26.709**	1.823**	5.061**	0.009ns
Y x B	8	12.509**	57.631**	22.469**	1.201ns
Y x A x B	24	5.786**	0.688ns	5.164**	0.193ns
Reps (Y x A x B)	144	8.867	8.347	5.193	0.249
Subplot factor (C)	1	59.925**	12.578**	232.966**	9.344**
A x C	3	5.971**	1.412ns	4.077**	0.024ns
B x C	4	24.347**	1.492ns	1.398ns	0.129ns
Y x C	2	16.041**	0.186ns	32.317**	1.274ns
A x B x C	12	1.662ns	1.237ns	2.981**	0.021ns
Y x B x C	8	3.648**	0.465ns	0.832ns	0.598ns
Y x A x B x C	30	1.312ns	0.910ns	2.406**	0.020ns
Error	180	5.692	0.910	2.830	0.137
Total	479				

WAS: Weeks after planting, **: Significant at 0.01 probability level, ns: not significant

The regression equation for the crop model is given as Equation 9 below:

$$Y = 13.69 + 0.83 \times 10^{-3}(\gamma_d D) + 9.33 \times 10^{7} C N^{3} I^{2} (\gamma_d)^{3} \qquad (9)$$

A *1:1* plot of the predicted and observed is shown in Figure 3.

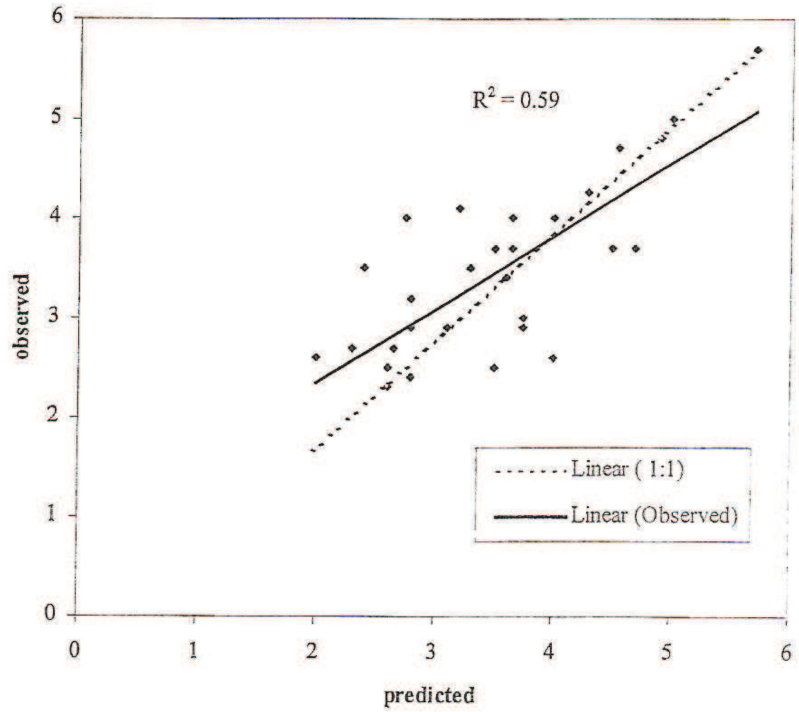

Figure 3: A comparison between observed and predicted maize grain yield

The difference between the predicted and observed data was not significant at 5% level. The model performance statistics on all plots showed that the *EF, RMSE, CRM* and R^2 were 0.91, 0.21, 0.18 and 0.59 respectively. The *RMS* describes the average absolute deviation between the predicted and observed yields. The smaller the *RMSE* value the better the model. There was little difference between the predicted and observed values (as shown by the *RMSE*) despite the variations in weather and soil properties during the 3-year on-farm trials. The positive value of *CRM* indicates that the majority of predicted values were less than the observed values. Similar results were obtained in experiments under field conditions by Daniel *et al.* (2000) and Jose *et al.* (2000). There was close agreement between predicted and observed values indicating good performance of the model and therefore can be applied in this area.

As the model is empirical, it can only be used in the study area with the given set of conditions. It is recommended that field experiments be planned and crop development stages monitored before the model can be applied in other areas. Also, further research is needed in this area to validate the model.

4. Conclusion

The following conclusions were drawn from the study:

i Tillage treatments and planting methods significantly affected the soil shear strength, moisture content and maize grain yield

ii An empirical model for predicting maize grain yield was developed for Samaru area.

iii The model showed good agreement between observed and predicted maize grain yield with *EF* of 0.90.

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