PERFORMANCE EVALUATION OF AN OX-DRAWN RIDGING PLOUGH IN A SOIL-BIN

S.H.M. Aikins[1] and J. Kilgour[2]
[1]Department of Agricultural Engineering, College of Engineering,
Kwame Nkrumah University of Science & Technology, Kumasi, Ghana
[2]Cranfield University at Silsoe, Cranfield University,
Silsoe, Bedfordshire, MK45 4DT, United Kingdom

ABSTRACT

An ox-drawn ridging plough was developed using the Godwin-Spoor narrow tine soil force prediction model. The plough was evaluated in a sandy loam soil in the soil-bin at Cranfield University, Silsoe. The objectives were to compare predicted with measured draught and vertical forces, and cross-sectional area of soil disturbance respectively. The experiments were arranged in a randomised complete block design with two blocks including ploughing to the right and left within the soil bin. The plough was run at a speed of 0.7m/s at depths between 0.10 and 0.25m at 0.05m intervals. Each run was replicated eight times. The main instrumentation employed was the extended octagonal ring transducer for soil force measurement. A profile gauge was used for taking soil profiles. The measured draught force was 19.9% greater than the predicted force. This was in good agreement with the narrow tine force prediction theory, which suggests that predicted draught and vertical forces should be within 15 – 20% of measured values. The measured vertical force was 37.1% smaller than the predicted force. This was a less satisfactory measure of agreement between predicted and measured force and may be attributed to the complex geometry of the ridging plough compared with the plane shape of the simple tine as used in the Godwin-Spoor tine force model. The measured area of soil disturbed was 52.3% smaller than the predicted area. This was in good agreement with the area prediction approach.

Keywords: Animal traction, ridging plough, evaluation, performance, soil-bin.

INTRODUCTION

Two of the major constraints limiting crop production in Northern Ghana are untimely land preparation and inadequate moisture availability to crop roots. Crop production in Northern Ghana is very dependent on rainfall. The distribution of rainfall during the growing season has been erratic. Consequently, the availability of water in the root zone of the crop during the growing period greatly impact on crop production and food security. The major crops grown in the area include maize, rice, sorghum, millet, cowpea, soybean, groundnuts, cassava, yam and cotton. The existing draught animal tillage system employs the hitching and harnessing of two oxen and a mouldboard plough. This is followed by ridging manually. This system is laborious, tiring and time consuming, yet planting has to be done timely in order to optimise crop yield. According to Hudson (1987), early planting is one of the most basic requirements for good crop production. This can be accomplished if land preparation is timely done.

Apart from the problem of timeliness of land preparation, there is inadequate disturbance of the soil. This leads to poor infiltration, runoff and soil erosion and crops experience water stress at some point during the growing period. Research on different tillage practices in Northern Ghana involving ox, tractor, manual and conservation tillage practices has consistently produced the highest yield from ox tillage and the lowest yield from conservation tillage (Afuakwa and Chamba, 1992; Agyare *et al*., 1996). Willcocks (1984) points out that the limited availability of water is the primary constraint to effective crop production in semi-arid regions. He suggests that dense sandy loam soils require some loosening to enhance water infiltration for effective crop growth and that deep tillage could be beneficial in increasing water availability to crop roots. Willcocks (1984) further suggested that deep tillage could be used to help increase crop-rooting depth and thereby increase crop yield. Ridging and tied ridges have been found to result in striking yield increases in semi-arid areas. The bunds increase water infiltration, improve soil physical properties, and decrease runoff and erosion. Consequently, fields with tied ridges have greater water storage capacity than either flat or open ridged fields. But ox-drawn ridging ploughs are not readily available in Northern Ghana. Therefore, an ox-drawn ridging plough was developed.

The objectives of the research were to compare predicted with measured draught and vertical forces, and to compare predicted with measured cross-sectional area of soil disturbance of the developed ox-drawn ridging plough.

MATERIALS AND METHODS

The research was carried out at Cranfield University, Silsoe in the United Kingdom between 1998 and 2000.

In the design of the ridging plough, consideration was given to prediction of soil draught and vertical forces, cross-sectional area of soil disturbance, oxen sustained and peak pull requirements, soil mechanical properties, and robustness as well as simplicity of design and manufacture.

Draught and vertical forces were predicted using the narrow tine force model (Godwin and Spoor, 1977; Godwin *et al*., 1984 and Wheeler and Godwin, 1996). The theoretical force model of Godwin and Spoor (1977), Godwin *et al*., (1984) and Wheeler and Godwin (1996) for a single tine as given in Equation 1 was used for the prediction of the draught force.

$$H_t = (\gamma d^2 N_\gamma + cdN_{ca} + qdN_q)\{w + d[m - \frac{1}{3}(m-1)]\}$$

$$\sin(\alpha + \delta) + c_a wd\cos\alpha \quad \cdots (1)$$

where

H_t= horizontal force component or draught force, (kN); V_t = vertical force component, (kN); c = soil cohesion, (kN/m^2); c_a = soil-interface adhesion, (kN/m^2); d = depth of tine from soil surface, (m); w = width of tine, (m); m = rapture distance ratio; q = surcharge pressure, (kN/m^2) (assumed zero in this research); g = dry bulk density, (kN/m^3); a = rake angle from forward horizontal, (degree); d = angle of soil-interface friction, (degree); N = dimensionless number; Suffixes to N: g = gravitational; ca = cohesive and adhesive and q = surcharge.

The prediction of the vertical force, V_t is based on the simplified vertical force component of a tine, Equation 2 (Godwin and Spoor, 1977; Godwin *et al*., 1984 and Wheeler and Godwin, 1996).

$$V_t = (\gamma d^2 N_\gamma + cdN_{ca} + qdN_q)[w + d(m - \frac{1}{3}(m-1))]\cos(\alpha + \delta) \qquad \ldots (2)$$

The N-factors in Equation 1 and Equation 2 depend on the roughness of the interface. Separate relationships are given for perfectly smooth ($\delta = 0$) and perfectly rough ($\delta = f$) interfaces and are computed using charts from Hettiaratchi *et al*., (1966). Equation 3 is used to extrapolate for values of δ not equal to 0 or ϕ for all *N* factors

$$N_{\delta=\delta} = N_{\delta=0}\left(\frac{N_{\delta=\phi}}{N_{\delta=0}}\right)^{\delta/\phi} \qquad \ldots(3)$$

According to Smith *et al*., (1989), the most important component of soil resultant force is draught or horizontal force, which, for a given speed determines the power required. The vertical component of soil resultant force determines the effectiveness of implement penetration. Accurate prediction of the tillage forces helps to minimise development costs and to maximise implement-working efficiency. Additionally, the determination of the draught and vertical forces facilitates the proper matching of implement size to the power source (Desbiolles, 1997). According to Godwin and Spoor (1977), predicted draught and vertical force should be 15 – 20% within the experimental value. This accuracy can be achieved only with careful measurement of soil parameters (Spoor, 1969). An aspect (depth to width) ratio of two to three was used hence the use of the narrow tine theory (Spoor, 1969; Smith *et al*., 1989). The rake angle used was 35°. Tine rake angle greatly influences the draught force. The draught increases slowly from rake angles between 10° and 50°. Above 50°, however, the rate of increase is very rapid. Spoor (1969) suggests that for minimum draught, rake angles of less than 50° should be used, providing that tines set at this inclination will do the job satisfactorily. In most agricultural situations, rake angles below 45° will give a downward component of the resultant force aiding penetration. At rake angles greater than 45°, the vertical force acts upwards tending to lift the implement out of work (Spoor, 1969).

The cross-sectional areas of soil disturbance were predicted according to the prediction approach of Negi *et al*., (1976). Negi *et al*., (1976) estimated the cross-sectional area of soil disturbed using Equation 4.

$$A_p = d^2 \cot\beta + dw \qquad \ldots (4)$$

where

A_p = predicted cross-sectional area of soil disturbed (m^2); d = depth of tine from soil surface, (m); w = width of tine, (m); β = soil shear plane angle, (degree).

Wheeler and Godwin (1996) suggest that the soil shear plane angle, β can be determined using Equation 5.

$$\beta = \arctan\left(\frac{1}{m - \cot\alpha}\right) \qquad (5)$$

where m = rupture distance ratio; a = rake angle from the forward horizontal, (degree).

According to Wheeler and Godwin (1996), the measured area could be about 50% smaller than the predicted area as shown in Fig. 1.

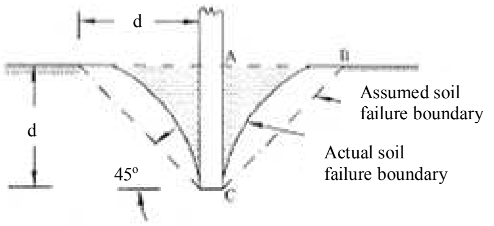

Fig. 1: Cross-Sectional Area of Soil Failure (Source: Wheeler and Godwin, 1996)

The ridging plough was evaluated in a sandy loam soil in the soil-bin at Cranfield University, Silsoe, United Kingdom in October, 1999. The experiments were arranged in a randomised complete block design with two blocks including ploughing to the right and left within the soil bin. The plough was run at a speed of 0.7m/s to simulate the speed of oxen. There were four treatments. This consisted of ploughing at depths between 0.10 and 0.25m at 0.05m intervals. Each run was replicated eight times. An extended octagonal ring transducer (EORT) on the soil bin carriage was employed as the major measurement system. The extended octagonal ring transducer has strain gauges wired in three complete Wheatstone bridge circuits and is described in detail by Godwin (1975). It measures the horizontal and vertical forces and their associated moments. The transducer signals are amplified using a DC differential amplifier, which both supplies the working potential for the strain gauge bridge circuit and amplifies the voltage output. The output can be printed on a personal computer in the control room. The EORT that was used is shown in Plate 1 mounted on the tool carriage.

Soil failure area profiles were taken with a soil profile gauge. A soil profile gauge consists of a yoke with equally spaced rods and a clamp. In taking soil area profile, the clamp was loosened and the rods were extended until they made contact with the soil. Afterwards the clamp was tightened and the resulting profile traced onto a broad sheet. The area was then determined using a measuring grid.

RESULTS AND DISCUSSION

Plate 1 shows the ridging plough that was developed. The ridging plough was connected to the extended octagonal ring transducer (EORT) via a hitch.

Comparison of Predicted with Measured Draught force

Fig. 2 illustrates the predicted and measured draught force plotted against the ploughing depth of the ridging plough. A polynomial curve describes the relationship between draught force

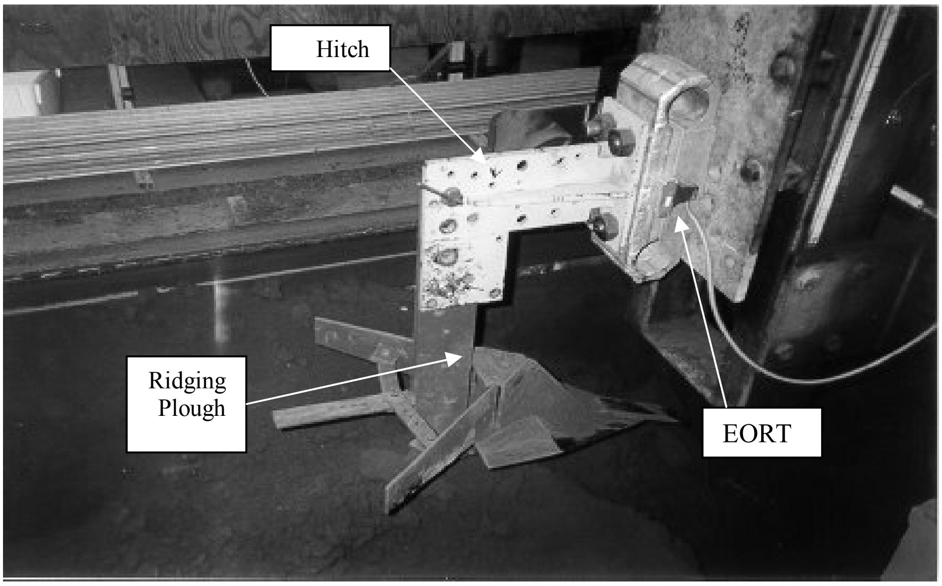

Plate 1: Ridging Plough and Extended Octagonal Ring Transducer

and working depth. It is evident that in general the measured draught, H_m was greater than the predicted draught force, H_p.

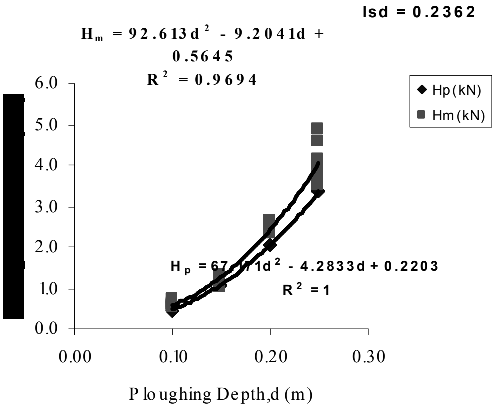

Fig. 2: Variation of draught force with ploughing depth

Regression analyses were applied to the relationship between measured and predicted draught force following the least squares method and selecting a linear relationship based upon that with the smallest error sum of squares and with the most significant regression coefficients, Fig. 3.

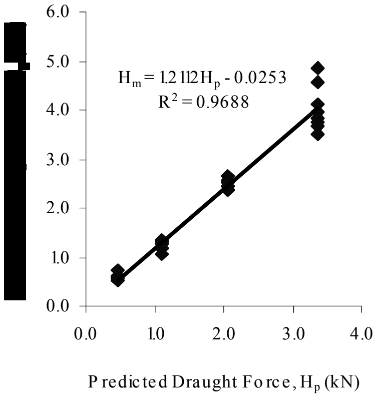

Fig. 3: Relationship between measured and predicted draught force

Table 1: Draught Force Prediction Error

Ploughing Depth, d (m)	Measured Draught Force, H_m (kN)	Predicted Draught Force, H_p (kN)	Prediction Error, E_p (%)
0.10	0.583	0.462	20.78
0.15	1.229	1.095	10.95
0.20	2.467	2.045	17.09
0.25	4.039	3.349	17.07

Source: Aikins (2000), p 188

The measured draught force data was subjected to an analysis of variance (ANOVA) to ascertain the effect of ploughing depth on draught force and also to find out the effect of implement run position within the soil bin on the draught force. The ANOVA was carried out using the MINTAB Statistical Software Release 13 (MINITAB Inc., 2000). The results showed that draught force measurements were unaffected by the implement run position within the soil bin. However, draught force was found to significantly increase with increasing ploughing depth. This observation is in agreement with the narrow tine draught force prediction model, which indicates that draught force is significantly influenced by depth of tillage. Tillage depth is the most significant factor influencing draught force (Desbiolles, 2003).

Draught force is a very important variable of interest in tillage implement development and use. Accurate prediction of implement draught is useful for matching implement size to the prime mover i.e. tractor or draught animal. In animal draught tillage, under-estimation of draught results in employing fewer animals than are required. The result could be over stressing or possibly death of the animals. On the other hand, over-estimation of draught force could result in employing more than the required number of draught animals or waste of resources. For the sandy loam soil employed, Equation 6 linking measured draught, H_m and predicted draught, H_p could be used to improve draught force prediction. In this case after an initial prediction using the narrow tine theory, the final prediction could be obtained by substituting the initial predicted draught force, H_p into Equation 6.

$$H_m = -0.0254 + 1.21H_p \qquad (6)$$

Comparison of Predicted with Measured Vertical force

The graph in Fig. 4 shows the predicted (V_p) and measured (V_m) vertical force against working depth, *d*. The relation between vertical force and ploughing depth is given by polynomial curves. It can be seen that the measured vertical force was consistently smaller than the predicted value. A clear observation is that penetration force increases with increasing depth.

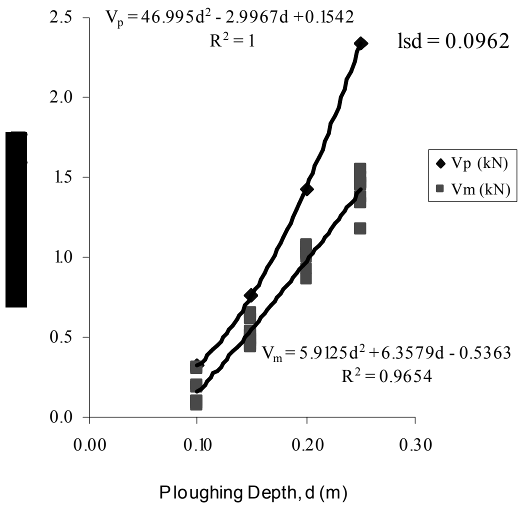

Fig. 4: Variation of vertical force with ploughing depth

Regression analyses were applied to the relationship between measured and predicted vertical force following the least squares method and selecting a linear relationship based upon that with the smallest sum of squares and with the most significant regression coefficients. The results showed a linear relationship between the two variables with adjusted R^2 = 95%, see Fig. 5.

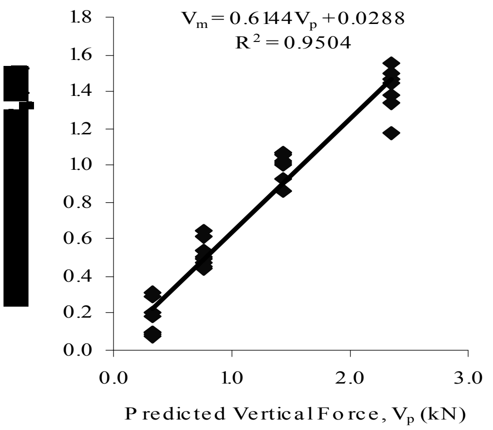

Fig. 5: Relationship between measured and predicted vertical force

The test of significance of the relationship indicated that the measured vertical force was significantly smaller than the predicted force with prediction error as indicated in Table 2. The measured vertical force was 37.1% smaller than the predicted force, taking overall mean values. This was a less good agreement with the narrow tine theory, which suggests that the predicted vertical force may differ from the measured value by 15 – 20% (Godwin and Spoor, 1977). The less satisfactory agreement is probably due to the complex geometry of the ridging plough in comparison with the geometry of the simple tine as used in the Godwin-Spoor tine force model. Payne (1956), Payne and Tanner (1959) and Hettiaratchi and Reece (1967) reported poorer comparison between predicted and measured vertical force.

Analysis of variance showed that vertical force was not significantly affected by soil-bin run position. On the other hand, the measured verti-

Table 2: Vertical Force Prediction Error

Ploughing Depth, d (m)	Measured Vertical Force, V_m (kN)	Predicted Vertical Force, V_p (kN)	Prediction Error, E_p (%)
0.10	0.169	0.323	-91.63
0.15	0.520	0.766	-47.22
0.20	1.002	1.431	-42.80
0.25	1.413	2.343	-65.89

Source: Aikins (2000), p 190

cal force increased significantly with increasing ploughing depth. An implement's weight and soil resistance influences the penetration depth. Thus good prediction of the vertical force is useful for improved penetration. From the regression analysis the Equation 7, relating measured vertical force, V_m and predicted vertical force, V_p can be used to deduce the desired vertical force.

$$V_m = 0.0288 + 0.6144\, V_p \tag{7}$$

This involves computing the vertical force, V_p using the narrow tine vertical force equation and substituting the resulting value in Equation 7 to obtain the new predicted vertical force. Alternatively, the predicted vertical force, V_p should be multiplied by 0.6144 to obtain the desired vertical force.

Comparison of Predicted with Measured cross-sectional area of soil disturbed

The plot of predicted and measured area of soil disturbed against ploughing depth is shown in polynomial curves, Fig. 6. It is clear that each measured area of soil disturbed was smaller than the corresponding predicted area.

Regression analysis of measured versus predicted area showed a linear relationship between the two variables with adjusted R^2 = 98.6%, Fig. 7.

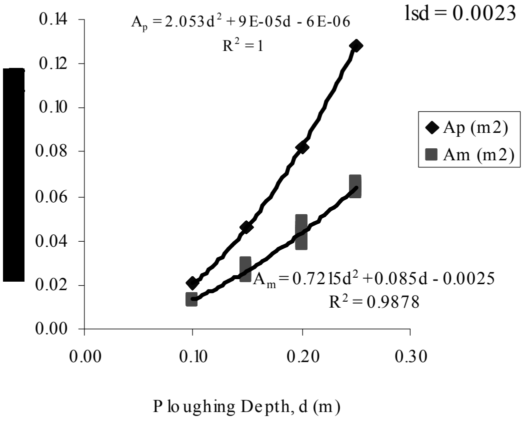

Fig. 6: Variation of area of soil disturbed with ploughing depth

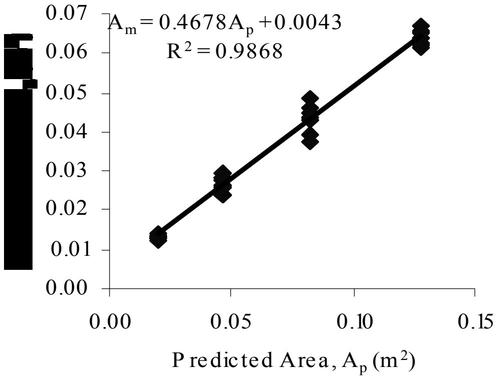

Fig. 7: Relationship between measured and predicted area of soil disturbed

Following the regression analyses it became necessary to evaluate the significance of the relationship. At the 0.05 significance level, it was found that the measured area of soil disturbed was significantly smaller than the predicted area with prediction errors given in Table 3. The measured area of soil disturbed was 52.3% smaller than the predicted area, taking overall mean values. This was in good agreement with the area prediction theory (Negi *et al.*, 1976; Wheeler and Godwin, 1996) which suggests that the measured area could be about 50% smaller than the predicted area.

Table 3: Area of Soil Disturbed Prediction Error

Ploughing Depth, d (m)	Measured Area of Soil Disturbed, A_m (m^2)	Predicted Area of Soil Disturbed, A_p (m^2)	Prediction Error, E_p (%)
0.10	0.01316	0.02053	-56.03
0.15	0.02665	0.04620	-73.36
0.20	0.04320	0.08213	-90.14
0.25	0.06390	0.12833	-100.83

Source: Aikins (2000), p 192

Analysis of variance of the measured area indicated that area of soil disturbed was not significantly affected by soil bin run position. However the cross-sectional area of soil disturbed increased significantly with increasing ploughing depth.

For the sandy loam soil employed, Equation 8 linking measured area of soil disturbance (A_m) and predicted cross-sectional area of soil disturbed (A_p) could be used to improve the prediction of area of soil disturbance.

$$A_m = 0.47\,A_p + 0.0043 \qquad (8)$$

In this case after an initial prediction of the area of soil disturbed A_p (Negi *et al*, 1976), the final prediction could be obtained by substituting the calculated value of A_p into Equation 8. Alternatively, the predicted area of soil disturbed, A_p should be multiplied by 0.477 to obtain the desired area.

CONCLUSION

Ox-Drawn Ridging Plough

The ox-drawn ridging plough was successfully developed using the Godwin-Spoor narrow tine model for soil force prediction.

Draught Force

The measured draught force was 19.9% greater than the predicted force taking overall means into consideration. This was in good agreement with the narrow tine force prediction model (Godwin and Spoor, 1977) which suggests that the measured draught force should be within 15 – 20% of the predicted force. This information is useful in matching implement size to the number of oxen required to draw the implement.

Vertical Force

The measured vertical force was 37.1% smaller than the predicted force taking overall mean values into consideration. This was a less good measure of agreement between measured and predicted force. Godwin and Spoor (1977) indicate that the measured vertical force should be within 15 – 20% of the predicted force. The less satisfactory agreement is probably due to the complex geometry of the ridging plough in comparison with the simple tine geometry considered in the narrow tine force prediction model.

Soil Disturbance

The measured area of soil disturbed was 52.3% smaller than the predicted area considering overall mean values. This was in agreement with the area prediction model (Negi *et al.*, 1976; Wheeler and Godwin, 1996) which suggests that the measured area could be about 50% smaller than the predicted area. There were significant differences in area of soil disturbed between ploughing depths. The cross-sectional area of soil disturbed at the 0.25-m ploughing depth was

5 times greater than the area of soil disturbed at the 0.10-m ploughing depth.

ACKNOWLEDGMENTS

The authors acknowledge with sincere appreciation and deep thanks to the World Bank for sponsoring the study through the Savanna Agricultural Research Institute of the Council for Scientific & Industrial Research, Ghana. The authors will also like to thank Prof. Michael John O'Dogherty and Dr. James L. Brighton all of Cranfield University, United Kingdom for providing useful advice.

REFERENCES

Afuakwa, J.J. and Chamba, E.B. (1991). Agronomy On-Station, Annual Report 1991, Tamale, Nyankpala Agricultural Experiment Station, Ghana. pp: 22 – 24.

Agyare, W.A., Kombiok, J.M. and Oduro, G. (1996). The Effect of Different Tillage Methods on the Yield of Maize, Annual Report 1996, Tamale, Savanna Agricultural Research Institute, Ghana. pp: 95 – 96.

Aikins, S.H.M. (2000). Animal Drawn Implement Development for Land Preparation and Moisture Conservation, Unpublished M.Phil. Thesis, MP/00/27, Silsoe, Cranfield University. 248 pages.

Desbiolles, J.M.A., Godwin, R.J., Kilgour, J. and Blackmore, B.S. (1997). 'A Novel Approach to the Prediction of Tillage Tool Draught using a Standard Tine, *Journal of Agricultural Engineering Research*, 66: 295 – 309.

Desbiolles, J.M.A. (2003). Key aspects of the mechanics of tillage points, Research Update - High Rainfall - September 2003, Naracoorte, SA cited [1 September 2004] Available from Internet -

http://www.unisa.edu.au/amrdc/Res/Proj/SeedTrials/Narrow_point_article_Kerribee.pdf

Godwin, R.J. (1975). 'An Extended Octagonal Ring Transducer for Use in Tillage Studies', *Journal of Agricultural Engineering Research,* 20: 347 – 357.

Godwin and Spoor, G. (1977). 'Soil failure with Narrow Tines', *Journal of Agricultural Engineering Research*, 22: 213 – 228.

Godwin, R. J., Spoor, G. and Soomro, M. (1984). 'The Effect of Tine Arrangement on Soil Forces and Disturbance', *Journal of Agricultural Engineering Research,* 30: 47 – 56.

Hettiaratchi, D.R.P., Witney, B.D. and Reece, A.R. (1966). 'The Calculation of Passive Pressure in two dimensional Soil Failure', *Journal of Agricultural Engineering Research* 11(2): 89 –107.

Hettiaratchi, D.R.P. and Reece, A.R. (1967). 'Symmetrical Three-dimensional Soil Failure', in *Journal of Agricultural Engineering Research*, 4 (3): 45 – 67.

Hudson, N. (1987). *Soil and Water Conservation in Semi-arid Areas*: FAO Soils Bulletin 57, Rome, FAO

MINITAB Inc. (2000). MINITAB™ Statistical Software Release 13 for Windows, USA

Negi, S., Mckyes, E., Godwin, R.J and Ogilvie, J.R. (1976). Development of Mechanization for The Efficient Injection of Liquid Slurry into Agricultural Soils, Report presented to Agriculture Canada, Engineering Research Services. pp: 14 - 18.

Payne, P.C.J. (1956). Relationship between the Mechanical Properties of Soils and the Performance of simple Cultivation Implements', *Journal of Agricultural Engineering Research*, 1: 23 – 50.

Payne, P.C.J. and Tanner, D.W. (1959). 'The Relationship between Rake Angle and the Performance of Simple Cultivation Implements'', *Journal of Agricultural Engineering Research* 4 (1): 312 – 325.

Smith, D.L.O., Godwin, R.J. and Spoor, G. (1989). 'Modelling Soil Disturbance due to Tillage and Traffic,' In: Larson, W.E (ed.) Mechanics and Related Process In Structured Agricultural Soils, Kluwer Ac. Publications, 121 – 136.

Spoor, G. (1969). 'Design of Soil Engaging Implements. Parts I and II", *Farm Machinery Design Engineering* 3:22–25, 28.

Wheeler, P.N. and Godwin, R.J. (1996). Soil Dynamics of Single and Multiple Tines at Speeds up to 20 km/h, *Journal of Agricultural Engineering Research,* 63: 243 – 250.

Willcocks, T. J. (1984). 'Tillage Requirements in Relation to Soil Type in Semi-arid Rainfed Agriculture', *Journal of Agricultural Engineering Research* 30: 327 – 336.