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Performance modelling and optimization of disc angle and tractor speed for a disc ridger in loamy soil using RSM

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A B S T R A C T

Ridging has been identified as a mechanized substitute for flat-land form and mounding in the cultivation of root and tuber crops. Manual ridging imposes high drudgery, consumes time and limits production scale. Therefore, mechanized ridging is necessary to improve efficiency, reduce cost and enable large-scale production. In this study, performance modelling and operational optimization of disc angle and tractor speed for a double-row disc ridger were established using CCRD in RSM. Quadratic models generated by RSM were used to predict optimum draught, wheel-slip and fuel consumption while maximizing cutting-depth and cutting-width. The results show that the ridger achieved optimum performance at 42.5^0 disc angle and 7.5 km/h tractor speed with a constant tilt angle of 25°. The regression model predicted optimal fuel consumption of 8.13 l/ha, 7.8 kN draught force, 2.8% wheel-slip, 29 cm depth and 277 cm width of cut, at the predicted disc angle and speed. The optimization analysis suggests that an increased disc angle and speed resulted in increased draught, fuel consumption, wheel-slip and cutting width and depth. To maximize operating efficiency, it is advised that ridging operations at the study site be conducted at the designated optimal speed and disc angle.

Keywords: Disc angle, Tractor-speed requirement, Draught, Wheel-slip, Tillage, Loamy soil, Optimization

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Introduction

The combination of statistical and mathematical tools makes Response Surface Methodology (RSM) an effective approach for developing, modifying, and optimizing various operations (Bayuo *et al.*, 2020; Abubakar and Iya, 2024). RSM has proven to be a useful method for thoroughly analyzing a problem in which a specific relevant response is typically affected by multiple predictor variables aimed at refining a predetermined response (Anderson and Whitcomb, 2016; Lamidi *et al.*, 2023). According to Lamidi *et al.* (2023), the initial purpose of employing RSM was to create models for experimental responses. However, applications of RSM evolved to develop models for optimizing numerical experiments (Bayuo *et al.*, 2020). According to Anderson and Whitcomb (2016), the primary goal of this design is to provide insight to response surfaces and identify areas of possible optimization.

The sustainability of agriculture relies on the profitability of farms, placing constant pressure on farmers to increase productivity while minimizing production costs through enhanced operational efficiency (Ren *et al.*, 2019).

The efficiency of tractor-implement operations is significantly influenced by the compatibility of the tractor and implement. Proper matching reduces loss of power, improves operational efficiency, lowers operating costs, and ensures fixed capital is optimally utilized (Barr *et al.*, 2020; Lemi *et al.*, 2023).

In order to develop and improve agricultural implements and choose the appropriate tractor, it is essential to determine the draught and power needed. Factors such as soil type, moisture content, working depth, and speed influence the power requirements of tillage implements (Oyelade and Oni, 2021). The energy required for tillage includes the power to overcome draught and the energy required to pull implements. Draught needed during tillage depends on soil characteristics, working depth, implement geometry, speed, and implement width (Abubakar and Iya, 2024). Major soil characteristics that affect tillage energy are moisture content, bulk density, penetration resistance, strength and texture of soil (Lemi *et al.*, 2023; Modi *et al.*, 2020). Evaluating the performance of tillage implements in terms of energy requirement is crucial.

Tillage is the mechanical modification or manipulation of the soil, which involves cutting, pulverizing and inverting to create an environment that is conducive to crop growth (Aikins *et al.*, 2021; Bekele, 2020). It is a process that can be physical, chemical, or biological, and is aimed at manipulating the soil to create optimal conditions for plant growth (Wasaya *et al.*,, 2019). Tillage is a crucial component of the root and tuber crop production and typically represents a significant part of the total energy expended in cultivation (Fasinmirin and Reichert, 2011). While mounding, ridging and flat-land forms are common tillage practices for root crop production, research suggests that mechanized ridging is a more effective alternative to mounding and flat-land forms (Amponsah *et al.*, 2014; Wandusim *et al.*, 2023). Key factors that influence the performance of disc ridgers include tilt angle (influence penetration), disc angle (influence width of cut) and tractor forward speed (Abdalla *et al.*, , 2014; Wandusim *et al.*, 2023).

In this study (1) performance modelling of disc angle and tractor speed for a double-row disc ridger was carried out, (2) optimum operational adjustments for disc angle and tractor speed were determined, (3) response variables such as working-depth, width of cut, wheel-slip, fuel-consumption and draught, were optimized based on data from field evaluation of the disc ridger.

Materials and Methods

Research site

The experiment was conducted at the Kwame Nkrumah University of Science and Technology (KNUST), Agricultural Research Station at Anwomaso, positioned at 6°41'56.75"N latitude, 1°31'25.85"W longitude, and an elevation of 274 meters above sea level (Wandusim *et al.*, 2023).

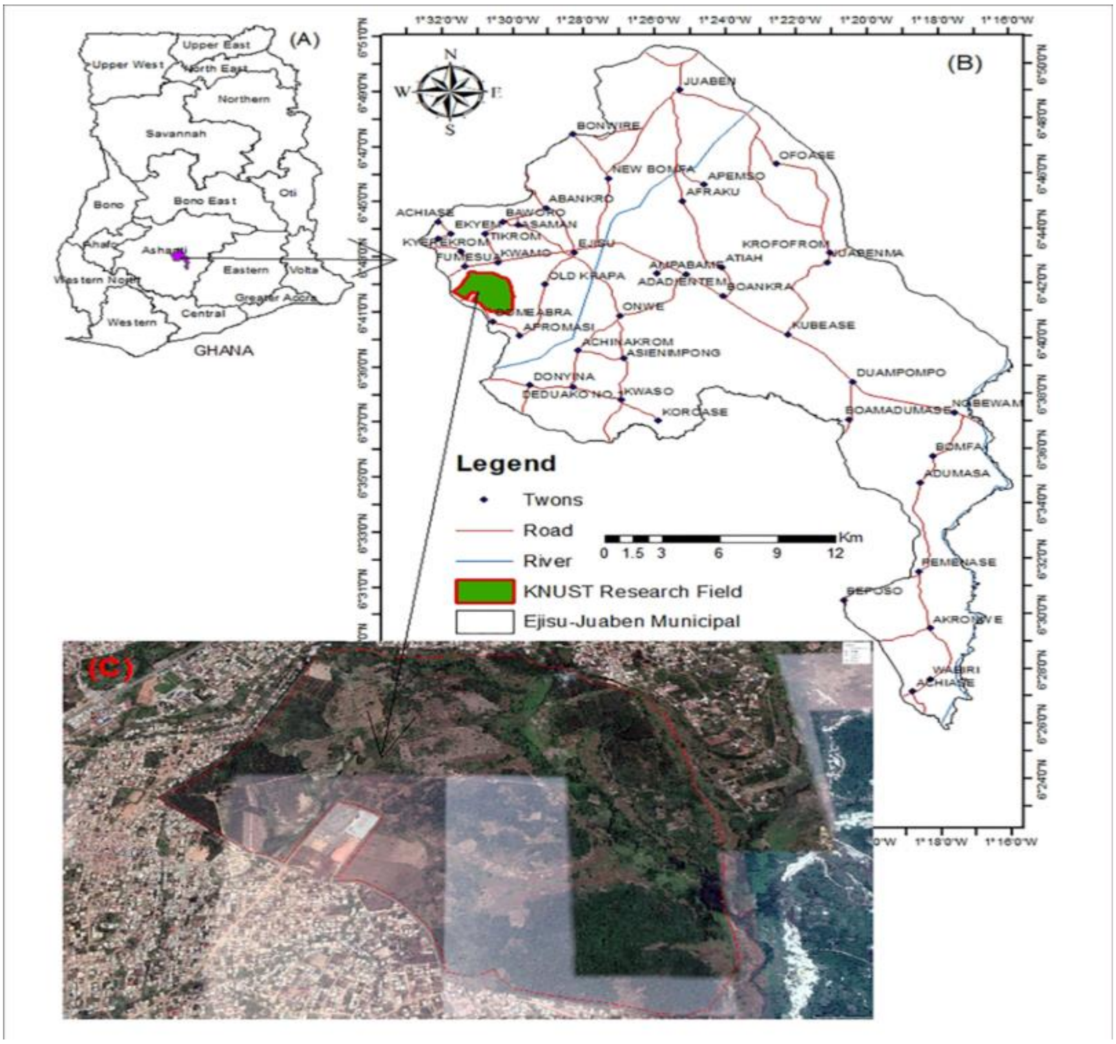

Fig. 1. Map of the study site showing (A) regions in Ghana, (B) Ejisu Municipality, and (C) KNUST (Sekyi-Annan *et al.*, 2021).

Experimental design

Experimental runs conducted for response optimization were generated using Central Composite Design (CCD) of Response Surface Methodology (Bayuo *et al.*, 2020; Chamoli, 2015). Two factors, five-factor levels each, constituted the design. Working-depth, width of cut, wheel-slip, fuel-consumption and draught were measured responses (Kolator, 2021). The two factors (disc angle and tractor speed) were set at high, centre, and low levels (+1, 0, and -1) respectively (Neba, 2020). This is presented in Table 1. MINITAB (Version 2019) and Design Expert (version 2023) were Statistical Software used to design the experiment and run the analysis. Equation 1 was used to create a rotatable experimental matrix with 13 runs.

$N = K^2 + 2K + C$ [Equation 1]

Where,

N = number of experimental runs
K = number of factors
C = center points

The experimental ranges for the two factors in Table 1, were taken from existing literature (Abdalla *et al.*, 2017; Mamkagh, 2019; Abdalla *et al.*,, 2014; Wandusim *et al.*, 2023) on the influence of speed and disc angles on tillage disc implements performance.

Table 1. Response Factor Optimization Design.

Factor	Symbol	Level		
		Low (-1)	Middle (0)	High (+1)
Disc angle	X_1	40°	42.5°	45°
Tractor speed	X_2	6 km/h	7.5 km/h	9 km/h

The regression equation was created by coding the test factors using Equation 2 (Malekjani and Jafari, 2020).

$$X_i = \frac{x_i - x_{io}}{\Delta x_{io}} \quad \text{[Equation 2]}$$

Where,

X_i = coded value of the ith factor or predictor variable
x_i = neutral value of the ith factor
x_{io} = neutral value ith factor at the centre point
Δx_{io} = step change value.

Mathematical correlation between responses $y_1 \ldots_5$ on the 2-factors were fitted to a second-order polynomial regression model (Chen *et al.*, 2023):

$$y_{1\ldots5} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \beta_{122} x_1 x_2^2 + \beta_{112} x_1^2 x_2 \quad \text{[Equation 3]}$$

Where,

y_1 = draught (kN)
y_2 = fuel consumption (l/ha)
y_3 = wheel-slip (%)
y_4 = width of cut (cm)
y_5 = working depth (cm)
x_1 = disc angle of ridger
x_2 = tractor speed
β_0 = constant
β_1 and β_2 = linear coefficients
β_{11} and β_{22} = quadratic coefficients
β_{12} and β_{21} = cross product coefficients
Each coefficient's significance in the equation was explained using P-values, R^2 and Adjusted R^2 (Bayuo *et al.*, 2020).

Table 2. Specifications of tractors and implements used.

Specification	Tractor (1)	Tractor (2)	Implement
Model	Valtra 795	New Holland 290	KNUST Disc Ridger
Make	4WD	4WD	2RDR-1.5m
Engine type	Diesel	Diesel	-
No. of cylinders	4	4	-
Cooling system	Water-cooled	Water-cooled	-
Engine power	75 hp	75 hp	-

Plate 2. New Holland (L) and Valtra (M) Tractors and disc ridger (R) in field operation.

Results and Discussion

Analysis of soil at the research site

Soil analysis test conducted at the research site prior to ridging is captured in Table 3. The sand, silt composition of the soil suggests that the soil is sandy-loam. Table 4 presents an overview of the experimental findings for a five-level, two-factor rotatable central composite design in RSM.

Table 3. Characteristics of soil at the research site.

Soil parameter	Values
Soil composition	
Sand	41 %
Silt	35 %
Clay	24 %
Classification	Loam
Average moisture content	13 %
Average bulk density	1.32 (g/m³)

Table 4. Experimental results for disc angle and tractor speed using the 2-row disc ridger on loamy soil.

Run	Factor 1	Factor 2	Responses				
	D_A (Deg.)	S_T (km/h)	D_I (kN)	F_C (l/ha)	W_T (%)	D_T (cm)	W_C (cm)
1	40	6	5.81	7.93	2.5	25	260
2	40	9	5.87	7.97	2.8	25	260
3	45	6	5.95	8.77	2.5	40	300
4	45	9	8.81	10.46	5.128	40	300
5	38.96	7.50	5.92	7.85	2.5	25	280
6	46.03	7.50	7.80	9.87	5.466	40	300
7	42.5	5.38	5.89	9.66	3.844	31	280
8	42.5	9.62	5.94	10.13	4.125	31	280
9	42.5	7.5	5.90	9.14	4.066	31	280
10	42.5	7.5	5.90	9.14	4.066	31	280
11	42.5	7.5	5.90	9.14	4.066	31	280
12	42.5	7.5	5.90	9.14	4.066	31	280
13	42.5	7.5	5.90	9.14	4.066	31	280

D_A = Disc angle (deg.); S_T = Tractor speed; D_I = Implement draught; F_C = Fuel consumption (l/h); W_T = Tractor wheel-slip (%); D_T = Tillage depth (cm); W_C = Width of cut (cm)

Disc ridger performance modelling

Multiple linear regression models were created to describe the correlation between x and y (independent and response variables), determining the slope and y-intercept that explain the regression line of best fit. The relationship between tractor-ridger performance parameters such as draught (y_1), fuel consumption (y_2), wheel-slip (y_3), depth of cut (y_4) and width of cut (y_5), was modelled using this regression equation. It also examined how these variables responded to changes in disc angle of the ridger (x_1) and tractor forward speed (x_2).

Diagnostics and Regression Models

The y-intercept, linear and quadratic coefficients of x_1 *and* x_2 for the dependent variables are stated below:

$$y_1 = -862.52 + 41.04x_1 + 140.57x_2 - 0.48{x_1}^2 - 0.75{x_2}^2 - 6.55x_1x_2 + 0.018x_1{x_2}^2 + 0.076{x_1}^2x_2$$

$$y_2 = -481.9441 + 22.6829x_1 + 58.7670x_2 - 2.6229{x_1}^2 - 0.2591{x_2}^2 - 0.8025x_1x_2 + 0.0284x_1{x_2}^2 + 0.0213{x_1}^2x_2$$

$$y_3 = -752.8596 + 40.7268x_1 + 64.1213x_2 - 4.3389{x_1}^2 - 0.5427{x_2}^2 + 3.4152x_1x_2 + 0.0675x_1{x_2}^2 - 0.0828{x_1}^2x_2$$

$$y_4 = -830.4641 + 24.5463x_1 + 167.0640x_2 - 3.9111{x_1}^2 - 0.0996{x_2}^2 - 11.1376x_1x_2 - 0.0000x_1{x_2}^2 + 0.2607{x_1}^2x_2$$

$$y_5 = -1171.22 + 15.44x_1 + 449.27x_2 + 0.30{x_1}^2 - 29.95{x_2}^2 - 10.55x_1x_2 + 0.70x_1{x_2}^2 + 0.00{x_1}^2x_2$$

Fitness of the regression model

Table 5 presents fitting characteristics of the regression models for different response variables such as $y_1 \dots y_5$. The table evaluates model performance based on Root Mean Square Error (RMSE), coefficient of determination (R^2), adjusted R^2, and statistical significance (P-value).

The models generally exhibit strong performance, with high R^2 values across all parameters, indicating a strong correlation between input variables and response variables. The low RMSE values for most models confirm their predictive accuracy. The statistical significance (p-values < 0.05 for all models) reinforces the reliability of the models, with the models for implement draught, cutting depth, and cutting width demonstrating the highest levels of significance ($p < 0.001$). However, the fuel consumption and wheel slip models have relatively lower adjusted R^2 values (0.791 and 0.754, respectively), indicating that additional influencing factors may need to be considered to improve model accuracy. Additionally, the higher RMSE for cutting width suggests some variability in predictions, which may require further refinement. This agrees with research by Wandusim *et al.* (2023), whose findings suggest that tractor speed and disc angle are directly proportional to draught, fuel consumption, wheel-slip, depth and width of cut.

Table 5. Fitting characteristics of the regression model.

Regression model	Fitting characteristics			
	RMSE	R^2	$AdjR^2$	P-value
Implement draught (y_1)	0.0195	0.9905	0.977	< 0.0001 ***
Fuel consumption (y_2)	0.233	0.9128	0.791	0.0208 **
Wheel slip (y_3)	0.295	0.8977	0.754	0.0301 **
working depth (y_4)	0.197	0.9980	0.996	< 0.0001 ***
Width of cut (y_5)	1.964	0.9750	0.939	0.00107 ***

*NB: **(p<0.01), very significant; ***(p<0.001), highly significant*

Relationship between disc angle and tractor speed on dependent variables

Figure 1 details the response surface plots illustrating the effect of disc angle (A) and speed (B) on key performance indicators.

The desirability plot (top-left) indicates that the highest desirability value of 0.92 is achieved at a disc angle of approximately 42.5⁰ and tractor speed of around 7.5 km/h. This suggests that these settings provide an optimal performance of the ridger under established moisture regimes and soil conditions in the study area.

The draught force plot (top-middle) shows that a lower draught value of 5.81 kN is observed at 42.5⁰ disc angle and 7.5 km/h tractor speed, while higher draught requirements are recorded at increased disc angle and tractor speed. This agrees with the literature on tillage disc implement draught requirement (Nkakini, 2015).

The fuel consumption plot (top-right) demonstrates that fuel usage remains within an optimal range of 8.13 l/ha at 42.5⁰ disc angle and 7.5 km/h tractor speed, with increased consumption observed as disc angle increases beyond 44⁰.

Tractor wheel-slip (bottom-left) exhibits minimal values (around 2.9%) at 42.5⁰ disc angle and 7.5 km/h tractor speed adjustments, whereas higher wheel-slip (>4.5%) occurred at increased disc angle and speed.

The depth of cut plot (bottom-middle) indicates a predicted cutting depth of 25.29 cm under optimal settings, with depth increasing as disc angle is adjusted beyond 44⁰. This confirms the influence of disc angle on soil penetration.

The width of cut plot (bottom-right) shows a predicted cutting width of 268 cm under optimal adjustment. The width increased slightly at higher disc angles, emphasizing the effect of implement geometry on field coverage.

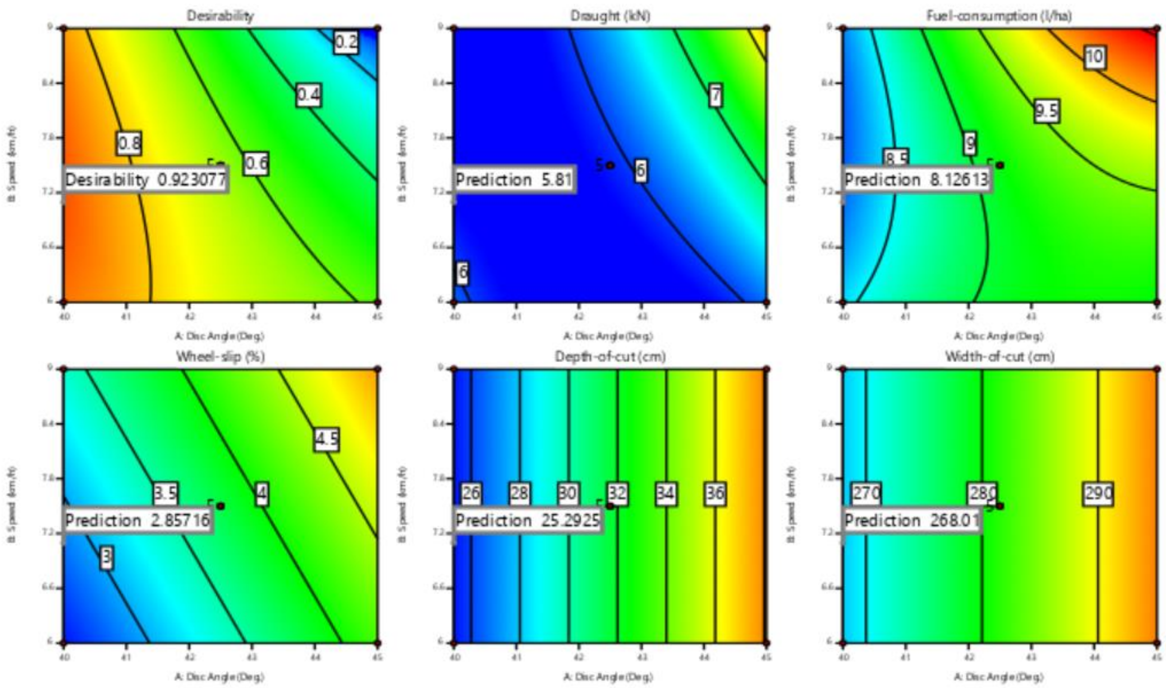

Fig. 2. Contour plots showing optimum values of performance parameters of the ridger.

Conclusion

Optimum draught and power requirement at optimum disc angle and tractor speed for 2-row disc ridger in a sandy-loamy soil were established. The regression model predicted disc angle and tractor forward speed required for optimum performance of the ridger. The results show that the ridger performed best at a disc angle of 42.5^0 and a tractor speed of 7.5 km/h, with the tilt angle set constant at 25^0. The optimization analysis demonstrates a high level of desirability (0.92) with efficient traction (2.86%), acceptable draught (5.81 kN), and fuel consumption value (8.13 l/ha). The results of this study suggest that optimizing disc angle and tractor speed could achieve desirable performance while minimizing energy consumption and improving the operational efficiency of the disc ridger. Future work should focus on fine-tuning these parameters to further increase the desirability score. Also, for purposes of generalization, performance evaluation of the ridger on different soil types and varying moisture regimes under the predicted optimal adjustment is recommended.

Author Contributions

Conceptualization, David Wandusim and Emmanuel Bobobee; Data curation, David Wandusim, Micheal Ampomah and Kwabena Abebrese; Formal analysis, Philip Laari; Investigation, David Wandusim, Micheal Ampomah and Kwabena Abebrese; Methodology, David Wandusim; Project administration, Emmanuel Bobobee, Joseph Akowuah and Eric Amoah; Resources, David Wandusim and Micheal Ampomah; Software, Philip Laari; Supervision, Emmanuel Bobobee, Joseph Akowuah and Eric Amoah; Validation, Emmanuel Bobobee and Joseph Akowuah; Writing – original draft, David Wandusim; Writing – review & editing, Emmanuel Bobobee, Joseph Akowuah and Eric Amoah. All authors have read and agreed to the published version of this manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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