



ORIGINAL RESEARCH ARTICLE

RESPONSE SURFACE MODELING OF SOIL MOISTURE CONTENT UNDER
DIFFERENT TILLAGE CONDITIONS

Nwachukwu C.P^{1*}, Umobi C.O¹, Okpala C.D¹, Nwanna E.C¹.

¹Department of Agricultural and Bioresources Engineering, Nnamdi Azikiwe University, Awka.

*Corresponding author's email: cp.nwachukwu@unizik.edu.ng

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ABSTRACT

This study investigates the impact of three key factors - irrigation deficit percentage, NPK application rate, and tillage - on soil moisture content, a crucial parameter in agricultural productivity. To achieve this, a field experiment was conducted at Nnamdi Azikiwe University's Department of Agricultural and Bioresources Engineering Experimental Site/Farm Workshop, Awka. The experiment utilized a central composite design in response surface methodology, incorporating three factors: irrigation deficit percentage, NPK application rate, and tillage. This design enabled the researchers to examine the individual and interactive effects of these factors on soil moisture content. The results of the study revealed that the model was highly significant, with an R-squared value of 0.9084. This indicates that approximately 91% of the variation in soil moisture content could be explained by the model. Furthermore, the analysis showed that irrigation deficit percentage, NPK application rate, and tillage were all significant factors influencing soil moisture content. However, the interaction terms between these factors were found to be non-significant. A key outcome of this study was the development of predictive models for soil moisture content under different tillage conditions, namely No Tillage, Conservative Tillage, and Conventional Tillage. These models could be employed to forecast soil moisture content for specified levels of irrigation deficit percentage and NPK application rate under each tillage condition. The findings of this research provide valuable insights into the effects of irrigation deficit percentage, NPK application rate, and tillage on soil moisture content. These insights could be applied to inform agricultural practices in similar regions, ultimately contributing to improved crop yields and sustainable agricultural management.

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1.0 Introduction

Water availability is a significant threat to crop production and food security, with only 4% of sub-Saharan Africa's arable land being irrigated (Kang et al., 2009; ACPC, 2011). As a result, agriculture in the region is predominantly rain-fed, making it highly vulnerable to climate variability and change. Agriculture is the primary source of livelihood and Gross Domestic Product (GDP) in many African countries, making it the most vulnerable sector to climate change and variability (Mendelson et al., 2008). Climate change poses a significant threat to sustainable development in Southeastern Nigeria, with expected impacts on agriculture and established farming systems (Gornall et al., 2010).

Climate change is defined as statistically significant variations in climate parameters, such as temperature and precipitation, that persist for extended periods (Eboh, 2009). These changes can manifest in various ways, including shifts in average climate conditions, increased climate variability, and altered frequency and magnitude of weather events. The impacts of climate change on agriculture are far-reaching, with expected changes in temperature, rainfall, ultra-violet radiation, and carbon dioxide levels affecting crop yields and food availability (Adamgbe and Ujoh, 2013). Long-term shifts in seasonal climatic patterns and increased intensity of weather extremes are already disrupting agriculture, with significant implications for food security.

Regions with predominantly rural economies and low levels of agricultural diversification, such as the Southeastern region of Nigeria, are at greater risk. The region's dependence on rain-fed agriculture, poor technology, low finance, and limited capacity to adapt to changing climatic conditions exacerbate its vulnerability. Nigeria's agricultural production has not kept pace with food production in recent decades, and there is a risk of further decline due to climatic factors (Chikezie *et al.*, 2015). Climate change is a global issue, but its impacts are more severe in developing countries, which have limited human, institutional, and financial capacity to adapt (UNFCC, 2007).

The consequences of climate change on food availability are significant, with increased intensity of storms, drought, and flooding, altered hydrological cycles, and precipitation variance all having implications for future food security (FAO, 2007). Abbaspour-Gilandeh and Sedghi (2015) and Vaitauskienė *et al.* (2017) characterize soil as a vital three-phase mixture consisting of solid particles, liquid water, and air. The interaction between soil and tillage tools plays a crucial role in determining tillage resistance and the overall quality of agricultural machinery performance. This relationship is essential when designing and optimizing tillage equipment (Li *et al.*, 2018; Zhao *et al.*, 2017; Zeng *et al.*, 2017). The complexity of the tillage process can be attributed to various factors, including soil composition, the dynamic properties of the machinery, and the adhesion and fragmentation of soil particles. The properties of soil, while intricate, are primarily shaped by tillage methods, composition, and moisture levels, among other influences (Schmalz *et al.*, 2013; Matin *et al.*, 2016; Wang *et al.*, 2019; Holthusen *et al.*, 2020). Soil moisture, defined as the water retained in an unsaturated zone, is critical for eco-hydrological processes. It significantly affects ecosystem development, plant growth, runoff responses, and the distribution of precipitation between evapotranspiration and deep infiltration (Hillel, 1998; Chaney *et al.*, 2015; He *et al.*, 2012). It is a key factor for ensuring stable crop growth (Lin *et al.*, 2005; Peng *et al.*, 2017), with its dynamics influenced by precipitation, evaporation, and soil properties such as density, porosity, and texture (Zucco *et al.*, 2014).

As a critical link between the edaphic zone and the atmosphere, soil moisture interacts significantly with the climate system, influencing both evapotranspiration and soil erosion in sloping areas. A comprehensive understanding of soil moisture dynamics is essential for analyzing changes in hydrothermal conditions, as well as the horizontal variations in moisture content, such as runoff during tillage (He *et al.*, 2012; Seneviratne *et al.*, 2010). Soil moisture tends to fluctuate spatially and temporally due to numerous factors, including climate variability, soil heterogeneity, tillage practices, and rainfall patterns (Jia *et al.*, 2017; 2018; Zucco *et al.*, 2014). Tillage serves as an important agricultural practice that enhances soil properties and boosts grain yield (Munkholm *et al.*, 2013; Pires *et al.*, 2017). It has a profound impact on growing conditions, soil moisture content, and overall crop performance, primarily by improving the chemical, physical, and biological attributes of the soil (De Cárcer *et al.*, 2019; Dekemati *et al.*, 2019; Romaneckas *et al.*, 2011; Wozniak, 2020). This study aims to simulate soil moisture content under various tillage practices, specifically considering irrigation deficits and differing NPK application rates through response surface methodology.

2. Materials and Method

2.1 Study Area

A field experiment was conducted at the Nnamdi Azikiwe University's Department of Agricultural and Bioresources Engineering Experimental Site/Farm Workshop, Awka. The experimental site is located within the geographical coordinates of 6°15'11.8"N - 6°15'5.3"E latitude and 7°7'118"N - 7°7'183"N longitude, with an altitude of 142m.

The site has distinct geographical characteristics, including sandy loam soil, savanna grassland vegetation, Imo shale geologic formation, and drainage from the Anambra River and its tributaries. The local climate is characterized by two distinct seasons: a dry season with high evapotranspiration and a rainy season with reduced evapotranspiration.

The annual climatic averages include rainfall of 1,500-1,600mm, wind speed of 1.73kmph, and relative humidity of 77%. The experimental site covers an area of 5,227.08 square meters, and the study was carried out from November 27, 2017, to February 22, 2018.

2.2 Field Preparation

The experimental field was situated on level ground and divided into three sections: A, B, and C. Each section measured 27m x 27m and was leveled for uniformity. Three tillage treatments were applied: conventional tillage in plot A, conservative tillage in plot B, and zero tillage in plot C. A central composite design (CCD)

was used to accommodate categorical and numeric factors. The design included two numeric factors (irrigation deficit and NPK application) and one categorical factor (tillage). The layout consisted of three plots, each containing nine subplots.

The experimental design involved varying tillage methods, irrigation deficit levels, and NPK fertilizer rates. The 27 subplots (3m x 3m each) were equipped with a drip irrigation system. Weather data were obtained from the Nigerian Meteorological Agency (NIMET), and average subplot readings were used for analysis. This experimental setup enabled a comprehensive evaluation of the effects of tillage, irrigation deficit, and NPK application soil moisture content. The land preparation was done using Mahindra tractor, the tillage implements were plough and harrow.

2.3 Soil moisture content

Soil moisture readings were taken daily at various depths (0-25cm, 25-50cm, 50-75cm, and 75-100cm) across different blocks throughout the crop growth period, using a soil moisture meter to measure the moisture content profiles at these specified depths.

2.4 Experimental design

The experiment was designed with various levels of tillage, NPK application rates and irrigation deficits as presented in table 1

Table 1: Independent variables and levels used for response surface design

Independent variable	Symbols	Ranges and levels		
		-I	0	+I
Irrigation Deficit(%)	A	10	30	50
NPK Application rate (KG/HA)	B	400	500	600
Tillage	C	1	2	3

3. Results and Discussion

3.1 Development of regression model

Central Composite Design (CCD) was used to optimize properties. The statistical combination of the independent variables along with the experimental response are presented in Table 2. Table 3 shows the analysis of the Sequential Model Sum of Squares for Soil Moisture Content. It is a statistical technique used to evaluate the fit of different polynomial models (linear, quadratic, cubic) to the data. From Table 3, the Linear vs Mean model is significant (p-value < 0.0001), indicating that a linear relationship between the variables is a good fit for the data. The 2FI (2-factor interaction) vs Linear model is not significant (p-value = 0.6834), suggesting that adding interaction terms between variables does not improve the model fit. The Quadratic vs 2FI model is also not significant (p-value = 0.2641), indicating that adding quadratic terms does not improve the model fit. The Cubic vs Quadratic model is aliased, meaning that the cubic terms are not estimable due to a lack of data. The analysis suggests that a linear model is the best fit for the Soil Moisture Content data.

Table 2: Experimental setup for 3 Level factorial response surface design

		Factor 1	Factor 2	Factor 3	Response
Std	Run	A: Irrigation deficit %	B: NPK Application Rate Kg/Ha	C:Tillage	Soil moisture content °C
22	1	50	600	3	10.93
17	2	30	600	2	9.25
10	3	10	400	2	11.31
18	4	30	500	2	9.11
23	5	10	500	3	12.01
24	6	50	500	3	10.28
7	7	30	400	1	12.4
21	8	10	600	3	12.57
14	9	10	500	2	10.12
25	10	30	400	3	10.39
8	11	30	600	1	13.5
2	12	50	400	1	11.31
12	13	10	600	2	12.88
20	14	50	400	3	9.37
4	15	50	600	1	12.14
11	16	50	400	2	9.24
19	17	10	400	3	11.6
3	18	10	600	1	14.96
27	19	30	500	3	11.21
13	20	50	600	2	9.82
16	21	30	400	2	10.29
5	22	10	500	1	14.06
1	23	10	400	1	13.6
15	24	50	500	2	9.89
26	25	30	600	3	12.35
6	26	50	500	1	11.91
9	27	30	500	1	12.72

1, 2 and 3 represents no tillage, conservative tillage and conventional tillage respectively.

3.2 Statistical analysis for soil moisture content

Table 3: Sequential Model Sum of Squares Soil Moisture Content

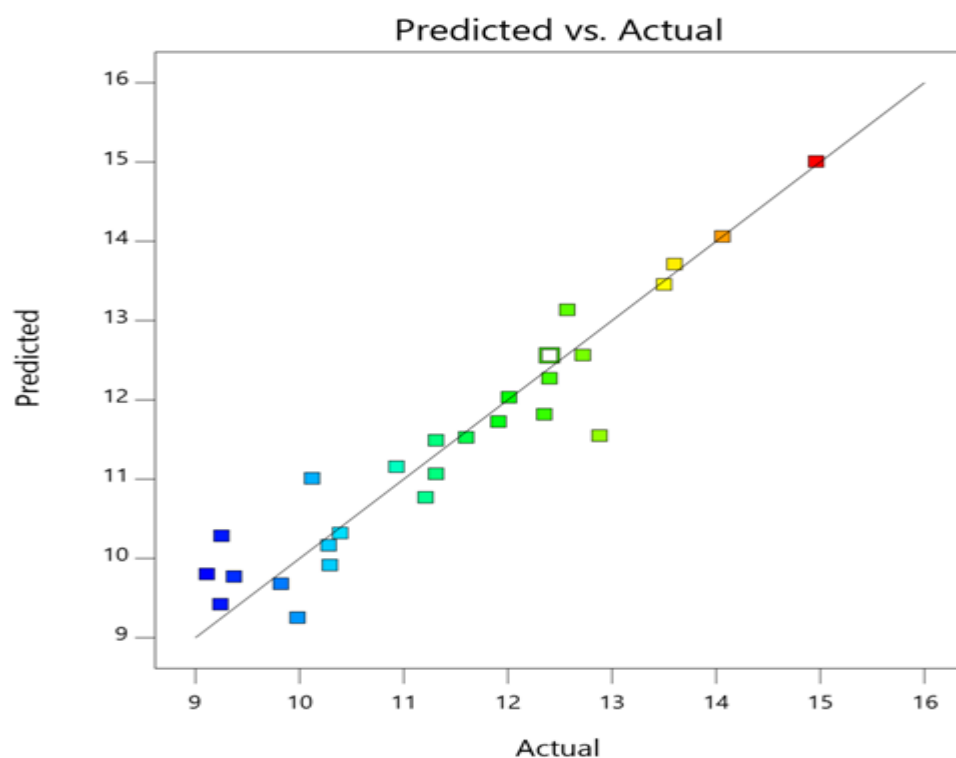
Sources	Sum of Squares	Df	Mean Square	F-value	p-value
Mean vs Total	3549.39	1	3549.39		
Linear vs Mean	57.75	4	14.44	36.97	< 0.0001 Suggested
2FI vs Linear	1.33	5	0.2666	0.6244	0.6834
Quadratic vs 2FI	1.18	2	0.5904	1.46	0.2641
Cubic vs Quadratic	3.59	8	0.4493	1.27	0.3843 Aliased
Residual	2.48	7	0.3548		
Total	3615.74	27	133.92		

Table 4 presents the results of an Analysis of Variance (ANOVA) for a response surface methodology (RSM) experiment. The experiment involves three factors: Irrigation Deficit Percentage (A), NPK Application Rate (B), and Tillage (C). The Table shows that the model is highly significant (p-value < 0.0001), indicating that the factors and their interactions have a significant impact on the response variable. The R-squared value (0.9084) indicates that about 91% of the variation in the response variable is explained by the model.

Table 4: Analysis of variance (ANOVA) for the fitted quadratic model for soil moisture content

Source	Sum of Squares	Df	Mean Square	F-value	p-value
Model	60.27	11	5.48	13.52	< 0.0001 Significant
A-Irrigation deficit%	17.74	1	17.74	43.78	< 0.0001
B-NPK Application rate	4.65	1	4.65	11.48	0.0041
C-Tillage	35.36	2	17.68	43.63	< 0.0001
AB	0.0374	1	0.0374	0.0923	0.7654
AC	0.2812	2	0.1406	0.3470	0.7123
BC	1.01	2	0.5073	1.25	0.3142
A ²	0.6468	1	0.6468	1.60	0.2257
B ²	0.5340	1	0.5340	1.32	0.2689
Residual	6.08	15	0.4052		
Cor Total	66.34	26			
Std. Dev.	0.6366	R ²	0.9084		
Mean	11.47	Adjusted R ²	0.8412		
C.V. %	5.55	Predicted R ²	0.6726		
		Adeq Precision	13.5567		

Among the individual factors, Irrigation Deficit Percentage (A), NPK Application Rate (B), and Tillage (C) are all significant, with p-values less than 0.0041. However, the interaction terms between these factors are not significant, indicating that the effects of these factors on the response variable are independent of each other.

**Figure 1:** Diagnostics plots of the fitted quadratic model for soil moisture content

Investigation on residuals to validate the adequacy of the model used was performed; residual is the difference between the observed response and predicted response. The plot of actual versus predicted (Fig 1) is used to examine the effects. Figure 1 shows that there is a very good correlation between the observed value and the value predicted by the model, the model does not show any variation of the constant variance

3.3 Model Equation for Soil moisture content

$$\text{Soil moisture content (No Tillage)} = 19.13667 - 0.093625A - 0.023079B - 0.000028A * B + 0.000821A^2 + 0.000030 B^2$$

The equation (3.1) can be used to make predictions about the response for given levels of each factor for Soil moisture content (No Tillage).

$$\text{Soil moisture content (Conservative Tillage)} = 17.97528 - 0.079208A - 0.027146B - 0.000028A * B + 0.000821A^2 + 0.000030B^2 \quad 2$$

The equation (3.2) can be used to make predictions about the response for given levels of each factor for Soil moisture content (Conservative Tillage).

$$\text{Soil moisture content (Conventional Tillage)} = 16.2088 - 0.081958A - 0.021512B - 0.000028A * B + 0.000821A^2 + 0.000030B^2 \quad 3$$

Eliminating the non-significant terms:

$$\text{Soil moisture content (No Tillage)} = 19.13667 - 0.093625A - 0.023079B - 0.000028A * B \quad 4$$

$$\text{Soil moisture content (Conservative Tillage)} = 17.97528 - 0.079208A - 0.027146B - 0.000028A * B \quad 5$$

$$\text{Soil moisture content (Conventional Tillage)} = 16.2088 - 0.081958A - 0.021512B - 0.000028A * B \quad 6$$

These equations are predictive models for soil moisture content under different tillage conditions: No Tillage, Conservative Tillage, and Conventional Tillage. Each equation is a quadratic polynomial that describes how soil moisture content changes in response to two factors: irrigation deficit percentage (A) and NPK application rate (B). The equations include linear, interaction, and quadratic terms to capture the relationships between these factors and soil moisture content. The coefficients in the equations represent the changes in soil moisture content resulting from changes in the factors. For instance, a negative coefficient for a factor indicates that an increase in that factor leads to a decrease in soil moisture content. The equations can be used to make predictions about soil moisture content for given levels of irrigation deficit percentage and NPK application rate under each tillage condition. The simplified equations (4-6) eliminate non-significant terms, providing a more streamlined model for predictions. The equations can be used to make predictions about the response for given levels of each factor for Soil moisture content.

Table 5: Optimization of Soil Moisture Content using Response Surface Methodology

Number	Irrigation deficit (%)	NPK application rate (Kg/Ha)	Tillage	Soil moisture Content (%)	Desirability	
1	11.594	596.406	2	10.396	1.000	Selected
2	14.127	600.000	2	10.236	0.989	
3	10.000	600.000	3	10.136	0.196	
4	10.000	599.010	3	12.123	0.196	
5	10.000	598.295	3	12.113	0.196	
6	10.940	600.000	3	12.060	0.190	
7	10.000	585.000	3	11.933	0.188	
8	10.000	576.223	3	11.820	0.181	
9	10.000	565.000	3	11.683	0.171	
10	15.638	600.000	3	11.699	0.158	

The responses of the variables in Table 5 were generated by Design Expert 11.0 software for the optimization based on the model obtained and the experimental data input. From Table 5, the run 1 order gave the optimum condition and was selected, the selected marked in run 1 order shows that it contains the best optimization results. The value obtained for moisture content in run 1 order was closed to the value obtained by Hossene *et al.*, (2015), in which they recorded soil moisture contents for silt loam soil and sandy loam soil values ranging from 7% to 8%. Runs 2-10 recorded desirability less than 1, desirability ranges from 0 to 1 for any given response, a value of 1 represents the ideal case, and a zero indicates that one or more responses fall outside desirable limits. The optimum values based on the run 1 order showed soil moisture content of 10.396%.

Table 6: Optimized and Observed values

	Tillage	Irrigation Deficit (%)	NPK Application rate (Kg/Ha)	Soil Moisture Content (%)
Optimized Parameters	Conservative	11.594	596.406	10.396
Observed Parameters	Conservative	7	500	14

The values in run 1 order were used for optimization and observations recorded in table 6. Conservative tillage, 7%, 500kg/Ha and 14% were obtained as the optimum values for tillage practice, irrigation deficit, NPK application rates and soil moisture content respectively. According to Broadbent (2015), conservative tillage was also selected as the best tillage method, Alteri (2011) also observed conservative tillage to be the best tillage method because it creates suitable soil environment for crop growth, and conserves soil and water energy through the reduction in tillage intensity.

Table 7: Evaluation Results

Evaluation Metrics	R ²	RMSE	D	CP _A
Value	0.86	0.92	0.74	0.26

From the evaluation results in Table 7; 0.86, 0.92, 0.74 and 0.26 were obtained for coefficient of determination (R²), Root mean square error (RMSE), index of agreement (d), and coefficient of performance (CP_A) respectively. The value of 1 for the coefficient of determination means that the dispersion for prediction is equal to that of the observation, R² value up to 0.6 is acceptable but R² value of 0.86 was obtained in the evaluation which is a high coefficient of determination. Root mean square error has a better agreement close to 0.0 (El-Sadek *et al*, 2003), RMSE value of 0.92 was obtained in the evaluation and this is within the acceptable range of RMSE. The index of agreement falls between 0 and 1 (Yaun *et al*, 2008), d value of 0.74 obtained in the evaluation is acceptable. Coefficient of performance approaches zero as the observed and predicted values get closer, CP_A value of 0.26 obtained in the evaluation is within acceptable range.

4. Conclusion

This study investigated the effects of irrigation deficit percentage, NPK application rate, and tillage on soil moisture content. The experiment was conducted at Nnamdi Azikiwe University's Department of Agricultural and Bioresources Engineering Experimental Site/Farm Workshop, Awka. The results showed that the model is highly significant, indicating that the factors and their interactions have a significant impact on soil moisture content. The R-squared value indicates that about 91% of the variation in soil moisture content is explained by the model.

The individual factors, irrigation deficit percentage, NPK application rate, and tillage, were all significant, indicating that they have a significant impact on soil moisture content. However, the interaction terms between these factors were not significant. The study developed predictive models for soil moisture content under different tillage conditions: No Tillage, Conservative Tillage, and Conventional Tillage. These models can be used to make predictions about soil moisture content for given levels of irrigation deficit percentage and NPK application rate under each tillage condition. The simplified models eliminate non-significant terms, providing a more streamlined model for predictions. Overall, the study provides valuable insights into the effects of irrigation deficit percentage, NPK application rate, and tillage on soil moisture content, and can be used to inform agricultural practices in similar regions.

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