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Determination of the effects of tillage on the productivity of a sandy loam soil using soil productivity models

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Abstract: Based on the hypothesis that soil properties and productivity components should be affected by different tillage methods, field and laboratory experiments were conducted to study the effects of zero tillage (ZT), one pass of disc plough tillage (P), one pass of disc plough plus one pass of disc harrow tillage (PH) and one pass of disc plough plus two passes of disc harrow tillage (PHH) on the distribution of the bulk density, available water capacity, pH, organic matter, available phosphorus, iron oxide and aluminium oxide at different soil depths, and their effects on the soil productivity. The available water capacity, pH, organic matter and available phosphorus were found to increase with the degree of tillage, while the bulk density, iron oxide and aluminium oxide were found to decrease with the degree of tillage. The results show that the soil productivity index was significantly ($P \leq 0.05$) affected by the tillage methods and found to increase with the degree of tillage.

Keywords: degree of tillage; soil depth; productivity index; soil properties

Soil is a vital component of crop production, but soil management operations are capable of increasing the productivity of the soil. The soil productivity is the capacity of a soil to produce a particular crop or sequence of crops under specified management practices. The productivity index (PI) is an algorithm based on the assumption that the soil is a major determinant of the crop yield because of the environment it provides for root growth (Lindstorm et al. 1992). An accurate estimate of the future soil productivity is essential to make agricultural policy decisions and to plan the use of land from a field scale to the national level (Agber 2011). Different methods have been developed which attempt to numerically relate the soil properties to its productivity (Nwite and Obi 2008). The model widely used today in the quantification of soil productivity is the PI model modified by Pierce et al. (1983). This PI is based on the use of physical and chemical properties to predict the effect of soil erosion on the productivity (Pierce et al. 1983).

Soil tillage is one cultural practice that affects the soil physical and chemical properties, and, hence, can make differences in the plant establishment, root growth, aerial cover and eventually the crop yield. Luder et al. (2019) conducted field trials to investigate how the tillage intensity modifies the small-scale spatial variability of soil and winter wheat parameters and found that the grain yields, grain protein concentration, grain nitrogen uptake and above-ground plant nitrogen were greater in a conventional tillage (CT) treatment than in a no-tillage (NT) treatment. Tillage distributes organic matter in the soil and, thus, improves the availability of nutrients for plant growth through the formation of clay humus com-

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plexes and the increase in the charged surfaces for nutrient binding (Nta et al. 2017). Consequently, the understanding of nutrient availability and crop nutrient uptake for agricultural production requires in-depth knowledge of different and complex interacting processes among the soil, plant, and environment. Fragile and sensitive ecosystems in arid and semi-arid countries and repeated droughts in recent years dictate the importance of the seed bed preparation with the aim of increasing the agricultural productivity, improving the soil moisture conditions and reducing wind and water erosion in fertile soils (Alam et al. 2014). The effect of tillage practices on the soil productivity in Taraba State has not been reported. Therefore, this study is an attempt to investigate the effects of different tillage systems on the productivity of the sandy loam soils of Taraba State, North-Eastern Nigeria which has a semi-arid climate using soil productivity models.

MATERIAL AND METHODS

Site description. The experiment was conducted at the Federal University, Wukari Research Farm (7°51' N, 9°47' E), in southern part of Taraba State, North-Eastern Nigeria. The top of the soil at the experimental site was sandy loam. It has two distinct seasons; wet and dry. The wet season starts from April and ends in October. The average rainfall varied from 1 100 to 1 250 mm, with temperatures ranging from 24 to 32 °C.

Experimental design and land preparation. The experiment was arranged in a randomised complete block design (RCBD) with four tillage treatments consisting of no-tillage (*NT*), disc ploughing only (*P*), disc ploughing followed disc harrowing (*PH*) and disc ploughing followed by disc harrowing twice only (*PHH*). A total land area of 80 m^2 each was mapped out for each of the tillage types. Each land was divided into 3 equal portions, with each replicate measuring 5 × 5 m (25 m^2). The replications were demarcated by 0.5 m wide pathways. The *NT* or zero tillage was undertaken with a contact herbicide, and a hoe and cutlass were used to clear the land after three days of herbicide application (Alam et al. 2014). The tillage operations were carried out using a New Holland model No. TT75 (New Holland, Italy). The ploughing was undertaken with a 3-disc plough while the harrowing was undertaken with a disc harrow.

Field methods. A detailed soil survey was conducted. A rigid method was employed for the surveying. A baseline and traverses perpendicular to the baseline were cut and observations were made at 100 m regular intervals. Soil samples were collected with an auger and core samplers at 0–20 cm, 20–40 cm and 40–60 cm depths, representing the top, sub and bottom soils, respectively, in each plot for the determination of the physicochemical properties. The soil samples were air-dried for a period of one week in a clean well-ventilated laboratory, homogenised by grinding, passed through a 2 mm (10 mesh) stainless-steel sieve and stored in labelled plastic cans ready for the laboratory analysis.

Laboratory methods. The collected samples were used to determine the soil physical and chemical properties. The particle-size distribution (soil texture) was determined using the Bouyoucos hydrometer method for mechanical analysis (Gee and Or 2002). The bulk density was determined by the core method of a known soil volume (Campbell and Henshall 1991). The available water capacity was determined with the pressure plate apparatus as described by Singh et al. (2013). The soil pH was measured electrometrically using a glass electrode pH meter (HI 8519, Hanna Instrument, Italy) in a soil-water ratio of 1 : 2.5 (Ibitoye 2006). The soil organic carbon was determined by the procedure of Walkley and Black using the dichromate wet oxidation method (Nelson and Sommers 1996). The organic matter was calculated by multiplying the organic carbon by 1.724. The available phosphorous was extracted using a Bray-1 solution and determined by molybdenum blue colorimetry (Frank et al. 1998). The extractable iron and aluminium were determined by the sodium citrate, sodium bicarbonate and sodium dithionite (CBD) method described by Parfitt and Childs (1988). All the reagents used in this study were of pure analytical grade and all the analyses were performed in triplicate.

Application of productivity index models. The Neill PI model modified by Pierce et al. (1983) was used. This model was based on simple measurable soil properties. The expression is:

$$PI = \sum_{i=1}^{n} A_i \times C_i \times D_i \times F_i \times L_i \times J_i \times Wf_i \quad (1)$$

where: PI – productivity index; A_i – sufficiency for the available water capacity for the i^{th} soil layer; C_i – sufficiency for the pH for the i^{th} soil layer; D_i – sufficiency for the bulk density for the i^{th} soil layer; F_i – sufficiency

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for the clay content for the i^{th} soil layer; L_i – sufficiency for the land slope for the i^{th} soil layer; J_i – sufficiency for the organic matter content for the i^{th} soil layer; Wf_i – root weighting factor (based on the depth of the root zone); n – number of horizons in the rooting zone (soil layer).

The *PI* model developed by Pierce et al. (1983) was expanded to capture the influence of the phosphorus (P), iron oxide (FeO) and aluminium oxide (Al_2O_3) by Agber (2011) as follows:

$$(PI_M) = \sum_{i=1}^{n} A_i \times C_i \times D_i \times F_i \times L_i \times J_i \times \times Wf_i \times P_i \times Fe_i \times Al_i \quad (2)$$

where: PI_M – modified Neill productivity index; P_i – sufficiency for the phosphorus content for the i^{th} soil layer; Fe_i – sufficiency for the iron oxide content in the i^{th} soil layer; Al_i – sufficiency for aluminium oxide content in the i^{th} soil layer.

Determination of the productivity index value. In these productivity indices, the productivity terms were normalised to range from 0.0 (complete inhibition of root growth) to 1.0 (noinhibition of root growth) based on a response function for each property (Kiniry et al. 1983) and the related levels of the soil properties to their sufficiency. Sufficiencies were assigned to thevsoil properties. The sufficiencies for the available water capacity, pH, bulk density, clay content, land slope, organic matter content and root weighting factor were adopted and used as described by Pierce et al. (1983), the sufficiency for the available phosphorus was adopted and used as described by Aduayi et al. (2002) and the sufficiencies for the extractable iron and aluminium were adopted and used as described by Ogunsola et al. (1989). The sufficiencies for each tillage types were multiplied to estimate the productivity indices.

Statistical analysis. The data collected were subjected to an ANOVA and the treatment means were separated using the *F*-LSD test at a 5% probability level (Hinkelmann and Kempthorne 1994).

RESULTS AND DISCUSSION

Effects of tillage on the physical properties of the soil. The parameters considered under the physical properties include the soil particle size distribution, bulk density (ρ_d) and available water capacity (*AWC*). Table 1 shows the effects of the tillage on the mean soil physical properties. The statistical analysis performed showed that the mean values of the sand and silt fractions were significantly affected by the tillage at all the investigated soil depths at a $P \leq 0.05$ level of significance.

Table 1. Effects of the tillage on the mean soil physical properties

Soil depth (cm)	Tillage type	Particle size distribution (%)			ρ_d (g·cm^{-3})	*AWC* (m·m^{-1})	Textural class
		sand	silt	clay			
0–20	*NT*	73.72	19.46	6.82	1.53	0.243	SL
	P	73.47	20.54	5.99	1.49	0.250	
	PH	74.61	18.75	6.64	1.46	0.267	
	PHH	75.18	18.53	6.29	1.37	0.275	
F-LSD$_{0.05}$		0.679	0.433	–	0.028	0.003	
20–40	*NT*	77.10	15.44	7.46	1.55	0.255	SL
	P	75.26	14.68	10.06	1.52	0.262	
	PH	75.48	17.22	7.30	1.47	0.268	
	PHH	78.26	15.38	6.36	1.41	0.282	
F-LSD$_{0.05}$		0.094	0.413	0.433	0.047	0.005	
40–60	*NT*	80.23	9.30	10.47	1.57	0.260	SL
	P	83.12	8.61	8.27	1.55	0.266	
	PH	82.42	8.57	9.01	1.48	0.274	
	PHH	83.15	9.43	7.42	1.45	0.288	
F-LSD$_{0.05}$		0.215	0.286	0.442	0.066	0.010	

AWC – available water capacity; ρ_d – bulk density; *NT* – no-tillage; *P* – disc ploughing only tillage; *PH* – disc ploughing followed by disc harrowing tillage; *PHH* – disc ploughing followed by disc harrowing twice only tillage; SL – sandy loam; *F*-LSD$_{0.05}$ – Fisher's least significant difference at a 5% probability level

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The clay fraction of the soil was not significantly affected by tillage at a soil depth of 0–20 cm, but was significantly affected by tillage at the depths of 20–40 cm and 40–60 cm at a $P \leq 0.05$ level of significance. The results show that the mean sand fraction of the soil ranged from 73.47 to 83.15%, the mean silt fraction ranged from 8.57 to 20.54% and the mean clay fraction of the soil varied from 5.99 to 10.47%. Generally, the mean values indicate that the sand fraction dominated the fine earth separate. This was followed by the silt fraction, while the clay fraction was the lowest. The soil texture in this area is mainly sandy loam for all the tillage types across all the soil depths.

The soil bulk density was significantly ($P \leq 0.05$) affected by the tillage methods and decreased with the degree of tillage, but increased with the soil depths. The lowest mean value of 1.37 $g \cdot cm^{-3}$ was obtained with the *PHH* tillage and a soil depth of 0–20 cm, while the highest mean value of 1.57 $g \cdot cm^{-3}$ was obtained at the *NT* treatment and a soil depth of 40–60 cm. The result is in line with the findings of Rashidi and Keshavarzpour (2008), who conducted a two year field experiment to investigate the effect of different tillage methods on the soil physical properties and crop yield of melons and reported that different tillage treatments significantly affected the soil bulk density during both years of study with the highest soil bulk density of 1.52 $g \cdot cm^{-3}$ obtained for the *NT* treatment and the lowest soil bulk density of 1.41 $g \cdot cm^{-3}$ obtained for the *CT* treatment. The higher values of the soil dry bulk density obtained on no tillage plots could be attributed to the fact that the soils in the no tillage plots were not disturbed in any case.

The results show that the *AWC* was significantly ($P \leq 0.05$) affected by the tillage methods at all the investigated soil depths and increased with the degree of tillage and the soil depths. The greatest amount of mean *AWC* (0.288 $m \cdot m^{-1}$) corresponded to the plough plus harrow twice tillage at a soil depth of 40–60 cm and the least (0.243 $m \cdot m^{-1}$) to the *NT* system at a soil depth of 0–20 cm. This agrees with Alam et al. (2014) who studied the effects of tillage practices on the soil properties and crop productivity in a wheat-mung bean-rice cropping system under subtropical climatic conditions and stated that at the end of the study, the maximum *AWC* was found in the deep tillage (16.50 cm) and the minimum *AWC* was found in the zero tillage (14.30 cm).

Effects of tillage on the chemical properties of the soil. The parameters considered under the chemical properties include the soil pH, organic matter (OM), available phosphorus (AP), FeO and Al_2O_3. Table 2 shows the effects of the tillage

Table 2. Effects of the tillage on the mean soil chemical properties

Soil depth (cm)	Tillage type	pH (H_2O)	Organic matter (%)	Available P (%)	FeO ($g \cdot kg^{-1}$)	Al_2O_3 ($g \cdot kg^{-1}$)
0–20	*NT*	6.78	6.40	17.15	6.9	1.0
	P	6.86	6.52	18.61	6.5	0.8
	PH	7.28	6.64	18.94	5.0	0.6
	PHH	7.41	6.68	19.87	4.4	0.5
F-$LSD_{0.05}$		0.084	–	0.046	0.846	–
20–40	*NT*	6.74	6.37	16.38	6.5	0.9
	P	6.78	6.48	17.85	5.5	0.8
	PH	6.92	6.62	18.71	4.8	0.5
	PHH	7.33	6.62	19.22	4.3	0.4
F-$LSD_{0.05}$		0.038	0.223	0.084	0.473	0.377
40–60	*NT*	6.65	6.24	16.37	5.7	0.7
	P	6.67	6.43	17.34	5.3	0.7
	PH	6.81	6.55	18.19	4.6	0.4
	PHH	6.98	6.60	18.85	3.8	0.4
F-$LSD_{0.05}$		0.065	0.038	0.065	0.660	0.188

NT – no-tillage; *P* – disc ploughing only tillage; *PH* – disc ploughing followed by disc harrowing tillage; *PHH* – disc ploughing followed by disc harrowing twice only tillage; FeO – iron oxide; Al_2O_3 – aluminium oxide; P – phosphorus; F-$LSD_{0.05}$ – Fisher's least significant difference at a 5% probability level

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on the mean soil chemical properties. The results show that the soil pH was significantly ($P \leq 0.05$) affected by the tillage methods and was found to increase with the tillage operations, but decreased with the soil depths. The maximum mean soil pH value of 7.41 was obtained at the *PHH* tillage and a soil depth of 0–20 cm, while the minimum mean soil pH value of 6.65 was obtained at the *ZT* or *NT* system and a soil depth of 40–60 cm. Lime accumulation at the surface, due to the slow mixing under the *NT* system leads to a higher pH in this layer (Blevins and Fery 1993). Chatterjee and Lal (2009) stated that the lower soil pH under the *NT* system compared with the *CT* is owing to the formation of organic acids and nitrification of the ammonium ions (NH_4^+) in the application of fertilisers and mineralisation of plant residue. This is in line with Gholami et al. (2014) who observed a significant difference between the mean of three tillage systems such that the lowest soil pH level corresponds to the *NT* system and the highest corresponds to the CT system.

The statistical analysis performed showed that the mean values of the OM content was not significantly affected by the tillage at a soil depth of 0–20 cm, but was significantly affected by the tillage at thevdepths of 20–40 cm and 40–60 cm at a $P \leq 0.05$ level of significance. The mean values of the OM content of the soil were found to increase with the degree of tillage, but decreased with the soil depths. The highest mean OM content of 6.68% was obtained at the *PHH* tillage and a soil depth of 0–20 cm, while the lowest mean OM content of 6.24% was obtained at the *ZR* or *NT* treatment and a soil depth of 40–60 cm. Zeliha and Ismail (2017) found dissimilar results where soils under a no-till condition generally contain a greater level of organic carbon than those under conventional till conditions.

The soil available phosphorus contents were significantly ($P \leq 0.05$) affected by the tillage methods at all the soil depths investigated and were found to increase with the degree of tillage, but decrease with the soil depths. The maximum mean available phosphorus content value of 19.87% was obtained at the *PHH* tillage and a soil depth of 0–20 cm, while the minimum mean available phosphorus content value of 16.37% was obtained at *ZR* or *NT* treatment and a soil depth of 40–60 cm. The result is consistent with Nta et al. (2017) who evaluated the effect of tillage on the soil physico-chemical properties in South-Western Nigeria and reported a greater available phosphorus content with tilled soils than untilled soils. The greater available phosphorus content found in the tilled soils might have been influenced by the soil pH since the availability of phosphorus and its solubility is pH dependent in accordance to the observation of Ozubor and Anoliefo (1999) that soils with a low pH value result in the reaction of phosphorus with aluminium and iron to form complex compounds, such as aluminium phosphate (Al_3PO_4) and iron phosphate ($FePO_4$), which are fixed in the soil and not readily available for plants.

The results show that the soil extractable iron oxide content was significantly ($P \leq 0.05$) affected by the tillage methods and decreased with the degree of tillage and the soil depths. The highest mean value of the extractable iron oxide content was 6.9 $g \cdot kg^{-1}$ at *ZR* or *NT* treatment and a 0–20 cm soil depth, while the lowest mean value of the extractable iron oxide content was 3.8 $g \cdot kg^{-1}$ at the *PHH* tillage and a 40–60 cm soil depth. The result agrees with Nta et al. (2017) who evaluated the effect of tillage on the soil physico-chemical properties in South-Western Nigeria and reported that the higher amount of mean soil extractable iron (64.75 $mg \cdot kg^{-1}$) corresponded to the *ZR* system and the lower amount of mean soil extractable iron (55.45 $mg \cdot kg^{-1}$) corresponded to the conventional plough tillage system.

The results show that soil extractable Al_2O_3 content was significantly ($P \leq 0.05$) affected by the tillage methods and decreased with the degree of tillage and the soil depths. The highest mean value of the Al_2O_3 content of 1.0 $g \cdot kg^{-1}$ was obtained at the *ZR* or *NT* treatment and a soil depth of 0–20 cm, while the lowest mean value of the aluminium oxide content of 0.4 $g \cdot kg^{-1}$ was obtained at the *PHH* tillage and a soil sample depth of 40–60 cm.

Effects of tillage on the soil productivity. Table 3 shows the average soil properties, ascribed sufficiency values and predicted productivity indices of the soils, while Table 4 shows the effects of the tillage on the soil productivity. The results show that the soil *PI* was significantly ($P \leq 0.05$) affected by the tillage methods and found to increase with the degree of tillage. The data showed that the mean values of the calculated *PI* were 0.192, 0.208, 0.224 and 0.256 for the *NT*, *P*, *PH* and *PHH* tillage systems, respectively, and the mean values of the calculated PI_M were 0.067, 0.095, 0.120 and 0.161 for the *NT*, *P*, *PH* and *PHH* tillage systems, respectively. The variation in the *PI* values depends on the initial properties of each soil within the root

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Table 3. Soil properties, ascribed sufficiency and calculated productivity index

Soil Property	Tillage types				Ascribed sufficiency			
	NT	*P*	*PH*	*PHH*	*NT*	*P*	*PH*	*PHH*
AWC ($m \cdot m^{-1}$)	0.253	0.259	0.270	0.282	1.000	1.000	1.000	1.000
pH (H_2O)	6.730	7.240	7.003	6.763	1.000	1.000	1.000	1.000
Bulk density ($g \cdot cm^{-3}$)	1.550	1.520	1.470	1.410	0.600	0.650	0.700	0.800
Clay content (%)	8.250	8.107	7.650	6.690	0.400	0.400	0.400	0.400
Land slope (%)	2.000	2.000	2.000	2.000	1.000	1.000	1.000	1.000
Organic matter (%)	6.337	6.477	6.603	6.633	1.000	1.000	1.000	1.000
Root weighting factor (cm)	80.000	80.000	80.000	80.000	0.800	0.800	0.800	0.800
Phosphorus (%)	16.630	17.930	18.610	19.310	0.900	0.930	0.950	0.980
Iron oxide ($g \cdot kg^{-1}$)	6.367	5.767	4.800	4.167	0.600	0.700	0.750	0.800
Aluminium oxide ($g \cdot kg^{-1}$)	0.867	0.767	0.500	0.433	0.650	0.700	0.750	0.800
Calculated *PI*					0.192	0.208	0.224	0.256
Calculated PI_M					0.067	0.095	0.120	0.161

NT – no-tillage; *P* – disc ploughing only tillage; *PH* – disc ploughing followed by disc harrowing tillage; *PHH* – disc ploughing followed by disc harrowing twice only tillage; *PI* – productivity index; PI_M – modified Neill productivity index

Table 4. Effects of the tillage on the soil productivity using productivity models

Productivity index	Tillage types				F-$LSD_{0.05}$
	NT	*P*	*PH*	*PHH*	
PI	0.1920	0.2080	0.2240	0.2560	0.0019
PI_M	0.0670	0.0950	0.1200	0.1610	0.0066

NT – no-tillage; *P* – disc ploughing only tillage; *PH* – disc ploughing followed by disc harrowing tillage; *PHH* – disc ploughing followed by disc harrowing twice only tillage; *PI* – productivity index; PI_M – modified Neill productivity index; F-$LSD_{0.05}$ – Fisher's least significant difference at a 5% probability level

zone, which affect the sufficiency of each soil property. The changes in the soil bulk density values influenced the *PI* values. The *PI* values were obviously higher than the PI_M values. These results showed that when three or more parameters, i.e. available phosphorus, FeO content and Al_2O_3 content were included in the model, the PI_M values decreased when compared with the PI values. The contribution of the iron and Al_2O_3 to the soil productivity decrease with their contents. The sufficiencies of the iron and aluminium oxides are low, therefore, they restricted the soil productivity. The results showed that the *PI* values were higher than the PI_M values; therefore, the PI_M model did not reflect the actual productivity level. The results also showed that the highest mean *PI* value of 0.256 and the PI_M value of 0.161 were obtained at the *PHH* tillage system, while the lowest mean *PI* value of 0.192 and PI_M value of 0.067 were obtained at the *ZT* or *NT* system. The high *PI* indicated a soil with improved soil properties; therefore, the most productive soil is the soil with the disc ploughing followed by *PHH* tillage system. The evaluation of the soil productivity was undertaken according to Fernando (2002). Comparing the calculated *PI* and PI_M values with the relative data of the *PI*, the productivity of the soils obtained with the *PI* is in the medium range (0.11–0.30), whereas with the $PI_{M,}$ the soil productivity is at a low (0.001–0.10) to moderate (0.11–0.30) range (Fernando 2002). The *PI* provides a single scale on which soils may be rated according to their suitability for crop production. The results indicated that the soil physical and chemical properties could be limiting or non-limiting factors on the productivity of the soils. According to Nwite and Obi (2008), a high soil *PI* is a good indicator of the soil capacity to support crop production for a long period of time.

CONCLUSION

Field and laboratory experiments were conducted to investigate the effects of tillage meth-

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ods on the soil productivity. The treatments consisted of four tillage methods, namely zero tillage, plough alone, plough plus harrow and plough plus harrow twice. Mechanical tillage (plough plus harrow twice) improves the soil properties and gave the best index of productivity. It is, therefore, recommended that seed bed preparation for crop production should be performed with mechanical tillage (plough plus harrow twice). However, to reduce the cost of the seed bed preparation, the plough plus harrow system should be adopted in the study area. The result of this study indicated that the effects of tillage on the productivity of the soil in the study area could be quantified. The sufficiency values of the soil properties, such as the available water capacity, bulk density, rooting depth and soil pH, could be used to quantify the productivity index of the soil. For further research, it is recommended that crops be planted to support these results with real yields and crop-specific behaviour in the given conditions.

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