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DSSAT-CSM Soil Module: Modeling Topsoil Water Holding Capacity in the two Dry Savanna Zones of Kano State, Nigeria.

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ABSTRACT

The objective of this study was to test the efficiency of the Hydraulic Pedotransfer Functions (PTFs) employed in the Decision Support System for Agrotechnology Transfer – Crop Simulation Model (DSSAT-CSM) in modeling topsoil WHC in Northern Guinea Savanna (NGS) and Sudan Savanna (SS) of Kano State in Nigeria. Coefficient of determination (R2), Root Mean Squared Error (RMSE), and Index of Agreement (d-index) were the three statistical methods used to test the fitness between predicted, and laboratory observed WHC of disturbed, auger sampled topsoil. Findings of the study established that the PTFs fitted in the algorithm of DSSAT-CSM soil water sub module made a significant topsoil WHC estimation in NGS with statistics $R^2 = 0.352$, RMSE = 0.03, and d-Index = 0.71. However, the model did not estimate the WHC validly in Sudan Savanna, with insignificant statistics of $R^2 = 0.031$, RMSE of 0.10, and 0.44 as the index of agreement. The conclusion drawn was that DSSAT made fair and poor predictions of topsoil WHC in NGS and SS soils respectively, irrespective of texture and other intrinsic properties. Based on the findings above, we recommend the development of local PTFs alternatives to be used with DSSAT's algorithm for Nigerian Savanna soils.

1. Introduction

Among the highly employed decision support tools in proffering remote recommendations to Nigerian Savanna farmers and its literature is the Crop Simulation Model (CSM) suite known as the Decision Support System for Agrotechnology Transfer (DSSAT) (Adnan et al., 2017a; Adnan et al., 2017b; Jibrin et al., 2012). The DSSAT-CSM is a computer system application that comprised CERES-MAIZE and RICE modules, CROPGRO module, other numerous modules, and sub-modules such as those for Weather, Crop Genetics, Crop Management, and Soil, which perform functions related to crop growth and cropping systems (Ines et al., 2001). Soil water submodule is where the entire soil water-related operations are being called before initializing a particular simulation run. Upon the input of soil Minimum Data Sets (MDS), a soil-based simulation could then be run. Soil MDS is a set of information beneath which the soil module cannot operate (Jones et al., 2003).

The soil water sub-module of the DSSAT model was algorithmically fitted with hydraulic PTFs. In the model suite, a matric point PTFs equations developed by (Ritchie et al., 1987)serve as an alternative to the field or laboratory-measured water contents at three matric potentials. The matric potentials are moisture contents at saturation (SAT), field capacity (FC), and permanent wilting point (PWP)(Hoogenboom et al., 1999). Estimation of the moisture above constants could only be achieved once stone, silt, clay, and organic carbon values were provided as independent predictor parameters to the DSSAT-CSM (Liu et al., 2011). After that, the WHC of such a soil, as the water available for plant growth could be obtained as the difference between water content at FC and that of moisture at PWP (Jones et al., 2001).Practical information on soil WHC is crucial in soil moisture modeling, land capability and suitability classifications, irrigation, and other hydrological studies (Sani, 2018). The expensive and tedious nature of moisture content determination, and the technical unavailability of such resources in developing countries like Nigeria, rendered such analyses nearly unattainable. Ascertaining the fitness of developed PTFs available in literature and software models, or developing local PTFs using any of the methods for doing so, could therefore serve as a pivot upon which secondary soil moisture determination techniques could rally in Nigeria.

An understanding of the nature of relationship and agreement between the developed DSSAT (Ritchie et al., 1987) PTFs estimated, and real-time, pressure plate analyzed WHC in a laboratory, could inform the extent to which researchers could depend on such estimation and remote sensing techniques. The objective of this work, therefore, is to evaluate the efficiency of DSSAT's Ritchie et al. (1987) point PTFs, in predicting WHC of topsoil in Sudan and Guinea Savannas of Kano State.

2.0 Materials and Methods

2.1 Study area

The study was carried out in SS and NGS Agro-Ecological Zones (AEZs) of Kano State in Nigeria. Eight (8) locations were selected in each AEZ (Figure 1). The soils across the sampled locations were generally Lexisols, with other minor soil types constituting Plinthosols, Cambisol and Gleysols (Shehu et al., 2018). The soils are well-drained and of Chad formation and Basement Complex parent materials (FDALR, 1990). The climate of the study locations is tropical wet and dry (Dugje et al., 2009). The cumulative annual rainfall in the past three seasons in the study area is about 800mm in SS and 1000mm in NGS (Shehu et al., 2018) as a unimodal occurrence between May and October, with an average annual temperature range of 200C – 340C from 2015 to date (NASA,2018).

2.2 Soil Sampling

Disturbed soil samples were collected from the topsoil (depth of 0-20cm) using an auger. The samples were air-dried, gently crushed with pistil and mortar, and sieved with 2mm mesh. Co-ordinates of the study locations were recorded.

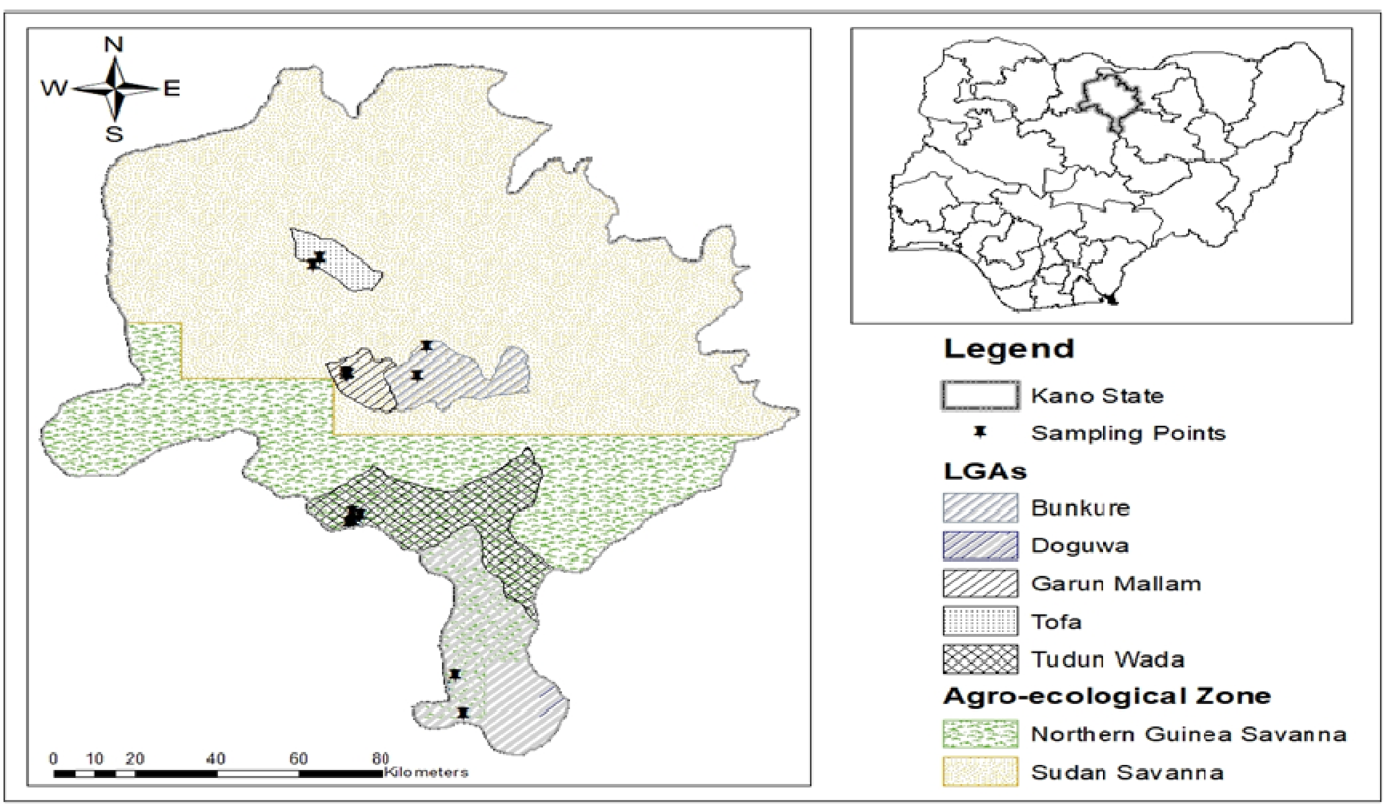

Figure 1: a map of Nigeria showing the area under investigation

2.3 Determination of Soil Physical and Chemical Properties

Soil samples were analyzed for physical and chemical properties; these were model predictor parameters (Particle Size Distribution - PSD, Organic Carbon – OC) for DSSAT's estimation. Particle Size Distribution was determined using the principle of Boyoucous hydrometer method as described in Gee and Or (2002). Organic Carbon content was determined using Walkley and Black wet oxidation method described in Walkley and Black (1934). These analyses were conducted at the Soil Science laboratory of Bayero University, Kano.

2.4 Estimation of Soil Moisture Retention

Topsoil WHC as the difference between moisture content at FC and PWP was estimated using pressure plate determined FC and PWP values in the laboratory of Soil Physics, Ahmadu Bello University Zaria and using the PTFs in DSSAT Model.

2.4.1 Laboratory Estimation of FC, PWP, and WHC

A 15 Bar Gas Pressure plate extractor was used for the determination of soil moisture at 0.3 Bar suction (FC), and 15 Bar suction (PWP) in gg^{-1} as described in CORP. (2009). Values obtained were then converted to volume basis in cm^3cm^{-3} using the formula:

θ= Volumetric moisture content
ṕs = Density of soil
ṕw= Density of water

WHC was then estimated by taking the difference between soil moisture at FC and PWP.

2.4.2 Estimation of FC, PWP, and WHC using DSSAT Model

DSSAT employs the PTFs of Ritchie that was developed in 1987(Gijsman et al., 2002) for soil moisture estimations of SAT, FC, and PWP expressed in cm^3cm^{-3} . The soil predictor parameters required were values of Stones, Silt, Clay, and OC in percentages. The developers set no limitations for its use, but the study of Gijsman et al. (2002) advised that the equations should not be used for organic soils or tropical soils with large amounts of low activity clays. The Predictor parameters were obtained from the laboratory analysis of the study samples. The Ritchie et al., (1987) PTFs equations as reported in Gijsman et al. (2002) are:

*SAT = 0.789 – 0.0037 * Sand% + 0.01 X OM – 0.017 * OM – 0.1315 * BD*

*DUL = DLL + W2 (1 – OM) – (BDM – BD) * 0.2 + 0.55 * OM*

*DLL = W1 (1 – OM) * (1 + BDM – BD) + 0.23 * OM*

Where:

BD = 100/[(OM%/0.224) + (100 – OM)/(BDM)]
W1 = 0.16 (for silt > 70%),
W1 = 0.0542 + 0.00409 x Clay% (for other soils),
W2 = 0.429 – 0.00388 x Sand% (for sand > 75%), and
W2 = 0.1079 + 0.000504 x Silt% for Silt > 70% and other soils)

OM = Soil Organic Matter (Organic Carbon x 1.724), BD = Bulk Density, BDM = Mineral Bulk Density, DLL = Moisture content at PWP, DUL = Moisture content at FC, SAT = Saturated moisture content

Note: The equations above were reported in the literature with other names such as (Ritchie et al., 1986), (Ritchie and Crum, 1989), etc. in (Gijsman et al., 2002). BDM was calculated as Mineral + Pore space (particle size-specific) but without OM. The SAT above was corrected to 0.95 * Porosity in Gijsman et al. (2002) as they reiterated the presence of many errors in the equations.

WHC was estimated by taking the difference between soil moisture at FC and PWP.

2.5 *Statistical Analysis*

The following model statistics were used to test the DSSAT's estimated soil moisture contents:

And

Where: O = laboratory observed moisture contents at a given matric potential, E = DSSAT estimated moisture contents at that potential. = mean of laboratory observed moisture, N = samples number, and i =number of observations.

The statistical significance of models estimations was tested by adapting the methodology of Oyeogbe and Oluwasemire (2013)

Table 1: *Locations, DSSAT-CSM predictor parameters, observed and simulated topsoil WHC of Sudan Savannah (SS) samples*

Coordinates	**L.G.A.**	**Stone (%)**	**Silt (%)**	**Clay (%)**	**OC (%)**	**BD (gcm^{-3})**	**Observed WHC (cm^3cm^{-3})**	**Simulated WHC (cm^3cm^{-3})**
11.75608N,08.5414E	Bunkure	-99	15	7	0.16	1.54	0.110	0.070
11.66945N,08.5218E	Bunkure	-99	9	1	0.30	1.52	0.170	0.058
12.01728N,08.3068E	Tofa	-99	5	5	0.04	1.55	0.188	0.046
11.99703N,08.2919E	Tofa	-99	19	7	0.12	1.53	0.108	0.077
11.68142N,8.36338E	G/Malam	-99	23	11	0.18	1.52	0.103	0.088
11.67693N,8.36921E	G/Malam	-99	27	17	0.42	1.48	0.178	0.106
11.67255N,8.36391E	G/Malam	-99	20	6	0.68	1.42	0.193	0.091
11.67329N,8.36670E	G/Malam	-99	12	2	0.31	1.49	0.221	0.065

Note: WHC = Water Holding Capacity, OC = Organic Carbon, BD = Bulk Density, G/Malam = Garun Malam, and L.G.A. = Local Government Area.

Table 1 portrayed the coordinates of sampled locations and the DSSAT-CSM's Ritchie et al., (1987) predictor Parameters of Sudan Savanna samples, while Table 2 is that of samples from Northern Guinea Savanna. The values of stone for all the samples are -99, which is the model's input for "No Available Data." From both tables, the soils are in the sandy class. These findings conform to that of a study by Shehu et al., (2018) that soils in Kano state are generally Sandy in terms of texture. Other attributes of the tables are Bulk Density (BD) in gcm^{-3}, observed and simulated WHC value in cm^3cm^{-3}. The BD in SS ranged from $1.42gcm^{-3}$ to $1.54gcm^{-3}$, higher than the range in NGS ($1.36 – 1.53gcm^{-3}$). The range is similar to that reported by Shehu et al., (2018) for both the savannas and could be connected with the low OC content of the soil as reported by Alhassan et al., (2018). Observed WHC ranged between 0.103 and 0.221 cm^3cm^{-3} characteristics of Sandy Loam and Loamy Sand soils as mentioned by Mueller et al.,(2014).

Table 2: *Locations, DSSAT-CSM predictor parameters, observed and simulated topsoil WHC of Northern Guinea Savannah (NGS) samples*

Coordinates	L.G.A.	Stone (%)	Silt (%)	Clay (%)	OC (%)	BD (gcm^{-3})	Observed WHC (cm^3cm^{-3})	Simulated WHC (cm^3cm^{-3})
10.7291N,08.5771E	Doguwa	-99	29	17	0.57	1.45	0.096	0.113
10.7513N,08.5810E	Doguwa	-99	17	17	0.37	1.55	0.088	0.085
10.7883N,08.6029E	Doguwa	-99	33	39	0.20	1.39	0.156	0.126
10.6728N,08.6285E	Doguwa	-99	33	13	0.20	1.46	0.101	0.111
11.2386N,08.3701E	T/Wada	-99	24	6	0.35	1.44	0.065	0.091
11.2395N,08.3818E	T/Wada	-99	18	1	0.63	1.36	0.082	0.084
11.2583N,08.3945E	T/Wada	-99	29	13	0.35	1.47	0.159	0.105
11.2685N,08.3771E	T/Wada	-99	8	6	0.44	1.53	0.092	0.062

Note: WHC = Water Holding Capacity, OC = Organic Carbon, BD = Bulk Density, G/Malam = Garun Malam, and L.G.A. = Local Government Area.

Figure 2 and Table 3 shows the performance of Ritchie at al.,(1987) in estimating WHC in SS of Kano state. The degree of fitness between the observed and simulated WHC values showed no significance as it gives an R^2 of less than 0.3 (fair fitness between observed and simulated WHC). They also informed that only about 10% of the general prediction error could be accounted by the model (RMSE = 0.10). Agreement between observed and simulated values was also lower compared to what was obtained in Northern Guinea Savanna. Similar findings were reported by Aliku and Oshunsanya(2016) for soils in rainforest, Savanna and derived savanna of Nigeria using the model SoilWat.

Table 3: *Model Statistics of Sudan Savanna for Topsoil WHC*

Observed WHC	Simulated WHC	Model Statistics	Model Statistics	
		R^2	RMSE	d-index
0.110	0.070	0.031	0.10	0.44
0.170	0.058			
0.188	0.046			
0.108	0.077			
0.103	0.088			
0.178	0.106			
0.193	0.091			
0.221	0.065			

R^2 *= Co-efficient of determination, RMSE = normalized Root Mean Squared Error, and d-Index = index of agreement.*

Figure 3 and Table 4 were the analyses of DSSAT-CSM soil module performance in NGS. Fitness between the real values and estimates is in the fair class with R2of 0.352. There was only a general model error (RMSE) of 0.03 and an agreement index of 0.71. This finding is at par with the findings of Sani (2018)on all textures of NGS except Sandy Clay Loam for varying soil moisture characteristics. The disparity in the two AEZS results could also be attributed to differences in pedological origin variability, or unique soil separates percentages in the zones as mentioned by Gijsman *et al*., (2002)

4.0 Conclusion and Recommendation

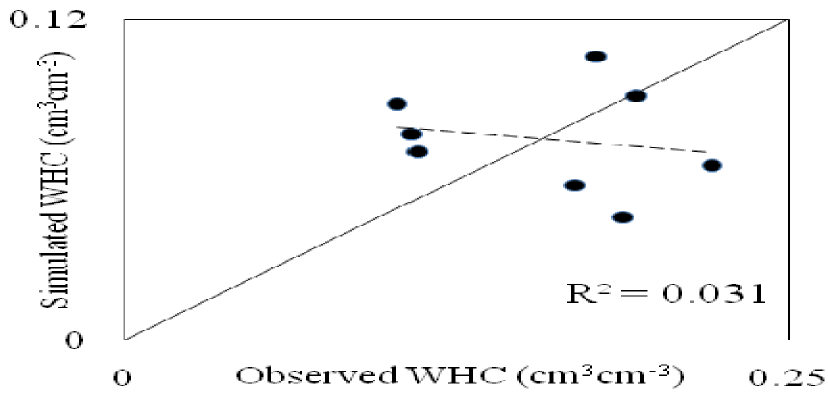

Figure 2: Degree of fitness between Simulated and observed WHC in Sudan Savanna of Kano

Table 4: *Model Statistics of Northern Guinea Savanna for Topsoil WHC*

Observed WHC	Simulated WHC	Model Statistics	Model Statistics	
		R^2	RMSE	d-index
0.096	0.113	0.352	0.03	0.71
0.088	0.085			
0.156	0.126			
0.101	0.111			
0.065	0.091			
0.082	0.084			
0.159	0.105			
0.092	0.062			

R^2 = *Co-efficient of determination, RMSE = normalized Root Mean Squared Error, and d-Index = index of agreement.*

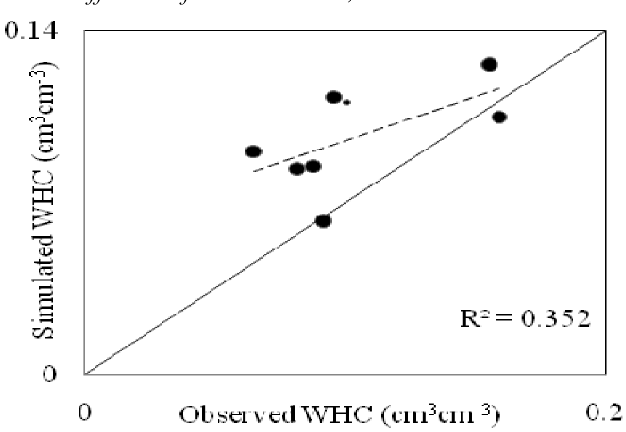

Figure 3: Degree of fitness between Simulated and observed WHC in NG Savanna of Kano

The PTF of Ritchie et al., (1987) in the soil module of DSSAT-CSM was unable to model soil WHC capacity significantly in Sudan Savanna of Kano State, but estimated it with fair fitness in Northern Guinea Savanna of the State. We, therefore, recommend the design of studies to develop local Pedotransfer functions for Standalone and integrated use with exotic crop models in Nigeria.

5.0 Acknowledgement

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