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MODELS FOR PREDICTING PORE SPACE INDICES OF AN IRRIGATED LOWLAND RICE SOIL IN A SUDAN SAVANNA OF NIGERIA

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ABSTRACT

Diffusion coefficients (Ds/Do) and pore tortuosity (τ) are important factors controlling gas transport in soils. They provide basis for better understanding of retention and movement of water and gas exchange in soil. Measurements of the gas diffusion coefficient are tedious, expensive and time consuming. This study therefore make use of easily measurable soil properties such as air-filled porosity(fa) and total porosity(Φ) in the prediction of gas diffusion coefficient and the pore tortuosity factor of an irrigated lowland soil of Sudan savanna zone of Nigeria. Six models that employ the use of either fa (Pennman,1940, Marshall, 1957 and Buckingham, 1904) or a combination of fa + Φ (Sallam et al.,1984, Millington,1959 and Jin and Jury,1996) were used for this prediction. Soil samples were collected at 0–20 cm depth and oven dried at 105 °C for 72 h. After drying, fa and Φ were calculated and later used in models for predicting Ds/Do and τ.** Result shows that gas diffusion coefficient varies between 0.027 to 0.106 $cm^2s^{-1}.cm^2s^{-1}$ for the fa predicted models and between 0.020 to 0.066 $cm^2s^{-1}.cm^2s^{-1}$ for the **(fa) plus total porosity (Φ) predicted models. Also, in terms of the tortuosity factor (τ), the fa predicted models varies between 1.515 to 6.604 for the soil gas diffusion coefficient while the (fa) plus total porosity (Φ) predicted models varies from 2.552 to 11.349 $m\ m^{-1}$ for the tortuosity factor (τ). Penman 1940 with the lowest coefficient of variation (23%) predicted the highest mean Ds/Do among the fa based model while Jin and Jurry predicted the highest among fa+Φ based model. Comparing Models based on fa or fa+ Φ, results showed that Ds/Do predicted using fa alone was higher as compared with values predicted with models based on fa + Φ. Result from this study confirm the applicability of the models as a viable alternative to the tedious, expensive and time consuming method of predicting soil pore indices of the Sudan savanna soil by measurements of soil air and water

Keyword: Diffusion coefficients, turtuosity factor, air filled porosity, total porosity and Models

INTRODUCTION

The nature and distribution of soil pore spaces greatly affect the availability of nutrients, water and air to plants and microbes living in the soil. Quantification of the pore space in terms of shape, size, continuity, orientation and arrangement of pores in soil system provides a realistic basis for understanding the retention and movement of water, gas exchange in soil (Pagliai and Vignozzi, 2006). Agricultural practices such as tillage and irrigation have being shown to cause a great fluctuation in the retention and movement of water, gas exchange between soil and atmosphere due to distruption in the distribution and orientation of this pores (Teepe *et al.*, 2004).Soil compaction resulting from either machinery traffic during tillage operations (Rollerson,1990) or foot traffic due to animal or human walking is a clear example of the statement above as reported by Nkongolo *et al.*, (2008).They explain that compaction of soil primary particles and aggregates closer together will significantly affect the balance between solids, air filled and water filled pore spaces (Bruand and Cousin 1995). Long term irrigation also has influence on the behaviour of the soil pores. For example, subjecting the soil to continuous flooding over a long term can cause massive modification of soil pore orientation, size and distribution, increased in migration of clay particles from the ploughed layer to the B horizon (Mathieu, 1982; Pagliai and Vignozzi, 2006). Compaction and water saturation of soils are reported to be the main barriers to soil gas transport, water being a more effective barrier (Papendick and Runkles, 1965; Moldrup *et al.,* 2000a; Neale *et al.,* 2000). The diffusion of gases in water is slower than their diffusion in air by a factor of 10^4 (Call, 1957; Moldrup *et al.*, 2000a; 2004; Thorbjørn *et al.*, 2008). Decrease in soil porosity due to structural degradation as a result of too much water applied to the soil has being reported by (Davidson and Swank, 1986). However, a slow and minimal decrease in soil surface porosity was reported by Pezzarossa *et al.*, (1991) with low amount of water applied as irrigation compared to the massive and severe decrease with impounding condition.

The movement of gases in the vadose zone is mainly driven by concentration gradients and diffusion coefficient (Jin and Jury, 1996; Neira *et al.,* 2015). Diffusive gas transport depends primarily on the total volume and the tortuosity of continuous air-filled pore space (Moldrup *et al.,* 2013). Advective gas transport is affected by gaseous permeability which, in turn, is dependent on total porosity, pore size distribution, and tortuosity of continuous air-filled pore space (Hillel, 2004). Factors like soil aeration (Buckingham, 1904; Taylor, 1949), fumigant emissions (Brown and Rolston, 1980), volatilization of volatile organic chemicals from industrially polluted soils (Petersen *et al*., 1996) and soil uptake and emissions of greenhouse gases (Smith *et al*., 2000; Kosugi *et al*., 2007) are all control by Gaseous diffusion in the soil.

Most of this diffusion processes are governed by soil pore space indices which include gas diffusion coefficient and the tortuosity (τ) of the pore spaces. The soil gas diffusion coefficient (Ds/Do) and its dependency on air-filled porosity (fa) govern most gas diffusion processes in soil (Ungureanu and Statescu 2010), whereas the pore tortuosity factor (τ) is a quantity which characterizes the convoluted nature of the porous pathways followed by diffusing species (Hudson and Aharonson 2008). Measurements of the gas diffusion coefficient are tedious, expensive and time consuming; this may have contributed to there being fewer studies on the relationship between the soil gas diffusion coefficient and other soil processes (Nkongolo *et al.*, 2010)

However, the prediction of gas diffusion coefficient and the pore tortuosity factor from easily measurable soil properties such as air-filled porosity has being considered as viable alternative to the tedious, expensive and time-consuming methods available by many authors (Nkongolo *et al*., 2000; Caron and Nkongolo, 2004). Models such as Buckingham (1904), Penman (1940), Marshall (1957) or Moldrup *et al.* (2000) are used for these purposes. Models predicting the gas diffusion coefficient and the pore tortuosity factor as a function of both air-filled porosity and total porosity (Millington, 1959; Sallam *et al*., 1984; Jin and Jury, 1996; Moldrup *et al*., 1997, 2003) are also available. Besides soil temperature and moisture (Davidson and Trumbore 1995), and indices of N availability (Kim and Dale 2008), only a few authors have focused on Ds/Do and τ as potential controlling factors for GHGs emissions.

Despite their relevance, there is a lack of comprehensive studies that analyse impacts of soil irrigation management on the hydraulic properties, gas diffusivity with respects to the soil pore space distribution especially in the northern Sudan savanna soil of Nigeria. The first objective of this study was therefore to predict pore space indices from routine measurements of soil air and water contents and existing diffusivity models. The second objective was to compare pore space indices predictive models based on air-filled porosity (fa) alone vs. models using air-filled porosity and total pore space (fa + Φ).

MATERIALS AND METHODS

Study Area

An experimental field located at irrigation research farm of Federal University Dutse, (Latitude 11° 46’ 39” N and Longitude 009°2 0’ 30” E) in the Sudan savanna ecological zone of Nigeria was used for the studies of influence of water management on soil gas diffusivity indices during the dry season of 2018.Climatically, the study area falls in the arid and semi-arid areas characterised with low rainfall and less vegetation cover conditions with average daily sunlight duration of about 9 hours. The mean annual rainfall is 72mm which comes between June to October (Usman *et al.*, 2013). The average annual temperature at the site is 26.5^0C with a mean minimum of 23 ^{o}C in January and a mean maximum of 34 ^{o}C in April (Ojoye, 2008). The mean relative humidity for the area is 97%. The soil can be characterised as fairly deep soils often covered by a sheet of laterite that has resulted from the weathering of Pre-Cambrian Basement Complex rocks formed by granites, schists and gneisses. Particle size analysis resulted in contents of sand, silt, and clay in the topsoil (0–20 cm depth) of 62.50, 22.72, and 14.78 %, respectively. The texture throughout the study area can be classified as Sandy loamy. Mean organic carbon contents of the top soils at the alternate wetting and drying (AWD) and Control plots (CF) plots were 0.80 and 0.68 %, respectively. The field was cropped with lowland rice in March 2018. Two different water management techniques were tested in the plots: Alternate wetting and drying (AWD) and Continuous flooding plots (CF) as the normal practices adopted by many farmers.

Experimental Design

This research site has 6 plots laid out in a randomized complete block design (RCBD) replicated three times with each of the water treatment forming the blocks. Each block/plot area is 50 m^2 (10 m x 5 m) and blocks are separated by 2 m discard between blocks and replicates. Nitrogen (N), potassium (K), and phosphorus (P) fertilizers were applied as NPK 20:10:10 fertilizer at the recommended dose of 120 kg N in the form of Urea, 40 kg P in the form of P_2O_5 and 40 kg K as K_2O per hectare. P and K fertilizers were applied as full doses during the transplanting. For the N, 60 kg N in the form of urea (granules) were applied as first dose (Top dressing) during transplanting and the second dose (basal application) of 60 kg N was applied in the form of Urea super granule USG (Briquet Urea) at four weeks after transplanting (4WAS). The USG was applied at the recommended dose of 100kg urea/ha (Chude *et al.*, 2011).

Soil Sampling

Soil samples were collected with a 5 cm diameter by 5 cm deep cylinder from three random site in each of the blocks/plot and brought to the laboratory for analysis. Soil fresh weights were measured, and then soil samples were oven dried at 105^0C for 72 hours until constant weight. Soil bulk density (ρb), total porosity (Φ), volumetric (θv) and gravimetric (θg) water contents, air-filled porosity (*f*a) and water-filled pore space (WFPS) were later calculated as described in Nkongolo *et al.* (2007).

The relative gas diffusion coefficient (Ds/Do) and the pore tortuosity factor (τ) were thereafter predicted using diffusivity models described and listed below by Nkongolo *et al.*, (2010a) and Panday and Nkongolo, (2016). The models predicted the relative gas diffusion coefficient (Ds/Do) either as a function of air-filled porosity (fa) alone:

$Ds/Do= fa^{1.5}$ (Marshall, 1957) ... (1)
$Ds/Do = fa^2$ (Buckingham, 1904) .. (2)

or as a quotient of air-filled porosity (fa) over total porosity (Φ):

$Ds/Do = fa^{3.1}/\Phi^2$ (Sallam *et al:* 1984) ....(3)
$Ds/Do = fa^{3.33}/\Phi^2$ (Millington, 1959) ..... (4)
$Ds/Do = fa^2/\Phi^{2/3}$ (Jin and Jury, 1996) .. (5)

In addition, Nkongolo *et al.*, (2010a) also predicted the pore tortuosity factor (τ) as either a function of air-filled porosity (fa) alone

$\tau = 1/fa^{0.5}$ (Marshall 1957) ....(6)
$\tau = 1/fa$ (Buckingham 1904) ....(7)
or as a quotient of total porosity (Φ) over air-filled porosity (fa):

$\tau = \Phi^2/fa^{2.1}$ (Sallam *et al.*, 1984) ..(8)
$\tau = \Phi^2/fa^{2.33}$ (Millington 1959) ..... (9)

Data Analysis

Info Stat Statistical Software 2012 was used to analyse data obtained from soil properties. Treatment effects on measured variables were tested by analysis of variance (ANOVA), and comparisons among treatment means were made using the Tukey test calculated at $P < 0.05$.

RESULTS

Table 1 shows the statistical summary of the relative gas diffusion coefficient (Ds/Do) of the soil for this study. The gas diffusion coefficient varies between 0.027 and 0.106 $cm^2s^{-1}.cm^2s^{-1}$ for the fa predicted models and between 0.020 and 0.066 $cm^2s^{-1}.cm^2s^{-1}$ for the (fa) plus total porosity (Φ) predicted models. Also, in terms of the tortuosity factor (τ), the fa predicted models varies between 1.515 and 6.604 for the soil gas diffusion coefficient while the (fa) plus total porosity (Φ) predicted models varies from 2.552 to 11.349 m m^{-1} for the tortuosity factor (τ). Based on the model performance for all the models (both fa and fa+Φ) considered in this study, Penman model recorded the highest mean Ds/Do 0.106 $cm^2s^{-1}.cm^2s^{-1}$ at the same time also having the lowest variability of 24% while Millington model predict the list Ds/Do of 0.020 $cm^2s^{-1}.cm^2s^{-1}$ at the same time having highest variability of 71%.The summary statistics for tortuosity factor shows Penman model recording the shortest soil path (1.515 m m^{-1}) taking by the gas. This was followed by Marshal Model. The pore geometry in the irrigation management was more tortuous in the continuous flooding system (Kreba, 2013), and soils with tortuous pores exhibit lower soil gas diffusivity than soils with better developed structure.

Table1: Summary of statistics and predicted relative gas discussion coefficients (Ds/Do) of Lowland rice soil in Sudan savanna of Nigeria

	Ds/Do calculated based on fa models			**Ds/Do calculated based on fa+Φ models**		
Summary of statistics	**Penman (1940)**	**Burkingham (1904)**	**Marshall *et al*.(1959)**	**Sallam *et al.* (1984)**	**Millington (1959)**	**Jin and Jury (1996)**
			$cm^2s^{-1}.cm^2s^{-1}$			
Mean	0.106	0.027	0.065	0.029	0.020	0.066
CV	0.239	0.473	0.357	0.658	0.710	0.403
Median	0.101	0.023	0.060	0.022	0.015	0.059
Standard Deviation	0.025	0.013	0.023	0.019	0.014	0.027
Kurtosis	-0.848	-0.211	-0.602	1.665	2.096	0.199
Skewness	0.354	0.713	0.531	1.183	1.290	0.689
Range	0.101	0.053	0.095	0.086	0.064	0.116
Minimum	0.063	0.009	0.029	0.006	0.003	0.026
Maximum	0.164	0.062	0.124	0.092	0.067	0.142

Table 2 shows the influence of different water management practices on soil pore indices. All the pore space indices observed from this study either with the fa or fa+Φ models were significantly ($p < 0.001$) affected by the irrigation management adopted for this study. For each of the model prediction, the mean soil gas diffusion coefficient was higher in the alternate wetting and drying (AWD) irrigation than the continuous flooding (CF) system (Table 2). The diffusion coefficient was highly predicted with Penman model than any other model. The tortuosity factor was also observed to be the lowest in the Penman predicted models among others. Model pair wise, the fa models predict higher average mean values of 0.074 $cm^2s^{-1}.cm^2s^{-1}$ Ds/Do than the fa+Φ models that predicted 0.047 $cm^2s^{-1}.cm^2s^{-1}$.The tortuosity factor predicted by the fa models were also lower (3.287m m^{-1}) compared to the fa+Φ model that predicted average mean value of 7.241m m^{-1}.

Table 2: Comparison between relative gas diffusion coefficient (Ds/Do) models

Models	**AWD**	**CF**
Penman (1940)	0.116^a	0.095^b
Buckingham (1904)	0.032^a	0.022^b
Marshall (1959)	0.075^a	0.056^b
Sallam et al. (1984)	0.037^a	0.021^b
Millington (1959)	0.026^a	0.014^b
Jin and Jury (1996)	0.079^a	0.053^b

AWD, alternate wetting and drying; CF, continuous flooding. Note: Within a row, values followed by a different letter are significantly different at P < 0.001.

Table 3: Summary of statistics and predicted pore tortuosity factor (τ) of a Lowland rice soil in Sudan savanna of Nigeria

Summary of statistics	**τ calculated based on fa models**		**τ calculated based on fa+Φ models**		
	Penman (1940)	**Burkingham (1904)**	**Marshall (1959)**	**Sallam et al. (1984)**	**Millington (1959)**
		m m^{-1}			
Mean	1.515	6.604	2.552	7.223	11.349
CV	0.000	0.239	0.120	0.445	0.501
Median	1.515	6.526	2.554	6.869	10.589
Standard Deviation	0.000	1.580	0.305	3.213	5.688
Kurtosis	-2.121	-0.467	-0.780	0.704	1.002
Skewness	-1.044	0.415	0.204	0.972	1.072
Range	0.000	6.478	1.235	13.383	23.900
Minimum	1.515	4.020	2.005	2.698	3.715
Maximum	1.515	10.498	3.240	16.080	27.615

Table 4: Comparison between the pore tortuosity models

Models	AWD	CF
Penman (1940)	1.515a	1.515a
Buckingham (1904)	5.925b	7.283a
Marshall (1959)	2.421b	2.683a
Sallam et al.(1984)	5.733b	8.713a
Millington (1959)	8.749b	13.948a

AWD, alternate wetting and drying; CF, continuous flooding. Within a row, values followed by a different letter are significantly different at P < 0.001.

DISCUSSIONS

The Penman diffusivity model (based on fa) predicted both the highest Ds/Do and the lowest tortuosity. This is understandable as this model is linear and uses a fa directly to compute Ds/Do and τ compared to other models that have power over the fa (Panday and Nkongolo 2016). The complexity involved in the used of both fa and Φ in the fa+Φ models may have result in the poor performance of models compared to the simpler fa models. The higher the porosity of denominator, the lower the diffusivity index predicted by that model. Similarly plots treated with alternate wetting and drying predicted the highest Ds/Do and lowest tortuosity factor.

One possible reason behind this increase in soil diffusivity index is the availability of more drained pores for gas transport that resulted from the drying period of the soil (Kreba *et al.*, 2017). Also, as the soil dries, it is expected that the matric potential of such soil will decrease thereby increasing its air-filled porosity. Decrease in soil matric potential in the AWD plots, subject the soil to dry condition with increase pressure making more pores drained and available for gas transport (Resurreccion *et al.*, 2007; Kuhne *et al.*, 2012). The AWD irrigation system had higher soil gas diffusivity and air-filled porosity than the continuous flooding system, possibly because the AWD system had higher organic matter contents and larger and more stable aggregates (Kreba, 2013), hence a larger volume of pore space and more continuous pores. Aeration in AWD soil can also influence the microbial population, activity and diversity of such plot (Schjonning *et al.*, 2003). Increased in population of microbes will translate to increase in activity which will in turn increase the C:N ratio of the soil. This result in the availability of larger and more stable aggregates (Kreba, 2013), hence a larger volume of pore space and more continuous pores. The cracks occurring during the drying periods of the AWD and the burrow activity of the macrobes can account for the increase in gas diffusivity observed as reported by Richter *et al.*, (1991) and Allaire *et al.,* (2008).

Lower values of soil pore space indices observed in the continuous flooding (CF) plots can be attributed to the degradation of soil structure due to impounding water on the surface of such plots. This modification causes a decrease in the pore spaces filled with air where gas diffusion occurs (Czyz, 2004; Fujikawa and Miyazaki, 2005). Destruction of soil structure leads to compaction of soil reflected with high bulk densities thus reducing gas diffusion rate within the soil (Neira *et al.*, 2015). Subjecting the soil to continuous flooding over a long term can cause massive modification of soil pore orientation, size and distribution, increased in migration of clay particles from the ploughed layer to the B horizon (Mathieu, 1982; Pagliai and Vignozzi, 2006). Compaction and water saturation of soils are reported to be the main barriers to soil gas transport, water being a more effective barrier (Papendick and Runkles, 1965; Moldrup *et al.*, 2000a; Neale *et al.*, 2000). The diffusion of gases in water is slower than their diffusion in air by a factor of 10^4 (Call, 1957; Moldrup *et al.*, 2000a; 2004; Thorbjørn *et al.*, 2008). Decrease in soil porosity due to structural degradation as a result of too much water applied to the soil has being reported by (Davidson and Swank, 1986). However, a slow and minimal decrease in soil surface porosity was reported by Pezzarossa *et al.*, (1991) with low amount of water applied as irrigation compared to the massive and severe decrease with impounding condition.

CONCLUSION

Pore space indices (Ds/Do and τ) were predicted using models based on either air filled porosity alone or a combination of air-filled porosity and total pore space. Models using fa only predicted the best pore space indices more than the fa+Φ models. Penman predicted the best (Ds/Do and τ) among all the models considered. The relationship between pore space indices varied significantly with water management practices. Soil gas diffusivity, air-filled porosity, and pore continuity were greater in the AWD than the continuous flooding system because the former had a better developed soil pore network due to larger and more continuous pores. This study shows that soil gas diffusion coefficients can be estimated quickly from routine measurements of soil water and air with the existing diffusivity models. The study also confirmed the applicability of the models in the prediction of gas diffusion coefficient and the pore tortuosity factor of a Sudan savanna soil of Nigeria.

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