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Relationship between soil pore space indices and greenhouse gases under the influence of irrigation water management in a rice field of Sudan Savanna soil of Nigeria

[1*]Girei, A. H., [1]Nabayi, A., [2]Amapu, I.Y., [3]Mudiare, O. J. and [2]Abdulkadir, A.

[1]*Department of Soil Science, Federal University Dutse*

[2]*Department of Soil Science, Ahmadu Bello University Zaria*

[3]*Department of Agricultural Engineering, Ahmadu Bello University Zaria*

Abstract

Soil air-filled pore spaces play a crucial role in the exchange of greenhouse gases between agricultural soils and the adjacent atmosphere. Soil bulk densities, air-filled porosity, total porosity were calculated from soil samples while Static chamber methods were used in the collection of gas samples for the measurement of greenhouse gases (CO_2, CH_4 and N_2O). Air-filled porosity alone and air-filled plus porosity calculated from the soil samples were fitted in models used for the prediction of relative gas diffusion coefficients (DS/Do) and the pore tortuosity factor (TF). The relationship between pore space indices and greenhouse gases emissions from such soil was also studied. The result shows the relationship between soil pore space indices (DS/Do and TF) and greenhouse gas emissions of rice fields under irrigation management with a correlation coefficient range from -0.04 to 0.57. Generally, the relationship between CO_2 and CH_4 with DS/Do predict either with air-filled alone or air-filled plus porosity models were negatively correlated in irrigated plots. However, N_2O emissions positively correlate with the DS/Do. Almost all the fluxes were positively correlated with the soil tortuosity factor predicted with all models. The result from these studies confirmed the contribution of irrigation water management practices adopted for this study revealing that air permeability may contribute to the variability of greenhouse gas emissions hence for our understanding of the dynamics of greenhouse fluxes from soil to be improved, we need to include soil diffusions coefficients (Ds/Do) and soil tortuosity factor (TF) in predictive models as controlling factors.

Keywords: Air-filled pore, Porosity, Greenhouse gases, DS/Do and TF, Models.

E-mail Address: gireihalilu@yahoo.com

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1.0 Introduction

Soil air-filled pore spaces play a crucial role in the exchange of greenhouse gases between agricultural soils and the adjacent atmosphere. Before their release to the atmosphere, greenhouse gases produced in soils pass through air-filled pore space through a process called diffusion. Hillel, (2003) and Neira, *et al.,* (2015) describe diffusion as the spontaneous movement of particles from a higher to a lower concentration due to kinetic energy that can occur either in a gaseous or liquid medium, with a net movement of the diffusing material. Soil physical properties such as texture and structure, conditioning, pore size distribution, tortuosity and connectivity are the primary conditioners of diffusive gas transport in soil (Nkongolo, *et al.,* 2010; Neira, *et al.,* 2015) chief among which is soil porosity. Variations with soil type and soil air-filled porosity control soil aeration and soil uptake and emissions of greenhouse gases. Nkongolo, *et al.,* (2010); Nkongolo and Caron (2006) reported that variation in the storage and supply capability of these pore spaces will provide the information needed for understanding gas flux from soils and in predictive models for greenhouse gases emissions.

The development of predictive models for greenhouse gases emissions from soils under irrigation production systems requires information on the most influential factors determining gas flux from such soils. Gas diffusion coefficient measurements are cumbersome, costly and time-consuming, which may have led to less research on the relationship between the coefficient of diffusion of soil gas and other soil processes. However, the prediction of the gas diffusion coefficient and the pore tortuosity factor from easily measurable soil properties such as air-filled porosity has being considered as a 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 $Ds/Do = f\ a^2$ Buckingham

(1904), $Ds = Do = 0.66fa$ Penman (1940), $Ds/Do = fa^{1.5}$, Marshall (1957) or $Ds_{100}/Do = 2fa^{3}_{100} + 0.04fa_{100}$ 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 ($Ds/Do = fa^{3.33}/\Phi^2$, Millington, (1959); $Ds/Do = fa^{3.1}/\Phi^2$, Sallam *et al*., (1984); $Ds/Do = fa^{2}/\Phi^{2/3}$, Jin and Jury, (1996); $Ds/Do= 0.66fa\,[fa/\Phi]^{(12-m)/3}$, Moldrup *et al*., (1997), (2003)) are also available.

Information on the most influential factors determining gas flux from soils under such system of production needed in predictive models for greenhouse gases emissions from such soils (Savanna soil) is also lacking. Thus, this study aims to determine the relationship between indices of soil pore space and emissions of greenhouse gases in the Sudan Savanna ecological zone of Nigeria.

2.0 Materials and Methods

2.1 Experimental site

The research was conducted at the Irrigation research farm of Federal University Dutse located between Latitude 11° 46,39N and Longitude 009°20,30E in the Sudan savanna ecological zone of Nigeria during the dry season of 2018. The zone is characterized by sparse vegetation cover and scattered trees resulting from low annual rainfall distribution of about 500 to 700mm that comes between June to October. Daily sunshine hours range from 9 to 10 hours and an annual average temperature range from 26.5^0C to 38^0C with minimum and maximum values attained during the months of January and April (Ojoye,2008).

The soil can be characterized 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.

Experimental Design

Two water management practices i.e. Alternate wetting and Drying (AWD) and Continuous flooding (CF) were deployed to test their efficacy in the management of lowland rice with respect to greenhouse gas emission. A total of six plots 50 m^2 (10 m x 5 m) was used for this experiment with each plot/block having a water management practices as the treatment. The experiment was laid out in randomize complete block design and replicated three times. Each block and replicates were separated by a discard of 2m.

Soil Sampling and Analysis

Both disturbed and undisturbed soil samples were collected from three random spots of each block. The disturbed soil samples collected with auger were bulked to form a composite sample per block, passed through a 2mm sieve and stored in a labelled sampling bag and transported to the laboratory for routine analysis. Particle size analysis was conducted using the Bouyoucos hydrometer method (Gee and Bauder, 1986). The USDA textural triangle was used to determine the textural class of the soil samples. Walkley-Black wet combustion method (1934) was used for Organic carbon (OC) determination, after which the OC values were multiplied by 1.724 to obtain the organic matter content of the soil (Jones, 2001). Soil pH in a soil-water suspension with a soil-to-water ratio of 1:2.5 (McLean, 1982) using a pH meter. The saturated hydraulic conductivity of the soil samples was determined by the constant head method (Klute and Dirksen, 1986).

A 5 by 5cm core ring was used in the collection of undisturbed soil samples whose fresh weights were measured, and then thereafter oven-dried at 105^0C for 72 hours until constant weight. They were collected after harvesting of the crop. Soil bulk density (ρb), total porosity (Φ), volumetric (θv) and gravimetric (θg) water contents, air-filled porosity (fa) 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= fa1.5 (Marshall, 1957) ..... (1)

Ds/Do = fa2 (Buckingham, 1904) …. (2)

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

Ds/Do = fa 3.1/Φ 2 (Sallam et al: 1984) ...... (3)

Ds/Do = fa 3.33/Φ 2 (Millington, 1959) ...... (4)

Ds/Do = fa 2 /Φ 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

τ = 1/fa 0.5 (Marshall 1957) ....(6)

τ = 1/fa (Buckingham 1904) ....(7)

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

τ = Φ2 /fa 2.1 (Sallam et al., 1984) …... (8)

τ = Φ2 /fa 2.33 (Millington 1959) ...... (9)

Gas sampling for CO_2, CH_4 and N_2O and flux measurement

Fluxes of CO_2, CH_4 and N_2O were measured from sowing to maturity using a static vented flux chamber technique described previously by Wang *et al.,* (2018). Briefly, the chamber consists of a permanent base inserted into the soil (with rice crops growing within); a lid equipped with a vent tube. The base was made of a PVC frame and buried to a depth of 5 cm to leave about 20 cm above the soil line. To allow for relatively free water and root movement, holes were perforated at the base below the soil line. Each plot/block contained one chamber deployed at least 30 cm to provide easy access to the chambers and to avoid soil disturbance during sampling.

GHG gas flux measurements were conducted when the criteria of AWD (15 cm water level below soil surface or the appearance of hair-like crack in such plots) treatments are met. To maintain consistency and uniformity, gas samples were collected from 9:00–11: 00 a.m during all samplings. All samples were collected at 0 min., 15min., 30min., and 45 min. after chamber closure using a 15-mL syringe. The samples were transferred to a vacuum vial of 10-mL capacity for further laboratory analysis.

The concentrations of CO_2, CH_4 and N_2O in each of the samplings were analyzed using a GC-2014 Shimadzu reference gas chromatograph equipped with three detectors. CO_2 was detected with an infrared thermal conductivity detector, CH_4 with a hydrogen flame ionization detector (FID) and N_2O was detected with an electron capture detector (ECD) in the laboratory of the International Centre for Tropical Agriculture (CIAT), Cali, Colombia.

The gas fluxes were calculated from the rate of change of the concentration of CO_2, CH_4 and N_2O in the chamber headspace using a linear regression method. Since the units associated with the gas standards were typically ppm. The standard curve relationship was applied to calculate gas concentrations of the samples, which gave the resulting unit in part per million (ppm). Since the rate of change of headspace traces gas concentration was constant (i.e. ppm(v) vs. time data is linear.

Data analysis

Minitab 16, was used to test the normality for the parameters studied, which was conducted using Anderson–Darling at P=0.05. All data collected were analyzed using Statistical Analyses System (SAS 9.4 SAS system for windows by SAS Institute Inc., Cary, NC, USA). Analysis of Variance (ANOVA) and Proc GLM was used to determine the significant treatment effect on the measured properties with the significant difference of $p<0.05$. Pearson's correlation and linear regression analysis were used to assess the relationship between soil pore space indices and greenhouse gas fluxes.

3.0 Result and Discussion

Soil properties of the Study Site

Table 1 shows some chemical and physical properties of the experimental research area determined. Soil reaction was found to be moderately acidic in water and strongly acidic in $CaCl_2$ with values ranging from 5.92 and 4.77 respectively. The organic carbon (OC) content and the Total Nitrogen (TN) were low with values of 0.61g kg^{-1} and 0.12g kg^{-1} in all fields respectively. Low OC contents of soils of the Nigerian savanna have been reported by Jones and Wild (1975) and Salako, (2003) who attributed this to continuous crop production on the same piece of land with poor sustainable management practices such as removal of crop residue and low addition of organic matter to the soils. This claim was further confirmed by Odunze (2017). Balasubramanian *et al.,* (1984) and Esu (1991) also reported that soils of the Northern Savanna of Nigeria are low in fertility status.

Pore Space Indices Predictive Models

Summary of statistics on the influence of water management on gas diffusion coefficient Ds/Do and pore tortuosity factor (τ) for the year 2018 are presented in tables 2 and 3 respectively. Ds/Do values predicted with all the models under both water management practices range from 0.002 to 0.266 $cm^2s^{-1}.cm^2s^{-1}$ (Table 2).

However, plots irrigated with AWD gave the highest average mean Ds/Do value of 0.101 $cm^2s^{-1}.cm^2s^{-1}$ compared to the CF plots that recorded an average mean value of 0.07 $cm^2s^{-1}.cm^2s^{-1}$ (Table 2). For the pore tortuosity factor (τ), CF plots recorded the lowest average mean (τ) value of 26.46 mm^{-1} as against the average mean (τ) value of 31.07 mm^{-1}attributed to the AWD plot (Table 3).

Greenhouse gas fluxes

Table 4 shows the magnitude and variation patterns of CO2, CH4 and N2O fluxes with the application of different irrigation management practices. Generally, a modest decrease in all the greenhouse gas fluxes was observed with all irrigation applications (Table 4). However, the application of AWD lowers the emission rate of the individual gases (CO2, CH4 and N2O) by 15, 73 and 17% compared to CF irrigation management as rightly observed from table 4.

Similarly, as observed from this study, a decrease in CO2 emissions with a reduction in irrigation water application was reported by Riya *et al.,* (2014) who reported 40% reduction of CO_2 (6,169 kg CO_2 ha^{-1}) emissions under AWD compared to emissions from continuous flooding.

The suppression of CH_4 emissions with soil water reduction can be related to variation in redox potential and microbial activity within the soil matrix resulting from shifts in the water regime accompanying alternate wetting and drying irrigation systems (Jiao *et al.,* 2006; Sun *et al.,* 2016).

Relationship between soil pore space indices and greenhouse gases under the influence of irrigation water management

Table 5 shows the relationship between soil pore indices (relative gas diffusion coefficients and soil tortuosity factor) and greenhouse gas emissions of rice field under irrigation management with a correlation coefficient range from -0.04 to 0.57. Generally, the relationship between CO_2 and CH_4 with DS/Do predict either with air-filled alone (Penman,1940, Marshall (1959) and Buckingham (1904)) or air-filled plus porosity (Sallam *et al.,* (1984), Millington (1959) and Jin and Jury, 1996) models under the influence of irrigation water management was negatively correlated as observed from table 5. However, N_2O emissions positively correlate with the DS/Do. Contrary, to the relationships with Ds/Do, almost all the fluxes were positively correlated with the soil tortuosity factor predicted with all models (Table 5). A positive correlation between soil tortuosity factor and greenhouse gas emissions from soil under the influence of irrigation water management was observed from this study (Table 5).

The negative correlation between CO_2 and CH_4 with Ds/Do is not surprising especially with the kind of land management practices (intensive puddling and ponding) adopted to create a desirable condition for rice crops. These operations destroy soil structure thereby reducing the number of available air-filled pore space thus allowing soil water content as the dominating factor controlling the emission of greenhouse gases from soils (Panday and Nkongolo, 2015). The role of land-use intensification and agriculture management practices on the uptake of CH_4 in soils has been reported by Mosier (1998). Reduction in gas diffusion due to compactness resulting from the puddling and ponding operation can slow down the movement of greenhouse gasses from such soil (Hansen *et al.,* 1992).

Changes in the quality of soil structure and water content due to tillage and compaction were reported to be having a strong influence on the uptake and movement of N_2O and CO_2 by Ball *et al.,* (1999). Anaerobic conditions due to the reduced number of air-filled pore spaces as a result of restriction of soil macroporosity by irrigation water application can also account for the negative correlation observed from these studies as reported by (Ball *et al.,* 1999). Since, methanotrophs that are responsible for CH_4 uptake in the soil difficultly survive in soils with lower Ds/Do (Hu *et al.,* 2001), methanogens responsible for the release of CH_4 from the soil can be suspected to be the dominant organism in such soil thus resulting in the relationship observed from this studies.

A negative correlation between CO_2 and soil gas diffusivity was reported by Nan *et al.,* 2016. Fang and Moncrief, 1999 and Jassal *et al.,* 2004 suggested possible limitations of CO_2 transport within the soil due to a decrease in effective diffusion resulting from an increase in soil moisture. Nkongolo *et al.,* (2010) reported CO_2 and CH_4 as two greenhouse gases commonly correlated with pore space indices. Several studies have reported the influence of soil pore structural indices in controlling the movement and emissions of greenhouse gases from soils Kruse *et al.,* (1996), Ball *et al.,* (1997), Hu *et al.,* (2001) and Nkongolo *et al.,* (2008). A positive correlation between N_2O emission with Ds/Do may have resulted from the anaerobic environment created due to poor soil structure resulting in the occurrence of nitrification within the soil (Ball *et al.,* 1997). Possibility of higher relative gas diffusivity, high air-filled porosity favoured by the presence of more pore continuity and air movement during the drying periods of alternate wetting and drying irrigation can be another possible reason for the positive correlation between the coefficient of soil diffusivity and N_2O emissions observed from this study since these can trigger the escape of more N_2O from the soil. Restriction of soil diffusivity can cause the consumption of N_2O below the soil layers thereby reducing emissions to the atmosphere (Ball *et al.,* 1999) Differences in chemical and physical properties of soil can account for the different relationships reported above for CH_4 and CO_2 and that of N_2O alone. Panday and Nkongolo (2015) reported a significant general correlation between soil pore indices and greenhouse gases emissions.

Table 1. Soil properties of the study area

Soil Properties	**Mean Value**
pH (water)	5.92
pH ($CaCl_2$)	4.77
OC (gkg^{-1})	0.61
Sand (%)	62.50
Silt (%)	22.72
Clay (%)	14.78
Texture	Sandy loamy

OC-organic carbon

Table 2. Summary of statistics and predicted relative gas diffusion coefficient (Ds/Do) of Lowland rice soil in response to different Irrigation management in Sudan savanna of Nigeria in 2018

Simple statistics	**Ds/Do calculated based on air-filled Porosity Models**			**Ds/Do Calculated based on air-filled porosity and Total Porosity Models**			
	Pen (1959)	Marsh (1959)	Buck (1904)	Sall (1984)	Marsh (1959)	JinJ (1996)	†Mean
				AWD			
Mean	0.06	0.27	0.01	0.01	0.01	0.26	0.101
SD	0.042	0.117	0.014	0.018	0.013	0.305	
CV	76.364	43.985	127.273	163.636	185.714	119.141	
				CF			
Mean	0.04	0.24	0.01	0.003	0.002	0.13	0.07
SD	0.023	0.077	0.005	0.004	0.002	0.112	
CV	56.098	32.218	100.000	133.333	100.000	86.154	

± SD-standard deviation, CV-coefficient of variation, Pen-Pennman, Marsh-Marshall, Buck-Buckingham, Sall-Sallam *et al.,* JinJ, Jin and Jury, Mill- Millington. †Mean- General mean of all models mean in a row

Table 3. Summary of statistics and predicted pore tortuosity factor (τ) of a Lowland rice soil in response to different Irrigation management in Sudan savanna of Nigeria in 2018

Simple statistics	**τ calculated based on air-filled Porosity** models			**τ calculated based on air-filled porosity and Total Porosity models**			
	Pen (1959)	Marsh (1959)	Buck (1904)	Sall (1984)	Mill (1959)	JinJ (1996)	. †Mean
			AWD				
Mean	1.52	4.54	16.99	47.59	114.56	1.20	31.065
SD	0	2.635	10.984	40.577	170.474	1.845	
CV	0.000	58.104	64.654	85.260	148.813	153.367	
			CF				
Mean	1.52	4.96	20.71	46.13	84.40	1.05	26.458
SD	0	2.774	12.738	32.265	60.095	1.254	
CV	0.000	55.984	61.518	69.942	71.204	119.885	

± SD-standard deviation, CV-coefficient of variation, Pen-Pennman, Marsh-Marshall, Buck-Buckingham, Sall-Sallam *et al.,* JinJ, Jin and Jury, Mill- Millington. †Mean- General mean of all models mean in a row

Table 4. Effects of Irrigation water management practices on greenhouse gas emissions (GHG) emissions of a rice field in Sudan Savanna soil of Nigeria.

	CO_2	**CH_4**	**N_20**
	……… $mg\ m^{-2}day^{-1}$ ………		
Irrigation (I)			
AWD	22662	1.82	3.83
CF	28506	11.40	5.32

AWD-alternate wetting and drying, CF-continuous flooding

Table 5. Linear regression analysis ($Y = Y_0 + aX^a$) between pore space indices (Ds/Do and TF) and greenhouse gases fluxes (CO_2, CH_4 and N_2O) under the influence of irrigation water management in a rice field in Sudan Savanna soil of Nigeria

	X	Y_0	a	r	R^2
Between pore space indices and CO_2 fluxes	DS/Dopen	36144.00	-1866.00	-0.468	0.219
	DS/Domarsh	-53170.00	40116.00	0.371	0.137
	DS/Dobuck	32614.00	-6620.00	-0.544	0.296
	DS/Dosall	31018.00	-5392.00	-0.568	0.323
	DS/Domill	30644.00	-7654.00	-0.563	0.317
	DS/Dojj	3358.00	-3186.00	-0.569	0.324
	TFpen	3276.00		0.000	0.000
	TFmarsh	20814.00	11057.00	0.171	0.029
	TFbuck	2166.00	243.06	0.161	0.026
	TFsall	25052.00	506.11	0.054	0.003
	TFmill	2594.00	-3.46	-0.044	0.002
	TFjj	2203.00	80.39	0.210	0.044
Between pores pace indices and CH_4 fluxes	DS/Dopen	11.28	-82.56	-0.298	0.089
	DS/Domarsh	13.07	-23.64	-0.238	0.057
	DS/Dobuck	9.31	254.73	0.302	0.092
	DS/Dosall	8.38	-176.04	-0.268	0.072
	DS/Domill	8.22	-244.06	-0.259	0.067
	DS/Dojj	9.56	-11.77	-0.303	0.092
	TFpen	12.00		0.000	0.000
	TFmarsh	5.45	0.27	0.060	0.004
	TFbuck	1.64	0.31	0.297	0.088
	TFsall	2.47	0.09	0.351	0.123
	TFmill	5.40	0.01	0.170	0.029
	TFjj	7.34	-0.69	-0.107	0.012
Between pores pace indices and N_20 fluxes	DS/Dopen	3.92	11.66	0.220	0.048
	DS/Domarsh	3.78	2.90	0.152	0.023
	DS/Dobuck	4.02	52.41	0.325	0.105
	DS/Dosall	4.11	46.40	0.369	0.136
	DS/Domill	4.12	68.91	0.382	0.146
	DS/Dojj	4.06	2.05	0.276	0.076
	TFpen	-4.00	8.00	#VALUE!	7E-1512
	TFmarsh	4.69	-0.03	-0.030	0.001
	TFbuck	4.75	-0.01	-0.053	0.003
	TFsall	4.73	0.00	0.069	0.005
	TFmill	4.54	0.00	0.024	0.001
	TFjj	4.57	0.00	0.002	0.000

Y-gases fluxes (CO_2, CH_4 and N_2O), Y_0 and a-coefficients, X-pore space indices, DS/Do- relative gas diffusion coefficients, TF-pore tortuosity factor, Pen-Pennman, Marsh-Marshall, Buck-Buckingham, Sall-Sallam *et al.,* JJ-Jin and Jury, Mill- Millington.

4.0 Conclusion

From this study, it can be concluded that greenhouse gas emission from the soil is greatly influenced by diffusivity since it affects it rate of its supply to the atmosphere. It also implies that application of low water content via shallow/ alternate wetting and drying promotes air permeability which will encourage the survival of methanotrophs (CH_4 consumers) making the soil too aerobic thereby slow down nitrification (Low N_2O production) and reduced organic matter decomposition (releases of CO_2) and application of frequent irrigation (continuous flooding) trigger the emissions of GHGs. Our regression analysis confirmed the contribution of irrigation water management practices adopted for this study revealing that air permeability may contribute to the variability of greenhouse gas emissions hence for our understanding of the dynamics of greenhouse fluxes from soil to be improved, we need to include soil diffusions coefficients (Ds/Do) and soil tortuosity factor (τ) in predictive models as controlling factors.

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