ISSN 0511-5728
The West Indian Journal of Engineering
Vol.41, No.1, July 2018, pp.23-30

Spatial Variability of Soil Thermal Conductivities within a Horizontal Gas Flaring Site Owaza, Southeast Nigeria

Onyekachi A. Irondi[a,Ψ] Moses O. Nwagbara[b], and Michael A. Okon[c]

[a,b] Department of Soil Science and Meteorology, College of Soil and Crop Sciences, Michael Okpara University of Agriculture, Umudike, Nigeria; E-mails: kachi.irondi@gmail.com; monwagbara@yahoo.com

[c]Department of Soil Science and Technology, School of Agriculture and Agricultural Technology, Federal University of Technology Owerri, Imo State, Nigeria; Email: michaelaokon@gmail.com

[Ψ] *Corresponding Author*

(Received 07 August 2017; Revised 20 November 2017; Accepted 17 December 2017)

Abstract: *Knowledge of spatial patterns of soil thermal conductivity is of great importance in agricultural meteorology where problems of heat exchange at the soil surface are encountered. This is significant for the environment, site-specific soil and crop management, as well as soil heat movement through soil profile. The study was conducted to determine the spatial pattern of soil thermal conductivities on 14 sample distance points away from a horizontal gas flaring site using the well-known Campbell (1985) equation model. Geostatistics (kriging) were used to describe the spatial pattern of the predicted soil thermal conductivities from each sample point and depth using ArcGIS version 10.1. From the results, predicted soil thermal conductivity varied from 1.49* $Wm^{-1}K^{-1}$ *to 4.89* $Wm^{-1}K^{-1}$*, and the standard deviation ranged from 0.05-0.29 at 0-30 cm. The surface and subsurface predictive spatial distribution maps generated showed clear positional similarity across the field with higher thermal values in the direction of flaring site. The geostatistical linear interpolation using kriging clearly conveys rare insight into the way predicted soil thermal conductivity varied within the horizontal gas flare site. The predictive spatial maps could be an effective tool to farmers, soil scientist, engineers and other land users to make informed decisions on appropriate distances away from a horizontal gas flare station for site-specific soil management. It is compelling, to recommend the discontinuity of horizontal gas flaring in the study area in order to avoid the direct thermal pollution on arable soil ecosystem.*

Keywords: *Gas flaring, Spatial variability, Soil thermal conductivity, Kriging, Site-specific soil management*

1. Introduction

Soil thermal properties are component of soil physics that are required in many areas of agronomy, agro-meteorology, climatology, soil science and engineering. In agriculture, microbial activity and seed germination are affected by their surrounding climate, which is influenced by soil thermal properties, especially the thermal conductivity (λ) (Abu-Hamdeh, 2000; Anandakumar et al., 2001; Bristow, 2002; Ekwue et al., 2006; Danelichen et al., 2013; Gao et al., 2009). Soil thermal conductivity describes the soil properties which govern the flow of heat through the soil. Accurate estimate of soil thermal conductivity is of prime importance in the numerical simulation of heat transmission through soils, and is considered one of the most important thermal properties of plant environment (Hillel, 2003). Thermal conductivity of soils is generally affected by soil texture and structure; increase with bulk density and moisture content, and decrease with organic matter content (Nakshabandi and Kohnke, 1965; Ghuman and Lal, 1985; Abu-Hamdeh, 2000; Abu-Hamdeh and Reeder, 2000). Thermal conductivity is also known to increase with temperature (de Vries, 1963; Sepaskhah and Boersma, 1979; Hopmans and Dane, 1986; Campbell et al., 1994) and mineral composition (de Vries, 1963).

In situ monitoring of λ as a function of volumetric moisture content (θ) can represent a significant challenge. Consequently, much effort has been made to develop λ (θ) models based on easily measurable soil parameters (Kersten, 1949; de Vries, 1963; Johansen, 1975; Campbell, 1985; Cote and Konrad, 2005). Campbell et al. (1994) highlighted that λ increases dramatically with temperature in moist soil, reaching values three to five times the ambient value at 90° Celsius (C). The determination of these soil thermal properties is therefore a very important factor in understanding spatial distribution of soil heat processes especially, the control of thermal and moisture regimes of soil in the field and the individual crop field and larger areas (Usowicz, 1991; Oladunjoye et al., 2013).

Gas flaring is the controlled burning of natural gases associated with oil production. It is the use of vertical or horizontal flare to burn off unwanted associated gas that are extracted from the earth along with the crude (Evoh, 2002; ENS, 2005). It is known that gas flaring in Nigeria has raised the average global temperature by about 0.5°C (Penner, 1999). The heat, toxins and particulates from gas flaring adversely affect vegetation, soil, water, humans, and livelihoods of the host communities. Typical gas flare in Nigeria oil field is located at ground level (horizontal flaring), and is usually surrounded by vegetation, farmlands and village huts 20-30 metres (m) away from the flare and the heat radiation is a function of the flare temperature; gas flow rate and geometrical design of flare jet (World Bank, 2009).

Information on the spatial variability of soil thermal conductivity of arable soils within a horizontal gas flaring site in Owaza is rare, hence the need for this present study designed to investigate and generate the spatial distribution maps of soil thermal conductivities of soils within the gas flaring site.

2. Materials and Methods

2.1 Study area

The study was carried out within the vicinity of horizontal gas flaring site of Shell BP gas flow station in Owaza, southeast Nigeria. The area is located within latitude 4^o 55$'$40.35^{o}N and longitude 7^o 10$'$55^{o}E. All in-situ field work was carried out within and outside the bond wall of the horizontal gas flaring where spatial variability was predictable due to the obvious variable soil characteristics as a result of the gas flare heat emission. Farming is the main socio-economic activity of the rural population with the growing of cassava (*Manihot esculenta*), maize (*Zea mays*), and vegetables (fluted pumpkin) in small plots at varying kilometres away from the flare site. Oil exploration started in the area in early 60’s with its resultant gas flaring. The geological material is coastal plain sand (Benin Formation) with a low land geomorphology of 50 m above sea level (Enwezor et al., 1990). The dominant soil is described as Typic Paleudult ranging from sandy to loamy textures (USDA-SSDS, 2003). The area is warm and humid. Isohyperthermic soil temperature and udic moisture regimes characterise the area (Chukwu, 2007). There are two distinct seasons in the study area, the dry and rainy season. These seasons are usually influenced by the tropical maritime air mass and the tropical continental air mass. The rainy season usually begins in March and is interrupted by a dry season in October. Annual rainfall ranges from 2,000-2,500 mm with mean temperature of 28-30^{o}C and relative humidity ranging from 55-85%.

2.2 Field studies and sample collection

Field reconnaissance survey was first carried out to determine the feasibility of the study and appropriate contacts and clarifications were given by the host community and Shell BP oil servicing company prior to several field trips to the gas flare site. The study was carried out in September 2016 when the soil was wet representing typical udic moisture regime. All data were taken when the horizontal gas flaring was on during noon between 1.00 to 3.00 pm local time, i.e. 13.00 to 15.00 Hours, Greenwich Mean Time (GMT) + 1.

Sampling procedure involved the use of a fibrous measuring tape (starting from the active point of the horizontal gas flaring jet), to mark out sample distance points at 50 m, 100 m, 200 m distances parallel to the active flaring point (sample points 1, 2 and 3), 50 m apiece distance to the left and right sides from the active flare point (sample points 4 and 5). Sample points 6 and 7 were taken behind the active gas flaring point at 50 m and 100 m respectively all within the bond wall of the gas flaring site whereas other sample points (sample points 8 through 14), were located outside the bond wall of the active flare point at varying distances (i.e. 400 m, 600 m, 800 m, 1 km, 2 km, 3 km and 4 k m) away from the active gas flaring point. These distances were taken to observe better the spatial scale variations of predicted soil thermal conductivities of the soils. All sample points were geo-referenced using a hand-held BHCNav GPS to generate their geographical coordinates for further geostatistical soil spatial analysis using kriging.

All data were collected at 0-15 cm and 15-30 cm sampling depths from each marked sample distance. These depths were chosen because they represent the moisture control section in the soil (USDA-SSDS, 2003). Also, these depths form the main root zone of most crops (Jang, 2004). Soil and air temperatures were estimated in situ using different mercury-in-glass thermometer at each sample point. Soil temperature data estimation involves immersing the bulb of the mercury thermometer 2-3 cm into 0-15 cm and 15-30 cm soil depths for five minutes each and readings (in degree Celsius) taken appropriately. The air temperature data were read for each sample point by using a hand held mercury thermometer at same points 26 m elevation from the ground level and readings (in degree Celsius) recorded after every five minutes.

Bulked soil samples from every sample point were collected using a cylindrical core sampler 3.5 cm in diameter and 6 cm in length. This involved driving the core samplers into the soil to collect undisturbed samples for soil moisture and bulk density determination. Disturbed samples were also collected from these points for analysis of selected physico-chemical properties of the soil using a hand held auger. A total of twenty-eight (28) soil samples from both sampling depths (0-15 cm and 15-30 cm) were collected for analysis of selected properties. All samples were bagged in a black polythene bag and properly labeled against each point.

2.3 Laboratory analysis

Samples were air dried, ground, and sieved through a 2 mm screen prior to analyses. Prepared samples were subjected to various analysis using standard procedures as described in the USDA Soil Survey Manual (USDA-SSDS 1993) at the Soil Physics Laboratory of National Root Crop Research Institute (NRCRI), Umudike, near Umuahia, Abia State, Nigeria. Particle size analysis was determined using the pipette method (Gee and Or, 2002).

Bulk density was analysed by the core sample method according to Blake and Hartage (1990) and gravimetric moisture content by the APHA (1985) method. Total porosity was calculated from the result of bulk density and particle density. Soil organic carbon was determined by the method of wet oxidation according to Nelson and Sommers (1982).

2.4 Determination of soil thermal properties

Soil thermal conductivities of the soil samples were predicted using the procedure of Campbell (1985) model following the example of Ekwue et al. (2005, 2006, and 2011). Parameter data were translated using pedo-transfer function of easily measured soil properties according to Bouma (1989). Soil dry bulk density, moisture content and percentage clay determined from the laboratory analysis were parameters inserted into the model equation. Using the Campbell (1985) model, the predicted soil thermal conductivities from different sample points were empirically determined using the model equation:

$$K = A + B\,\theta_v - (A - D)\exp[-(C\,\theta_v)^E] \quad (1)$$

where:

K = Soil thermal conductivity (W m^{-1} $^{o}C^{-1}$),

θ_v = Volumetric water content

ρb = Soil dry bulk density (Mg m^{-3})

Mc = Clay mass fraction from particle size analysis.

A, B, C, D and E are Soil dependent coefficients which are related to soil properties and are readily available. Campbell (1985) gave the values of the coefficients as:

$$A = 0.65 - 0.78\,\rho b^{2.5} \quad (2)$$

$$B = 1.06\,\rho b\,\theta_v \quad (3)$$

$$C = 1 + 2.6\,Mc^{-0.5} \quad (4)$$

$$D = 1 + 0.03 + 0.10\,\rho b \quad (5)$$

$$E = 4 \quad (6)$$

2.5 Data analyses

Descriptive statistics of mean, standard deviation and coefficient of variation were used to characterise the selected soil thermal properties using MS Excel spreadsheet (version 2013) software package according to Cruz (2013). Correlation analyses with the predicted soil thermal properties and selected physical properties were employed to measure the degree of relationship between soils using the procedure of Cohen *et al.* (2013). A more detailed geostatistical spatial analysis using geographic information system (GIS) analysis was carried out in the Cartographic/GIS Laboratory of the Department of Geography and Environmental Management, University of Port Harcourt, Port Harcourt. Kriging method was used in ArcGIS 10.1 environment to describe the structures of the spatial maps of the predicted soil thermal properties at different sample distance points away from the gas flaring site.

Attribute tables were created for each parameter and their coordinates in Excel format before importation in ArcGIS environment. The generated predictive maps were used to describe the spatial and temporal variability of the predicted soil thermal conductivities at 0-15 cm and 15-30 cm sampling depths.

3. Results and Discussion

3.1 Soil Physico-Chemical Properties

The organic carbon (OC) from the different sample distances ranged from 0.91 % to 2.81 %. Clearly, sample distances (1 through 5) within the flare bond wall exhibited increased values of OC unlike values outside the bond wall (see Table 1). The increased OC content at closer sample points to the flare point could be attributed to prolonged accumulation of carbon due to flaring that emits carbon compounds.

Table 1. Organic carbon (OC) and particle size distribution of different soil sample points at 0-30 cm depth

Sample Distance	Organic Carbon (%)	Particle Size Distribution Sand (%)	Silt (%)	Clay (%)	USDA Soil Textural Class
50 m	2.81 ± (0.10)	87.35 ± (1.00)	5.80 ± (0.40)	6.85 ± (0.10)	Sand
100 m	2.62 ± (0.10)	87.17 ± (0.07)	6.47 ± (0.20)	6.35 ± (0.20)	Sand
200 m	2.72 ± (0.04)	86.75 ± (1.00)	6.90 ± (0.15)	6.35 ± (1.00)	Sand
50 m-R	2.58 ± (0.05)	86.60 ± (2.00)	6.15 ± (0.10)	7.25 ± (2.00)	Sand
50 m-L	2.21 ± (0.03)	85.53 ± (0.61)	6.63 ± (0.20)	7.85 ± (0.13)	Sand
50 m-B	1.65 ± (0.05)	83.97 ± (0.20)	7.17 ± (0.10)	8.85 ± (0.10)	Loamy sand
100 m-B	1.01 ± (0.06)	84.30 ± (0.25)	6.75 ± (0.35)	8.95 ± (0.05) `	Loamy sand
400 m	1.53 ± (0.03)	84.30 ± (2.05)	6.15 ± (2.00)	9.63 ± (0.10)	Loamy sand
600 m	0.91 ± (0.10)	81.37 ± (1.53)	5.17 ± (0.05)	10.05 ± (0.04)	Loamy sand
800 m	1.22 ± (0.05)	78.73 ± (1.00)	9.80 ± (0.17)	9.98 ± (0.30)	Loamy sand
1 km	1.31 ± (0.06)	75.70 ± (0.50)	13.32 ± (0.10)	11.46 ± (1.00)	Loamy sand
2 km	1.34 ± (0.04)	72.60 ± (0.30)	15.48 ± (0.20)	11.92 ± (0.20)	Loamy sand
3 km	1.40 ± (0.15)	77.30 ± (0.25)	10.70 ± (0.30)	12.0 ± (2.00)`	Loamy sand
4 km	1.44 ± (0.10)	77.77 ± (0.10)	9.69 ± (0.10)	12.54 ± (0.10)	Loamy sand

Keys: 50 m-R and 50 m-L = 50 m interval distance points to the right and left from the active flare point, 50 m-B and 100 m-B = 50 m and 100 m distance points behind the active flare point, Values in bracket = Standard deviation. All values are means of three replicate samples.

From the particle size analysis, the texture of sample points within the flare bond wall were predominantly sandy and loamy sand outside the bond wall. Sand content ranged from 77.30 % to 87.35 %. Silt ranged from 5.80 % to 15.48 % and was low at closer sample distances to the flare, with higher values away and outside the flare zone. Similarly, the clay content exhibited a similar trend like silt and ranged from 6.35 % to 12.54 % (see Table 1). The high sand content across sample distances within the flaring point could be attributed to increased soil temperature as a result of heat radiation from the flare which induced dehydration of 2:1 clay minerals in the soil leading to strong interaction among the clay particles which in turn yielded less clay and more of larger particles (Arocena and Opiom, 2003). Increased sand content within the flare vicinity agrees with previous research of Abu-Hamedh (2000) and Ekwue et al. (2005, 2006).

The soil bulk density through the sample distances varied from 1.42 Mg/m3 to 2.50 Mg/m3 from farthest point away from the flare to the closest point. In contrast, the total porosity varied from 6.0 % to 46 % at the closest to the farthest points, respectively (see Table 2). The bulk density values of the soil across sample distances within the flare vicinity went up too high (above normal values), which could be attributed to the extreme compaction of the soils near the flare site as a result of prolonged and continuous flaring (over 50 years) in the area.

The tremendous heat and emission of toxic compounds could have resulted in soil surface sealing, hence the rare increase in bulk density values of sample points within the flare site. Heat induces increase in bulk density through its influence on mineralisation, caking of soil and infiltration of heavy metals. Similarly, the decreased porosity towards the flare vicinity was a direct effect of high bulk density. The variation in gravimetric moisture content was low within the flare sample distances and varied from 5.25 % to 29.73 % (see Table 2).

Clearly, the low moisture content across sample distances around the flare zone could be attributed to high evaporation due to the enormous heat radiation from the flare site. This is in good agreement with previous work by Botkin and Keller (1998) which showed that increased soil temperature due to tremendous heat emission from gas flaring is the major cause of low soil moisture content within the flaring vicinity. Low soil moisture content leads to reduction in the rate of translocation of nutrients within the plant system as well as microbial activities. The soil temperature varied from 25.5^{o}C to 45^{o}C from the farthest sample distance away to the closest sample distance to the flare respectively. Induced flare radiation within the flare bond wall, must have raised the soil temperature (Orubu, 2002). Similarly, the air temperature varied from 26^{o}C to 48^{o}C (Table 2). The air temperature was the highest across sample points within the flare bond wall. This could be attributed to increased atmospheric temperature caused as a result of high thermal energy within the flare.

3.2 Predicted Soil Thermal Conductivity

Considering the studied depth (0-30 cm), the predicted soil thermal conductivity varied from 1.58 Wm^{-1} K^{-1} to 4.89 Wm^{-1} K^{-1} whereas the standard deviation (SD) ranged from 0.06 to 0.28 (see Table 2). High predicted soil thermal conductivity predominates sample points within the bond wall of the horizontal gas flaring site. Increased soil temperature at closer sample points and subsequent increase in soil bulk density, led to greater contacts between soil solid particles which resulted in increased predicted soil thermal conductivity within the flare site. This agrees with the findings of Campbell et al. (1994) and Smits et al. (2013) that soil thermal conductivity increases with rising temperature.

Table 2. Bulk density, total porosity, gravimetric moisture content, air/soil temperatures, thermal conductivity of different sample points at 0-30cm depth

Sample Distance	Bulk Density (Mg/m^3)	Total Porosity (%)	Gravimetric Moisture Cont. (%)	Soil Temp. (^{o}C)	Air Temp. (^{o}C)	Predicted Thermal Conductivity ($Wm^{-1}K^{-1}$)	Soil Coordinates Latitude (N)	Longitude (E)
50 m	2.50 ± (0.06)	6.0 ± (1.30)	5.25 ± (0.50)	45.0 ± (0.50)	48 ± (0.20)	4.89 ± (0.19)	4°58^{1}48.67°	7°10^{1}59.79°
100 m	2.45 ± (0.05)	8.0 ± (0.75)	5.35 ±(0.65)	43.5 ± (0.30)	46 ± (0.60)	4.69 ± (0.27)	4°58^{1}48.28°	7°11^{1}0.79°
200 m	2.38 ± (0.05)	11 ± (0.55)	5.60 ±(0.60)	42.5 ± (0.40)	44 ± (0.50)	4.33 ± (0.10)	4°58^{1}46.98°	7°11^{1}0.34°
50 m-R	2.15 ± (0.05)	15 ± (0.52)	7.82 ±(1.40)	40.5 ± (0.50)	42 ± (0.50)	3.40 ± (0.20)	4°58^{1}46.03°	7°11^{1}0.05°
50 m-L	2.07 ± (0.14)	22 ± (1.10)	8.53 ±(1.10)	39.5 ± (0.50)	41 ± (1.50)	3.10 ± (0.09)	4°58^{1}46.09°	7°10^{1}59.17°
50 m-B	1.59 ± (0.07)	37 ± (1.33)	13.41 ± (1.22)	34.0 ± (0.50)	35 ± (0.50)	1.65 ± (0.10)	4°58^{1}49.54°	7°10^{1}57.12°
100 m	1.57 ± (0.07)	36 ± (0.54)	15.54 ± (2.05)	32.5 ± (0.30)	34 ± (0.50)	1.65 ± (0.13)	4°58^{1}52.82°	7°10^{1}58.57°
400 m	1.55 ± (0.08)	34 ± (0.73)	19.69 ± (2.05)	35.5 ± (0.40)	37 ± (1.00)	1.72 ± (0.19)	4°58^{1}56.38°	7°10^{1}58.48°
600 m	1.54 ± (0.16)	36 ± (1.33)	21.93 ± (2.00)	31.0 ± (2.00)	33 ± (1.00)	1.76 ± (0.25)	4°58^{1}58.97°	7°10^{1}57.98°
800 m	1.54 ± (0.06)	42 ± (1.75)	21.85 ± (2.15)	31.0 ± (0.50)	30 ± (1.00)	1.73 ± (0.29)	4°58^{1}56.89°	7°10^{1}56.84°
1 km	1.45 ± (0.06)	45 ± (1.15)	23.56 ± (1.50)	28.5 ± (1.00)	30 ± (2.00)	1.54 ± (0.28)	4°58^{1}53.14°	7°11^{1}02.80°
2 km	1.42 ± (0.08)	46 ± (1.30)	25.79 ± (1.52)	26.5 ± (1.50)	28 ± (2.00)	1.49 ± (0.05)	4°58^{1}57.40°	7°11^{1}14.02°
3 km	1.44 ± (0.05)	46 ± (2.04)	26.79 ± (0.58)	25.5 ± (1.50)	28 ± (1.32)	1.57 ± (0.06)	4°58^{1}57.40°	7°11^{1}14.02°
4 km	1.42 ± (0.04)	46 ± (1.51)	29.73 ± (2.00)	23.5 ± (0.50)	26 ± (1.00)	1.58 ± (0.06)	4°59106.91°	7°11^{1}12.09°

Keys: 50 m-R and 50 m-L = 50 m interval distance points to the right and left from the active flare point, 50 m-B and 100 m-B = 50m and 100 m distance points behind the active flare point, values in bracket = Standard deviation. All values are means of three replicate samples.

Udoinyang (2005) further opined that the higher values of soil thermal conductivity closer the gas flare sample points could be as a result of intense heat and higher temperature generated by the flare. Similarly, Ikelegbe (1993) and Orubu (2002) observed that gas flaring generates tremendous heat, which is felt over an average radius of 0.5 kilometres thereby causing soil thermal pollution. Increased bulk density of soils closer to the flare point results in more intimate contact between the individual particles, and this brings about increases in thermal conductivity (Nakshabandi and Kohnke, 1965).

The soil thermal conductivity also increases with water content because the thickness and geometric arrangement of water layer around soil particles improve thermal contact between soil particles; hence increase in predicted soil thermal conductivity (Hillel, 1998). This is not in agreement from the result of this study as predicted soil thermal conductivity was the highest across sample points with low moisture content (see Table 2). Obviously, the increase in soil thermal conductivity within the gas flare vicinity could be as a result of increase in soil temperature and high bulk density due to high heat radiation. Furthermore, many authors indicted increase in bulk density and moisture content as a cause of increase in thermal conductivity (Oladunjoye and Sanuade, 2012; Rubio et al., 2009; Singh and Devid, 2000).

Figure 1 displays the variability pattern of soil thermal conductivity of the studied depths (0-15 cm and 15-30 cm) from different sample distances away from flare. Clearly, both depths exhibited increased thermal conductivity values from sample points within the flare point with 0-15 cm depth showing greater increase in predicted thermal conductivity values by sample distances within the flare site.

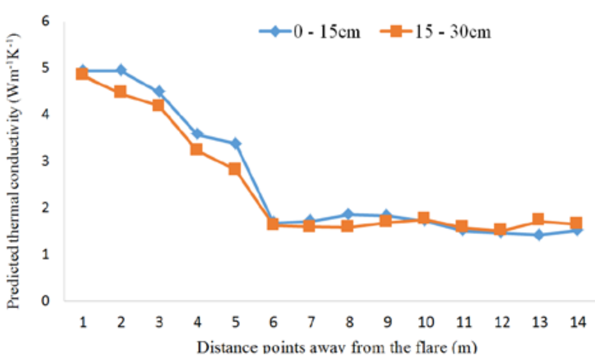

Figure 1. Studied depths and soil thermal conductivity variations across sample distance points away from the flare point

Similarly, Figure 2 shows higher soil thermal conductivity variability trend as influenced by soil temperature from different sample points. It could be observed that at increased soil temperature, the soil thermal conductivity subsequently increased within the flare bond wall in the direction of flaring and decreased sharply and continuously away from the flare zone. This agrees with the findings of Campbell et al. (1994) and Smits et al. (2013).

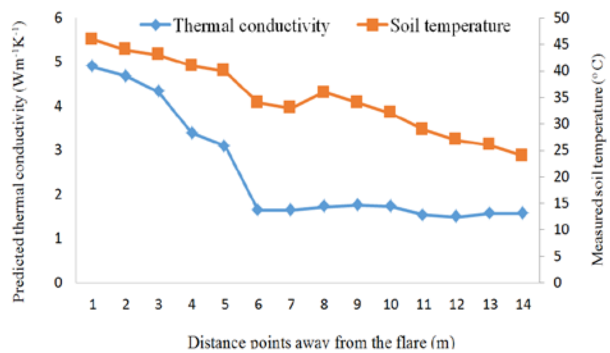

Figure 2. Soil temperature and thermal conductivity variations across sample distance points away from the flare point

The variations between bulk density and predicted soil thermal conductivity from different sample points away from flare clearly showed higher predicted soil thermal conductivity and bulk density trend across sample points within the gas flaring bond wall and decreased away (see Figure 3).

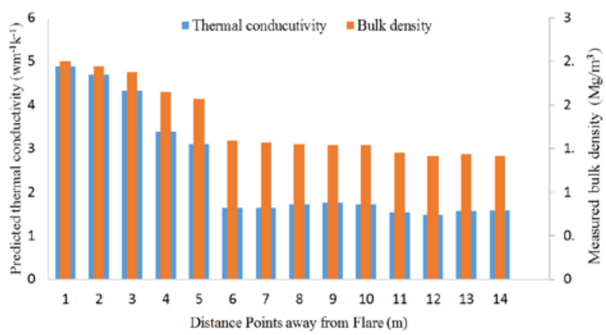

Figure 3. Bulk density and thermal conductivity variations across sample distance points away from the flare point

In contrast, the influence of moisture content on predicted soil thermal conductivity at closer sample distances towards the flare point was low (see Figure 4). That is, at low moisture content experienced within the flare vicinity sample points, the predicted soil thermal conductivity increased the highest. This results for bulk density agreed with many authors (Oladunjoye and Sanuade, 2012a; Rubio et al.,2009; Singh and Devid, 2000), but not with moisture content who stated that increased bulk density and moisture content results to increase in predicted soil thermal conductivity. This could be attributed to the increased soil temperature and prolonged heat emission from the flare site which could have resulted in high evaporation at closer sample points to the flare vicinity.

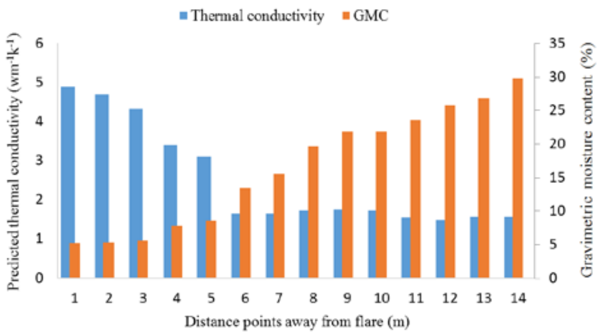

Figure 4. Moisture content and thermal conductivity variations across sample distance points away from the flare point

The predicted soil thermal conductivity versus bulk density relationship showed a strong positive linear correlation with r^2 = 0.98 (Figure 5a). In contrast, the predicted soil thermal conductivity relationship with moisture content exhibited a negative non-linear correlation with r^2 = 0.75 (Figure 5b), whereas the slope of the regression line and intercept are -0.13 and 4.62 respectively. That shows that at low moisture content, the predicted soil thermal conductivity increased and decreased with increasing moisture content.

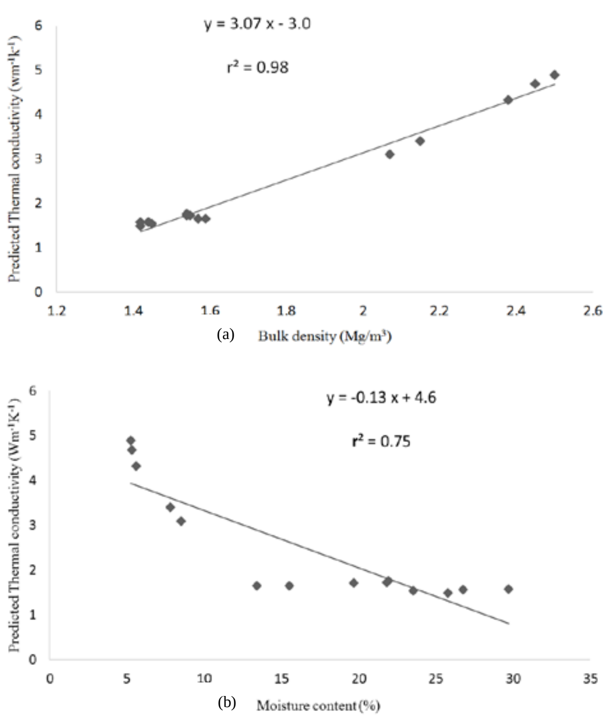

Figure 5. Predicted values of soil thermal conductivity with (a) bulk density (b) moisture content

3.3 Predictive variability maps of soil thermal conductivity

Krigged maps shows that the spatial distribution of predictive soil thermal conductivities from different sample distance points away from the active gas flaring point were the main output of the geostatistical spatial analyses. From the GPS readings, the coordinates of the active point of flare were situated north-west direction at $4^o\,58^{'}\,47.35^o$N and $7^o\,10^{'}\,58.45$ at an elevation of 26 m. Regions in the map with darker colour represent zones with higher thermal conductivity values whereas regions with lighter colour represent moderate to low values (see Figure 6). High resolution of geostatistical maps has an edge in thorough characterisation of soils on site-specific basis than maps created for mapping units which implies that detailed and precise observation can be made on the spatial distribution of soil properties especially the thermal properties that cannot be routinely determined in the laboratory. Cruz-Rodriguez (2004), in agreement stated that detailed observations can be made on the distribution of soil properties when considering land use.

From a detailed observation of the spatial maps for predictive soil thermal conductivities at 0-15 cm surface depth (Figure 6a) and 15-30 cm sub-surface depth, (Figure 6b), the parameter was found to increase from north to west in the direction of flaring in both depths, but decreased with increasing distance away from point of flaring. There was obvious positional similarity in both depths of increase in predicted soil thermal conductivity concentrated in multi-regions in north-western direction of the map. The distribution map revealed that the parameter decreased from north to east, with a fairly uniform distribution with patches from east to south.

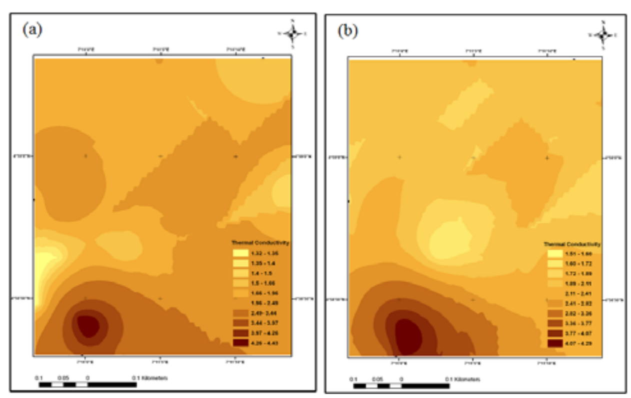

Figure 6. Kriged maps of predictive soil thermal conductivity from different sample distance points away the horizontal active gas flaring site at (a) 0-15 cm and (b) 15-30 cm depths

From the spatial maps, predictive soil thermal conductivity was generally high and above standard range of measurements (0.02-4 $Wm^{-1}K^{-1}$) for 50 m, 100 m and 200 m sample distances in surface and subsurface depth. Thus, predictive soil thermal conductivity was generally higher in the surface (0-15 cm) depth than the subsurface 15-30 cm depth.

Although, high predictive soil thermal conductivity was concentrated north-western within the flare point, the spatial variability appeared to be more continuous and uniform to the north-eastern section of the field. However, few mosaic patches appeared around the mid-northern zone in both depths especially the subsurface depth. It was, therefore, possible that the enormous heat radiation and dispersion from the horizontal gas flaring jet was the major cause of thermal fluxes and disruptions across sample distances that experienced above standard measurement range.

4. Conclusion

The spatial characterisation of soil thermal conductivity through ordinary kriging clearly conveys rare insight into the spatial patterns of predicted soil thermal conductivity within and farther distances from a gas flaring site. Results showed predicted soil thermal conductivity increasing at low moisture content, increased sand content, bulk density and soil temperature within the flaring site but decreased at increasing distance away from the site. On the contrary, the increased soil thermal conductivity values at low moisture content within the flare bond wall sample points disagree with previous assertions of increase soil thermal conductivity with increased moisture content. It could be inferred that tremendous heat from the horizontal gas flaring, justifies this divergent result of this present study.

The major implication of this study from the generated maps is that the predicted soil thermal conductivities map from sample points within the flare bond wall has been negatively disrupted resulting in soil fertility loss and reduced ecosystem services. The predictive spatial maps generated could be helpful to the farmers, soil scientists and other land users to make informed decisions on the appropriate distance (at least 4 km away) from a flare location for optimum land use plan for agriculture and residential buildings, taking into account the spatial heterogeneity of the maps. The findings of this study have established the need for site-specific soil quality status monitoring as required in precision agriculture.

Further studies could examine the in situ measurement of soil thermal conductivity using KD2 Pro thermal analyser and comparing with the predictive values using Campbell (1985) model.

Acknowledgements:

The authors are grateful to Mr. Elvis and Ebube Dike, who played a pivotal role in helping us gain rare access to the horizontal gas flare study site, and to Professor Edwin I. Ekwue, Coordinator of the Biosystems Engineering programme at The University of the West Indies, St Augustine, Trinidad and Tobago for his uncommon guide in using Campbell's (1985) model.

References:

Abu-Hamdeh, N.H. (2000), "Effect of tillage treatments on soil thermal conductivity for some Jordanian clay loam and loam soils", *Soil Tillage Research*, Vol.56, pp.145-151.

Abu-Hamdeh, N.H., and Reeder, R.C. (2000), "Soil thermal conductivity: Effects of density, moisture, salt concentration, and organic matter", *Soil Science Society of America Journal*, Vol. 64, pp.1285-1290.

Anandakuma, K., Venkatesan, R and Prabia, T.V (2001), "Soil thermal properties at Kalpakkam in coaster south India", *Proceedings of the Indian Academy of Science*, Vol.110, No.3, pp.239-245.

APHA (1985), *Standard Methods for the Examination of Waste Wate*r, 15th Edition, American Public Health Association, Washington DC.

Arocena, J.M., and Opio, C. (2003), "Prescribed fire-induced changes in properties of sub-boreal forest soils", *Geoderma*, Vol.113, No.1, pp.1-16.

Blake, G.R. and Hartage, K.H. (1990) In: Klute. A. (ed), *Methods of Soil Analysis Part and Physical and Mineralogical Methods*, Agronomy Monogram 9, 2nd Edition, The American Society of Agronomy/Soil Science Society of America, Madison, Wisconsin, p.363-375 .

Botkin, D.B. and Keller, E.A. (1990), *Environmental Science Earth as a living Planet*, 2nd Edition, John Wiley and Sons, Canada.

Bouma, J. (1989), "Using soil survey data for quantitative land evaluation", *Advances in Soil Science*, Vol.9, pp.177-213.

Bristow, K.L. (2002), "Thermal conductivity", In: *Methods of Soil Analysis. Part. 4. Physical Methods*, SSSA Book Series 5, Soil Science Society of America, Madison, Wisconsin, p.1209-1226

Campbell, G.S. (1985), *Soil Physics with BASIC: Transport Models for Soil–Plant Systems*, Elsevier, New York.

Campbell, G.S., Jungbauer, J.D., Bidlake, W.R. and Hungerford, R.D. (1994), "Predicting the effect of temperature on soil thermal conductivity", *Soil Science*, Vol.158, pp.307-313.

Chukwu, G.O. (2007), *Soil Fertility Capability Classification for Seed Yam (Dioscorea rotundata Poir) on Acid Soils of South-Eastern Nigeria*, Unpublished PhD thesis Submitted to Federal University of Technology, Minna, Niger State, Nigeria, 190 pp.

Cohen, J., Cohen, P., West, S. G., and Aiken, L.S. (2013), *Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences*, Routledge, London.

Côté, J., and Konrad, J.M. (2005), "A generalised thermal conductivity model for soils and construction materials. Canadian", *Geotechnical Journal*, Vol.42, pp.443-458.

Cruz, C.D. (2013), "Genes: A software package for analysis in experimental statistics and quantitative genetics", *Acta Scientiarum Agronomy*, Vol.35, No.3, pp.271-276.

Danelichen, V.H.M., Biudes, N.S., Souza, M.C., Machado, N.G., Curado, L.F.A. and Nogueira, J. (2013), "Soil thermal diffusivity of a gleyic solonetz soil estimated by different methods in the Brazilian Pantanal", *Open Journal of Soil Science*, Vol.13, No.3, pp.15-22.

De Vries, D.A. (1963). "Thermal properties of soils", in: Van Wijk, W.R. (ed.), P*hysics of Plant Environment*, North-Holland, Amsterdam, pp. 210-235.

Ekwue, E.I., Stone, R.J. and Bhagwat, D. (2006), "Thermal conductivity of some compacted Trinidadian soils as affected by peat content", *Biosystems Engineering*, Vol.94, pp.461-469.

Ekwue, E.I., Stone, R.J. and Bhagwat, D. (2011), "Thermal conductivity of some common soils in Trinidad", *West Indian Journal of Engineering*, Vol.33, pp.4 -11.

Ekwue, E.I., Stone, R.J., Maharaj, V.V. and Bhagwat, D. (2005), "Thermal conductivity and diffusivity of four Trinidadian soils as affected by peat content", *Transactions of the ASAE*, Vol.57, pp.1803-1815.

ENS (2005), *Gas Flaring in Nigeria: A Human Rights, Environmental and Economic Monstrosity*, Climate Justice Programme and Environmental Rights Action/FOE Nigeria, Netherlands, June, pp. 4-25.

Enwezor, W.O., Udo E.J., Ayorade, W.A., Adepuju, J. and Chude V.O, (1999), "A review of soil and fertiliser use research in Nigeria", In: *Literature Review on Soil Fertility Investigation in Nigeria*, Federal Ministry of Agriculture and Natural Resources, Lagos, pp.53-100

Evoh, C. (2002), *Gas flares, oil companies and politics in Nigeria*. http://www.waado.org/environmental/oil companies/gasflarespolitics.

Gao, Z., Fan, X and Bian, L. (2009), "An analytical solution to one dimensional thermal conduction-convection in soil", *Soil Science*, Vol.168, No.2, pp.99-107.

Gee, G.W. and Or, D. (2002), "Particle-size analysis", In: Dane, J.H. and Topp, G.C. (ed.) *Methods of Soil Analysis. Part. 4. Physical methods*, SSSA Book Series 5, Soil Science Society of America, Madison, Wisconsin, p.255–293.

Hillel, D. (2003), *Introduction to Environmental Soil Physics*, Academic Press, London, 484 pp

Hopmans, J.W., and Dane. J.H. (1986), "Thermal conductivity of two porous media as a function of water content, temperature and density", *Soil Science*, Vol.142, pp.187-195.

Ikelegbe, O.O. (1993), "Pollution in Nigeria, cause, effect and control", *Proceedings of the 20th Nigeria Geographical Association Conference*, Minna, Nigeria, November, pp.17-18

Jang, H.D. (2004), "Environment and crops", In: Uwehi, Z.S. (ed.), *Principles of Environmental Management*, ONAKS Press, Ibadan, pp.106-130

Johansen, O. (1975), *Thermal Conductivity of Soils*, Ph.D. dissertation. Norwegian University of Science and Technology, Trondheim (CRREL draft transl. 637, 1977).

Kersten, M.S. (1949), "Thermal properties of soils", *Bulletin 28: Engineering Experiment Station*, University of Minnesota, Minneapolis, MN.

Nakshabandi, G.A. and Kohnke, H. (1965), "Thermal conductivity and diffusivity of soils as related to moisture tension and other physical properties", *Agricultural Meteorology*, Vol.2, pp.271-279.

Nelson, D.W. and L.E. Sommers. (1982), "Total carbon, organic carbon, and organic matter", In: Page, A.L. et al. (ed), *Methods of soil analysis. Part 2*, 2nd edition, Agronomy Monogram 9, 2nd Edition, The American Society of Agronomy/Soil Science Society of America, Madison, Wisconsin, pp.539-579.

Oladunjoye, M.A. and Sanuade, O.A. (2012), "In situ determination of thermal resistivity of soil: case study of Olorunsogo power plant, southwestern Nigeria", *ISRN Civil Engineering*, Vol.2012, doi:10.5402/2012/591450.

Oladunye, M.A, Sanuade, O.A. and Olaojo A.A. (2013), "Variability of soil thermal properties of a seasonal cultivated agricultural teaching and research farm, University of Ibadan, South Western Nigeria", *Global Journal of Science Frontier Research Agriculture and Veterinary*, Vol.13, No.8, pp.1- 25.

Penner, J.E. (1999), *Aviation and Global Atmosphere: Inter Governmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, pp 2-4.

Rubio, M.C., Cobos, D.R., Josa, R. and Ferrer, F. (2009), "A new analytical laboratory procedure for determining the thermal properties in porous media, based on the American standard D5334-05", *Estudios en la Zona no Saturada del Suelo*, Vol.IX, pp.18-20.

Sepaskhah, A.R., and Boersma, L. (1979), "Thermal conductivity of soils as a function of temperature and water content", *Soil Science*, Vol43, pp.439-444.

Singh, D.N. and Devid, K. (2000), "Generalised relationships for estimating soil thermal Resistivity", *Experimental Thermal and Fluid Sciences*, Vol.22, pp.133-143.

Smits K.M., Sakaki T., Howington S.E., Peters J.F. and Illangasekare T.H. (2013), "Temperature dependence of thermal properties of sands across a wide range of temperatures (30-70°C)", *Vadose Zone Journal*, Vol.12: doi 10.2136/vzj2012.0033.

ACE (1988), *Technical Manual: Arctic and Subarctic Construction: Calculation Methods for Determination of Depths of Freeze and Thaw in Soils, TM 5-852-6/AFR 88-19*, U.S. Army Corps of Engineers (ACE), Vol.6, Equation 2-1

Udoinyang, G.U. (2005), "The effects of gas flaring on sweet potato production in the Niger Delta, Nigeria", *Journal of Ecosystem*, Vol.10, pp.77-86.

USDA-SSDS (1993), Soil Survey Manual. Agricultural Handbook. No 18, USDA Soil Survey Division Staff/ U.S. Government Print Office. Washington, DC.

USDA-SSDS (2003), *Keys to Soil Taxonomy*, USDA Soil Survey Division Staff/ Department of Agriculture: Natural Resources Conservation Service.

Usowicz, B. (1991), *Studies on the Dependence of Soil Temperature on Its Moisture in Field*, Thesis, Academy of Agriculture, Lublin.

World Bank (2009), *Satellite Observations Show Declining Levels of Gas Flaring, Greenhouse Emissions*, News Release No. 2010/143, Global Gas Flaring Reduction Public-Private Partnership, Washington, D.C.

Authors' Biographical Notes:

Onyekachi A. Irondi *is a research student in the Department of Soil Science and Meteorology, College of Crop and Soil Sciences, Michael Okpara University of Agriculture Umudike, Nigeria. He recently completed his MSc program in Soil Physics and Conservation. His research interests are in environmental soil pollution and remediation, Soil and Water conservation, Agro-climatology and environmental management.*

Moses O. Nwagbara *is a practicing Climatologist and member of Nigerian Meteorological Society, Soil Science Society of Nigeria, Association of Nigerian Geographers, Nigerian Environmental Society and CLIVAR-GEWEX Africa Climate Panel. His research interests are Climate Change, Agro-climatology, Environmental Management, Biodiversity, Climate Trend Modelling, Climate-Water-Plant Relations and Soil Climate.*

Michael A. Okon *is a Lecturer II in the Department of Soil Science and Technology, School of Agriculture and Agricultural Technology, Federal University of Technology Owerri, Nigeria. He is currently a PhD student at the Department of Soil Science and Meteorology, Michael Okpara University of Agriculture Umudike, Nigeria. His research interest is in soil hydrology and soil water relations.*

■