Evaluation of soil properties of the Sudan Savannah ecological zone of Ghana for crop production.

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ABSTRACT

Low soil fertility and limited ability of farmers to purchase fertilizers in the Sudan savannah zone of Ghana has resulted in the decline in the yield of cereals over the years. There is, therefore, the need to identify soil parameters that are critical to crop production, to manage them effectively and improve fertilizer use efficiency to increase crop yield. To achieve this, an area of about 1.5 km^2 was divided into grid cells ($100m^2$) and characterised for their soil properties (organic carbon, pH, and soil texture). Data collected was used in a pedo-transfer function to estimate additional soil parameters that were not measured (i.e. wilting point, field capacity, available water and saturation). These were used as input to the crop simulation model (APSIM- Agriculture Productions Systems sIMulator) to simulate sorghum grain yield for each grid cell. Linear regression and factor analysis were also employed in explaining the data. Grain yield ranged from 402 to 1092 kg ha^{-1} with a mean of 673 kg ha^{-1} using 2005 weather data and 228 to 907 kg ha^{-1} with a mean of 427 kg ha^{-1} using 2000 weather data without fertilizer application. The model was sensitive to all input parameters. Soil texture and organic carbon were identified to have significant effect on crop yield. Soil organic carbon is, therefore, to be managed for the development of a good tilth and hence sustainable yields of sorghum at the study site.

Original scientific paper. Received 19 Sept 17, reviewed 10 May 18

Introduction

In the Sudan savannah zone of Ghana, sorghum (Sorghum bicolor (L) Moench) is an important food staple and raw material in the local brewery industry. The yield of this crop, however, has been on a continuous decline over the past decades (Braimoh & Vlek, 2005). This has been attributed to the erratic nature of rainfall that characterises the area and low soil fertility. The farming system in the area is characterised by low input system. In time past, the fertility of the fields were maintained or restored by leaving fields to fallow over several years. This practice is no longer effective due to an increasing pressure on land expansion for food production and other demands.

The concept of geo-statistics and crop modelling was employed in this study to access the relationship between soil properties and grain yield. To achieve this, spatial variation in both soil parameters and grain yield were exploited.

Crop yield has been explained to be a function of a host of factors, including soil properties, field topography, climate, biological factors, and management. Soil spatial variability (i.e heterogeneity) resulting from inherent soil properties and differential management practices is also known to be a major contributor to variability in crop yield. In certain years as much as 85% of the yield variability can be explained by a combination of soil properties and topographic features (Yang *et al*., 1998; Jiang & Thelen 2004).

The variation in crop yield over space has been documented by many researchers for several crops. Casanova *et al*., (1999) reported on rice yield variations due to variations in soil properties. Analysis of spatial and temporal trends from yield map data for cereals was also studied by Blackmore *et al.,* (2003). Stewart *et al*., (2002) studied the relationship between the quality of durum wheat and soil factors using interpolated data on soil and wheat properties to illustrate their variation in space.

To assess the distribution of grain yield in the study area, a crop simulation model; Agricultural Production Systems sIMulator (APSIM), was used. The model was calibrated and evaluated for the study site in an earlier study (MacCarthy *et al.,* 2009). Crop simulation models (CSM) have the potential of estimating crop yield based on input data. One of the main goals of crop simulation models is to estimate agricultural production as a function of weather and soil conditions as well as crop management (Hoogenboom, 2000). Data on soils, weather, crop, management practices were used to simulate crop yield and other soil processes.

Considering the low crop yield and limited ability of farmers to purchase fertilizers in the area, there is the need to identify soil parameters that are critical to crop production so as to manage them effectively to increase crop yield and improve efficiency of mineral fertilizer used. The objectives of this study were to: (i) assess the relationship between soil input parameters and grain yield (ii) identify most critical soil parameter for sorghum production.

Materials and Methods

Site description and data collection

The study was conducted at 5 km to the west of Navrongo which falls within the Sudan Savannah agro-ecological zone in Ghana, West Africa. The region is bordered by latitude 10° 15" and 11° 10" N and 0° 0" and 1° 45" W. The dominant soil types at the study site are eutric arenic and loamic protovertic, all in the uplands (WRB, 2015). Mean annual precipitation (15-years mean) is 731 mm

A landscape of 1.5 square kilometres was divided into square grids of 100 by 100 meters each by running parallel traverses each of a kilometre in length perpendicular to a baseline of 1.5 km making a total of 176 samples per depth. At each of the 176 vertex 5 soil samples were taken and bulked into one composite sample for each of the two depths (0-15 cm and 15-30 cm). The samples were thoroughly mixed, air dried and sieved prior to analysis. Soil samples were analysed for organic carbon (Walkley & Black, 1934), pH (1:2.5 C_aC_{l2}: Benton, 2012), available P (Bray 1), available K (0.5 M ammonium acetate), and CEC (summation of exchangeable cations- index cation method) and soil texture (percentage sand, silt and clay - Hydrometer method). Wilting point, field capacity, available water, and saturation were estimated parameters using a pedo-transfer function (Saxton *et al*., 1986). Soil data used (Table 1) were extracted from MacCarthy *et al.,* (2013).

Data analysis

Geo-statistical analysis. The spatial structure of the soil parameters were analysed using semi-variogram analysis with normalized data. A semi-variogram was calculated for each soil property (Journel & Huijbregts 1978; Isaaks & Srivastava, 1989):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[z(x_i + h) - z(x_i) \right]^2 \quad [1]$$

where γ(h) is the experimental semi-variogram value at a distance interval h; N(h) is number of sample value pairs within the distance interval h; $z(x_i)$ and $z(x_i+h)$ are sample values at two points separated by the distance h. The parameters of the best-fit empirical model were used to interpolate the respective soil parameters in space using ordinary kriging technique.

Soil parameter estimation and spatial yield analysis.

Agricultural Production Systems sIMulator (APSIM), a crop model calibrated and validated for the study area (MacCarthy *et al.*, 2009), was used to model grain yield at each grid point using weather data from 2000 and 2005. To model the spatial distribution of grain yield as a factor of soil parameters, point data (MacCarthy *et al.,* 2013) of measured soil parameters (SOC, pH, and soil texture (sand, silt and clay) were used to simulate the impact of soil parameters on yield. Data on soil wilting point, field capacity available water and saturation were generated using a pedo-transfer function (Saxton *et al.,* 1986) with the soil texture and SOC as input data. Two simulations were run, one with no inorganic fertilizer input, and the other with 40 and 30 kg ha^{-1} N and P inorganic fertilizers respectively. Simulated grain yield at point locations for 2005 weather data were then interpolated over the landscape to illustrate the spatial distribution of yield as affected by the input data.

Validation.

Maps of the various soil parameters were compared to the crop yield map constructed with values from the APSIM cropping system model. Secondly, data points from a number of experiments on sorghum yield response to N fertilization located in the landscape (details available in MacCarthy *et al.*, 2009) were used to validate the yield map using the root mean square error (RMSE) method.

Statistical analysis

Coefficient of variation (CV) was computed as an indicator of variability of soil properties. Pearson's correlation analysis was performed among soil properties. Factor analysis was then used to define groups of correlated variables. Two sets of data were used: (i) soil data from field survey (raw data: 2000 and 2005 yield estimates) and (ii) data extracted from geostatistical analysis of the raw data (processed data: 2005 yield estimate data). Principal component method of factor analysis was used. Factors were extracted using the principal component method and the quartimax (orthogonal rotation). Eigen values accounting for 90% of the variance were used in further analysis. Partial correlation coefficients, which are referred to as factor loadings were the basis for selecting variables from each factor. The new variables which are also known as latent variables represent underlying factors which are directly unobservable. A linear regression procedure was then used to analyse the relationship between the latent variables and sorghum grain yield. Grain yield was the independent variable and the latent variables were the dependent variables. The model was in the form $Y= b_0 + b_1L_1 + b_2L_2$, where Y is grain yield, b_0 is the intercept, b_1 and b_2 are coefficients and L_1 and L_2 are the latent variables.

Results and discussions

Conventional statistical analysis

An overview of the soil parameters analysed for the landscape is presented in Table 1. The mean values and variability of measured variables were different for the two sampling depths. The soils in the landscape are sandy loam, with a mean sand content of 69.8 and 64.9 percent in the top and sub–soils, respectively. The soil texture is largely influenced by the granitic parent material. The coefficient of variation was generally higher in the topsoil than the subsoil. The CV in the soil parameters ranged from 10 % to 89 % for the pH and available P respectively in the topsoil. In the subsoil, variability was from 13 % in pH and 67 % in CEC. The summary of the processed data is presented in Table 2. The data had lower CV compared to the raw data with a range from 2 – 27% for pH and soil organic carbon respectively.

TABLE 1

Descriptive statistics of top and subsoil parameters taken at grid scale

	(0 – 15 cm)				(15-30 cm)			
Parameter	Mean	Max	Min	CV(%)	Mean	Max	Min	CV(%)
pH	5.46±0.04	8.12	4.48	10	5.46±0.03	8.38	4.59	13
SOC (mg g^{-1})	4.00± 0.17	11.60	0.70	56	2.70±0.13	10.20	0.70	36
$P_{available}$ (mg kg^{-1})	6.32±0.42	44.20	0.93	89	5.90±0.40	31.40	1.10	65
$K_{available}$ ($mgkg^{-1}$)	73.6±2.91	230.00	8.22	52	71.50±1.96	165	29.10	35
CEC (cmol(+) kg^{-1}	4.94±0.22	21.40	1.51	60	6.30±0.25	35.20	2.05	67
Sand (%)	69.80±0.88	71.70	18.10	17	64.90±0.67	92.40	23.0	20
Silt (%)	23.30±0.71	63.60	3.50	36	24.0±0.70	63.0	0.2	42
Clay (%)	6.90±0.30	32.00	1.2	58	11.1±0.28	34.0	0.9	55

Source: MacCarthy et al., 2013

TABLE 2

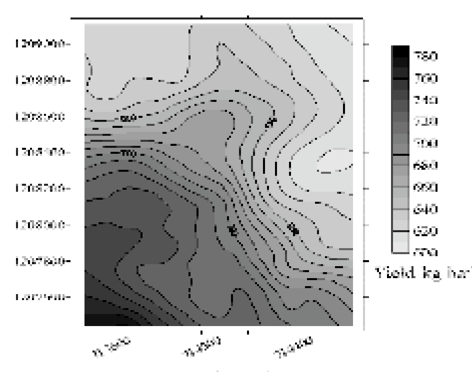
Descriptive statistics of selected soil (0-15 cm) processed data used in factor analysis procedure

Variable	*Mean*	*Maximum*	*Minimum*	*Std dev*	*CV*
pH	5.46±0.39	5.68	5.30	0.11	2
SOC (mg g^{-1})	4.01±0.17	6.30	2.20	1.10	27
Sand (%)	69.02±0.86	81.16	52.27	6.34	9
Silt (%)	24.08±0.70	34.05	15.08	4.76	19
Clay (%)	6.87±0.30	9.13	4.37	1.23	17

Simulated grain yield distribution on landscape

Sorghum grain yield as modelled with APSIM (using soil data from Table 1) ranged from 402 to 1092 kg ha^{-1} with an average grain yield of 673 kg ha^{-1} within the landscape when no fertilizers were applied (Fig. 1a) using 2005 weather parameters. Coefficient of variation in measured grain yield was 15. Applying 40 and 30 kg ha^{-1} N and P fertilizers, respectively improved sorghum grain yield to between 1314 to 3027 kg ha^{-1} with a mean of 2390 and a coefficient of variation of 14 % (Fig. 1b). The differences in variability of grain yield with and without mineral fertilizer application was rather small (1 %). This could imply that other factors (such as intensity of rains for nutrient mobility) may be influencing the effectiveness of mineral fertilizers.

(a)



(b)

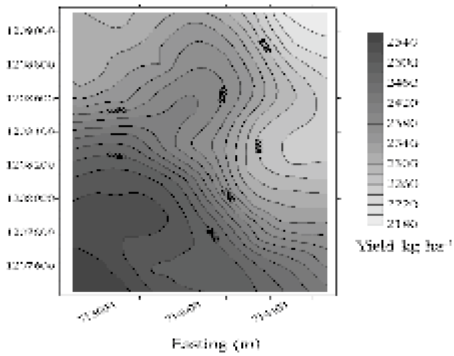


Fig. 1. Spatial distribution of sorghum grain yield in the selected landscape for 2005.
Yield expressed in kg ha^{-1}; x-axis is easting, y-axis is northing, a: simulations without fertilizer application, b: simulation with 40 and 30 kg ha^{-1} N and P (respectively) applied.

The pattern of grain yield distribution was similar to that of SOC (top soil), (comparing Figs. 1a and 1b with Fig. 2).

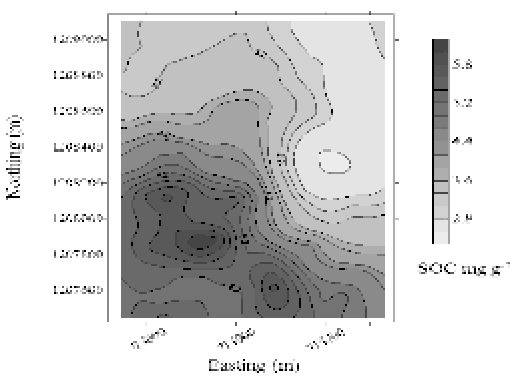


Fig. 2. Spatial distribution of soil organic carbon (SOC) in the selected landscape.
SOC is expressed in mg g^{-1}; x-axis is easting, y-axis is northing.

The model was sensitive to all input parameters as indicated by the Pearsons correlation coefficients (Table 3) with grain yield which range from 0.68 to 0.95. Soil organic carbon showed the strongest correlation with grain yield. Increasing sand content negatively influenced grain yield and could be probably due to its negative impact on soil water holding capacity (Wopereis *et al.*, 2006). Point data extracted from the spatial maps of all input parameters and grain yield (with no fertilizer application) were analysed using Pearson's correlation matrix (Table 3). Not accounted for in the yield maps were the interactions between points in 3-dimensional way, which take into account, for instance, runoff. The model nonetheless illustrates a grain yield pattern in smallholder farmers' fields with similar characteristics to those described by other authors (e.g. Prudencio, 1983; Defoer *et al.,* 2000; Wopereis *et al.,* 2006).

TABLE 3

Pearson's correlation matrix (for processed data used for factor analysis)

	SOC	*pH*	*Sand*	*Silt*	*Clay*	*Yield*
SOC	1	0.85***	-0.74***	0.68***	0.88***	0.95***
pH		1	-0.76***	0.76***	0.76***	0.82***
Sand			1	-0.96***	0.85***	-0.73***
Silt				1	0.79***	0.71***
Clay					1	0.85***
Yield						1

Significant level: *** (1%)

The release of nutrients from soil organic matter and the uptake of nutrient from soils are processes that are largely influenced by soil moisture and soil temperature. These processes are also affected by atmospheric temperature and rainfall. In sandy soils, nutrient loss by leaching is a critical issue and is aggravated by large rainfall amounts and intensities. The higher the rainfall amounts, the higher the potential to lose nutrients through leaching. The cumulative rainfall amount over the growth period for 2000 weather data was 747 mm compared with 538 mm for 2005 rainfall data (Fig. 3).

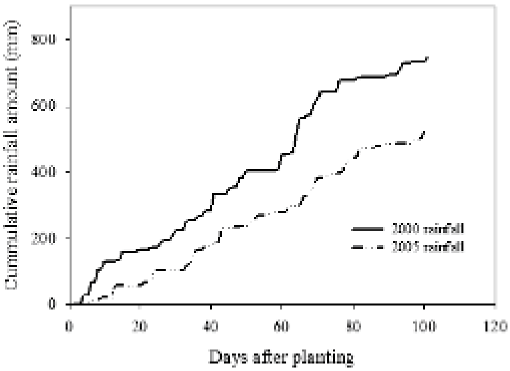


Fig. 3. Cumulative rainfall distribution for two years (2000 and 2005) using rainfall data for Navrongo in Upper East region of Ghana.

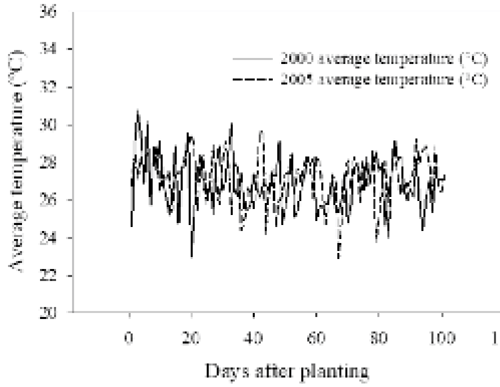


Fig. 4. Average temperature values for 2000 and 2005 during the growth duration of plants, using temperature data for Navrongo, Ghana

With rainfall data for 2000, an average of about 7.8 mm rainfall was received daily. With the 2005 rainfall data, about 5.4 mm of rainfall was received daily. Hence, the potential for nutrient loss through leaching is higher with the 2000 cumulative rainfall compared with 2005 rainfall amounts. Average temperatures for the two years during the growing season were, however, comparable (Fig. 4). The average temperatures were 26.9 ^{0}C and 27.1 ^{0}C, maximum temperatures were 30.8 ^{0}C and 29.7 ^{0}C for 2000 and 2005 weather data during the growth periods with both data respectively. Rainfall then, may be the factor controlling nutrient dynamics as baseline soil parameters, crop management practices (such as sowing density, time and quantity of fertilizer used) and air temperature data used for the two simulations are not significantly different.

Factor analysis using processed data

Groups of correlated variables for this study were defined using the principal component method of factor analysis, retaining variables that cumulatively contribute to 90 percent of the total variance. The first factor recorded an eigen value of 5.0 representing 84 percent of the total variance while factor 2 recorded an eigen value of 0.61 which represents 8.8 percent of the total variance. The two factors cumulatively explained 93 percent of the total variance. The succeeding eigen values cumulatively explained about 7 percent of the variance and were hence not considered for further analysis. The rotated factor loadings are presented in Table 4. The criteria used to select a particular variable are the absolute value of the coefficients and the relative difference in values in relation to the other variables in the factor. The latent variables that represent factor 1 (equations 2 and 3) are a complex variable representing soil structure. Percen-tage sand, silt, clay and SOC of the soils were the first four highest coefficients. Though sand content had the largest absolute coefficient in factor 1, its impact is negatively correlated to sorghum yield.

TABLE 4

Quartimax rotated factor loadings determined for soil parameters selected to create latent variables

Variable	*Processed data*		*Raw data*		
	Factor 1	*Factor 2*	*Factor 1*	*Factor 2*	*Factor 3*
	Coefficients				
SOC	0.89	0.46	0.43	0.96	0.20
pH	0.88	0.08	0.04	0.40	0.03
Sand	-0.96	-0.21	-0.91	-0.03	-0.02
Silt	0.93	0.32	0.99	0.04	0.01
Clay	0.94	0.14	0.30	-0.02	0.03
Eigenvalues	5.02	0.61	2.79	1.16	0.94
% of variance	84.2	8.8	55.6	21.4	12.68
*Cum %	84.2	93.0	55.6	77.1	89.8

*Cum: cumulative

Factor analysis revealed particle size distribution and soil organic carbon as critical variables that limit sorghum production in the study area. These parameters contribute to soil structure, hence the latent variable for factor one is soil structure. Factor two is dominated by soil organic carbon which is due to the fact that its coefficient is the largest in this factor. Table 5 presents the coefficients and statistics of models relating sorghum yield with the latent variables indicated in Equations 2 and 3.

Yield = 672.9 + 39.6 (factor 1) + 15.6 (factor 2) [2]

Yield = 672.9 + 39.6 (soil structure) + 15.6 (soil organic carbon) [3]

TABLE 5

Coefficients and statistics of multiple regression models relating grain yield with the latent variables identified for the study

	Coefficients	*Standard errors*	*T*	*Probability*
	Processed data for 2005 (R^2 = 0.90)			
Soil structure	40	0.166	239	0.00
Soil organic carbon	16	0.166	94	0.00
Intercept	673	0.166	4065	0.00
		Raw data		
		2005 (R^2 = 0.98)		
Soil structure	17	1.10	44	0.02
Soil organic carbon	98	1.10	158	0.01
Soil organic carbon	18	1.10	163	0.06
Intercept	673	1.09	616	0.00
		2000 (R^2 = 0.92)		
Soil structure	94	2.11	54	0.04
Soil organic carbon	21	2.11	98	0.03
Soil organic carbon	16	2.11	34	0.00
Intercept	459	2.10	616	0.00

Factor analysis using raw data

As in the earlier analysis, factors explaining up to 90 % or more of the total variance were extracted. This resulted in three factors. Factor 1 explained about 56% of the total variance and together with factor 2, 77 percent of the variance was explained (Table 4). Using the 3 factors extracted in a regression analysis resulted in a regression coefficient (R^2) of 0.92 and 0.98 with 2000 and 2005 weather data respectively. However, only the coefficient for factor 3 was significant ($p = 0.001$) in the linear regression in both years. It was easier to identify latent variables from the analysis using processed data than when the raw data was used. Although yield statistics for 2000 and 2005 differ significantly, the results of the regression analysis using yield data from the two years were similar (Table 5). The most dominant variable in factor 3 which was significant in the regression model is soil organic carbon using data from each of the two years.

General discussion

The processed data produced clearer relationship between grain yield and the soil parameters than using raw data. This may be attributed to the lower CV observed in the variables in the processed data. Soil organic carbon and soil texture (clay and sand) were the two critical parameters identified in this study to have highly influenced sorghum yield. The importance of SOC and clay content has been reported in other studies (Wopereis *et al*., 2006; Zingore *et al.,* 2007; MacCarthy *et al.,* 2009) and has been attributed to their remarkable influence on the CEC and water holding capacity of soils. Clay content of soils, however, cannot be improved significantly through management practices except to reduce its further loss. SOC, however, can be manipulated through management practices such as green manure and compost application among others. Hence SOC is the parameter that may be targeted to help improve yield of sorghum on smallholder farms in the study area. It is important to indicate however, that a cause-effect relationship cannot be drawn directly from these models (Equations 2 and 3) but rather they can be used to derive reasons for yield variations. These then can be used to design management strategies to improve crop yields. The Sudan Savannah ecology is dominated by sandy soils. Particle size distribution is of utmost concern in terms of the water holding capacity of these soils. The SOC required to improve the water holding capacity were largely below critical levels needed to promote optimum crop yield (Landon, 1991).

Conclusion

Factor analysis and linear regression helped in identifying soil parameters that are critical for sorghum yield in the study area. Soil organic carbon showed the highest correlation with grain yield. Particle size distribution, thus sand, silt and clay content as well as soil organic carbon were identified to have significant influence on sorghum yield. Out of these parameters, only SOC can be significantly manipulated to increase crop yield on poor sandy soils. Factor analysis enabled us to identify soil parameters that are critical for sorghum production in the study area. Fertilizer application increased sorghum yield but did not impact on the spatial variations in yield. Temporal variations in grain yield due to differences in weather parameters were significant.

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