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Spatial Analysis of Soil Fertility Using Geographical Information Systems Technology

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Abstract

The research evaluated soil fertility condition of River Otamiri watershed in southeastern Nigeria in relation to topographic heterogeneity using GIS technique. GPS was used to determine the geodetic coordinate of the sampling points and site elevation. Soil samples were collected and analyzed using standard soil analysis method to determine major soil fertility parameters including soil pH, organic carbon, effective cation exchange capacity, soil particles distribution, total nitrogen and available phosphorus. These parameters were evaluated and spatially interpolated to determine its variation along topographic positions using ArcView 3.2a. The results showed that the area is dominated by sandy soil with a little percentage of clay and silt. The area is acidic with pH as 4.67 – 5.6 for the upper and lower layers and5.6 – 5.5 at crest and valley bottom and lower at the midslope. The study also showed low organic carbon [0.118 – 1.735%], *ECEC [0.676 – 3.764 meq/100g for upper soil layer, 5.34 – 4.27 meq/100g for lower soil layer and lower at the midslope], low total nitrogen concentration range of 0.008 – 0.068% and 0.018 – 0.048% for upper and lower soil layers. Total nitrogen decreased with depth. This suggests that the fertility condition of the soil may not support crops that do not survive in acidic soil. Hence, to widen the range of species that can be planted in this watershed, proper management practices to maximize nutrient cycling and nutrient use efficiency should be employed.*

Key words: soil fertility, site elevation, geographic information system, soil parameters, watershed, spatial analysis

Introduction

Farmers in Nigeria, and elsewhere, have always struggled with the availability of information about the soil. Without these information and guidance, the agricultural sector faces a lot of wastage and decrease in profit margin (Shephard and Soule, 1998). In southeastern Nigeria, as elsewhere, soil fertility is of critical importance and significantly affects the value and productivity of a parcel of land. One problem associated with watersheds in the region especially when it is within human habitats is loss of soil fertility. There has been uncertainty over the fertility status of soils around the Otamiri River watershed (Ushie et al, 2005 and Matthews-Njoku and Onweremadu, 2007). Also, Onweremadu et al (2008) believed that activities around the watershed, namely, mining and exploitation of sand and gravel and farming, have affected the soil fertility. The focus of this paper is to investigate the soil fertility condition paying attention to the soil characteristics and soil fertility properties. The study expect to identify soil nutrients concentration at different points and depths in the watershed, soil physical and chemical properties of the watershed, map the soil properties of the selected area and assess the soil fertility properties of the watershed using GIS.

Description of the Study Area

This study was conducted within the River Otamiri watershed covering about 262.5km^2 and lying between latitudes 5^{0}22”52’N and 5^{0}23” 54.16’N and longitudes 5^{0}59”34.4’E and 6^0 59” 18.68” E.

The soils of study area, mainly ferralsols, are generally, derived from coastal plain sands (known as Benin formation) of the oligocene-miocene era. The ochrosols variety has iron concretions, while the oxysols variety does not have concretions developed essentially on sedimentary rocks (Areola, 1983). The soils, deeply weathered, are red and yellowish brown posses abundant free iron oxides. According to Areola (1983) in southeastern Nigeria, the predominant loose sandy soils have completely broken down structurally due to over-cultivation. From the hill summits and slopes, the soils have been washed away leaving fragments of degraded laterite crusts strewn all over the land surface. It is within the humid tropics, characterized by an annual rainfall range of 2250-3500mm. Daily temperature are generally high with a mean of 27^0C in all seasons.

Depleted rainforest vegetation dominates the site which has a sloping topography. The slopes have southwest orientation and run into the River Otamiri in Owerri West Local Government Area of Imo State in southeastern Nigeria. Little arable farming is practiced on this landscape due to fragility of soil, although population presence is gradually impacting on it (Ajayi et al, 2003 and Onweremadu, 2007).

Materials and Methods

Reconnaissance survey was carried out and the sampling sites were geo-referenced using a handheld Global Positioning System (GPS) Receiver. The geo-referencing focused on 3-dimensional measurement (that is, latitude, longitude and altitude).

On the sampling sites, 3 transects (representing 3 physiographic units of the site, namely crest, midslope and valley bottom) 100m apart, made of 3 points (A, B, C for crest) each, dug to 2 depths (0-15 and 16-30cm) where sampled to give a total of 18 soil samples (Tables 1, 2 and Figure 1).

The soil auger used for the collection was marked at depth with the aid of a nail and a meter rule. This was inserted into the ground by turning in a clockwise direction until the marked depth was reached. It was then pulled upward to remove the soil. The soil at the tip of the auger was collected into a zip lock plastic bag and represents the soil at the depth. The bagged samples were taken to the laboratory of the Federal University of Technology, Owerri where they were air-dried and sieved using 2mm sieve in readiness for laboratory analysis. The test involved determination of the soil pH, soil mechanics, organic carbon, calcium and magnesium, exchangeable bases (Na+ and K+), exchangeable acidity, phosphorus and total nitrogen,

The effects of physiography (crest, midslope and valley bottom) and depth (0-15cm and 16-30cm) on fertility parameters were analyzed using GIS technique. The coordinates of sampling points were converted to meters and used to spatially geo-reference the area and build digital elevation model as shown in Figure 1. The database was then imported into an ArcView 3.2a GIS Software for the analysis which interpolates grid on inverse distance weight and the data was presented in a spatial format.

Result and Discussion

From the basic standard soil analysis performed, various distinct modifications on soil fertility parameters were observed. Topographic variation appears to lead to compositional heterogeneity within the study area enabling the occurrence of variation in soil fertility condition. The experimental variation in various soil parameters along the topographic positions were illustrated on Table 3, 4 and5.

At both depths, the soil is generally sandy. Sandiness decreases down slope and silt size and clay size fraction increases towards the valley bottom for both soil depths. Generally, sand size fraction followed by clay fraction dominates the study area at both depths (see Tables 3 and 4). This is attributed to parent material and climate of the study area as presented in Brandy et al, (1999).

Clay and silt percentage are higher at the valley bottom suggesting that both sizes are easily transported from summits to depressions. This could be to their smaller and lighter nature when compared with heavier sand size fraction. These are illustrated on Figures 3 and 4.

Variation of pH with topographic position is illustrated in Figure 4 and 5 for upper and lower soil layers respectively. At both depths and along the slope, the pH ranges from 4.67 –5.62 as indicated in Tables 1 and 2. Within the crest the pH is strongly (5.0-5.5) and become very strongly acidic (4.5-5.0) at the mid slope. The soil pH is subsequently increased at the lower landscape (valley bottom).

Higher pH at the crest is attributed to cropping history and parent material while low pH at the midslope is attributed to leaching of cations (which provide the OH^-ions). Eventually all the Ca^+ and Mg^+ etc are replaced by Al^{3+} and H^+. At crest, leaching is minimal and concentration of base cations (Ca^+, Ma^+ and Na^+) on the exchange complex is large. Increase in soil pH at the bottom valley is linked to high ECEC and clay fraction.

Effective cation exchange capacity concentration ranges from 0.676-3.764meq/100g in the upper soil layer and 534-4.274meq/100g in the lower soil layer. Its variation along the slope is illustrated for upper and lower soil layers respectively. Higher ECEC concentration was noticed at the crest and

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valley bottom and lower at the midslope, suggesting higher concentration of organic carbon and clay fraction at the crest and valley bottom and low at the midslope. Low ECEC at the midslope is attributed to low pH as ECEC decreases with acidification (Igwe et al, 1995)

The spatial variation of organic carbon content along the topographic positions at both upper and lower layers of the study area were also revealed.In the upper layer of the soil, organic carbon is highest at the crest and decreases along the slope with little increase at the valley bottom. Decrease at the midslope is attributed to low soil pH and to low total organic carbon value and this agrees with the findings of Stephenson (1994), possibly, due to low organic matter decomposer on acidic soil. Subsequent increase in organic carbon percentage at some points in the valley bottom is due to high pH and transportation of organic compounds from the crest to the valley bottom. This increase can also be attributed to high clay particles fraction suggesting clay as a primary variable in controlling the variability of soil organic carbon.

Total nitrogen concentration range of 0.008 to 0.068% and 0.018-0.048% for upper and lower soil layers was revealed. The study also showed that total nitrogen decreases with depth. It is observable that total nitrogen is highest at the crest and decreases down the slope. This is attributed to high organic carbon. Total nitrogen decrease at the midslope is attributed to leaching erosion and runoff. Nitrogen is always present in soil solution and will move with soil water [See Figure 5].

Lower total nitrogen at the valley bottom is suggested to be as a result of high pH and denitrification, while high pH stimulates nitrogen volatilization.

Available phosphorus concentration ranges from 12.9 –25.2ppm and 8.4-19.6 ppm for upper and lower soil layer respectively. From Figure 6, it is observable that available phosphorus decreases down the slope showing marked increase at the valley bottom. This increase is attributed to high clay particle fraction because most fine to medium texture soils has large capacity to hold phosphorus by absorption and precipitation. According to Mclean,(1982) this may also be as a result of higher pH which is within the range ±5.5-7.5.Decrease at the midslope is attributed to low pH which promotes fixing of inorganic phosphorus with positive ions such as Al^{3+} to form aluminum phosphate. The decrease can also be associated with soil erosion as phosphorus is closely attached to soil material.

The study reveals that the soil of the study area is acidic with the pH range of 4.67 –5.67 at both soil depths (0-15cm and 16-30cm). Generally the soil is sandy with low organic carbon (0.118-1.735%), low ECEC (0.604-4.224) and low total nitrogen and available phosphorus.

The result also shows decrease in value of organic carbon, total nitrogen and available phosphorus with depth. The result also indicates decrease in value of all soil fertility parameters tested for, at the midslope.

Conclusion

This study revealed the soil fertility condition of the River Otamiri watershed and presented soil fertility parameter variations with topographical heterogeneity. The results further showed that the study area has low nutrient values at all topographic positions and more at the midslope. These properties are attributed to climate, vegetation, parent material, leaching, run-off and soil erosion. The results also revealed that the soil is dominated by sand, and acidic at all points with pH higher at the crest and valley bottom. Based on these observations, the fertility condition of the soil can only support crops that require minerals and nutrients that are soluble and available in an acidic soil and suitable for plants with long taproot (Uzoho and Oti, 2005). Such plants include azalea, rhododendron, blue berries, white potatoes, tomato, carrot, and conifer tress, etc.

The inability of some crops to thrive comfortably in this area is attributed to low pH which is one factor that affects other soil fertility parameters and properties such as solubility of minerals, nutrients, activity of microorganisms. It inhibits organic matter break down and results to accumulation of organic matter as well as the tie up of nutrients particularly nitrogen that are held in organic matter. This soil fertility condition is attributed to leading, runoff, soil erosion, soil structure, climate, and parent material. To salvage the situation resulting from nutrient loss, proper management practices to maximize nutrient cycling and nutrient use efficiency should be adopted.

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Table 1: Details of the Study Site

Sampling Point	Proximity to the River (m)	Elevation(m)
Crest		
A	210	58
B	210	57
C	210	59
Mid slope		
D	110	47
E	110	46
F	110	47
Valley Bottom		
G	10	39
H	10	38
L	10	39

Table 2: Sampling points, topographic features and coordinates

Sampling Points	Elevation(m)	Latitude	Longitude
A	58	$5^0$22”51.52’N	$6^0$59” 34.04’E
B	57	$5^0$22”51.30’N	$6^0$59”24.82’ E
C	59	$5^0$22”51.33’N	$6^0$59”16.28’ E
D	47	$5^0$23”4.86’N	$6^0$59”33.77’ E
E	46	$5^0$23”4.67’N	$6^0$59”24.64’ E
F	47	$5^0$23”4.96’N	$6^0$59”16.37’ E
G	39	$5^0$23”16.50’N	$6^0$59”33.68’ E
H	38	$5^0$23”16.56’N	$6^0$59”25.15’ E
I	39	$5^0$23”16.48’N	$6^0$59”16.68’ E

Table 3: Characterization of upper layer soil of the study area (0 - 15cm)

Sampling points	Organic Carbon (%)	PH (H_2o	Sand %	Silt %	Clay %	Total Nitrogen (%)	Available Phosphorus (PPM)	ECEC (meq/100g)
Crest								
A1	1.207	5.04	93.7	3.3	3.0	0.058	22.4	1.054
B1	1.735	4.99	91.7	3.3	5.0	0.068	25.2	3.764
C1	1.257	5.11	97.7	1.3	1.0	0.059	16.1	3.554
Midslope								
D1	0.958	4.98	95.7	0.3	4.0	0.030	14.0	1.604
E1	0.998	5.13	91.8	3.2	5.0	0.024	16.1	0.904
F1	0.599	4.94	87.7	3.3	9.0	0.019	12.9	0.676
Valley Bottom								
G1	0.608	5.55	87.7	3.3	9.0	0.11	17.9	2.883
H1	0.189	5.31	85.7	7.3	7.0	0.008	18.4	1.954
I1	1.037	5.47	89.2	4.8	6.0	0.032	13.3	2.444

ECEC=effective cation exchange capacity and ppp=parts per million

Table 4: Characterization of Lower Layer Soil of the Study (16-30cm)

Sampling points	Organic Carbon(%)	PH (H_2o	Sand %	Silt %	Clay %	Total Nitrogen(%)	Available Phosphorus (PPM)	ECEC (meq/100g)
Crest								
A2	0.938	5.08	95.7	2.0	3.0	0.028	18.9	1.383
B2	1.337	4.67	87.7	9.0	5.0	0.048	19.6	4.274
C2	0.818	5.02	98.7	0.3	1.0	0.024	13.3	1.094
Midslope								
D2	0.618	5.45	89.2	1.8	9.0	0.020	8.4	0.534
E2	0.459	5.95	89.2	4.8	6.0	0.018	11.9	0.645
F2	0.898	4.70	91.7	3.3	5.0	0.024	14.7	1.175
Valley Bottom								
G2	0.359	5.45	83.7	4.2	12.0	0.014	16.8	1.296
H2	0.118	5.33	85.7	5.3	9.0	0.015	17.5	0.875
I2	1.638	5.62	83.7	5.3	11.0	0.021	13.6	1.304

ECE C=effective cation exchange capacity, ppm=parts per million

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Figure 5: Chemical properties of soil samples from the study area

Horizon / Sample	Depth (cm)	O.C (%)	pH (H_2O)	TN (%)	Av.P (ppm)	Ca (meq/100g)	Mg (meq/100g)	K (meq/100g)	Na (meq/100g)	ECEC (meq/100g)	Ca/Mg	Al (meq/100g)
Crest												
A1	0 - 15	1.207	5.04	0.058	22.4	0.4	0.17	0.002	0.032	1.054	2.35	Trace
A2	16 - 30	0.938	5.08	0.028	18.9	0.6	0.25	0.001	0.032	1.383	2.4	Trace
B1	0 - 15	1.736	4.99	0.068	25.2	2.5	0.83	0.002	0.032	3.764	3.01	0.34
B2	16 - 30	1.337	4.67	0.048	19.6	2.7	1	0.001	0.023	4.274	2.7	Trace
C1	0 - 15	1.257	5.11	0.059	16.1	2.6	0.67	0.002	0.032	3.554	3.88	Trace
C2	16 - 30	0.818	5.02	0.024	13.3	0.47	0.18	0.001	0.023	1.074	2.61	Trace
MEAN		1.2155		0.0475	19.25	1.545	0.516667	0.0015	0.029	2.517	2.83	
MIDSLOPE												
D1	0 - 15	0.958	4.98	0.03	14	0.8	0.33	0.001	0.023	1.604	2.43	Trace
D2	16 - 30	0.618	4.97	0.02	8.4	0.18	0.08	0.0008	0.023	0.534	2.25	0.27
E1	0 - 15	0.998	5.13	0.024	16.1	0.26	0.07	0.001	0.023	1.204	3.72	Trace
E2	16 - 30	0.459	4.95	0.018	11.9	0.17	0.05	0.0002	0.023	0.643	3.4	Trace
F1	0 - 15	0.599	4.94	0.019	12.9	0.08	0.03	0.001	0.015	0.676	2.67	Trace
F2	16 - 30	0.898	4.7	0.024	14.7	0.42	0.13	0.0002	0.023	1.173	3.23	Trace
MEAN		0.755		0.0225	13	0.318333	0.115	0.0007	0.021667	0.972	2.95	

FOOTSLOPE

G1	0 - 15	0.608	5.52	0.011	11.9	1.7	1	0.001	0.032	2.883	1.7	Trace
G2	16 - 30	0.359	5.45	0.014	9.8	0.8	0.33	0.0009	0.015	1.296	2.43	Trace
H1	0 - 15	0.189	5.31	0.008	8.4	0.49	0.18	0.002	0.032	0.954	2.72	Trace
H2	16 - 30	0.118	5.33	0.015	10.5	0.42	0.13	0.002	0.023	0.875	3.23	0.35
I1	0 - 15	1.037	5.47	0.032	13.3	1.6	0.67	0.0009	0.023	0.964	2.39	Trace
I2	16 - 30	0.638	5.62	0.021	12.6	0.8	0.33	0.0009	0.023	1.304	2.43	Trace
MEAN		0.4915		0.016833	11.08	0.968333	0.44	0.001283	0.024667	1.379	2.48	

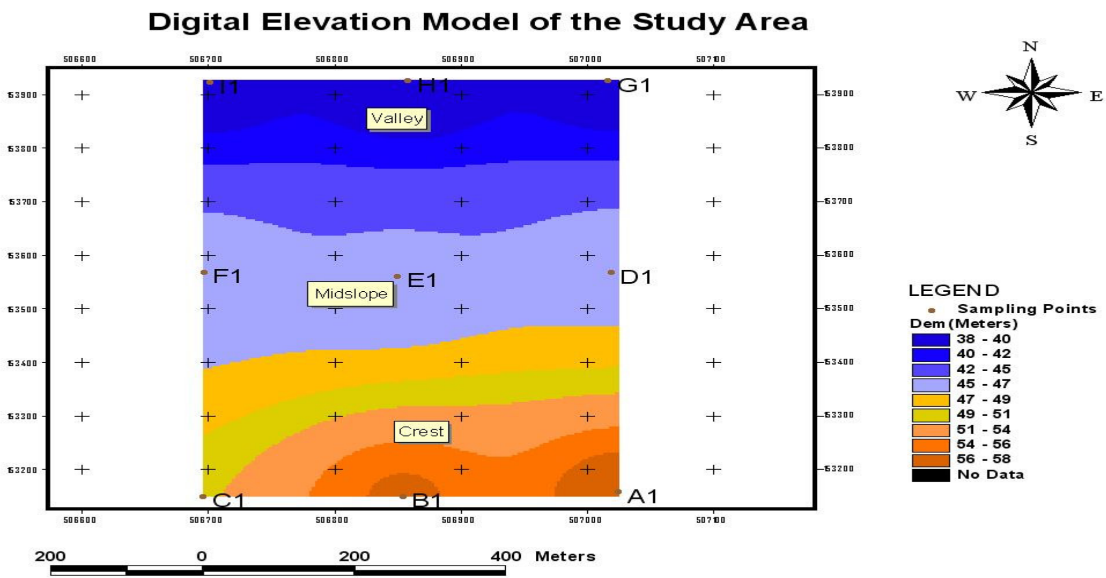


Figure 1: Digital Elevation Model of study area.

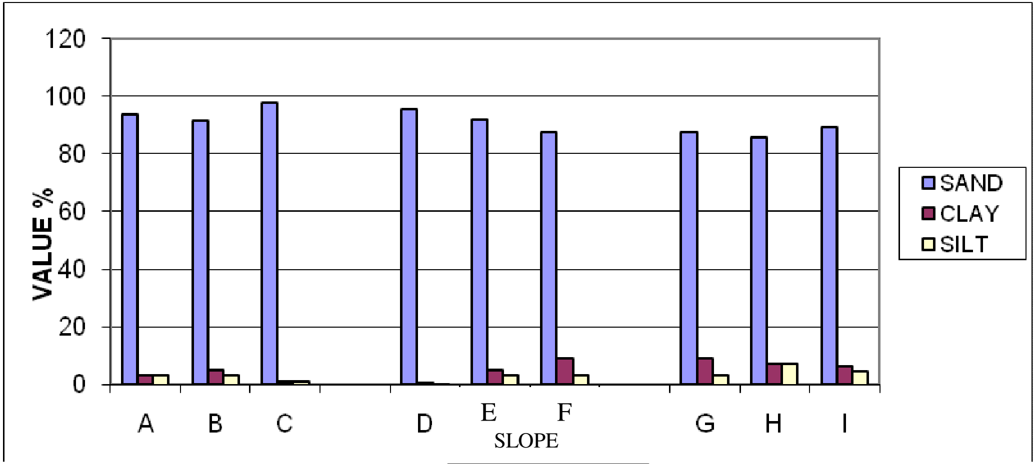
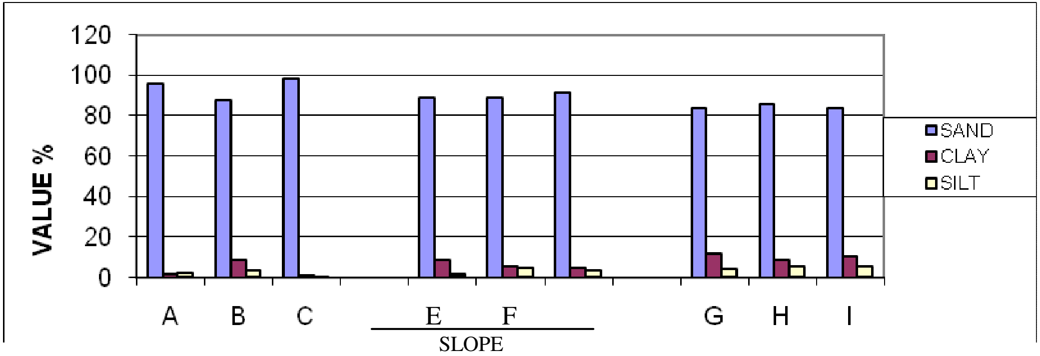


Figure 2: Variation of soil texture along the slope (0 – 15cm)

Figure 3: Variation of soil texture along the slope (16 – 30cm)



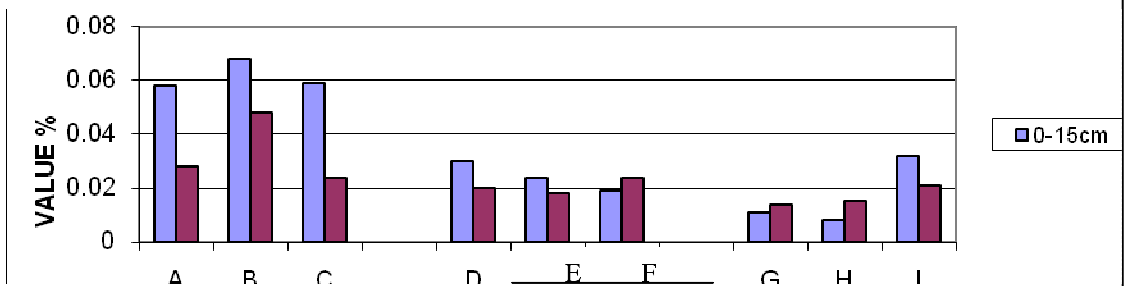


Fig 4: Soil total nitrogen variation

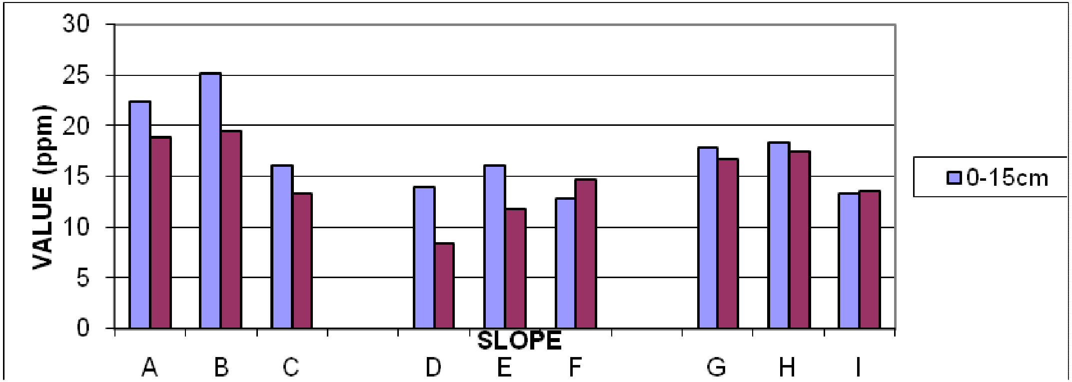


Figure 6: Soil available phosphorus variation of study area.