American Academic Scientific Research Journal for Engineering, Technology, and Sciences
ISSN (Print) 2313-4410, ISSN (Online) 2313-4402
https://asrjetsjournal.org/index.php/American_Scientific_Journal/index

Total Nutrient Element Status of Subsistence Agriculture Soils in Angola

Lídia P. de S. Teixeira[a]*, Ian A. Simpson[b]

[a]School of Biological and Environmental Sciences, University of Stirling, Stirling FK9 4LA, Scotland, UK
[b]Archaeology Department, Durham University, Durham DH1 3LE, UK
[a]Email: sousateixeira@hotmail.com
[b]Email: ian.simpson@durham.ac.uk

Abstract

Soil nutrient status in subsistence agricultural soils of Angola is poorly understood yet is vital in planning support and development of agricultural systems. This paper establishes the total nutrient status for two contrasting subsistence agricultural areas in Angola, within Huambo and Luanda provinces. Based on the World Reference Base for Soil Resources criteria (IUSS Working Group WRB, 2015, 2022) four soil catenas in each of Huambo and Luanda Provinces are classified as haplic Ferralsols and eutric Cambisols respectively. Mean and range total nutrient element values for twelve elements are determined (N, Ca, K, Mg, Mn, P, S, Zn, Cu, Mo, Fe, Al) with the results showing high variability and indicating that the haplic Ferralsols are below sub-Saharan averages for these elements while the eutric Cambisols are above these averages. Statistical analyses of relationships between soil nutrients and landscape factors by applying ANCOVA and pairwise comparisons using Tukey and Bonferroni tests indicate that underlying parent material has the biggest influence on element concentrations, further modified by slope processes; profile pedogenesis has had minimal contribution to element variances. Our findings highlight the need for detailed local analyses when planning supportive and effective nutrient management interventions.

Keywords: Soil nutrients; nutrient variances; landscape relationships; Ferralsols; Cambisols.

1. Introduction

Soils are an essential natural resource making major contribution to human well-being by providing important ecosystem services that includes vital nutrient elements for plant growth [1, 2]. Nutrients and their chemical and biological interactions in the soil form the basis for development and yield of agricultural crops, with knowledge of nutrient status in soils essential for assessment of soil quality leading to the practice of sustainable agriculture and influencing human, animal, and soil health [3].

Received: 3/9/2024
Accepted: 5/9/2024
Published: 5/19/2024
----

* Corresponding author.

Determining the amounts of nutrient elements in soil generates information about soil fertility and agricultural management potential. In the developing countries of sub-Saharan Africa knowledge of soil nutrient status is well recognised as an important tool in land assessment and endeavours to increase the success and sustainability of crop production [4]. Angola is no exception where satisfying basic food needs as environment changes requires development of new policies in the agricultural sector and, as a foundation for this, better understanding of the patterns and dynamics of nutrient variation in agricultural soils. This is particularly the case in systems of subsistence agriculture where nutrient status is poorly understood.

In light of these imperatives, our research aim is to create new knowledge on the status of total soil nutrient elements in two contrasting but intensively cultivated small-farm subsistence regions in Angola - within Huambo and Luanda Provinces [5]. Focused on four representative catenas in each of these provinces, our first objective is to characterise and classify the soils of these localities based on the FAO World Reference Base for Soil Resources field and laboratory criteria [6, 7]. From this foundation, our second objective is to assess total levels of macro- and micro- nutrients, acidity (pH) with depth in profile and across the four catenary sequences in each of the two regions, indicating total nutrient elements reserves. To give context to these analyses the findings are compared with similar studies from sub-Saharan Africa, placing the Angola analyses on a continuum of nutrient element levels across sub-Saharan Africa [2, 4, 8, 9]. Our third objective is to assess the relationships between nutrient levels and landscape factors that includes site, position within the catena and profile depth. This offers a way of explaining, and potentially predicting, the distributions of soil elements within the Angolan landscape. Together, the analyses embedded within the aim and objectives of the research indicate nutrient reserves and potential of two important subsistence agricultural regions in Angola and give foundations and base lines for planning future land management that recognises regional and local variabilities.

2. Materials and Methods

2.1 Study areas

Huambo Province, Angola, is located in the highland central region of Angola, 450km southeast of the capital Luanda and is in the tropical climate zone with a rainy and a dry season (Köppen, Cwb) (Figure 1). The rainy season generally lasts eight months with the possibility of rain starting in September and ending in mid-May. The average annual precipitation ranges from ca. 1200 mm to 1500 mm with an average annual temperature between ca. 22°C and 24°C. The province is one of the richest agricultural in the country and in recent years (since the end of the civil war in 2002) agricultural land use extent is amongst the fastest increases in the country. More than 50% of the population works in agricultural production, with 85% of this group working in subsistence agriculture using rudimentary production tools [10]. The main crops are maize and millet/sorghum, following by beans, sweet potatoes, and coffee.

Luanda Province, Angola, is located in lowland Angola, around Luanda, the country's capital and largest city and with the Atlantic coast forming its western boundary (Figure 2). It has a hot semi-desert climate (Köppen, Bsh) with a mean temperature of ca. 25.4°C and a yearly precipitation of ca. 387mm but with high variability. It is the richest and most developed province in the nation, home to large industrial services, commercial centres and one of the largest agricultural centres in country (the Quiminha area, government owned and managed) created after the end of the civil war. Despite these developments rudimentary subsistence agriculture continues to predominate and supports a significant population. Agricultural activity is based on the production of cassava, bananas, and vegetables.

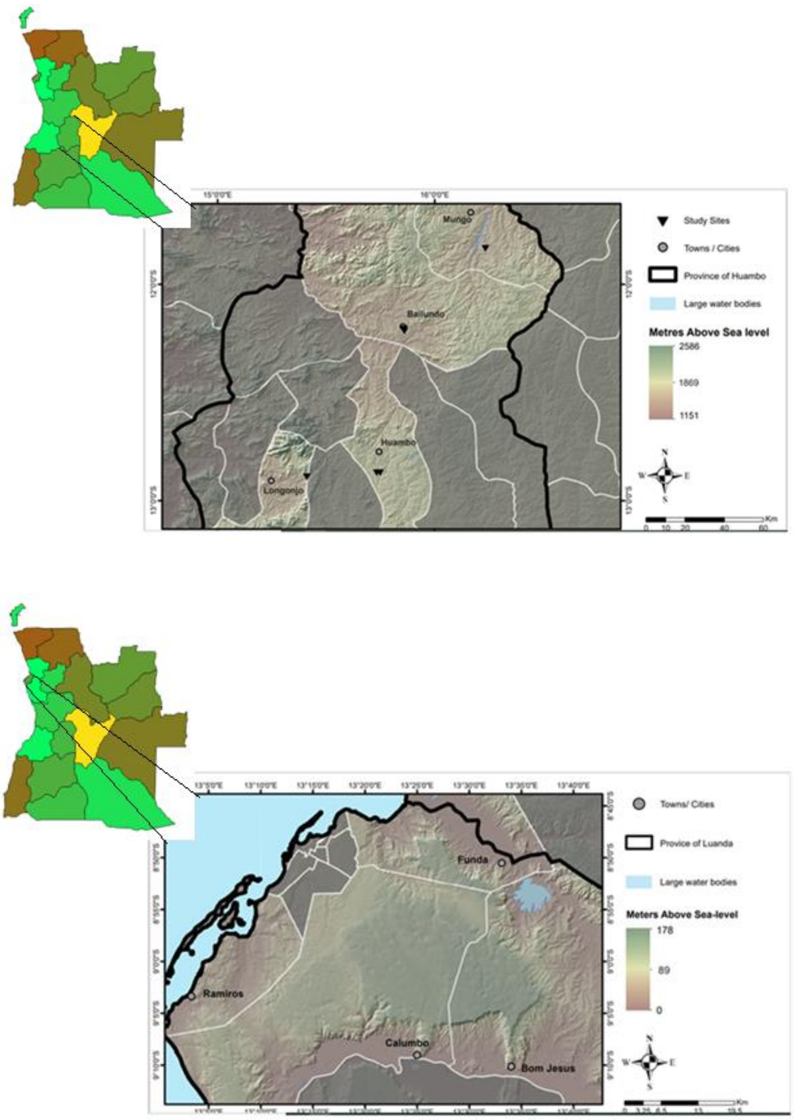


Figure 1: Study Provinces in their Angolan setting with location of study areas. a) Huambo Province - Bailundo, Lepi (Longonjo), Mungo and Ngongoinga; b) Luanda Province - Bom Jesus, Funda, Ramiro and Talelo (Calumbo)

2.2 Field Survey and sampling

Four representative localities within Huambo Province and four representative localities within Luanda Province were selected for sampling and analyses. The locations in Huambo Province were at Bailundo (12°11′45″S 15°51′20″E), Mungo (11°40′S 16°10′E), Ngongoinga (12°54′24″S 15°11′11″E) and Lepi (12°52′S 15°24′E) (Figure 1) in undulating moderately sloping topography. Locations in Luanda Province were at Talelo (08^{O}54'09'S 1322'20^{O}E), Funda (08°46′37″S 13°22′18″E, Bom Jesus (9°10′07″S 13°34′00″E) and Ramiros (9.0513°S 13.0192°E) on undulating, gently sloping topography. (Figure 2). The catenary sequences at each locality were typically 500m in length and three soils profiles assessed corresponded to upper, middle and lower areas of the catena. The twenty-four 1xx0.5x0.8m profiles, approximately to crop rooting depth, were hand-dug. Soil profiles were described in the field to give horizon definitions (A_1, A_2, and B) using Munsell Colour, texture class (including stoniness) and structure class. Bulk soils sample were systematically collected at 10cm intervals down the profile giving a total of 152 samples for analyses and undisturbed samples were collected in 8x5x5cm Kubiena tins from the A_2 horizon for micromorphological investigation.

2.3 Laboratory analyses

All analyses were undertaken at the Instrumentation and Micromorphology Laboratories, University of Stirling. For particle size distributions analyses air dried <2mm fraction samples were dispersed with sodium hexametaphosphate with four-hour agitation. Particle size fractions were determined by laser diffraction with a calibrated LS Coulter Counter (model (LS 230) on three replicate samples. Representative samples of undisturbed soils were collected from the A_2 horizon of each profile to enable assessment of weatherable minerals and clay pedofeatures for soil classification. Thin section manufacture following standard procedures of acetone replacement of water, resin impregnation and curing, mounting on a glass slide, slicing then lapping to 30µm thickness followed by petrological microscope assessment with description of features following international protocols [11, 12]. Further characterisation of mineral grains was undertaken by scanning electron microscopy (SEM/EDX), Zeiss EVO/MA15 operating under variable pressure (60 Pa). Slides were viewed using a backscatter detector with an accelerating voltage of 20 kV, a filament current of 2.542 A and a beam current of 100 µA with working distance of 8.5 mm to optimise EDX detector geometry Point counts were performed with a count time of 20 seconds with identified automatically using Zeiss Aztec software; element concentrations (wt %) for each analysis were normalised to 100%.

Air dried <2mm fraction samples for macro- and micro- element analyses were digested with HNO_3 and sealed heating with Sartorius brand Mars / CEM model microwave synthesis giving total extraction. Element determination with replicates was then undertaken by ICP-MS (iCAP 6000 series) to give ppm values. Nitrogen and carbon contents were analysed using a FlashSmart elemental analyser. Samples were samples combusted at 950^{0}C in oxygen with alumina and copper oxide catalyst and helium gas carrier. N and C were determined using a Multi-separation column (SS, 2m, 6x5mm. Part # 260 07920) at 50^{0}C with standards used to calculate percentage. pH measurement was undertaken in both H_2O and in $CaCl_2$ (0.125m) solution. pH values of suspensions were given by pH meter model 292 Pye Unicam. Exchangeable cations (CEC) of the top 20 cm within soil profiles were displaced by leaching soil within a solution of potassium chloride. In the leachate, exchangeable calcium and magnesium were determined by atomic absorption spectrometry and exchangeable acidity by nitration against standard sodium hydroxide solution. Determination of CEC and the related base saturation (BS) BS was undertaken on the 10 and 20 cm depth samples (A_1 horizon) based on the formulae CEC = Ca + Mg + H and BS = 100 (Ca + Mg)/CEC.

2.4 Statistical analyses

Through application of software jamovi version 2.3 debug, the macro- and micro- nutrient total levels data were subjected to descriptive statistical analysis to obtain the mean, maximum, minimum, median, and standard deviation, together with ANCOVA analyses and pairwise comparison using Tukey and Bonferroni tests. Due to limited degrees of freedom in the sampling design, interaction terms could not be fully evaluated; nonetheless, trends in the data by site, hillslope position and soil depth are identified. Statistical test results were assessed at 0.05 significance level.

3. Results and Discussion

3.1 Field survey and soil classification

The Soil Atlas of Africa [13] classifies the soils of Huambo Province as haplic and xanthic Ferralsols and soils within Luanda Province as predominantly chromic Luvisols with areas of eutric Cambisols and eutric Fluvisols [6, 7, 14]. Our observation of field and laboratory properties tests and refines these classifications giving a secure soil classification foundation for the assessment of total nutrient element status.

At Huambo, soil profiles (Table 1) typically comprise A_1, A_2 and B horizons with diffuse boundaries separated by Munsell hues that range from 7.5R through 7.5YR to 10YR, values ranging between 2 and 6, and chromas ranging from 1 to 8. Soils typically have reduced hue and chroma values in lower profiles of the catena. Field textures are silt loams and silty clay loams throughout the profiles and across the catenas with well-developed granular micro-aggregations. Clay content is relatively high, and down profile increases together with micromorphological evidence of clay accumulation as coatings and fills indicates clay mobilisation. Organic carbon content in the A_1 horizon is low, although can be as high as 5% at 10cm depth. Cation exchange capacities of A_1 horizons are low and range from 3.95 to 13.96 $cmol_c\ kg^{-1}\ clay^1$, while % base saturation is in general also low although with some high peaks. This reflects the high frequency of weathering resistant quartz and low frequencies (<10%) of more weatherable Ca- and Na- plagioclases and K- feldspars.

These observations are consistent with Ferralic horizon diagnostic criteria and a haplic Ferralsol soil classification across the Huambo study areas [6, 7]. There are however localised profile variations reflecting movement of clay through the profile and across the catena resulting in argic horizon attributes [15]. Munsell colour contrasts indicating redox reactions suggest that profiles lower in the catena have a greater soil wetness periodicity than those higher in the catena.

Table 1: Field and laboratory data sets for soil classification, Huambo Province

Soil Profile	Horizon	Depth (cm)	Munsell colour	Field Texture	Field Structure	Clay %	Silt %	Sand %	Organic carbon %	% Weatherable coarse minerals	Clay accumulation features	Base Saturation (%)	CEC $cmol_c$ kg^{-1} $clay^1$
Bailundo upper	A1	10	10YR 6/6	silty loam	Granular, well developed	17.38	81.13	1.0	1.4			43.88	7.13
		20	10YR 6/6			16.30	69.67	14.01	0.8			45.88	4.43
		30	10YR6/6			21.82	71.90	6.28	0.6			-	-
	A2	40	10YR 6/8	silty loam	Granular, well developed	31.42	68.59	0.01	0.4	(<10%), Quartz dominant	Coatings	-	-
		50	10YR 6/8			29.42	70.09	0.49	0.2	(<10%), Quartz dominant	Coatings	-	-
	B	60	10YR 5/8	silty loam	Granular, well developed	-	-	-	0.2			-	-
		70	10YR 5/8			-	-	-	-			-	
Bailundo middle	A1	10	10YR 6/8	silty loam	Granular, well developed	20.12	78.74	1.11	2.4			62.27	6.36
		20	10YR 6/8			11.11	75.3	13.58	1.7			71.23	5.56
		30	10YR 6/8			23.61	75.70	0.65	1.3			-	-
	A2	40	10YR 5/8	silty loam	Granular, well developed	24.09	75.11	0.80	1.6	(<10%), Quartz dominant	None observed	-	-
		50	10YR 5/8			21.20	76.83	1.98	0.8	(<10%), Quartz dominant	None Observed	-	-
	B	60	10YR 5/6	silty loam	Granular, well developed	29.82	70.17	0.00	1.1			-	-
		70	10YR 5/6			-	-	-	-			-	
Bailundo lower	A1	10	10YR 4/3	silty loam	Granular, well developed	12.93	76.59	10.49	0.9			56.44	7.35
		20	10YR 4/3			15.89	81.08	3.02	0.8			54.74	7.07
		30	10YR 5/4			16.29	80.13	3.56	0.3			-	-
	A2	40	10YR 5/4	silty loam	Granular, well developed	18.72	78.58	2.71	0.5	(<10%), Quartz dominant	Coatings, Fills	-	-
		50	10YR 4/4			18.19	69.82	11.98	0.2	(<10%), Quartz dominant	Coatings, Fills	-	-
	B	60	10YR 4/4	silty loam	Granular, well developed	18.55	72.92	8.52	0.0			-	-
		70	10YR 4/4			20.91	73.74	5.35	-			-	
Mungo upper	A1	10	7.5R 3/6	silty loam, silty clay loam	Granular, well developed	22.56	70.45	7.21	1.5			41.29	4.09
		20	7.5R 3/6			25.12	69.89	5.0	1.0			39.29	3.95
		30	7.5R 3/6			31.54	68.45	0.00	0.6			-	-
	A2	40	7.5R 3/8	silty loam, silty clay loam	Granular, well developed	30.77	69.16	0.4	0.4	(<10%), Quartz dominant	None observed	-	-
		50	7.5R 3/8			30.41	68.73	0.86	0.4	(<10%), Quartz dominant	None observed	-	-
	B	60	7.5R 3/8	silty loam, silty clay loam	Granular, well developed	-	-	-	-			-	
		70	7.5R 3/8			-	-	-	-			-	
Mungo middle	A1	10	7.5R 3/2	silty loam, silty clay loam	Granular, well developed	14.42	70.60	14.98	2.8			41.47	9.57
		20	7.5R 3/2			18.43	61.88	19.70	1.6			23.09	9.36
		30	7.5R 3/2			25.25	64.84	9.91	1.2			-	-
	A2	40	7.5R 3/6	silty loam	Granular well developed	31.78	67.71	0.51	0.9	(<10%), Quartz dominant	Coatings	-	-
		50	7.5R 3/6			30.69	69.31	0.00	1.1	(<10%), Quartz dominant	Coatings	-	-
	B	60	7.5R 3/6	silty loam	Granular, well developed	21.05	64.46	15.48	0.3			-	-
		70	7.5R 3/6			-	-	-	-			-	-
Mungo lower	A1	10	7.5YR 6/2	silty loam, silty clay loam	Granular, well developed	-	-	-	3.2			10.14	8.9
		20	7.5YR 6/2			-	-	-	4.6			42.68	13.96
		30	7.5YR 6/2			-	-	-	7.4			-	-
	A2	40	7.5YR 3/1	silty loam, silty clay loam	Granular, well developed	-	-	-	15.0	(<10%), Quartz dominant	Coatings	-	-
		50	7.5YR 3/1			-	-	-	3.7	(<10%), Quartz dominant	Coatings	-	-
	B	60	7.5YR 2/1	silty loam	Granular, well	-	-	-	5.5			-	-

		70	7.5YR 2/1		developed	-	-	-	-			-	-
		80	7.5YR 2/1			-	-	-	-			-	-
Lepi upper	A1	10	7.5 YR 4/3	silt loam	Granular, well developed	5.05	71.06	6.01	2.1			18.56	2.95
		20	7.5 YR 4/3			19.23	79.35	1.51	1.5	(<10%), Quartz dominant	Coatings, Fills	73.18	5.97
		30	7.5 YR 4/3			22.90	51.48	43,47	0.6	(<10%), Quartz dominant	Coatings, Fills	-	-
Lepi middle	A1	10	7.5YR 3/6	silt loam, slightly silt clay loam	Granular, well developed	29.74	66.60	0.02	1.1			23.51	5.23
		20	7.5YR 3/6			29.74	69.43	0.82	0.8	(<10%), Quartz dominant	Coatings	20.96	5.06
		30	7.5YR 3/6			33.38	70.34	29.74	0.4	(<10%), Quartz dominant	Coatings	-	-
Lepi lower	A1	10	7.5R 4/4	silt loam, silt clay loam	Granular, well developed	18.91	67.01	0.00	0.4			75.53	3.02
		20	7.5R 4/4			22.09	67.72	10.19	1.0	(<10%), Quartz dominant	Fills	27.94	7.77
		30	7.5R 4/4			32.99	58.41	22.71	-	(<10%), Quartz dominant	Fills	-	-
Ngongoinga upper	A1	10	10YR 5/3	silty loam, silty clay loam	Granular, well developed, subangular blocky	17.19	72.48	10.53	5.0			33.07	4.78
		20	10YR 5/3			26.92	72.02	1.05	1.1			32.1	7.07
		30	10YR 5/3			25.83	70.74	3.45	0.4			-	-
	A2	40	10YR 6/6	silty loam, silty clay loam	Granular, well developed, subangular blocky	29.46	70.43	0.09	0.3	(<10%), Quartz dominant	Coatings	-	-
		50	10YR 6/6			-	-	-	0.3	(<10%), Quartz dominant	Coatings	-	-
	B	60	10YR 6/6	silty loam, silty clay loam	Granular, well developed, subangular blocky	-	-	-	-			-	-
		70	10YR 6/16			-	-	-	-			-	-
Ngongoinga Middle	A1	10	10YR 5/3	silty loam	Granular, well developed, subangular blocky	16.12	68.34	15.55	0.9			18.03	5.86
		20	10YR 5/3			27.53	71.63	0.82	0.6			23.85	5.25
		30	10YR 5/3			26.65	73.09	0.24	0.5			-	-
	A2	40	10YR 6/4	silty loam	Granular, well developed, subangular blocky	32.75	67.25	0.00	0.4	(<10%), Quartz dominant	Coatings	-	-
		50	10YR 6/4			37.55	62.43	0.00	0.3	(<10%), Quartz dominant	Coatings	-	-
	B	60	10YR 6/6	silty loam	Granular, well developed, subangular blocky	-	-	-	0.2			-	-
		70	10YR 6/6			-	-	-	-				
Ngongoinga Lower	A1	10	10YR 4/1	silty loam, silty clay loam	Granular, well developed, subangular blocky	-	-	-	2.3			28.92	7.88
		20	10YR 4/1			-	-	-	1.4			14.64	7.5
		30	10YR 4/1			-	-	-	1.2			-	-
	A2	40	10YR 6/3	silty loam, silty clay loam	Granular, well developed, subangular blocky	-	-	-	0.7	(<10%), Quartz dominant	Coatings	-	-
		50	10YR 6/3			-	-	-	0.7	(<10%), Quartz dominant	Coatings	-	-
	B	60	10YR 6/3	silty loam, silty clay loam	Granular, well developed, subangular blocky	-	-	-	0.5				
		70	10YR 6/3			-	-	-	-				

The Luanda Province soil profiles (Table 2) typically comprise A_1, A_2 and B horizons with diverse Munsell hues that range from 5R to 10YR, but which retain the same hue in each profile, values ranging between 1 and 8 and varying between profile, and chromas ranging from 1 to 8 also varying between profile horizons. Field textures are silt loams and silty clay loams throughout the profiles and across the catenas, with the exception of the coastal Ramiro site where field textures are dominantly sandy loams. Field structures are well-developed granular and sub-angular blocky aggregations. Percentage clay content is relatively high with low variability through the profile although at some locations clay content declines down the profile. Ramiro is again an exception, having low percentage clay contents. Micromorphological evidence of clay accumulation as coatings and fills indicates mobilisation of the clay fraction in all profiles. Organic carbon content in A_1 horizons are low, ranging from <0.1 to 4.3% and declining through the top 30cm of the profile. Cation exchange capacities of A_1 horizons are also low and range from 0 to 16.84 $cmol_c$ kg^{-1} $clay^1$. In contrast, % base saturation is typically high and above 50% but with a range from 0 - 90.97%. The weatherable mineral fraction is >10% and comprises Ca- and Na- plagioclases and K- feldspars; quartz is the dominant weathering resistant mineral.

These observations contrast with the Luvisol classification criteria set out in the World Reference Base (WRB) for Soil Resources [6,7] with clay enhanced argillic horizon expected to be lower in the profile. Rather, and although Munsell colour hues are consistent within each profile, the criteria presented in Table 2 are more diagnostic of Cambic horizons and a Cambisol classification across the Luanda study area. Base saturation data (%) are only available for the A_1 horizon at 10 and 20cm depths and so it is not possible to be definitive on the eutric nature of the Luanda soils, but the high % base saturation values strongly indicate that these soils may be classified as eutric Cambisols.

Table 2: Field and laboratory data sets for soil classification, Luanda Province

Soil Profile	Horizon	Depth (cm)	Munsell colour	Field Texture	Field structure	Clay %	Silt %	Sand %	Organic carbon %	% Weatherable coarse minerals	Clay accumulation features	Base Saturation (%)	CEC $cmol_c$ kg^{-1} $clay^1$
Bom Jesus upper	A1	10	7.5R 3/1	silt loam	Granular, well developed	23.59	75.72	0.67	0.8			60.71	4.07
		20	7.5R 3/1			23.91	74.24	1.85	0.8			83.08	9.45
		30	7.5R 3/1			23.6	75.18	1.22	0.7			-	-
	A2	40	7.5R 3/2	silt loam	Granular, well developed	22.25	76.58	1.18	0.6	(>10%)	Coatings, Fills	-	-
		50	7.5R 3/2			22.02	75.43	2.53	0.7	(>10%)	Coatings, Fills	-	-
	B	60	7.5R 3/3	silt loam	Granular, well developed	19.11	79.04	0.70	0.7			-	-
		70	7.5R 3/3			-	-	-	-			-	-
Bom Jesus middle	A1	10	7.5R ½	silt clay loam	Granular, well developed	30.34	68.36	1.30	1.4			76.51	10.22
		20	7.5R ½			27.08	72.59	0.35	1.0			84.14	10.09
		30	7.5R ½			32.07	67.95	<0.01	0.8			-	-
	A2	40	7.5R 1/3	silt clay loam	Granular, well developed	29.47	70.39	0.15	0.8	(>10%)	Coatings, Fills	-	-
		50	7.5R 1/3			28.26	71.61	0.28	0.8	(>10%)	Coatings, Fills	-	-
	B	60	7.5R 3/3	silt clay loam	Granular, well developed	25.78	71.61	0.14	0.7			-	-
		70	7.5R 3/3			-	-	-	0.6			-	-
Bom Jesus lower	A1	10	7.5R ½	silt clay loam, silt loam	Granular, well developed	28.64	70.52	0.83	1.8			85.34	10.91
		20	7.5R ½			29.84	69.75	0.39	1.2			-	-
		30	7.5R ½			28.53	70.63	0.85	1.2			-	-
	A2	40	7.5R 1/3	silt clay, slightly silt loam	Granular, well developed	23.33	75.36	1.30	1.0	(>10%)	Fills	-	-
		50	7.5R 1/3			28.37	70.58	1.06	1.0	(>10%)	Fills	-	-
	B	60	7.5R 3/3	silt clay, silt loam	Granular, well developed	24.44	73.83	1.74	1.0			-	-
		70	7.5R 3/3			-	-	-	-			-	-

Funda upper	A1	10	2.5YR 7/3	silt clay loam, silt loam	Apedal, crack	22.38	69.37	8.29	2.5			84.43	10.28
		20	2.5YR 7/3			22.18	73.69	4.13	1.6			79.77	11.86
		30	2.5YR 6/3			21.89	78.02	2.76	1.6			-	-
	A2	40	2.5YR 6/3	silt clay loam, silt loam	Apedal, crack	21.58	73.25	5.19	1.9	(>10%)	Coatings, Fills	-	-
		50	2.5YR 5/2			19.8	76.39	3.79	5.6	(>10%)	Coatings, Fills	-	-
	B	60	2.5YR 5/2	silt clay loam, silt loam	Apedal, crack	10.91	86.08	2.99	10.1			-	-
Funda middle	A1	10	2.5YR 5/2	silt loam	Subangular blocky, well developed	21.39	69.70	8.88	4.3			87.89	13.21
		20	2.5YR 5/2			25.65	72.10	2.24	1.6			0	0
		30	2.5YR 5/2			23.83	74.08	2.09	1.5			-	-
	A2	40	2.5YR 5/4	silt loam	Subangular blocky, well developed	24.98	73.73	1.28	1.5	(>10%)	Coatings, Fills	-	-
		50	2.5YR 5/4			24.28	73.25	2.49	1.2	(>10%)	Coatings, Fills	-	-
	B	60	2.5YR 4/4	silt loam	Subangular blocky, well developed	22.31	75.44	2.24	1.2			-	-
		70	2.5YR 4/4			22.78	75.39	1.82	1.5			-	-
		80	2.5YR 4/4			24.1	73.13	2.77	-			-	-
Funda lower	A1	10	2.5YR 5/2	silt loam	Subangular blocky, well developed	17.86	70.99	11.13	1.7			0	0
		20	2.5YR 5/2			17.59	73.87	8.51	1.2			0	0
		30	2.5YR 5/2			19.02	75.27	5.67	1.2			-	-
	A2	40	2.5YR 5/4	silt loam	Subangular blocky, well developed	16.19	73.41	10.40	1.1	(>10%)	Fills	-	-
		50	2.5YR 5/4			13.12	73.67	13.31	1.0	(>10%)	Fills	-	-
	B	60	2.5YR 4/4	silt loam	Subangular blocky, well developed	14.84	76.70	8.46	1.1			-	-
		70	2.5YR 4/4			13.78	77.47	8.75	1.1			-	-
		80	2.5YR 4/4			13.61	74.47	11.92	-			-	-
Talelo upper	A1	10	5R 5/6	silt loam	Granular, well developed	16.24	78.75	4.99	0.8			87.13	12.43
		20	5R 5/6			20.03	77.85	2.15	0.4			89.23	14.86
		30	5R 4/6			24.60	74.33	1.07	0.4			-	-
	A2	40	5R 54/6	silt loam	Granular, well developed	20.92	75.15	3.92	0.4	(>10%)	Coatings, Fills	-	-
		50	5R 4/4			21.28	75.39	3.22	0.4	(>10%)	Coatings, Fills	-	-
	B	60	5R 4/4	silt loam	Granular, well developed	17.17	76.66	6.18	0.7			-	-
		70	5R 4/4			-	-	-	-			-	-
Talelo middle	A1	10	5R 5/6	silt loam	Granular, well developed	16.29	69.71	13.96	0.6			87.54	16.84
		20	5R 5/6			17.82	70.64	11.53	0.9			62.00	16.84
		30	5R 6/6			17.63	69.67	12.71	0.7			-	-
	A2	40	5R 6/6	silt loam	Granular, well developed	21.72	74.90	3.39	0.6	(>10%)	Coatings	-	-
		50	5R 5/4			18.46	74.85	6.68	0.4	(>10%)	Coating	-	-
	B	60	5R 5/4	silt loam	Granular, well developed	16.53	67.30	16.14	0.3			-	-
		70	5R 5/4			16.81	76.65	6.54	0.3			-	-
		80	5R 5/4			17.49	79.51	2.98	-			-	-
Talelo lower	A1	10	7.5YR 7/6	silt loam	Granular, well developed	16.73	66.03	16.98	1.0			90.97	8.86
		20	7.5YR 7/6			18.00	68.47	13.53	0.8			81.45	8.63

		30	7.5YR 7/8			22.84	69.73	7.45	0.6			-	-
	A2	40	7.5YR 7/8	silt loam	Granular, well developed	21.01	65.03	13.94	0.6	(>10%)	Coatings	-	-
		50	7.5YR 4/6			22.50	63.90	13.61	0.3	(>10%)	Coatings	-	-
	B	60	7.5YR 4/6	silt loam	Granular, well developed	24.43	61.74	13.80	0.3			-	-
		70	7.5YR 4/6			17.11	42.20	40.69	0.4			-	-
		80	7.5YR 4/6			-	-	-	-			-	-
Ramiro upper	A1	10	10YR 8/4	sandy loam, silt loam	Granular, well developed	26.59	72.45	0.86	0.2			50.53	3.23
		20	10YR 8/4			11.33	37.56	51.11	0.1			33.15	3.59
		30	10YR 8/6			20.31	65.56	14.11	0.09			-	-
	A2	40	10YR 8/6	sandy loam, silt loam	Granular, well developed	4.35	18.41	77.25	0.07	ND	ND	-	-
		50	10YR 8/6			2.42	9.92	87.65	0.04	ND	ND	-	-
	B	60	10YR 8/6	sandy loam, silt loam	Granular, well developed	9.86	26.60	63.53	0.07			-	-
		70	10YR 8/6			-	-	-	-			-	-
Ramiro middle	A1	10	10YR 8/4	sandy loam, silt loam	Granular, well developed	3.52	17.36	79.30	0.1			87.89	13.21
		20	10YR 8/4			11.87	58.49	29.62	0.2			53.99	3.48
		30	10YR 8/6			4.29	18.89	76.83	<0.1			-	-
	A2	40	10YR 8/6	sandy loam, silt loam	Granular, well developed	3.57	14.85	81.59	0.06	ND	ND	-	-
		50	10YR 8/6			9.49	42.55	47.96	0.05	ND	ND	-	-
	B	60	10YR 8/6	sandy loam, silt loam	Granular, well developed	7.49	35.89	56.59	0.06			-	-
		70	10YR 8/6			2.39	11.47	86.15	0.04			-	-
		80	10YR 8/6			3.89	17.55	78.56	0.03			-	-
Ramiro lower	A1	10	10YR 8/4	sandy loam, silt loam	Granular, well developed	7.69	45.60	46.71	0.1			46.46	4.48
		20	10YR 8/4			7.75	44.00	48.96	0.1			43.38	0
		30	10YR 8/6			6.87	33.35	59.77	0.1			-	-
	A2	40	10YR 8/6	sandy loam, silt loam	Granular, well developed	7.52	37.60	54.88	0.06	ND	ND	-	-
		50	10YR 8/6			3.21	13.31	83.58	0.07	ND	ND	-	-
	B	60	10YR 8/6	sandy loam, silt loam	Granular, well developed	7.69	36.83	55.50	0.06			-	-
		70	10YR 8/6			8.19	37.42	54.40	0.06			-	-
		80	10YR 8/6			6.26	26.55	67.19	0.06			-	-

3.2 Mean and range nutrient element status

Summary statistics of twelve elements (N, Ca, K, Mg, Mn, P, S, Zn, Cu, Mo, Fe, Al together with pH) including mean and range values of macro- and micro- elements are given for the Huambo Province haplic Ferralsols and the Luanda Province eutric Cambisols (Table 3); these are also expressed as box plots in Figure 3. The statistics indicate variability in nutrient reserves across the study areas and give a basis for broader sub-Saharan regional comparisons (Table 4). Analytical methods are different in these regional studies and caution is needed when considered in relation to the Angola data sets, but Total X-ray Fluorescence (TXRF) does give comparable results corrected to ICP-MS while low total nutrient reserves are indicated when less that plant available nutrient comparators.

The values for nitrogen (N; ppm) range between 21-7,842 for Huambo Province and 0.03-16,975 for Luanda Province; mean values range across the four catenas from 449-1,245 at Huambo and 37-4,386 at Luanda. Boyer [16] reports that tropical soils generally have low N levels, but apart from the high mean value evident at Bom Jesus the results reported here are either close to or below those predicted for this region of Africa [9]. Explanation for the low levels may be related to lack of grazing and associated microbial activity [17] and in lower profile horizons that are less weathered there may be changes in nitrogen forms as a result of water movement within the profile [18].

Considering calcium (Ca; ppm), potassium (K; ppm) and magnesium (Mg; ppm) macro- nutrients, the calcium range at Huambo is 25-34,758 with mean ranges from 653-7,674 and at Luanda there is a 0.03-224,403 range with mean ranges from 209-79,236. Potassium values range from 0.02-1,372 with mean ranges of 327-570 at Huambo and ranges of 0.02-23,968 and mean ranges of 970-14,678 at Luanda. Magnesium values range from 0.03-844 with mean ranges from 121-340 at Huambo, and at Luanda there is a 0.02-26,063 range and mean range of 214-9,388. Total calcium, potassium and magnesium levels from the Huambo Ferralsols are at or below the means for these elements across sub-Saharan Africa and which may the result of long-term weathering, pH mediated mobilisation and high iron and aluminium concentrations (Table 3; [19, 4]. Ferralsols are typically nutrient poor with potassium becoming scarcer before magnesium and calcium in managed soils [20, 21]. At Luanda, mean values for these elements are generally high with with two catenas having higher means for calcium, three catenas having higher or close to means for potassium compared to the sub-Saharan Africa means, and with magnesium much higher than modelled spatial predictions of available concentrations in sub-Saharan Africa. These high values are associated with parent material weathering and limited down profile mobilisation because of the hot semi-desert climate [22].

Results for the phosphorus macro-nutrient range from 0.02-537 ppm at Huambo with a mean range across the four catenas of 49-329 ppm. These values are generally low in comparison to the regional data sets, again emphasising the low nutrient status in Huambo Ferralsols. Phosphorus values at Luanda are higher with a range from 0.02-2257 ppm and a mean range from 116-1559 ppm although only two catena locations are consistently higher than the regional data set indicators; such variability may be the result of the type of soil treatment [23]. Regardless of soil classification phosphorus is a relatively little leached element and bound by abundant aluminium and iron oxides in highly weathered soils and as evidenced by high iron and aluminium values in the profiles examined [24]. Furthermore, the very weak leaching of phosphorus for hundreds of thousands of years is one of the major causes of the low level of phosphorus in ferralitic soils [16]. Soil phosphorus scarcity in family farming regions of sub-Saharan Africa is common [25].

In considering micro- element concentrations attributed to weathering processes [26], at Huambo the manganese range is 3.75-540 ppm with mean range across the four catenas of 106-301 ppm; the zinc range is 0.02-36.9 ppm with a mean range from 6.9-22.3; the copper range is 0.02-326 ppm with a mean range from 6.16-43.9 ppm and the molybdenum range is 0.02-0.04 ppm. Observed micro-nutrient values from the Huambo catenas are generally lower than regional total nutrient values, with the exception of copper at the Lepi catena. At Luanda, the manganese range is 0.04-15,632 ppm with a mean range across the four catenas of 632-9573 ppm; the zinc range is 0.04-49,260 ppm with a mean range from 25.9-12,484; the copper range is 0.04-48,744 ppm with a mean range of 5.66-16,577 and the molybdenum range is 0.03-25,921 with a mean range of 213-9336 ppm. Luanda soil micro-nutrient concentrations are greater than regional and global averages (Table 4) and confirm high to low micro-nutrient status contrasts between the Luanda Cambisols and Huambo Ferralsols respectively.

Table 3: Summary statistics of total soil nutrient elements (ppm/kgmg^{-1}), haplic Ferralsols, Huambo Province* and eutric Cambisols, Luanda Province** Angola (N, Ca, K, Mg, Fe, Mn, P, S, Zn, Cu, Mo, Al and pH.

	N						Ca				
	Mean	Median	St. Dev	Max	Min		Mean	Median	St. Dev	Max	Min
*Bailundo**	463	365	407	1493	37		653	615	332	1215	104
*Lepi**	1245	388	1943	7842	21		1112	591	1337	5303	155
*Mungo**	1008	601	1022	3451	113		7674	571	11529	34758	25.5
*Ngongoinga**	449	281	388	1327	78		925	831	537	1822	305
*Talelo***	501	451	340	1314	0.03		2651	2412	1302	5368	0.02
*Ramiro***	37	35.1	23.9	92.9	0.03		209	141	231	835	0.03
*Funda***	640	519	367	1777	204		79236	75555	48482	224403	4.44
*Bom Jesus***	4386	764	5723	16975	495		19865	20810	11023	36045	6888

	K						Mg				
	Mean	Median	St. Dev	Max	Min		Mean	Median	St. Dev	Max	Min
*Bailundo**	327	317	161	756	104		127	129	38.1	205	61.4
*Lepi**	570	525	310	1372	125		340	300	217	844	102
*Mungo**	450	407	230	909	151		121	96.7	90.4	413	0.03
*Ngongoinga**	386	447	191	562	0.02		170	173	58.9	242	46.6
*Talelo***	14678	14482	6257	23968	0.02		9388	11182	4449	14967	0.02
*Ramiro***	970	977	277	1930	556		214	200	68.2	424	94.7
*Funda***	9223	9401	3159	14931	0.82		7231	7937	4998	26063	0.03
*Bom Jesus***	13275	11546	3514	19914	9858		7062	6421	1566	9983	5525

	Fe						Mn				
	Mean	Median	St. Dev	Max	Min		Mean	Median	St. Dev	Max	Min
*Bailundo**	1704	922	2005	8882	635		106	99.1	61.1	205	10
*Lepi**	45788	59274	24126	69029	12287		195	198	122	408	22.8
*Mungo**	4909	978	6810	21520	407		115	92.2	126	502	6.53
*Ngongoing**	8569	3298	15906	50583	478		301	231	178	540	2.75
*Talelo***	48709	54500	19084	81212	0.04		9573	9445	4081	15632	0.04
*Ramiro***	2320	2258	664	4405	1302		632	637	180	1259	363
*Funda***	32337	35190	9110	39682	3.63		6016	6131	2060	9738	0.53
*Bom Jesus***	24052	32925	19432	47186	35.7		9533	9933	2306	12988	6429

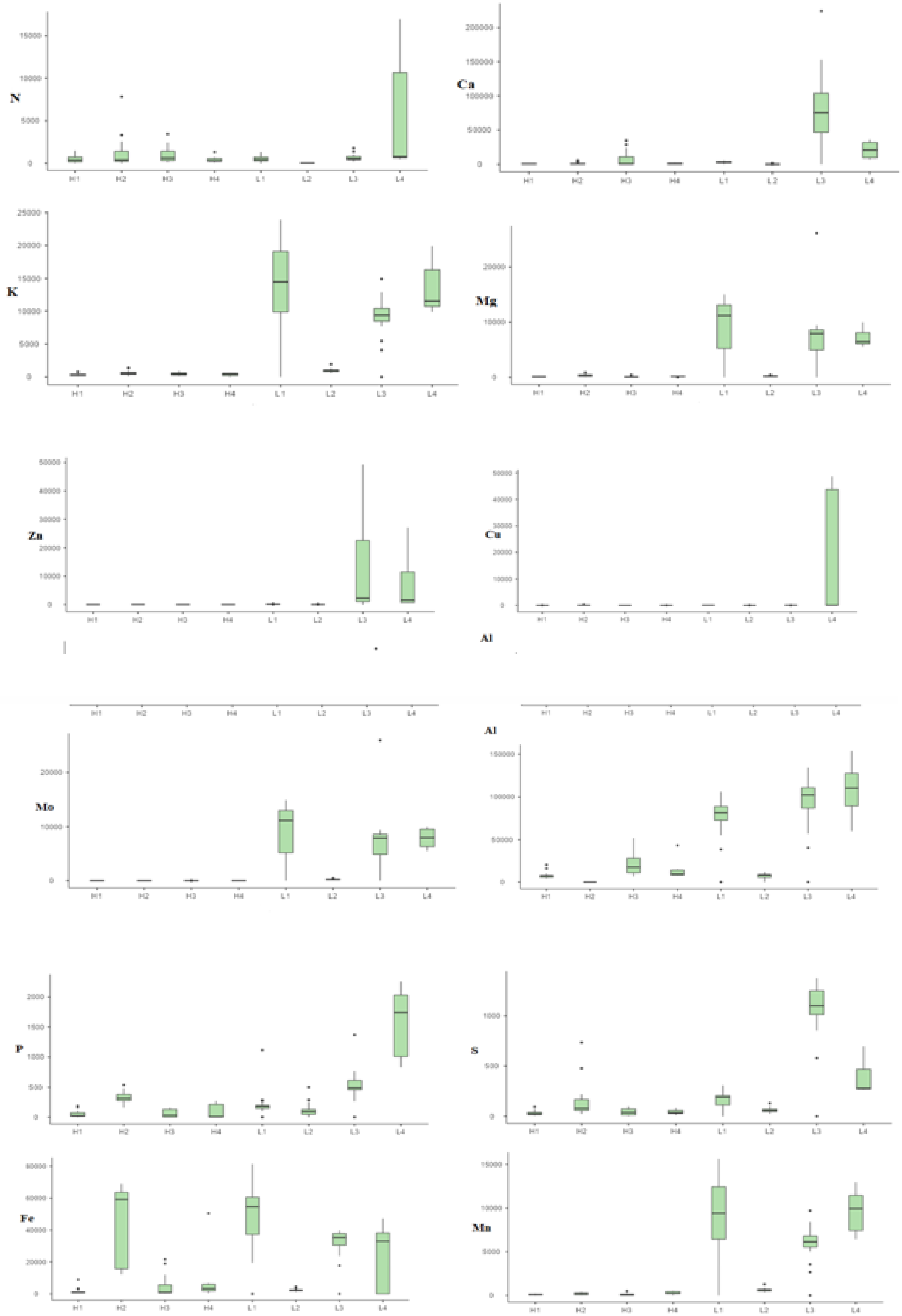
	P						S				
	Mean	Median	St. Dev	Max	Min		Mean	Median	St. Dev	Max	Min
*Bailundo**	49	22.2	56.6	189	0.07		33.6	25.3	25.7	96.6	6.46
*Lepi**	329	313	98.5	537	159		156	80.6	185	736	24.9
*Mungo**	64	31.4	65.5	155	0.03		42.7	37.8	32.9	101	3.52
*Ngongoinga**	84	6.01	121	270	0.03		42	37.3	24.6	82.7	11

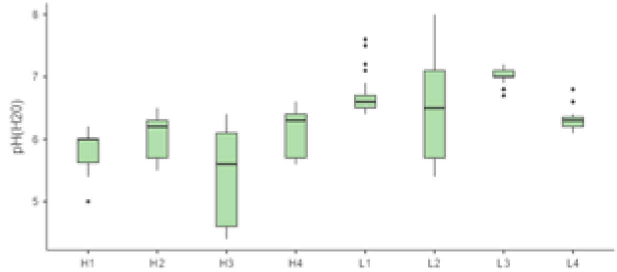
*Talelo***	217	179	214	1112	0.02		167	190	74.5	310	0.02
*Ramiro***	116	92.4	109	502	0.03		62	58.4	23.9	132	25.2
*Funda***	521	489	251	1366	0.05		1061	1100	299	1375	0.11
*Bom Jesus***	1559	1741	544	2257	827		365	281	130	698	268

			Zn						**Cu**		
	Mean	Median	St. Dev	Max	Min		Mean	Median	St. Dev	Max	Min
*Bailundo**	8.2	5.63	7.31	23.2	0.1		3.23	1.66	5.28	21.9	0.03
*Lepi**	22.3	21.4	8.21	36.9	10		43.9	27.4	73	326	9.51
*Mungo**	3.74	3.03	2.9	8.72	0.02		4.52	4.21	3.83	12.2	0.02
*Ngongoinga**	6.9	4.87	6.13	15.8	0.03		6.17	6.37	4.56	16.2	0.52
*Talelo***	179	153	82.3	353	0.04		37.6	40	17.5	64.6	0.04
*Ramiro***	25.9	16.3	39.1	191	1.89		5.66	3.37	7.24	31.1	0.41
*Funda***	12484	2264	17228	49260	0.1		37.1	38.6	11.2	50.2	0.04
*Bom Jesus***	7023	1663	8925	27134	687		16577	41.2	22449	48744	25.6

			Mo						**Al**		
	Mean	Median	St. Dev	Max	Min		Mean	Median	St. Dev	Max	Min
*Bailundo**	0.0317	0.03	0.00786	0.04	0.02		8047	7378	4048	20366	4188
*Lepi**	0.0265	0.03	0.00493	0.03	0.02		0.0282	0.02	0.0101	0.04	0.02
*Mungo**	0.0218	0.02	0.00393	0.03	0.02		21384	17646	13322	51993	6691
*Ngongoinga**	0.03	0.03	0	0.03	0.03		13885	9546	11293	43108	7706
*Talelo***	9336	11121	4425	14885	0.04		76407	81495	22893	106278	0.03
*Ramiro***	213	199	67.9	422	94.2		7268	8356	3086	12182	0.02
*Funda***	7191	7894	4971	25921	0.03		94743	102425	30777	134294	8.64
*Bom Jesus***	7871	7945	1664	9928	5495		108860	110106	26982	153770	59901

			pH(H_20)		
	Mean	Median	St. Dev	Max	Min
*Bailundo**	5.84	6	0.322	6.2	5
*Lepi**	6.09	6.2	0.343	6.5	5.5
*Mungo**	5.39	5.6	0.718	6.4	4.4
*Ngongoinga**	6.11	6.3	0.369	6.6	5.6
*Talelo***	6.72	6.6	0.339	7.6	6.4
*Ramiro***	6.56	6.5	0.86	8	5.4
*Funda***	7.01	7	0.136	7.2	6.7
*Bom Jesus***	6.31	6.3	0.163	6.8	6.1


N
Ca
K
Mg
Zn
Cu
Al
Mo
Al
P
S
Fe
Mn



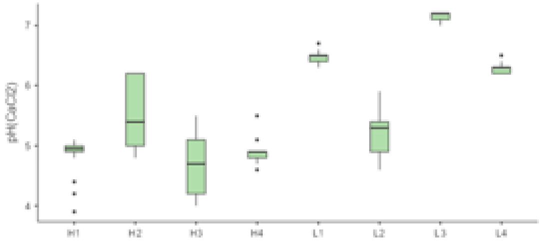


Figure 3: Box plots showing variations in soil nutrient element concentrations in four catenas in Huambo province (H1 - H4; haplic Ferralsols) and Luanda Province (L1 - L4; eutric Cambisols). y axis is nutrient concentration in ppm and pH value

Table 4: Mean values of total soil nutrient elements (ppm / mgkg^{-1}) in haplic Ferralsols, Huambo* Province Angola and eutric Cambisols, Luanda** Province Angola with published element contents in African and global soils

Element	Bailundo*	Ngongoinga*	Mungo*	Lepi*	Bom Jesus**	Funda**	Talelo**	Ramiro**	A	B	C	D
	Ppm											
N	463	449	1008	1245	4386	640	501	37	-	-	-	981
Ca	653	925	7674	1112	19865	79236	2651	209	13300	-	9780	330-1820
K	327	386	450	570	13275	9223	14678	970	26600	-	10893	62-180
Mg	127	170	121	340	7062	7231	9388	214	-	-	-	60-170
P	49	84	64	329	1559	521	217	116	2000	-	143	480
S	33.6	42	42.7	156	365	1061	167	62	-	-	-	-
Fe	1704	8569	4909	45788	24052	32337	48709	2320	67300	-	27954	-200
Mn	106	301	115	195	9533	6016	9573	632	1600	437	466	117
Zn	8.2	6.9	3.74	22.3	7023	12484	179	26	120	64	29	5
Cu	3.23	6.17	4.52	43.9	16577	37.1	37.6	6	60	20-30	17	3
Mo	0.0317	0.03	0.0218	0.0265	7871	7191	9336	213	-	0.1-> 7	-	-
Al	8047	13885	21384	0.0282	108860	94743	76407	7268	91500	-	33927	900-998

A: [2] total element concentration by TXRF analyses corrected to ICP-MS Na_2O_2, sub-Saharan Africa; B: [8] soil trace elements, worldwide mean contents; C: [4] further total element concentration by TXRF analyses, sub-Saharan Africa (0-20cm and 20-50cm profile depths; D: [9] Mehlich 3 plant available nutrients, except total P - 0-20cm, 20-50cm and up to 125cm profile depths - and machine learning modelling to give soil nutrient maps of Sub-Saharan Africa.

3.3 Nutrients and landscape relationships.

Statistical relationships between soil nutrients and landscape factors including site, profile depth and position in the catena (profile) give explanation of soil nutrient concentrations and highlight variabilities in nutrient concentrations across the study areas. Overall - for both study areas and all catenas - ANCOVA analyses indicates that (i) 'Site' was highly statistically significant ($P < 0.001$); (ii) 'Hillslope Position' was significant ($P < 0.05$); and (iii) 'Depth' was not statistically significant ($P > 0.05$). Pairwise comparison using Tukey and

Bonferroni tests, which show similar test probabilities, disaggregates the ‘site’ statistics for the nutrients considered (Table 5). Of the sixteen different Huambo and Luanda sites pairwise combinations, there are significant differences in twelve pairs for both Mn and Al, eleven for both K and Mo, ten for Mg, nine for Fe, eight for S, six for P, four for N, Ca and Cu and three for Zn. These observations highlight soil nutrient contrasts between Huambo haplic Ferralsols and Luanda eutric Cambisols (Table 5) and can be attributed to underlying parent materials [27,28].

Considering the detail of these analyses for Huambo Province, the ANCOVA analyses indicate that, with the exception of Nitrogen, all soil nutrient elements show statistically significant differences in relation to site (Table 6). However, pairwise comparisons with Tukey and Bonferroni tests indicates that only iron of the nutrients considered shows a statistically significant between two of the Huambo sites; all other nutrient elements have no significant difference between sites (Table 5). Furthermore, no significant correlations were observed between nitrogen, phosphorus, and potassium elements in Huambo province, with the exception of Mungo (Table 7). These statistical findings suggest variance in soil nutrients is evident across all sites but less so between sites and points to a spatial scaling of mineral diversity in the underlying Precambrian rock parent material, overlain in places by Quaternary deposits [29, 30]. Nitrogen levels can be attributed to biological input to soils independent from geology [31].

Contrast in nutrient concentrations resulting from slope position are less pronounced in their probability values but still significant, testifying to the action of slope processes in influencing distribution of elements [32]. Elements showing contrast across catenas are calcium, potassium, phosphorus, sulphur, iron and molybdenum (Table 6) and assessment of box-plot graphs indicates soil nutrient values have a tendency to be slightly higher in the mid-slope profiles at Huambo (Figure 4). Within profile variances with depth are much less pronounced in their differences with only potassium, manganese and zinc showing contrasts with depth (Table 6), indicating limited and similar pedogenesis influences on both macro- and micro- nutrients within the profiles.

In Luanda province all soil nutrient elements without exception show statistical differences in relation to site (Table 8). Further detail of site contrasts is given by the pairwise Tukey and Bonferroni tests showing the same significances and demonstrate statistically significant variances in all nutrients between the four catena sites. Out of the six possible combinations, there are two significant pairs for Zn, three significant pairs for N, Ca, Mg, Cu, Mo, Al, four significant pairs for K, P, Fe, S and five significant pairs for Mn (Table 5). Similarly, and as at Huambo there were no significant correlations between nitrogen, phosphorus, and potassium nutrient elements with the exception of the Talelo catena where there is significant positive and strong correlation between nitrogen and potassium (Table 9).

The observations from Luanda point to mineral diversity in the geological recent Neogene and Palaeogene parent material together with the association of nitrogen and biological process [29, 31]. As at Huambo, contrasts in soil nutrient concentrations across the catena’s are not strongly evident but are still statistically significant. Nitrogen, magnesium, sulphur, iron, zinc, copper, and molybdenum all show statistical contrasts at this spatial scale as does pH (Figure 4; Table 8). Assessment of box-plot graphs indicates that the upper-slope profiles hold the greatest nutrient reserves within the Luanda catenas. Statistically significant in-profile variances with depth are limited to only Nitrogen, reflecting biological contributions to the profile and the limited influence of pedogenesis in redistributing soil nutrient [33].

Our findings from both Huambo - haplic Ferralsols and Luanda -eutric Cambisols suggest that underlying parent material has the biggest influence on element concentrations, further modified by slope processes. While soil profile weathering undoubtedly contributes to the soil nutrient elements within profiles, pedogenesis has been consistent across profiles and has had a minimal contribution to the variances and nutrient contrasts observed.

Table 5: Post-hoc pairwise comparisons of nutrient elements in soil catena sites, Huambo and Luanda Provinces, Angola, with p-values for Tukey and Bonferroni tests. Comparisons based on estimated marginal means

Comparison (N)								
site		site	Mean Difference	SE	df	t	T_{ukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-3957.1	705	138	-5.6147	< .001	< .001
	-	Funda	-296.5	684	138	-0.4335	1.000	1.000
	-	Lepi	60.1	885	138	0.0679	1.000	1.000
	-	Mungo	-838.9	725	138	-1.1575	0.942	1.000
	-	Ngongo	-601.9	725	138	-0.8305	0.991	1.000
	-	Ramiro	234.4	673	138	0.3483	1.000	1.000
	-	Talelo	-120.4	690	138	-0.1746	1.000	1.000
Bom Jesus	-	Funda	3660.6	673	138	5.4412	< .001	< .001
	-	Lepi	4017.2	880	138	4.5664	< .001	< .001
	-	Mungo	3118.2	716	138	4.3554	< .001	< .001
	-	Ngongo	3355.2	716	138	4.6864	< .001	< .001
	-	Ramiro	4191.5	660	138	6.3477	< .001	< .001
	-	Talelo	3836.7	679	138	5.6501	< .001	< .001
Funda	-	Lepi	356.6	870	138	0.4098	1.000	1.000
	-	Mungo	-542.4	696	138	-0.7793	0.994	1.000
	-	Ngongo	-305.4	696	138	-0.4388	1.000	1.000
	-	Ramiro	530.9	629	138	0.8446	0.990	1.000
	-	Talelo	176.1	654	138	0.2693	1.000	1.000
Lepi	-	Mungo	-899.0	891	138	-1.0088	0.972	1.000
	-	Ngongo	-662.0	891	138	-0.7429	0.995	1.000
	-	Ramiro	174.3	870	138	0.2004	1.000	1.000
	-	Talelo	-180.5	873	138	-0.2069	1.000	1.000
Mungo	-	Ngongo	237.0	735	138	0.3226	1.000	1.000
	-	Ramiro	1073.3	686	138	1.5642	0.771	1.000
	-	Talelo	718.5	702	138	1.0240	0.970	1.000
Ngongo	-	Ramiro	836.3	686	138	1.2188	0.925	1.000
	-	Talelo	481.5	702	138	0.6862	0.997	1.000
Ramiro	-	Talelo	-354.8	638	138	-0.5560	0.999	1.000

Comparison (Ca)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-19066	6453	138	-2.9544	0.070	0.103
	-	Funda	-77911	6263	138	-12.4404	< .001	< .001
	-	Lepi	-1798	8101	138	-0.2220	1.000	1.000
	-	Mungo	-651	6636	138	-0.0981	1.000	1.000
	-	Ngongo	-6761	6636	138	-1.0188	0.971	1.000
	-	Ramiro	1713	6163	138	0.2780	1.000	1.000
	-	Talelo	-1498	6316	138	-0.2371	1.000	1.000
Bom Jesus	-	Funda	-58845	6160	138	-9.5525	< .001	< .001
	-	Lepi	17267	8055	138	2.1436	0.393	0.947
	-	Mungo	18415	6556	138	2.8090	0.101	0.159
	-	Ngongo	12304	6556	138	1.8769	0.569	1.000
	-	Ramiro	20779	6046	138	3.4365	0.017	0.022
	-	Talelo	17568	6218	138	2.8255	0.097	0.152
Funda	-	Lepi	76113	7968	138	9.5520	< .001	< .001
	-	Mungo	77260	6374	138	12.1220	< .001	< .001
	-	Ngongo	71150	6374	138	11.1633	< .001	< .001
	-	Ramiro	79624	5756	138	13.8335	< .001	< .001
	-	Talelo	76413	5986	138	12.7648	< .001	< .001
Lepi	-	Mungo	1148	8160	138	0.1406	1.000	1.000
	-	Ngongo	-4963	8160	138	-0.6082	0.999	1.000
	-	Ramiro	3511	7964	138	0.4409	1.000	1.000
	-	Talelo	301	7990	138	0.0376	1.000	1.000
Mungo	-	Ngongo	-6110	6728	138	-0.9082	0.985	1.000
	-	Ramiro	2364	6283	138	0.3762	1.000	1.000
	-	Talelo	-847	6425	138	-0.1318	1.000	1.000
Ngongo	-	Ramiro	8474	6283	138	1.3488	0.878	1.000
	-	Talelo	5264	6425	138	0.8193	0.992	1.000
Ramiro	-	Talelo	-3211	5843	138	-0.5495	0.999	1.000

Comparison (K)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-12975	969	138	-13.396	< .001	< .001
	-	Funda	-9032	940	138	-9.609	< .001	< .001
	-	Lepi	169	1216	138	0.139	1.000	1.000
	-	Mungo	-237	996	138	-0.238	1.000	1.000
	-	Ngongo	-117	996	138	-0.118	1.000	1.000
	-	Ramiro	-891	925	138	-0.964	0.979	1.000
	-	Talelo	-14447	948	138	-15.240	< .001	< .001
Bom Jesus	-	Funda	3943	925	138	4.265	< .001	0.001
	-	Lepi	13144	1209	138	10.872	< .001	< .001
	-	Mungo	12738	984	138	12.946	< .001	< .001
	-	Ngongo	12858	984	138	13.068	< .001	< .001
	-	Ramiro	12084	907	138	13.316	< .001	< .001
	-	Talelo	-1472	933	138	-1.577	0.763	1.000
Funda	-	Lepi	9201	1196	138	7.693	< .001	< .001
	-	Mungo	8794	957	138	9.194	< .001	< .001
	-	Ngongo	8915	957	138	9.319	< .001	< .001
	-	Ramiro	8141	864	138	9.423	< .001	< .001
	-	Talelo	-5415	898	138	-6.027	< .001	< .001
Lepi	-	Mungo	-406	1225	138	-0.332	1.000	1.000
	-	Ngongo	-286	1225	138	-0.233	1.000	1.000
	-	Ramiro	-1060	1195	138	-0.887	0.987	1.000
	-	Talelo	-14616	1199	138	-12.188	< .001	< .001
Mungo	-	Ngongo	120	1010	138	0.119	1.000	1.000
	-	Ramiro	-654	943	138	-0.693	0.997	1.000
	-	Talelo	-14209	964	138	-14.736	< .001	< .001
Ngongo	-	Ramiro	-774	943	138	-0.821	0.992	1.000
	-	Talelo	-14330	964	138	-14.860	< .001	< .001
Ramiro	-	Talelo	-13556	877	138	-15.457	< .001	< .001

Comparison (Mg)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-6938.9	847	138	-8.1903	< .001	< .001
	-	Funda	-7184.7	822	138	-8.7385	< .001	< .001
	-	Lepi	-13.4	1063	138	-0.0126	1.000	1.000
	-	Mungo	-253.4	871	138	-0.2909	1.000	1.000
	-	Ngongo	-34.2	871	138	-0.0392	1.000	1.000
	-	Ramiro	-230.3	809	138	-0.2847	1.000	1.000
	-	Talelo	-9306.8	829	138	-11.2239	< .001	< .001
Bom Jesus	-	Funda	-245.7	809	138	-0.3038	1.000	1.000
	-	Lepi	6925.6	1058	138	6.5489	< .001	< .001
	-	Mungo	6685.5	861	138	7.7681	< .001	< .001
	-	Ngongo	6904.8	861	138	8.0229	< .001	< .001
	-	Ramiro	6708.6	794	138	8.4515	< .001	< .001
	-	Talelo	-2367.8	816	138	-2.9008	0.080	0.121
Funda	-	Lepi	7171.3	1046	138	6.8554	< .001	< .001
	-	Mungo	6931.2	837	138	8.2838	< .001	< .001
	-	Ngongo	7150.5	837	138	8.5458	< .001	< .001
	-	Ramiro	6954.3	756	138	9.2033	< .001	< .001
	-	Talelo	-2122.1	786	138	-2.7003	0.131	0.218
Lepi	-	Mungo	-240.0	1071	138	-0.2241	1.000	1.000
	-	Ngongo	-20.8	1071	138	-0.0194	1.000	1.000
	-	Ramiro	-216.9	1046	138	-0.2075	1.000	1.000
	-	Talelo	-9293.4	1049	138	-8.8603	< .001	< .001
Mungo	-	Ngongo	219.3	883	138	0.2482	1.000	1.000
	-	Ramiro	23.1	825	138	0.0280	1.000	1.000
	-	Talelo	-9053.3	843	138	-10.7336	< .001	< .001
Ngongo	-	Ramiro	-196.2	825	138	-0.2378	1.000	1.000
	-	Talelo	-9272.6	843	138	-10.9936	< .001	< .001
Ramiro	-	Talelo	-9076.4	767	138	-11.8319	< .001	< .001

Comparison (P)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-1509.8	79.6	138	-18.963	< .001	< .001
	-	Funda	-463.2	77.3	138	-5.995	< .001	< .001
	-	Lepi	-61.9	99.9	138	-0.619	0.999	1.000
	-	Mungo	-284.7	81.9	138	-3.477	0.015	0.019
	-	Ngongo	-16.1	81.9	138	-0.196	1.000	1.000
	-	Ramiro	-48.1	76.0	138	-0.632	0.998	1.000
	-	Talelo	-162.3	77.9	138	-2.083	0.431	1.000
Bom Jesus	-	Funda	1046.6	76.0	138	13.771	< .001	< .001
	-	Lepi	1448.0	99.4	138	14.569	< .001	< .001
	-	Mungo	1225.2	80.9	138	15.147	< .001	< .001
	-	Ngongo	1493.8	80.9	138	18.468	< .001	< .001
	-	Ramiro	1461.8	74.6	138	19.595	< .001	< .001
	-	Talelo	1347.5	76.7	138	17.565	< .001	< .001
Funda	-	Lepi	401.4	98.3	138	4.083	0.002	0.002
	-	Mungo	178.5	78.6	138	2.270	0.318	0.693
	-	Ngongo	447.1	78.6	138	5.686	< .001	< .001
	-	Ramiro	415.1	71.0	138	5.846	< .001	< .001
	-	Talelo	300.9	73.9	138	4.074	0.002	0.002
Lepi	-	Mungo	-222.8	100.7	138	-2.213	0.350	0.798
	-	Ngongo	45.8	100.7	138	0.455	1.000	1.000
	-	Ramiro	13.8	98.3	138	0.140	1.000	1.000
	-	Talelo	-100.5	98.6	138	-1.019	0.971	1.000
Mungo	-	Ngongo	268.6	83.0	138	3.236	0.032	0.042
	-	Ramiro	236.6	77.5	138	3.052	0.054	0.076
	-	Talelo	122.4	79.3	138	1.544	0.782	1.000
Ngongo	-	Ramiro	-32.0	77.5	138	-0.413	1.000	1.000
	-	Talelo	-146.3	79.3	138	-1.845	0.591	1.000
Ramiro	-	Talelo	-114.3	72.1	138	-1.585	0.759	1.000

Comparison (S)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-332.71	45.8	138	-7.2705	< .001	< .001
	-	Funda	-1028.60	44.4	138	-23.1616	< .001	< .001
	-	Lepi	3.27	57.4	138	0.0569	1.000	1.000
	-	Mungo	-118.25	47.1	138	-2.5129	0.199	0.367
	-	Ngongo	-5.19	47.1	138	-0.1103	1.000	1.000
	-	Ramiro	-31.35	43.7	138	-0.7174	0.996	1.000
	-	Talelo	-135.16	44.8	138	-3.0177	0.059	0.085
Bom Jesus	-	Funda	-695.89	43.7	138	-15.9306	< .001	< .001
	-	Lepi	335.98	57.1	138	5.8818	< .001	< .001
	-	Mungo	214.46	46.5	138	4.6133	< .001	< .001
	-	Ngongo	327.52	46.5	138	7.0454	< .001	< .001
	-	Ramiro	301.36	42.9	138	7.0287	< .001	< .001
	-	Talelo	197.55	44.1	138	4.4806	< .001	< .001
Funda	-	Lepi	1031.87	56.5	138	18.2620	< .001	< .001
	-	Mungo	910.35	45.2	138	20.1425	< .001	< .001
	-	Ngongo	1023.41	45.2	138	22.6441	< .001	< .001
	-	Ramiro	997.25	40.8	138	24.4331	< .001	< .001
	-	Talelo	893.44	42.4	138	21.0474	< .001	< .001
Lepi	-	Mungo	-121.52	57.9	138	-2.1002	0.420	1.000
	-	Ngongo	-8.46	57.9	138	-0.1462	1.000	1.000
	-	Ramiro	-34.62	56.5	138	-0.6130	0.999	1.000
	-	Talelo	-138.43	56.7	138	-2.4433	0.229	0.443
Mungo	-	Ngongo	113.06	47.7	138	2.3699	0.265	0.537
	-	Ramiro	86.90	44.6	138	1.9506	0.519	1.000
	-	Talelo	-16.91	45.6	138	-0.3711	1.000	1.000
Ngongo	-	Ramiro	-26.16	44.6	138	-0.5872	0.999	1.000
	-	Talelo	-129.97	45.6	138	-2.8528	0.091	0.140
Ramiro	-	Talelo	-103.81	41.4	138	-2.5053	0.202	0.375

Comparison (Fe)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-22329	4516	138	-4.944	< .001	< .001
	-	Funda	-30976	4383	138	-7.068	< .001	< .001
	-	Lepi	-7025	5669	138	-1.239	0.919	1.000
	-	Mungo	-44372	4644	138	-9.555	< .001	< .001
	-	Ngongo	-3493	4644	138	-0.752	0.995	1.000
	-	Ramiro	-1212	4312	138	-0.281	1.000	1.000
	-	Talelo	-47167	4420	138	-10.671	< .001	< .001
Bom Jesus	-	Funda	-8648	4311	138	-2.006	0.482	1.000
	-	Lepi	15304	5637	138	2.715	0.127	0.209
	-	Mungo	-22043	4588	138	-4.805	< .001	< .001
	-	Ngongo	18836	4588	138	4.106	0.002	0.002
	-	Ramiro	21116	4231	138	4.991	< .001	< .001
	-	Talelo	-24839	4351	138	-5.709	< .001	< .001
Funda	-	Lepi	23951	5576	138	4.295	< .001	< .001
	-	Mungo	-13396	4460	138	-3.003	0.061	0.089
	-	Ngongo	27483	4460	138	6.162	< .001	< .001
	-	Ramiro	29764	4028	138	7.389	< .001	< .001
	-	Talelo	-16191	4189	138	-3.865	0.004	0.005
Lepi	-	Mungo	-37347	5710	138	-6.541	< .001	< .001
	-	Ngongo	3532	5710	138	0.619	0.999	1.000
	-	Ramiro	5813	5573	138	1.043	0.967	1.000
	-	Talelo	-40142	5591	138	-7.180	< .001	< .001
Mungo	-	Ngongo	40879	4708	138	8.683	< .001	< .001
	-	Ramiro	43159	4397	138	9.816	< .001	< .001
	-	Talelo	-2795	4496	138	-0.622	0.999	1.000
Ngongo	-	Ramiro	2281	4397	138	0.519	1.000	1.000
	-	Talelo	-43674	4496	138	-9.714	< .001	< .001
Ramiro	-	Talelo	-45955	4089	138	-11.238	< .001	< .001

Comparison (Mn)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-9443.82	632	138	-14.9412	< .001	< .001
	-	Funda	-5996.19	613	138	-9.7755	< .001	< .001
	-	Lepi	-54.87	793	138	-0.0692	1.000	1.000
	-	Mungo	-87.30	650	138	-0.1343	1.000	1.000
	-	Ngongo	-7.56	650	138	-0.0116	1.000	1.000
	-	Ramiro	-684.68	604	138	-1.1344	0.948	1.000
	-	Talelo	-9528.08	619	138	-15.4021	< .001	< .001
Bom Jesus	-	Funda	3447.63	603	138	5.7142	< .001	< .001
	-	Lepi	9388.95	789	138	11.9003	< .001	< .001
	-	Mungo	9356.53	642	138	14.5721	< .001	< .001
	-	Ngongo	9436.26	642	138	14.6963	< .001	< .001
	-	Ramiro	8759.14	592	138	14.7908	< .001	< .001
	-	Talelo	-84.26	609	138	-0.1384	1.000	1.000
Funda	-	Lepi	5941.32	780	138	7.6128	< .001	< .001
	-	Mungo	5908.90	624	138	9.4657	< .001	< .001
	-	Ngongo	5988.63	624	138	9.5934	< .001	< .001
	-	Ramiro	5311.51	564	138	9.4218	< .001	< .001
	-	Talelo	-3531.89	586	138	-6.0239	< .001	< .001
Lepi	-	Mungo	-32.43	799	138	-0.0406	1.000	1.000
	-	Ngongo	47.30	799	138	0.0592	1.000	1.000
	-	Ramiro	-629.81	780	138	-0.8074	0.992	1.000
	-	Talelo	-9473.21	783	138	-12.1060	< .001	< .001
Mungo	-	Ngongo	79.73	659	138	0.1210	1.000	1.000
	-	Ramiro	-597.38	615	138	-0.9708	0.978	1.000
	-	Talelo	-9440.79	629	138	-15.0029	< .001	< .001
Ngongo	-	Ramiro	-677.11	615	138	-1.1003	0.956	1.000
	-	Talelo	-9520.52	629	138	-15.1296	< .001	< .001
Ramiro	-	Talelo	-8843.40	572	138	-15.4521	< .001	< .001

Comparison (Zn)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-6965.56	2420	138	-2.87843	0.085	0.130
	-	Funda	-12169.69	2348	138	-5.18209	< .001	< .001
	-	Lepi	-401.98	3038	138	-0.13233	1.000	1.000
	-	Mungo	17.68	2488	138	0.00710	1.000	1.000
	-	Ngongo	36.20	2488	138	0.01455	1.000	1.000
	-	Ramiro	538.71	2311	138	0.23312	1.000	1.000
	-	Talelo	34.27	2368	138	0.01447	1.000	1.000
Bom Jesus	-	Funda	-5204.12	2310	138	-2.25291	0.327	0.724
	-	Lepi	6563.59	3021	138	2.17293	0.375	0.882
	-	Mungo	6983.24	2458	138	2.84072	0.094	0.145
	-	Ngongo	7001.76	2458	138	2.84826	0.092	0.142
	-	Ramiro	7504.27	2267	138	3.30981	0.026	0.033
	-	Talelo	6999.83	2332	138	3.00222	0.061	0.089
Funda	-	Lepi	11767.71	2988	138	3.93839	0.003	0.004
	-	Mungo	12187.36	2390	138	5.09940	< .001	< .001
	-	Ngongo	12205.89	2390	138	5.10715	< .001	< .001
	-	Ramiro	12708.39	2158	138	5.88801	< .001	< .001
	-	Talelo	12203.96	2245	138	5.43670	< .001	< .001
Lepi	-	Mungo	419.65	3060	138	0.13715	1.000	1.000
	-	Ngongo	438.18	3060	138	0.14321	1.000	1.000
	-	Ramiro	940.68	2986	138	0.31498	1.000	1.000
	-	Talelo	436.25	2996	138	0.14561	1.000	1.000
Mungo	-	Ngongo	18.52	2523	138	0.00734	1.000	1.000
	-	Ramiro	521.03	2356	138	0.22115	1.000	1.000
	-	Talelo	16.59	2409	138	0.00689	1.000	1.000
Ngongo	-	Ramiro	502.51	2356	138	0.21329	1.000	1.000
	-	Talelo	-1.93	2409	138	-8.01e-4	1.000	1.000
Ramiro	-	Talelo	-504.44	2191	138	-0.23022	1.000	1.000

Comparison (Cu)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-16534.9	2664	138	-6.2076	< .001	< .001
	-	Funda	114.0	2585	138	0.0441	1.000	1.000
	-	Lepi	-321.9	3344	138	-0.0963	1.000	1.000
	-	Mungo	-76.3	2739	138	-0.0279	1.000	1.000
	-	Ngongo	-36.9	2739	138	-0.0135	1.000	1.000
	-	Ramiro	271.0	2544	138	0.1065	1.000	1.000
	-	Talelo	78.3	2607	138	0.0300	1.000	1.000
Bom Jesus	-	Funda	16648.9	2543	138	6.5479	< .001	< .001
	-	Lepi	16212.9	3325	138	4.8763	< .001	< .001
	-	Mungo	16458.6	2706	138	6.0825	< .001	< .001
	-	Ngongo	16498.0	2706	138	6.0971	< .001	< .001
	-	Ramiro	16805.9	2496	138	6.7341	< .001	< .001
	-	Talelo	16613.1	2566	138	6.4733	< .001	< .001
Funda	-	Lepi	-436.0	3289	138	-0.1326	1.000	1.000
	-	Mungo	-190.4	2631	138	-0.0724	1.000	1.000
	-	Ngongo	-150.9	2631	138	-0.0574	1.000	1.000
	-	Ramiro	157.0	2376	138	0.0661	1.000	1.000
	-	Talelo	-35.8	2471	138	-0.0145	1.000	1.000
Lepi	-	Mungo	245.6	3368	138	0.0729	1.000	1.000
	-	Ngongo	285.0	3368	138	0.0846	1.000	1.000
	-	Ramiro	592.9	3287	138	0.1804	1.000	1.000
	-	Talelo	400.2	3298	138	0.1214	1.000	1.000
Mungo	-	Ngongo	39.4	2777	138	0.0142	1.000	1.000
	-	Ramiro	347.3	2593	138	0.1339	1.000	1.000
	-	Talelo	154.6	2652	138	0.0583	1.000	1.000
Ngongo	-	Ramiro	307.9	2593	138	0.1187	1.000	1.000
	-	Talelo	115.2	2652	138	0.0434	1.000	1.000
Ramiro	-	Talelo	-192.7	2412	138	-0.0799	1.000	1.000

Comparison (Mo)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-7874.94302	844	138	-9.3342	< .001	< .001
	-	Funda	-7273.83452	819	138	-8.8842	< .001	< .001
	-	Lepi	31.49461	1059	138	0.0297	1.000	1.000
	-	Mungo	-40.58750	868	138	-0.0468	1.000	1.000
	-	Ngongo	-40.58162	868	138	-0.0468	1.000	1.000
	-	Ramiro	-359.60335	806	138	-0.4464	1.000	1.000
	-	Talelo	-9383.24653	826	138	-11.3637	< .001	< .001
Bom Jesus	-	Funda	601.10850	805	138	0.7464	0.995	1.000
	-	Lepi	7906.43763	1053	138	7.5079	< .001	< .001
	-	Mungo	7834.35552	857	138	9.1413	< .001	< .001
	-	Ngongo	7834.36140	857	138	9.1413	< .001	< .001
	-	Ramiro	7515.33967	790	138	9.5077	< .001	< .001
	-	Talelo	-1508.30351	813	138	-1.8556	0.584	1.000
Funda	-	Lepi	7305.32913	1042	138	7.0129	< .001	< .001
	-	Mungo	7233.24702	833	138	8.6811	< .001	< .001
	-	Ngongo	7233.25291	833	138	8.6811	< .001	< .001
	-	Ramiro	6914.23118	752	138	9.1887	< .001	< .001
	-	Talelo	-2109.41201	783	138	-2.6954	0.133	0.221
Lepi	-	Mungo	-72.08211	1067	138	-0.0676	1.000	1.000
	-	Ngongo	-72.07623	1067	138	-0.0676	1.000	1.000
	-	Ramiro	-391.09796	1041	138	-0.3756	1.000	1.000
	-	Talelo	-9414.74114	1044	138	-9.0138	< .001	< .001
Mungo	-	Ngongo	0.00588	880	138	6.69e-6	1.000	1.000
	-	Ramiro	-319.01585	821	138	-0.3884	1.000	1.000
	-	Talelo	-9342.65903	840	138	-11.1232	< .001	< .001
Ngongo	-	Ramiro	-319.02173	821	138	-0.3884	1.000	1.000
	-	Talelo	-9342.66492	840	138	-11.1232	< .001	< .001
Ramiro	-	Talelo	-9023.64319	764	138	-11.8125	< .001	< .001

Comparison (Al)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-100785	6118	138	-16.474	< .001	< .001
	-	Funda	-86687	5937	138	-14.601	< .001	< .001
	-	Lepi	-6074	7680	138	-0.791	0.993	1.000
	-	Mungo	7955	6291	138	1.265	0.910	1.000
	-	Ngongo	-13429	6291	138	-2.135	0.398	0.968
	-	Ramiro	804	5842	138	0.138	1.000	1.000
	-	Talelo	-68330	5988	138	-11.412	< .001	< .001
Bom Jesus	-	Funda	14098	5840	138	2.414	0.243	0.478
	-	Lepi	94711	7636	138	12.403	< .001	< .001
	-	Mungo	108740	6215	138	17.497	< .001	< .001
	-	Ngongo	87356	6215	138	14.056	< .001	< .001
	-	Ramiro	101589	5732	138	17.723	< .001	< .001
	-	Talelo	32455	5894	138	5.506	< .001	< .001
Funda	-	Lepi	80614	7554	138	10.672	< .001	< .001
	-	Mungo	94643	6042	138	15.664	< .001	< .001
	-	Ngongo	73259	6042	138	12.125	< .001	< .001
	-	Ramiro	87491	5457	138	16.034	< .001	< .001
	-	Talelo	18357	5675	138	3.235	0.032	0.043
Lepi	-	Mungo	14029	7735	138	1.814	0.612	1.000
	-	Ngongo	-7355	7735	138	-0.951	0.980	1.000
	-	Ramiro	6878	7550	138	0.911	0.985	1.000
	-	Talelo	-62256	7574	138	-8.220	< .001	< .001
Mungo	-	Ngongo	-21384	6378	138	-3.353	0.022	0.029
	-	Ramiro	-7151	5956	138	-1.201	0.931	1.000
	-	Talelo	-76285	6091	138	-12.525	< .001	< .001
Ngongo	-	Ramiro	14233	5956	138	2.390	0.255	0.510
	-	Talelo	-54901	6091	138	-9.014	< .001	< .001
Ramiro	-	Talelo	-69134	5539	138	-12.480	< .001	< .001

Comparison (pH(H2O)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-0.4848	0.122	138	-3.958	0.003	0.003
	-	Funda	-1.2568	0.119	138	-10.575	< .001	< .001
	-	Lepi	-0.1652	0.154	138	-1.075	0.961	1.000
	-	Mungo	-0.2584	0.126	138	-2.052	0.451	1.000
	-	Ngongo	0.4416	0.126	138	3.506	0.014	0.017
	-	Ramiro	-0.8659	0.117	138	-7.403	< .001	< .001
	-	Talelo	-0.9398	0.120	138	-7.840	< .001	< .001
Bom Jesus	-	Funda	-0.7721	0.117	138	-6.604	< .001	< .001
	-	Lepi	0.3195	0.153	138	2.090	0.427	1.000
	-	Mungo	0.2264	0.124	138	1.819	0.608	1.000
	-	Ngongo	0.9264	0.124	138	7.446	< .001	< .001
	-	Ramiro	-0.3811	0.115	138	-3.321	0.025	0.032
	-	Talelo	-0.4550	0.118	138	-3.856	0.004	0.005
Funda	-	Lepi	1.0916	0.151	138	7.218	< .001	< .001
	-	Mungo	0.9984	0.121	138	8.254	< .001	< .001
	-	Ngongo	1.6984	0.121	138	14.042	< .001	< .001
	-	Ramiro	0.3910	0.109	138	3.579	0.011	0.013
	-	Talelo	0.3170	0.114	138	2.791	0.106	0.168
Lepi	-	Mungo	-0.0932	0.155	138	-0.602	0.999	1.000
	-	Ngongo	0.6068	0.155	138	3.919	0.003	0.004
	-	Ramiro	-0.7006	0.151	138	-4.635	< .001	< .001
	-	Talelo	-0.7746	0.152	138	-5.108	< .001	< .001
Mungo	-	Ngongo	0.7000	0.128	138	5.482	< .001	< .001
	-	Ramiro	-0.6074	0.119	138	-5.094	< .001	< .001
	-	Talelo	-0.6814	0.122	138	-5.588	< .001	< .001
Ngongo	-	Ramiro	-1.3074	0.119	138	-10.965	< .001	< .001
	-	Talelo	-1.3814	0.122	138	-11.329	< .001	< .001
Ramiro	-	Talelo	-0.0739	0.111	138	-0.667	0.998	1.000

Comparison (PH(CaCl2)								
site		site	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
Bailundo	-	Bom Jesus	-1.4288	0.1072	138	-13.332	< .001	< .001
	-	Funda	-2.3321	0.1040	138	-22.423	< .001	< .001
	-	Lepi	-0.0274	0.1345	138	-0.203	1.000	1.000
	-	Mungo	-0.6507	0.1102	138	-5.904	< .001	< .001
	-	Ngongo	0.1670	0.1102	138	1.515	0.798	1.000
	-	Ramiro	-0.3918	0.1023	138	-3.829	0.005	0.005
	-	Talelo	-1.6548	0.1049	138	-15.776	< .001	< .001
Bom Jesus	-	Funda	-0.9033	0.1023	138	-8.830	< .001	< .001
	-	Lepi	1.4014	0.1338	138	10.476	< .001	< .001
	-	Mungo	0.7781	0.1089	138	7.148	< .001	< .001
	-	Ngongo	1.5958	0.1089	138	14.658	< .001	< .001
	-	Ramiro	1.0370	0.1004	138	10.327	< .001	< .001
	-	Talelo	-0.2260	0.1033	138	-2.188	0.365	0.849
Funda	-	Lepi	2.3047	0.1323	138	17.417	< .001	< .001
	-	Mungo	1.6814	0.1058	138	15.886	< .001	< .001
	-	Ngongo	2.4991	0.1058	138	23.611	< .001	< .001
	-	Ramiro	1.9403	0.0956	138	20.298	< .001	< .001
	-	Talelo	0.6773	0.0994	138	6.813	< .001	< .001
Lepi	-	Mungo	-0.6233	0.1355	138	-4.600	< .001	< .001
	-	Ngongo	0.1943	0.1355	138	1.434	0.840	1.000
	-	Ramiro	-0.3645	0.1323	138	-2.756	0.115	0.186
	-	Talelo	-1.6274	0.1327	138	-12.266	< .001	< .001
Mungo	-	Ngongo	0.8176	0.1117	138	7.318	< .001	< .001
	-	Ramiro	0.2588	0.1043	138	2.481	0.213	0.401
	-	Talelo	-1.0041	0.1067	138	-9.411	< .001	< .001
Ngongo	-	Ramiro	-0.5588	0.1043	138	-5.356	< .001	< .001
	-	Talelo	-1.8218	0.1067	138	-17.075	< .001	< .001
Ramiro	-	Talelo	-1.2629	0.0970	138	-13.015	< .001	< .001

Table 6: ANCOVA Statistical comparisons between elements within sites, profiles, and depths, Huambo Province haplic Ferralsols

Ca	Sum of Squares	df	Mean Square	F	p
site	4.04E+08	3	1.35E+08	11.18	***<.001***
depth	3.86E+07	1	3.86E+07	3.2	0.08
profile	3.14E+08	2	1.57E+08	13.03	***<.001***

N	Sum of Squares	df	Mean Square	F	p
site	6.03E+06	3	2.01E+06	1.9417	0.136
depth	34682	1	34682	0.0335	0.856
profile	2.68E+06	2	1.34E+06	1.2965	0.283

K	Sum of Squares	df	Mean Square	F	p
site	510011	3	170004	5.35	***0.003***
depth	246920	1	246920	7.77	***0.008***
profile	388708	2	194354	6.12	***0.004***

Mg	Sum of Squares	df	Mean Square	F	p
site	497168	3	165723	13.471	***<.001***
depth	1509	1	1509	0.123	0.728
profile	88422	2	44211	3.594	0.035

P	Sum of Squares	df	Mean Square	F	p
site	854540	3	284847	46.708	***<.001***
depth	14511	1	14511	2.379	0.13
profile	68731	2	34365	5.635	***0.006***

S	Sum of Squares	df	Mean Square	F	p
site	152991	3	50997	6.2082	***0.001***
depth	351	1	351	0.0428	0.837
profile	46282	2	23141	2.8171	***0.07***

Fe	Sum of Squares	df	Mean Square	F	p
site	2.21E+10	3	7.37E+09	186.53	***<.001***
depth	6.93e0+7	1	6.93E+07	1.75	0.192
profile	1.27e0+9	2	6.33E+08	16.03	***<.001***

Mn	Sum of Squares	df	Mean Square	F	p
site	213116	3	71039	8.168	***<.001***
depth	56457	1	56457	6.491	***0.014***
profile	16709	2	8354	0.961	0.39

Zn	Sum of Squares	df	Mean Square	F	p
site	3292.2	3	1097.4	31.957	***<.001***
depth	295.9	1	295.9	8.617	***0.005***
profile	61.1	2	30.5	0.889	0.418

Cu	Sum of Squares	df	Mean Square	F	p
site	18089	3	6030	3.773	***0.017***
depth	1076	1	1076	0.673	0.416
profile	2207	2	1104	0.69	0.506

Mo	Sum of Squares	df	Mean Square	F	p
site	9.67E-04	3	3.22E-04	18.2354	***<.001***
depth	1.52E-06	1	1.52E-06	0.0857	0.771
profile	1.64E-04	2	8.22E-05	4.6529	***0.014***

Al	Sum of Squares	df	Mean Square	F	p
site	4.38E+09	3	1.46E+09	26.12	***<.001***
depth	1.52E+08	1	1.52E+08	2.72	0.105

pH (H2O)	Sum of Squares	df	Mean Square	F	p
site	4.333	3	1.4443	97.8	***<.001***
depth	0.354	1	0.354	24	***<.001***
profile	5.728	2	2.8638	193.9	***<.001***

Table 7: Statistical relationships between nitrogen, phosphorus and potassium, Huambo Province haplic Ferralsols - Spearmans Rank analyses

Mungo

		N	K	P
N	Spearman's rho	—		
	p-value	—		
K	Spearman's rho	0.603 *	—	
	p-value	0.012	—	
P	Spearman's rho	0.706 **	0.255	—
	p-value	0.002	0.322	—

Note. * p < .05, ** p < .01, *** p < .001

Bailundo

		N	K	P
N	Spearman's rho	—		
	p-value	—		
K	Spearman's rho	0.350	—	
	p-value	0.168	—	
P	Spearman's rho	0.150	0.211	—
	p-value	0.579	0.415	—

Note. * p < .05, ** p < .01, *** p < .001

Ngongoinga

		N	K	P
N	Spearman's rho	—		
	p-value	—		
K	Spearman's rho	0.203	—	
	p-value	0.432	—	
P	Spearman's rho	-0.358	-0.258	—
	p-value	0.174	0.336	—

Note. * p < .05, ** p < .01, *** p < .001

Lepi

		N	K	P
N	Spearman's rho	—		
	p-value	—		
K	Spearman's rho	-0.533	—	
	p-value	0.148	—	
P	Spearman's rho	-0.390	0.610	—
	p-value	0.300	0.081	—

Note. * p < .05, ** p < .01, *** p < .001

Table 8: ANCOVA Statistical comparisons between elements within sites, profiles, and depths, Luanda Province - eutric Cambisols

	N				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	2.53E+08	3	8.43E+07	210.9	***<.001***
depth	3.58E+06	1	3.58E+06	8.96	***0.004***
profile	1.48E+08	2	7.40E+07	185.02	***<.001***

	K				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	2.46E+09	3	8.20E+08	81.531	***<.001***
depth	1.38E+07	1	1.38E+07	1.368	0.246
profile	1.35E+07	2	6.73E+06	0.669	0.515

	P				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	2.64E+07	3	8.80E+06	89.007	***<.001***
depth	270227	1	270227	2.735	0.102
profile	30358	2	15179	0.154	0.858

	Fe				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	2.48E+10	3	8.27E+09	97.3029	***<.001***
depth	249742	1	249742	0.00294	0.957
profile	1.27e0+9	2	6.36E+08	7.48466	***0.001***

	Zn				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	2.06E+09	3	6.88E+08	27.53	***<.001***
depth	5.44E+07	1	5.44E+07	2.18	0.144
profile	9.58E+08	2	4.79E+08	19.17	***<.001***

	Ca				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	9.10E+10	3	3.03E+10	46.799	***<.001***
depth	6.24e0+8	1	6.24e0+8	0.962	0.33
profile	6.02e0+8	2	3.01e0+8	0.464	0.631

	Mg				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	1.09E+09	3	3.62E+08	42.8463	***<.001***
depth	353546	1	353546	0.0418	0.838
profile	9.10E+07	2	4.55E+07	5.3841	***0.007***

	S				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	1.32E+07	3	4.41E+06	201.5	***<.001***
depth	26278	1	26278	1.2	0.277
profile	267839	2	133920	6.12	***0.003***

	Mn				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	1.13E+09	3	3.77E+08	86.83	***<.001***
depth	6.54E+06	1	6.54E+06	1.51	0.223
profile	1.13E+07	2	5.67E+06	1.31	0.277

	Cu				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	3.27E+09	3	1.09E+09	511.889	***<.001***
depth	1.36E+06	1	1.36E+06	0.64	0.426
profile	2.48E+09	2	1.24E+09	581.828	***<.001***

	Mo				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	1.11E+09	3	3.71E+08	44.6771	***<.001***
depth	814161	1	814161	0.0981	0.755
profile	1.09E+08	2	5.44E+07	6.5597	***0.002***

	Al				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	1.34E+11	3	4.47E+10	85.2515	***<.001***
depth	5.42e0+6	1	5.42e0+6	0.0103	0.919
profile	2.54e0+8	2	1.27e0+8	0.2424	0.785

	pH(H2O)				
	Sum of Squares	**df**	**Mean Square**	**F**	**p**
site	5.48	3	1.8278	39	***<.001***
depth	1.65	1	1.6534	35.3	***<.001***
profile	3.88	2	1.9389	41.4	***<.001***

Table 9: Statistical relationships between nitrogen, phosphorus and potassium, Luanda Province eutric Cambisols, Spearmans Rank Analyses

Bom Jesus

		N	K	P
N	Spearman's rho	—		
	p-value	—		
K	Spearman's rho	-0.168	—	
	p-value	0.492	—	
P	Spearman's rho	-0.242	-0.295	—
	p-value	0.318	0.221	—

Note. * p < .05, ** p < .01, *** p < .001

Talelo

		N	K	P
N	Spearman's rho	—		
	p-value	—		
K	Spearman's rho	0.721 ***	—	
	p-value	< .001	—	
P	Spearman's rho	-0.222	0.044	—
	p-value	0.332	0.850	—

Note. * p < .05, ** p < .01, *** p < .001

Ramiro

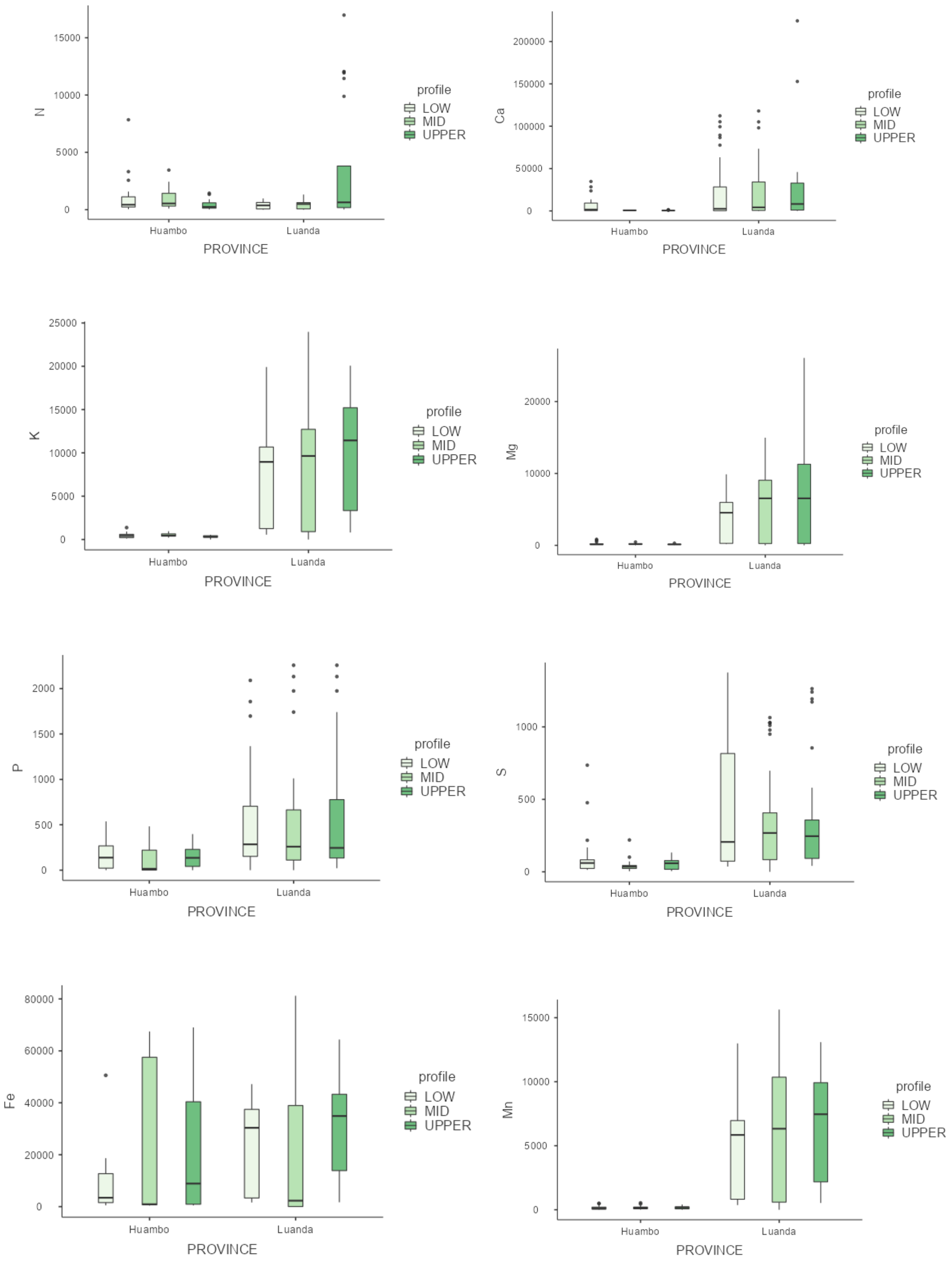
		N	K	P
N	Spearman's rho	—		
	p-value	—		
K	Spearman's rho	-0.052	—	
	p-value	0.810	—	
P	Spearman's rho	0.389	-0.196	—
	p-value	0.060	0.346	—

Note. * p < .05, ** p < .01, *** p < .001

Funda

		N	K	P
N	Spearman's rho	—		
	p-value	—		
K	Spearman's rho	0.413	—	
	p-value	0.057	—	
P	Spearman's rho	-0.241	-0.182	—
	p-value	0.278	0.415	—

Note. * p < .05, ** p < .01, *** p < .001


N
PROVINCE
Huambo
Luanda
profile
LOW
MID
UPPER
Ca
K
Mg
P
S
Fe
Mn

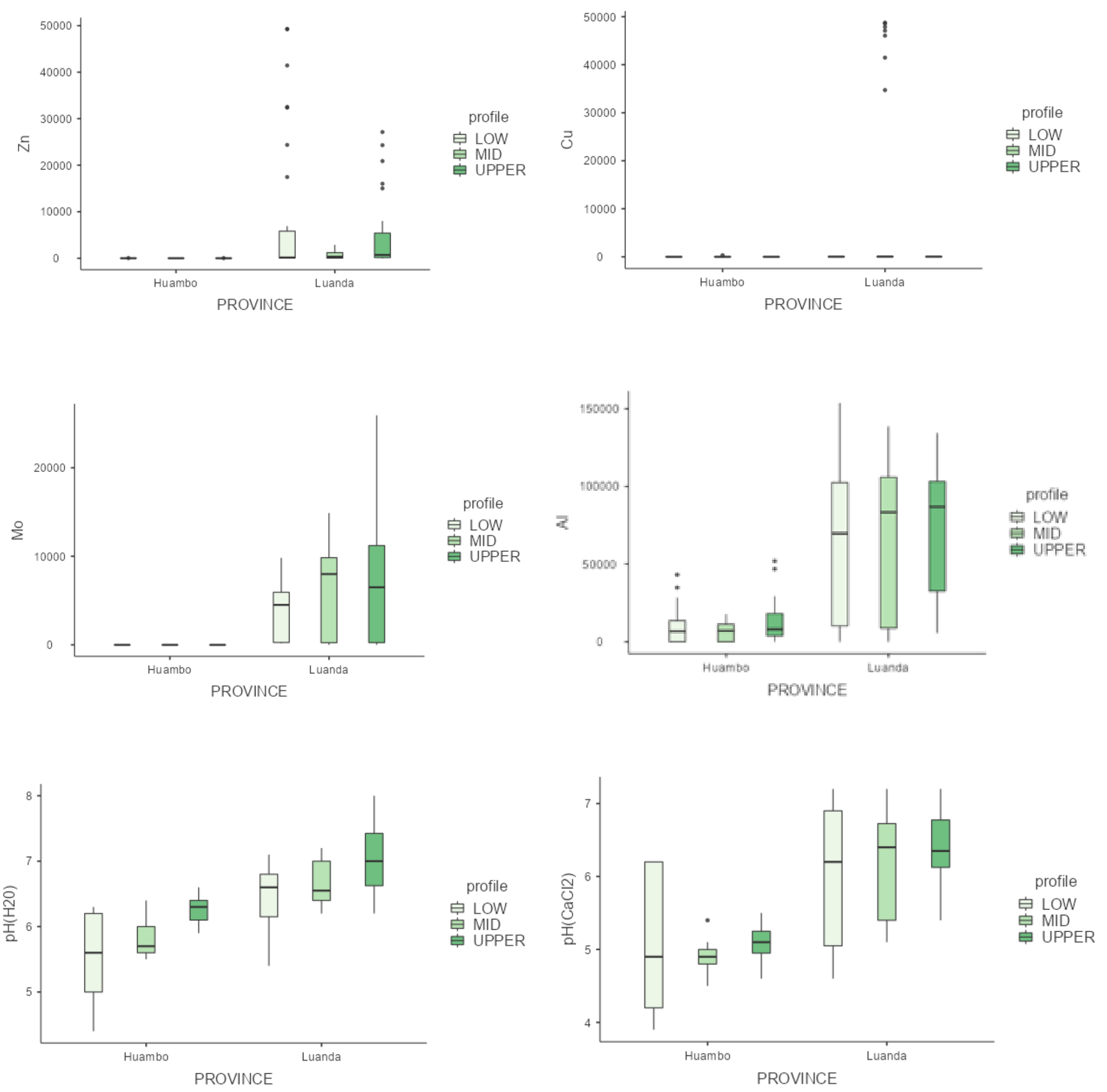


Figure 4: Box-plots of soil nutrient concentration along hillslope profiles, Huambo Province (haplic Ferralsols) and Luanda Province (eutric Cambisols)

4. Conclusions

Up-to-date knowledge and understanding of the nutrient status of soils is of vital importance in giving a baseline for land capabilities and how best to intervene with effective fertiliser and land management practices that enhance productive sustainable agriculture [34]. While we acknowledge the spatial limitations in our study - our sample transects and profiles are a tiny fraction of the soil landscape we are considering, there has been no attempt to model or extrapolate to a wider area, and no consideration of climate-sequences - nevertheless our findings do highlight a wide range of nutrient element concentrations within and between haplic Ferralsols - a common soil class in Angola - and eutric Cambisols, managed for subsistence agriculture in Huambo and Luanda Provinces, Angola. This range included absence, deficiency and even excesses in certain localities. Comparatively, nutrient status in the two provinces is different; in general, the macro and micronutrients concentrations are higher in Luanda Province (Bom Jesus, Funda, Talelo and Ramiro) than in Huambo Province

(Bailundo, NGongoinga, Mungo and Lepi). Locally, soil nutrient concentrations vary with slope location. These variances can best be explained by differences in underlying parent material influenced by long-term mineral weathering and slope processes including human induced erosion of soils [35]. Land management practices in modifying organic input to soils may explain variances in nitrogen concentrations. Profile pedogenic factors has a more limited influence than parent material and slope on nutrient element variances. Our findings correspond with similar studies from elsewhere in sub-Saharan Africa [34, 36, 37, 38, 39) although at odds with some studies of the nutritional status of African soils that have high rates of nutrient depletions resulting from high population density, continuous cultivation and rugged and mountainous terrain [40, 41].

As yet, such findings are slow to find their way into policy making for subsistence agriculture and the related agricultural extension advisory services. At the very least, our findings open the question of which localities are more suitable for agriculture, or more directly, which soils will be best able to produce food in a sustainable way, enhance soil health maintain and improve human health, be self-sufficient and regenerative, and produce sufficient food to a growing population [30, 42, 43]. Our analyses can also provide a foundation for determining where subsistence agriculture with local historical and ecological knowledge can transform infertile, carbon poor, tropical soils into durable fertile rich and productive soils that can support agriculture ecologically and in a socially sustainable way [44, 45, 46, 47, 48].

In recognising the diversity of soil nutrient reserves, even within distinct soil classes, and to support and encourage subsistence farming, we highlight the need for detailed local analyses so that supportive intervention can be designed and planned for maximum effectiveness. This may involve identifying appropriate levels of introduced macro- and micro- nutrients as well as offering guidance on crops suitable for the nutrient reserves of a locality, and on crop rotations that are effective in conserving nutrients. We also recognise that, at least in Huambo Province, slope processes are influencing the distribution of nutrients and that steps are needed to reduce these erosive effects. Supporting subsistence agriculture in a changing environment and on which so many of sub-Saharan Africa’s populations relies is a major challenge for agricultural policy makers and planners. Understanding soil nutrient levels and distributions is an important part of this vital endeavor.

Acknowledgments

Lídia Teixeira is grateful to her family for all their support and for encouraging her to continue to believe. We gratefully acknowledge the Ministry of Higher Education, Science and Technology of Angola for supporting this research together with the financial support of INAGBE. We are grateful for the invaluable laboratory technical support of Ian Washbourne, University of Stirling.

References

[1] D.B. Smith, L.G. Woodruff, R.M. O'Leary, W.F. Cannon, R.G. Garett, J.E. Kilburn and M.B. Goldhaber. "Pilot studies for the North American soil geochemical landscapes project - site selection, sampling, protocols, analytical methods and quality control protocols" *Applied Geochemistry*, vol. 24, pp. 1357-1368, 2009.

[2] E.K. Towett, K.D. Shepherd and G. Cadisch. "Quantification of total element concentrations in soils using total X-ray fluorescence spectroscopy (TXRF)". *Science of the Total Environment*, vol. 463, pp. 374-388, 2013.

[3] J. Kihara, P. Bolo, M. Kinyua, J. Rurinda and K. Piikki. "Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops." *Environmental Geochemistry and Health*, vol. 42, pp. 3015-3033, 2020.

[4] E.K. Towett, K.D. Shepherd, J.E. Tondoh, L.A. Winowiecki, T. Lulseged, M. Nyambura, A. Sila, T.G. Vågen and G. Cadisch. "Total elemental composition of soils in Sub-Saharan Africa and relationship with soil forming factors." *Geoderma Regional*, vol. 5, pp. 157-168, 2015.

[5] L.P. de S. Teixeira. "Geochemical, textural and micromorphological properties of Angolan agroecosystem soils in relation to region, landscape position and land management". PhD Thesis, University of Stirling, Scotland, UK, 2022.

[6] IUSS Working Group WRB. *World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. update 2015.* Rome: World Soil Resources Reports No. 106, FAO, 2015, pp. 192.

[7] IUSS Working Group WRB. *World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps.* 4th edition. Vienna: International Union of Soil Sciences (IUSS), 2022, pp. 236.

[8] A. Kabata-Pendias and A.B. Mukherjee. "Soils" in *Trace elements from soil to human.* Berlin, New York: Springer Science & Business Media, 2007, pp. 9-38.

[9] T. Hengl, J.G. Leenaars, K.D. Shepherd, M.G. Walsh, G.B. Heuvelink, T. Mamo, H. Tilahun, E. Berkhout, M. Cooper, E. Fegraus, E. and I. Wheeler, I. "Soil nutrient maps of Sub-Saharan Africa: assessment of soil nutrient content at 250 m spatial resolution using machine learning." *Nutrient Cycling in Agroecosystems* vol. 109, pp. 77-102, 2017.

[10] P.M. Kiala and I.A. Simpson. "Evidencing Local Climate Change and Its Implications for Subsistence Agriculture Planning in Huambo Province Angola, Southern Africa." *American Academic Scientific Research Journal for Engineering, Technology, and Sciences*, vol. 92, pp. 135–152, 2023.

[11] S. Bullock, N. Fedoroff, A. Jongerius, G. Stoops and T. Turisna, T. *Handbook for soil thin section description.* Wolverhampton: Waine Research Publications, 1985, pp. 152.

[12] G. Stoops. *Guidelines for analysis and description of soil and regolith thin sections.* 2nd Edition. Madison, Wisconsin: Soil Science Society of America, 2021, pp. 240.

[13] A. Jones, H. Breuning-Madsen, M. Brossard, A. Dampha, J. Deckers, O. Dewitte, T. Gallali, S. Hallett, R. Jones, M. Kilasara, P. Le Roux, E. Micheli, L. Montanarella, O. Spaargaren, L. Thiombiano, E. Van Ranst, M. Yemefack, R. Zougmoré (eds.). *Soil Atlas of Africa.* Luxembourg: European Commission, Publications Office of the European Union, 2013, pp. 176.

[14] B.J. Huntley. "Soil, water and nutrients". In: Ecology of Angola: Terrestrial Biomes and Ecoregions. (pp. 127-147). Cham: Springer International Publishing, 2023, pp. 127-147.

[15] M.B. Sharu, M. Yakubu, S.S. Noma and A.I. Tsafe. "Characterization and classification of soils on an agricultural landscape in Dingyadi District, Sokoto State, Nigeria". *Nigerian Journal of Basic and Applied Sciences*, vol. 21, pp. 137-147, 2013.

[16] J. Boyer. *Propriedades dos solos e fertilidade.* Salvador: Universidade Federal da Bahia, 1971, pp. 196.

[17] J.N. Aranibar, I.C. Anderson, H.E. Epstein, C.J.W. Feral, R.J. Swap, J. Ramontsho, J. and S.A. Macko. 2008. "Nitrogen isotope composition of soils, C3 and C4 plants along land use gradients in southern Africa". *Journal of Arid Environments*, vol. 72, pp. 326-337, 2008.

[18] P. Gupta, and I. Rorison. "Seasonal differences in the availability of nutrients down a podzolic profile." *Journal of Ecology*, vol. 63, pp. 521-534, 1975.

[19] S.R. Cavichiolo. "Perdas de solo e nutrientes por erosão hídrica em diferentes métodos de preparo do solo em plantio de Pinus taeda" Doctoral programme Thesis, Universidade Federal do Paraná, Curitiba, 2005.

[20] P. Musinguzi, J.S. Tenywa, P. Ebanyat, T.A. Basamba, M.M. Tenywa, D.N. Mubiru and Y.L. Zinn. "Soil organic fractions in cultivated and uncultivated Ferralsols in Uganda". *Geoderma Regional*, vol. 4, pp.108-113, 2015.

[21] A.E. Hartemink and A.J. Van Kekem. "Nutrient depletion in Ferralsols under hybrid sisal cultivation in Tanzania". *Soil Use and Management*, vol. 10, pp. 103-107, 1994.

[22] F.A. de.Oliveira, Q.A.D.C. Carmello and H.A.A. Mascarenhas. "Disponibilidade de potássio e suas relações com cálcio e magnésio em soja cultivada em casa-de-vegetação". *Scientia Agricola* vol. 58, pp. 329-335, 2001.

[23] S.T. Spera, H.P.D. Santos, R.S. Fontaneli and G.O. Tomm. "Effect of crop-livestock under no-tillage on some soil physical attributes after ten years". *Bragantia*, vol. 69, pp. 695-704, 2010.

[24] A. Melese, H. Gebrekidan, M. Yli-Halla and B. Yitaferu. "Phosphorus status, inorganic phosphorus forms, and other physicochemical properties of acid soils of Farta district, northwestern highlands of

Ethiopia". *Applied and Environmental Soil Science*, vol. 2015, pp. 1-11, 2015.

[25] G. Nziguheba, S. Zingore, J. Kihara, R. Merckx, S. Njoroge, A. Otinga, E. Vandamme and B. Vanlauwe "Phosphorus in smallholder farming systems of sub-Saharan Africa: implications for agricultural intensification". *Nutrient Cycling in Agroecosystems*, vol. 104, pp.321-340, 2016.

[26] P.R.S. Vendrame, O.R. Brito, C. Quantin and T. Becquer. "Availability of copper, iron, manganese and zinc in soils under pastures in the Brazilian Cerrado". *Pesquisa Agropecuária Brasileira*, vol. 42, pp. 859-864, 2007.

[27] R.J.A.B. da Silva, Y.J.A.B. da Silva, P. van Straaten, C.W.A. do Nascimento, C.M. Biondi, C.M. Y.J.A.B da Silva, and J.C. de Araújo Filho. "Influence of parent material on soil chemical characteristics in a semi-arid tropical region of Northeast Brazil". *Environmental Monitoring and Assessment*, vol. 194, 331, 2022.

[28] D. Dortzbach, M.G. Pereira, L.H.C.D. Anjos, A. Fontana and E.D.C. Silva. "Genesis and classification of soils from subtropical mountain regions of southern Brazil". *Revista Brasileira de Ciência do solo*, vol. 40, e0150503, 2016.

[29] B.J. Huntley. “Landscapes: Geology, Geomorphology and Hydrology”. In: Ecology of Angola. Springer, 2023. http://doi.org/10.1007/978-3-031-18923-4_4.

[30] J.G. Cobo, G. Dercon, G. and Cadisch, G. "Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress." *Agriculture, Ecosystems & Environment*, vol. 136, pp. 1-15, 2010.

[31] L. Augusto, D. Achat, M. Jonard, D.F. Vidal, B. Ringeval. "Soil parent material - a major driver of plant nutrient limitations in terrestrial ecosystems". *Global Change Biology* vol. 23, pp. 3808-3824, 2017.

[32] K.D. Chadwick and G.P. Asner. "Tropical soil nutrient distributions determined by biotic and hillslope processes". *Biogeochemistry*, vol. 127, pp. 273-289, 2016.

[33] M.M. Stone, J. Kan and A.F. Plante. 'Parent material and vegetation influence bacterial community structure and nitrogen functional genes along deep tropical soil profiles at the Luquillo Critical Zone Observatory". *Soil Biology and Biochemistry*, vol. 80, pp.273-282, 2015.

[34] B.M. Butler, J. Palarea-Albaladejo, K.D. Shepherd, K.M. Nyambura, E.K. Towett, A.M. Sila and S. Hillier. "Mineral–nutrient relationships in African soils assessed using cluster analysis of X-ray powder diffraction patterns and compositional methods.". *Geoderma*, vol. 375 114474, 2020.

[35] O. Olatunji, O. Ogunkunle, O. and F.O. Tabi. "Influence of parent material and topography on some

soil properties in southwestern Nigeria". *Nigerian Journal of Soil and Environmental Research*, vol. 7, pp. 1-6, 2007.

[36] C. Aponte, T. Marañón, and L.V. García. "Microbial C, N and P in soils of Mediterranean oak forests: influence of season, canopy cover and soil depth". *Biogeochemistry,* vol. 101, pp. 77-92, 2010.

[37] S. Uroz, C. Calvaruso, M.P. Turpault, A. Sarniguet, W. de Boer, J.H.J. Leveau and P. Frey-Klett. "Efficient mineral weathering is a distinctive functional trait of the bacterial genus Collimonas". *Soil Biology and Biochemistry*, vol. 41, pp. 2178-2186, 2009.

[38] R. Finlay, H. Wallander, M. Smits, S. Holmstrom, P. Van Hees, B. Lian and A. Rosling, A. "The role of fungi in biogenic weathering in boreal forest soils". *Fungal Biology Reviews*, vol. 23, pp. 101-106, 2009.

[39] M. Lego, D. Singh and S. Tsanglao. “Effect of differnt levels of NPK on growth, yeild and economic of Capsicum (*Capsicum annuum* L.) cv, Asha under shade nethouse cultivation”. *International Journal of Agricultural Science and Research (IJASR),* vol. 6, pp. 5-8, 2016.

[40] M. Bekunda, E. Nkonya, D. Mugendi and J.J. Msaky. "Soil fertility status, management, and research in East Africa". *East African Journal of Rural Development*, vol. 20, pp. 94-112, 2002.

[41] H. Hailu, T. Mamo, R. Keskinen, E. Karltun, H. Gebrekidan and T. Bekele. "Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia". *Agriculture & Food Security*, vol 4, pp.1-10, 2015.

[42] T. Higa and J. F. Parr. *Beneficial and effective microorganisms for a sustainable agriculture and environment.* Atami: International Nature Farming Research Center, 1994. https://api.semanticscholar.org/CorpusID:16595978}.

[43] L.K. Abbott and D.A. Manning. “Soil health and related ecosystem services in organic agriculture’. Sustainable Agriculture Research, vol. 4 (526-2016-37946), 2015.

[44] D. Solomon, J. Lehmann, J.A. Fraser, M. Leach, K.Amanor, V. Frausin, S.M.Kristiansen, D. Millimouno and J. Fairhead. “Indigenous African soil enrichment as a climate-smart sustainable agricultural alternative’. *Frontiers in Ecology and the Environment,* vol. 14, pp. 71-76, 2016.

[45] R. Chikowo, S. Zingore, S. Snapp and A. Johnston. “Farm typologies, soil fertility variability and nutrient management in smallholder farming in sub-Saharan Africa”. *Nutrient cycling in agroecosystems,* vol. 100, pp. 1-18, 2014.

[46] P. Chase and O. Singh. “Soil nutrient and fertility in three traditional land use systems of Khonoma, Nagaland, India”. *Resources and Environment,* vol. 4, pp. 181-189, 2014.

[47] P. Tittonell, A. Muriuki, C.J. Klapwijk, K.D. Shepherd, R.Coe and B. Vanlauwe. "Soil heterogeneity and soil fertility gradients in smallholder farms of the East African highlands". *Soil Science Society of America Journal,* vol. 77, pp. 525-538, 2013.

[48] S. Zingore, H.K. Murira, R.J. Delve and K.E. Giller. "Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe". *Agriculture, Ecosystems and Environment,* vol. 119, pp. 112-126, 2017.