Geochemical, textural and micromorphological properties of Angolan agroecosystem soils in relation to region, landscape position and land management

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ABSTRACT

Angola is a country rich in natural resources, containing enormous water resources and a vast area of land yet to be developed. It has a mostly young population, where subsistence family farming supports 90% of the rural population. The country was once an agricultural power in the colonial era, but today its production levels are low, and while soils are potentially suitable for agriculture the status of nutrient elements and related management practices are poorly understood. The concepts of soil improvement are related to the sustainability approaches needed for new agricultural developments in Angola. This project studies Angolan soils with the aim of contributing to a better understanding of the status of nutrient elements and the factors that determine their levels. The objectives of the thesis are to: a) Determine nutrient element status in the agricultural regions of Luanda and Huambo in Angola, the areas of greatest agricultural expansion in the country. Soil sampling for this purpose was based on catena-based soil transects and field profile horizon characteristics of the region's Ferralsols soils. Soils from two provinces were subject to chemical, physical and micromorphological analysis with the aim of understanding aspects related to characteristics mentioned above and their genesis. Analyses was based on Coulter Counter (textural), ICP-MS (Inductively Coupled Plasma Mass Spectrometry), thin section micromorphology and associated SEM-EDX (Scanning Electron Microscopy-Energy dispersive X-ray spectroscopy) analyses. Levels and locations of nitrogen (N), phosphorus (P), potassium (K) and pH values. b) explain the nutrient element levels in terms of the relative contributions of micromorphological properties, soil texture and cultural amendment of soils. Weathering assessments were undertaken through thin section micromorphology, highlighting both physical and chemical weathering fronts on mineral grains; texture was assessed by using particle size analysis in combination with analysis related pedogenic- features in thin section; and the nature of soil amendments undertaken by subsistence farmers has been assessed through a series of farmer interviews. The findings of this study show that the contents of the macronutrients are higher than the micronutrients. This study shows that the soils have a silty clay loam and silt loam textural classes, with exception of the Ramiro region which, presented a sand texture. Moreover, the textural classes were observed to be related to nitrogen (N) status in relation to profile and depth. The micromorphological and microchemical analysis showed the high degree of weathering of these soils and kaolinite and quartz as the main mineral present, while the highest level of K and P were observed in the fine material. Integration of soil nutrient element status and the explanatory factors has a fundamental significance for Angola and the Southern Africa region with the Southern African Development Community (SADC) now expressing an interest in applying the findings into developing new policies to support subsistence farmers.

Keywords: Nutrient Status, Micromorphology, Soil, Angolan, Agro ecosystem

Acronymous

CAN (Calcium Ammonium Nitrate)

CPLP (Community of Portuguese Language Countries)

CEC Cation Exchangeable Capacity

FAO (Food and Agriculture Organization of the United Nations)

GDP (Gross Domestic Product)

ICP-MS (Inductively Coupled Plasma Mass Spectrometry)

MINAGRIP (Ministry of Agriculture and Fisheries)-Angola

MAP (Ministry of Agriculture and Fisheries of Angola)

NPK (Nitrogen, Phosphorous, Potassium)

PSD (Particle Size Distribution)

PTFE (Polytetrafluoroethylene)

Southern African Development Community (SADC)

SEM-EDX (Scanning Electron Microscopy-Energy dispersive X-ray spectroscopy)

cm-centimetre

ha-hectare

BJ- Bom Jesus

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Chapter I: Introduction

Photo: Agricultural field-Luanda. Source: LT, 2019

1.1-Introduction

About 95% of global food production depends on soil (FAO, 2022). A non-renewable resource, indispensable for food production, it contains most of the crucial nutrients for plant growth, soils are the basis of agriculture as elsewhere in the world, also in Angola unsustainable agricultural practices, overexploitation of natural resources and population growth are putting more pressure on soils in Angola. The physical, chemical, and biological characteristics of soils are of vital importance in countries where agriculture plays a primary role in the national economy, and in particularly for the lives of farmers. Pedological analysis, the field and laboratory study of soils as natural landscape bodies, plays a fundamental role in agricultural management systems and practices with the purpose of delivering enhanced sustainability of ecosystems and quality of the environment (Basher, 1997). Thus, a chemical and mineralogical analysis of soils is vital to obtain new understanding of chemical pathways in the environment and in doing so enhance the quality of agricultural products and ensure the sustainability of the agricultural system. Soils differ from region to region, from area to area in quantity (layer thickness) and quality. Soils of tropical and subtropical regions where chemical weathering predominates fundamentally differs from soils of regions higher latitudes where physical weathering is more prevalent. Every rock and every mineral decompose in a unique way. Smaller portions disintegrate more intensely than the more massive parts, and certain constituents of the rocks are more soluble than others. Other contributions to soil nutrient status incudes amendments as part of agricultural land management and the continuous use of the soil under conventional practices can influence its productivity (Matson, Parton et al. 1997, Hurni, Abate et al. 2010) as well as mediating changes in organic matter, soil structure nutrient flow, root growth and water movement.

So, the information on the status of nutrients in soils is essential to provide better mechanisms necessary for a sustainable agriculture. Factors such as fertilization, soil texture, weathering (soil micromorphological characteristics) influence the chemical, physical and biological properties of soils and consequently on the nutrient status.

However, there is a scarcity of scientific research in Angola that exposes a knowledge gap in many areas and more specifically in the soils field. This fact has an impact on the sustainable management of agricultural land by farmers and on research work.

It is the purpose of this thesis to establish the contributions of weathering, traditional land management and soil texture to nutrient status in Angolan agricultural soils. In doing so the thesis offers new understanding of chemical pathways in environmental and soil systems that are of vital importance in sustaining local agricultural communities.

This research seeks to evaluate nutrient element status in Angolan agricultural soils and explain these the identified levels and patterns by assessing the relative contributions of cultural residues on soil nutrient dynamics, geological weathering (micromorphological features), and soil texture.

1.2-Thesis aims and objectives

Angola, a country located in the southern part of the African continent, has an extension of arable land abundant water, good solar radiation throughout the year, factors that empower it to become a major agricultural producer through environmentally friendly processes. The government is committed to agriculture as a way of enhancing diversification of the economy and reducing the country's dependence on oil. For agriculture to be effective, changes are necessary in academic research, business knowledge and government oversight; furthermore, data on soils and agricultural systems does not exist or are outdated and the reasons for that are the lack of research. It is urgent and vital to do more to understand and improve the use of agricultural soils and so this program of research will integrate chemistry and sustainability approaches to give new understanding of chemical element cycling and nutrient availability within agricultural soils in Angola. This will be applied to and traditional agriculture system.

At the same time this research seeks to deepen knowledge about weathering, soil erosion and movement of soils and sediments making it a contribution not only to Angola but for the southern part of the African continent.

To address to this aim, this programme of research will create new understanding of nutrient status in Angolan agricultural Ferralsols. Key new knowledge will include:

- Current nutrient status of Angolan agricultural soil profiles; this will include –
    - profile based bulk chemistry analyses.
    - micromorphological assessment of nutrient location within the soil architectures

The objectives are, explain nutrient levels as a function of –

- geological weathering.
- cultural amendments – including biochar contributions.
- landscape erosion modification

and assess relative contributions of these processes to nutrient levels

In doing so the programme of research will set element analyses in a broader landscape-based framework and help identify more focussed and sensitive methods and mechanisms aimed at correction and improvement of deficiencies in agricultural soil nutrient status

1.3-Literature review

1.3.1-Angola soils

The Republic of Angola is situated on the west coast of Africa, bounded to the north and east by the Democratic Republic of Congo with Zambia to the east, Namibia to the south and the Atlantic Ocean to the west. It has a territorial area of 1,246,700 km^2, situated between 4º 22' and 18º 02' south latitude, and 11º 41' and 24º 05' east longitude with a coastline of 1.650 km alongside the Atlantic Ocean and a land border 3 times this length. The population is estimated at around 34 million for the year 2021 inhabitants (world bank), the country is constituted in18 provinces with its capital at Luanda. Angola is rich in natural resources and agricultural land. It is the founder of the Community of Portuguese Speaking countries

(CPLP) and since 1992 belongs to the Southern African Development Community (SADC) (Figure 1.1).

Angola is a country with potential in its natural resources and minerals, and its soil is part of this potentiality. Its territory has a diversity of soils resulting from different ecosystems. Most soils in Angola are of two types: Ferralsols and Arenosols. Updated studies of Angolan soils are scarce. First information on Angola's soil paedology dates to the forties. According Sertoli (1956) the study of Angolan soils began in a more accentuated manner by various private and research bodies. From these studies emerge the first project that gave rise to the general map of Angola's soils (Sertoli, 1956). Later, another project emerges with a nature covering the entire territory of Angola called "the generalized map of the soils of Angola," encompassing the characteristics of typology, classification, and geographical distribution of existing soils in Angola. This important document was updated and in 1997 the "4th approximation" WRB classification as it is known until today. The origin of soil formation in Angola is affected by factors such as evaporation, wind, and rain. Figure 1.2 represents the map and stratigraphic profile of the soils of Angola. As already mentioned, the predominant group of soils are Ferrasols and Arenosols with incidence in the areas of the central and Western plateau and in half of the eastern area, respectively.

At central and Western plateau is constituted by Ferrasols soils. These soils are highly weathered with red or yellow colour due to the oxidation of their iron and aluminium quantities and have large horizon boundaries. Its profile encompasses the A1, A2, B1, B2 and C1 horizons. Among these horizons, B2 is the one that is most evident for its thickness and especially for its structure and porosity. Moreover, typically have low water- holding capacity, and suffer the loss of nutrients and organic matter due to leaching. Besides, they have weak cation exchange capacity and degree of base saturation. The water suitability for agriculture is correlated with the mode of conservation of the soil at the surface, thus enabling its use for crops during the year. Its material disintegrates into small aggregates of quartz, kaolinite, and different amounts of iron (goethite) and aluminium (gibbsite) oxides. Depending on the ferrosol's soils have more or less well defined humiferous horizons and clay-poor horizons, clearly visible and with a certain thickness. 23% of Angola's territory is covered by Ferralsols (Mendelsohn 2019).

The Eastern part is formed by the Arenosols or psammitic group covering 53% of Angola (Mendelsohn, 2019). This type of soils has sand in its composition and quartz grains, has a high-water infiltration capacity and they are deficient in mineral nutrients. Besides, they have low accumulation of organic matter. Due to its characteristics (low content of nutrients and organic matter), its agricultural suitability is low. However, they can be improved for agricultural exploitation for the cultivation of vegetables, millet, and sorghum. This improvement can be done with specific fertilizers and proper treatment.

Geologically Angola is a country with soils rich in metals such as iron (Fe), manganese (Mn), titanium (Ti) and chromium (Cr), as well copper (Cu), lead (Ag), zinc (Zn), tungsten (W), nickel (Ni), lithium (Li), cobalt (Co), gold (Au) and silver.

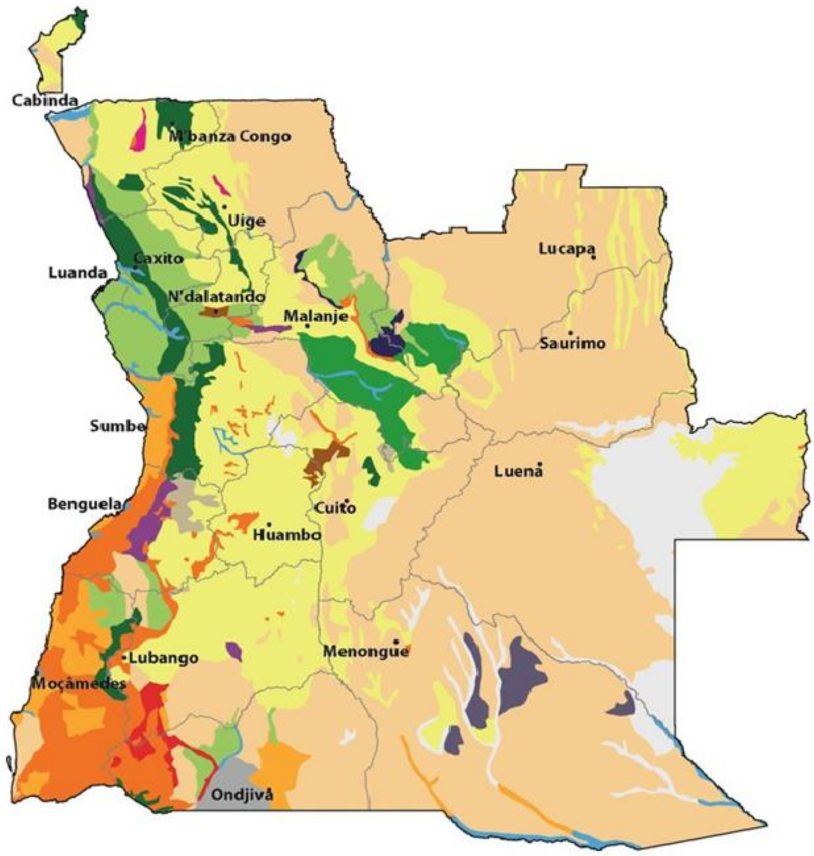


Figure 1. 1: Outline the main soil types of Angola, illustrating the predominance of Arenosols in the eastern half of the country, and Ferralsols across the western and central plateau. Source (Mendelsohn., 2019)

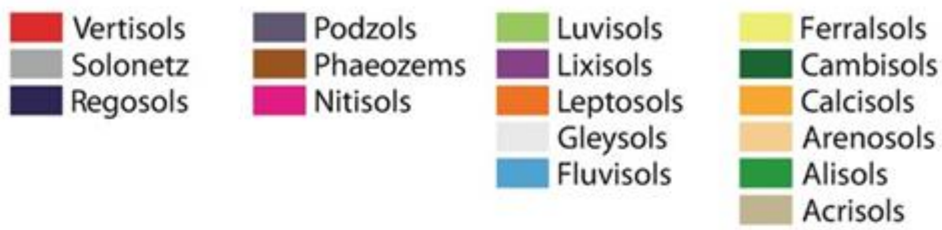


Figure 1. 2: Legend of Angola soils map. Source (Mendelsohn., 2019)

1.3.2-Agriculture in Angola

Modern & traditional fertiliser practice in Angola

Due to the different concepts that the terms modern and traditional agriculture suggest, for the purpose of this thesis these will be defined as follows: Modern agriculture is scientific and specialized, characterized by low labour inputs, uses modern techniques and technologies, such as the study of soils, agricultural machinery, monoculture, and high agricultural yield. Traditional agriculture uses artisanal techniques, polyculture (produces various products in the same field) and relies on indigenous knowledge. Farmers have always developed mechanisms and methods, beneficial in terms of food security and the conservation of biodiversity (Altieri 2004). Traditionally, Angola is a country with a great territorial extension rich in natural and mineral resources and agriculture has always been a source of sustenance for the local communities prior to and after colonization (1900-1975). Practiced through to today, for most of the rural population traditional agriculture is a dry farming without additional resource water provided by the farmer; the soil is fed only with rainwater and / or groundwater. Moreover, the production is a subsistence production, producing the minimum amount, without surplus, for the needs of the farmer and his family. Agricultural products are maize, cassava, bananas, sweet potatoes, and peanuts. The technical level is primitive because they do not use chemicals or sophisticated equipment. Families who cultivate the land (parents and children) make their own environmental interpretation from traditional knowledge and pass this knowledge from generation to generation. They do not use chemicals or heavy machinery.

Many farmers use a combination of different utensils or equipment and types of power to aid in this activity. Hoes, machetes, animal traction plough are the most used. Soil preparation and fertilization include burnings, crop rotation (beans / beans, corn) and the use of organic matter such as cattle manure and compost. In addition, a small percentage of farmers make use of inorganic fertilizer, but not dosed for lack of scientific knowledge. In this type of agriculture, the crops produced are cassava, corn, vegetables, beans, and fruits.

Modern agriculture appeared in Angola during the colonial period, related to demographic and political factors. These factors forced local farmers to use the land more intensively, resulting in soil exhaustion. The use of fertilizers, pesticides and machinery has grown to sustain intensive agriculture. Modern agriculture aims to supply various businesses and accelerate development, and as agricultural production has grown Angola has become a leading exporter of cotton and coffee. In 1975 when the nation became independent sugar, sisal, and corn (from traditional cultivation) played key role in the country's economy (Valério and Fontoura 1994).

With the end of colonization, the new government had as a slogan for the country's development - 'agriculture is the basis and industry the decisive factor'. Agriculture is a more elaborate process today and is planned to have positive impacts on the economy and ecosystems. Currently in Angola, agriculture is characterized by private investments in large cultivation areas (farms) but still with few development results (Ovadia 2015). Characterized using technology, chemical fertilizers and liming, the products include corn, beans, rice, manioc, and some animal breeding such as cattle and chickens. Modern agriculture is hugely dependent on irrigation, drainage, technology, and science with Angola having development support of other nations including China, Italy, Belarus, Germany, and Brazil for the development of its agriculture.

1.3.3-Nutrients-macro and micro

Knowing the soil fertility of an area is one of the key factors in the context of sustainable agricultural production. This analysis is essential so that the farmer can diagnose the chemical and physical conditions, nutritional levels, acidity, and the size of the particles, allowing to determine the need for liming, and which nutrients must be supplied through fertilization. For this it is necessary to analyse the nutrients on soils.

Nutrients constantly required by plants can be grouped into soil macronutrients and micronutrients. Macronutrients- a chemical element necessary in greater amounts (approximately) 50 mg/kg in the plant for the growth of plants. Includes Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg) and Sulphur (S). Micronutrients- a chemical elements needed in only extremely tiny amounts (< 50 mg/kg in the plant) for the growth of plants. Examples are Boron (B), Zinc (Zn), Iron (Fe), Manganese (Mn), Copper (Cu), and Molybdenum (Mo). The chemical factors associated with the dynamics of nutrients in the soil range from the presence of toxic elements, organic matter, mineralogical composition of the soil. In addition, the reactions of sorption, precipitation, and salinity. Moreover, a balance between the concentrations of different soluble nutrients in the soil must exist. Most of the tissue of the plants is synthesized by the nutrients and more than 90 percent of the (dry weight) plant tissues are composed of Carbon (C), Oxygen (O) and Hydrogen (H). Carbon and Oxygen are obtained by air through photosynthesis. Hydrogen is supplied from the water contained in the soil. The rest, with exception of some nitrogen supplies, are obtained from the soil solids. Of the essential elements, only 5-6 percent are derived from soil constituents. However, the nutritional elements obtained from the soil are those that limit the development of crops. Plants absorb chemical elements without which or in the absence of one or more the development of the plant is affected. Nutrients are essential elements of plant growth, and these must have ideal concentrations and in usable forms for good growth of the plants. Table 1.1 shows the location of macro and micronutrients, carbon and hydrogen in the periodic table and their form of absorption. All are fundamental for plant growth, flower, and fruit formation. Nutrients are added to the soil when they do not have them in the required amounts. While the soil solution acts as the main source of nutrients, plants are also able to modify the chemistry of the rhizosphere, the root environment. Through nutrient uptake, roots deplete the immediate soil solution causing diffusion gradients of some elements (such as K and P), convective flow and desorption of elements from the surfaces of clays and organic matter. Additional nutrients enter the soil solution through organic matter decomposition, from the atmosphere and from the soil minerals. Lack of macronutrients in soil occurs due to limited availability and poor balance with other nutrients thus affecting plant growth. The primary macronutrients, Nitrogen (N), Phosphorus (P) and Potassium (K) are supplied to the soil as fertilizers and as manure. Secondary macronutrients, Calcium (Ca), and Magnesium (Mg) are added to acid soils via limestone although may also be available depending on rock type – and associated weathering. Sulphur (S) enters the soil through fertilizers such as manure. Micronutrients or trace elements are used in exceptionally low quantities by higher plants, being present in the soil moderately and reduced availability. As a result, even though plants absorb them little, the effects of agricultural production over the years reduce the amount of these elements present in the soil. Table 5 presents the nutrients classification.

Macronutrients are needed in greater quantity with Nitrogen required in largest quantity (apart from C and H) by plants. It interacts with Phosphorus (P), Sulfur (S) and Potassium (K). This element when absorbed, is reduced, and is incorporated in organic compounds. Adsorption occurs in the form of nitrates (NO_3^-). The adsorption of ammonia (NH_4^+) restricts the absorption of cations. Phosphorus is absorbed from soil solution in the anionic form. It originates as carbon-based polyphosphate complexes including adenosine triphosphate (ATP) and adenosine diphosphate (ADP). Deficiency of phosphorus causes serious problems to metabolism and plant development. It also causes a reduction in the number of fruits and seeds. An excess implies deficiency of micronutrients such as Iron (Fe) and Zinc (Zn). Potassium concentration in plant tissues varies according to species and agricultural management. Chemically it does not form a covalent bond and so does not form stable complexes; it can therefore be limiting in soil systems. It acts as an enzyme activator, in protein metabolism, and in photosynthesis. Potassium together with calcium and magnesium has the function of maintaining the ionic balance with the anions. Micronutrients are required less by plants but may be critical to plant growth. The amount and availability of micronutrients depends on the minerals of the rocks from which the soil originates. Soils with low content of clay, acidic soils, and soils with low content of organic matter often have a deficit of micronutrients. Under acidic conditions, the concentration of soluble micronutrients can be toxic to plants. Under basic conditions, the availability of micronutrient cations is maximal.

Table 1. 1: Macronutrients, Micronutrients, Carbon, Oxygen and Hydrogen

Basic	Absorbed form	Primary macro	Absorbed form	Secondary macro	Absorbed form	Secondary micro	Absorbed form
Carbon C^6	CO_2	Nitrogen, N^7	NO_3^-, NO_2^-; NH_4^+	Calcium Ca^{20}	Ca^{2+}	Iron, Fe^{26}	Fe^{2+}
Oxygen, O^8	H_2O	Potassium, K^{19}	K^+	Magnesium, Mg^{12}	Mg^{2+}	Manganese, Mn^{25}	Mn^{2+}
Hydrogen, H^1	H_2O	Phosphorus, P^{15}	$H_2PO_4^-$; HPO_4^-	Sulphur, S^{16}	SO_4^{2-}	Cupper Cu^{29}	Cu^{2+}
						Zinc Zn^{30}	Zn^{2+}
						Molybdenum, Mo^{42}	$HMoO_4^-$
						Chlorine Cl^{12}	Cl^-

The numbers above the letter refer to the atomic number of the element; the number with + or – refer to the charges of ions.

1.3.4-Erosion-topography

Soil erosion is a major threat in many areas of the world (Pennock 2019). It is a complex process and therefore subject to different definitions. Although erosion is a natural process, it has been intensifying due to human activity (Champion 1933, Pimentel and Kounang 1998, Toy, Foster et al. 2002). According to FAO (2019), there are 3 types of erosion, wind, water, and tillage. The same source states that in wind erosion, the soil breaks down due to the forces exerted by wind on the soil surface, and this type of erosion occurs in Middle East and North Africa region. Water erosion often surface runoff is concentrated in small channels, known as rill erosion, or deeper incision known as ravine erosion. Tillage erosion causes thinning of soil in top slope areas and can result in super-thickened deposition soil bottom slope positions (Pennock 2019). Every year close to 10 million hectares of agricultural land are lost due to soil erosion, which results in a decrease in agricultural land available for world food production (Lal and Moldenhauer 1987). Moreover, when soil is eroded nutrient such nitrogen, phosphorus, potassium and calcium are lost (Lal and Moldenhauer 1987).

Climate, soil, and topographic characteristics determine runoff and erosion potential (El-Swaify 1997). Accelerated soil erosion is often associated with deficient vegetative land cover (Langdale, Blevins et al. 1991, Wolfe and Nickling 1993, Fattet, Fu et al. 2011, Sun, Shao et al. 2014, Blanco-Canqui and Wortmann 2017). On the other hand, the size and stability of soil aggregates are factors that affect the susceptibility of the soil to wind erosion (Fattet, Fu et al. 2011, (Sirjani, Sameni et al. 2019) as well soil texture (Belnap, Phillips et al. 2007, Sirjani, Sameni et al. 2019).

Soil erosion is acts differently in regions with different climatic zones, and water erosion is more common in humid areas, and wind erosion predominates in arid regions although both types of erosion can occur in arid or semi-arid regions (Du, Dou et al. 2016). Soil erosion is very high in Africa (Ananda and Herath 2003) and Angola is not different. In Africa this phenomenon is under more serious threat due to enormous pressure on land, associated with lack of proper land management practices, awareness of farmers and application of specific policies to mitigate soil erosion (Lal and Moldenhauer 1987, Lal 1995, Fenta, Tsunekawa et al. 2020) On the other hand, about 50% of the soil in Africa is classified as Arenosols, Latosols and Ferrasols and these soil types have inherent low fertility due to limited nutrient reserves (Wolka, Mulder et al. 2018). Eroded soil carries away vital plant nutrients such as nitrogen, phosphorus, potassium, and calcium (Pimentel, 2006) and nutrients in general (Zheng 2005, Pansak, Hilger et al. 2008, Wolka, Mulder et al. 2018). Moreover, erosion reduces soil's organic matter content and as result impact in aggregate stability and water holding capacity (Wolka, Mulder et al. 2018). In addition, the topography, precipitation, wind and exposure together influence the susceptibility to soil erosion (Pimentel 2006). Soil erosion (by water) is strongest in areas with steep slopes and where rainfall and runoff meet terrain with little vegetation cover or other protective measure (Vrieling, Hoedjes et al. 2014). Much of the country (Angola) comprises igneous granites modified by metamorphism. This rock produces siliceous sand which gives rise to soils with little cohesion and poor fertility. With Angola's tropical climate rains are strongly erosive and numerous, causing soil deformations as furrows, holes, and with gravity causes ravines to emerge. Civil engineering and quarrying can also contribute to soil erosion as often the natural vegetation cover is not restored after earthworks.

Soils with nutritional resources reduced by erosion consequently has low plant growth, thus affecting the productivity.

1.3.5- Understanding geochemistry

Weathering

Weathering is a typically destructive process, which allows the development of new minerals from altered ones. It is the most fundamental of the geomorphic processes, acting in a marked way in the creation and modification of landforms and also, in the formation of soils (Deepthy and Balakrishnan 2005).

Chemical weathering

Weathering is the physical and chemical processes of altering rocks when exposed to the atmospheric conditions of a climatic region. Rocks of different geological origins and located in different climatic regions consequently have different reserves of different elements. Water is the primary agent of weathering entering pores and fissures in rocks, reacting with the components of the mineral structure, and giving rise to soils with distinct characteristics. The physical and chemical properties of water play a key role in weathering processes; its density in the liquid phase varies with temperature, it is expansive during freezing, and its surface tension is greater than other fluids. Chemical weathering acts on rock minerals by a range of chemical reactions including dissolution, hydrolysis, carbonation, oxidation, and reduction resulting in release of elements and clay formation, in turn influencing the nutrient status of soils (Jackson, 1959). Outline of these critical processes is given below:

Dissolution: This is the first and most important chemical weathering process with certain minerals or rocks such as halite, calcite, dolomite, gypsum, and limestone more readily dissolved by water than others. Pure water when mixed with other chemical agents, such as oxygen and carbon dioxide, substantially increase its efficiency in weathering.

$CaSO_4.2H_2O \leftrightarrow Ca^{2+} + SO_4^{2-} + H_2O$

Anhydrite

$CaCO_3 \leftrightarrow Ca^{2+} + CO_3^{2-}$

Calcium carbonate (found in calcite and aragonite)

$NaCl \leftrightarrow Na^{+} + Cl^{-}$

Sodium chloride

Hydration: This process is based on the addition of water within a mineral and its adsorption through the crystalline reticulum. When hydrated, the minerals expand. In contrast, the dehydration mineral loses water when the volume is reduced, e.g.: reaction of hydration, transformation of anhydrite into gypsum

$CaSO_4 + 2H_2O \rightarrow CaSO_4.H_2O$

Hydrolysis: This is the reaction between mineral and water, or, more precisely, between the H or OH ions of the water and the ions of the mineral. An example of the hydrolysis is decomposition of the silicates (micas, feldspars, clay), e.g.: hydrolysis of alkali feldspar

$KalSi_3O_8 + 4H_2O \rightarrow K^+ + OH^- + Al_3^+ + 3OH^- + 4H^+ + SiO_8^{4-}$

Carbonation: This involves the reaction between a solution H_2CO_3 and minerals. All water in contact with air contains dissolved carbon dioxide: $CO2 + H_2O \leftrightarrow H_2CO_3$. In weathering, the action of surface water makes carbonation a common phenomenon in nature. Iron, calcium, potassium, or sodium are the most susceptible minerals to the action of carbonic acid. Carbonation is more common in calcareous rocks. In tropical regions, carbonation is intense, stimulated by CO_2 from vegetation.

Oxidation and Reduction. Oxidation: This occurs in surface soils when water with oxygen penetrates the subsoil. In this process, the oxygen reacts with the minerals containing Iron, Manganese, and sulphur. The iron (Fe^{++}) present in many minerals (pyrite, olivine, augite, and biotite) is transformed into ferric compound (Fe^{+++}). The ferrous compounds have a greenish-grey colour, and the ferric a yellow colour; if hydration occurs at the same time, yellow limonite forms. In the humid regions, iron oxides transmit reddish brown or yellow colours to the mantle of weathering depending on the degree of oxidation and the amount of water present in the iron oxide. Red, brown, or yellow colours of sedimentary rocks (sandstone or calcareous) indicate oxidized environment.

Studies on weathering are rare in Africa and Angola in particular. However, are necessary because there is a rich and infinity of information to be discovered.

1.3.6-Land management in Angola – synthesis

The economies of most African countries rely heavily on agriculture that uses rainwater as the main engine of economic growth. Angola is one of the countries in Africa with enormous potential for agricultural development. In a country with elevated levels of poverty, agriculture plays a significant role in self-sufficiency and food security. Furthermore, it is an excellent source that generates employment in rural areas and is responsible for the development of other economics sectors. Its surplus is raw material for the manufacturing industry and for commercialization.

Angola was in the colonial period a self-sufficient country in agricultural terms. The country was an exporter of coffee and corn, beans, and palm oil. Huambo and Bié were in this era the biggest food producing provinces in Angola.

The more than 20 years of civil war with the consequence displacement of populations from rural areas to cities, abandoning agricultural production, to mined lands dragged the country towards the loss of power in agriculture. As a result, the country became dependent on exports, driving it towards mostly subsistence farming.

For the question under study, family farming will be defined the same as traditional farming as that which is practiced by farmers or “peasants” without the use of advanced techniques and means. In addition, they produce for their subsistence and the surplus for domestic markets, production is based on knowledge acquired by generations (Loomis 1984). Land management, preparation, cultivation and, harvesting in traditional farming are the result of cumulative experience.

The agricultural sector in Angola is controlled by the Ministry of Agriculture and Fisheries (MINAGRIP). This government body, in partnership with different national and international entities, administers policies and programs related to farming. Due to climatic and geographical attributes of the country, there are three agro-ecological zones. The North with a humid climate, the South with a semi-arid climate and the central plateau with a sub-humid climate. It is in the highlands of central Angola where farming is most intensively practiced, in the provinces of Huambo, Bié, Benguela and Huila. Followed the provinces of Uíge, Bengo, Zaire, Malanje and Cuanza Norte and Cuanza Sul.

The family farmer in Africa is mostly characterized by having a family with men marrying one or more wives and living under the traditional authority of the village chief “soba” (Jul-Larsen and Bertelsen 2011, Almeida 2015). Jul-Larsen (2011) states that the category of family farmer in underdeveloped countries is selective as not all peasants become a family farmer because not all will be able to access financial credit. The “soba” makes the most important decisions in the village, plays the role of judge in managing conflicts and he is the link between communities and local governments (Carranza, Treakle et al. 2014).

Land management is another of the major problems facing African farmers, due to the characteristics of the soils, very hard when dry and with limited stability when wet (Pal, Kadu et al. 2003, Erkossa, Stahr et al. 2005) In Angola, the preparation of the soil for farming is done with deforestation or felling of trees, burning the residues of this process.

Men and women work the land, the latter being 54 percent of agricultural workers (FAO, 2008).

In relation to access to land, the size of properties is often small, with sizes ranging from two to three hectares. These parcels are in different zones denominated in three categories. Ochumbo is the area used for the cultivation of vegetables and fruit trees, is located near to houses; Ongongo is a slightly larger area, is located far away field, it is the most common; Onaka, small swampy field, situated near rivers and drainage systems.

Many small farmers cultivate the land with large work aided by hand tools such as hoes or machetes, others own animals or rent traction animals (oxen) to assist in the land preparation and weeding. Farmers are totally dependent on the distribution of rainfall. Irrigation is done with rainwater (only when it rains) and some of them use artesian boreholes. After harvesting the crop, the waste is left in the soil as a form of protection.

The treatment and conservation of the soil is done with the use of inorganic fertilization and liming. Fertility in Africa has always been below average when compared to other continents (Morris 2007) and represent only a third of these inputs (inorganic fertilizers) (Smaling 1993, Morris 2007, Ngetich, Shisanya et al. 2012) The importation of fertilizers and animal feed are other aspects of the day-to-day life for most of these small African farmers (De Jager, Nandwa et al. 1998) and in Angola the situation is similar. In the case of Angola, the most frequently used are NPK (Nitrogen, Phosphorous, Potassium), Urea, and ammonium sulphate. Some studies show that the use of fertilizers by farmers is Sub-Saharan African is low ((Kaaya, Mwangi et al. 1996, Chianu, Chianu et al. 2012) being only a tenth of the world average (Vlek 1990).

The lack of animals that can provide this material and the lack of knowledge make this practice still little used in these regions. Animal manure as cattle, sheep and goats are the most used (Lekasi, Tanner et al. 2001). Kitchen scraps are not much used. Add that due to the species of the African soils, the organic product does not solve the deficient fertility of these soils. On the other hand, some of the constrains to the fertilizers in Angola are marked by small markets, lack of credit, lack of knowledge on fertilizer use. Moreover, the availability of fertilizers when necessary and high prices of products are also crucial factors.

Although with many technical and knowledge limitations, traditional farming practiced by farmers in Angola has undergone changes and adaptations, building balances between existing resources and communities.

1.4- Overarching research aims for the thesis

Culturally African agricultural soils are essential for the socio-economic development of the region (Chianu et al., 2012). On the other hand, there is an agrarian stagnation on the continent due to misuse of one of its main resources (soil) (Lal, 1987) as well the lack of knowledge.

The aim of this study is to gain knowledge of the nutrient status of soil in Southern Africa region and the relationship of factors associated with the gap of knowledge (soil texture, land management and weathering in terms of soil micromorphology) that contribute to its status. Figure 1.1 is a representative synthesis of the steps involved in this research.

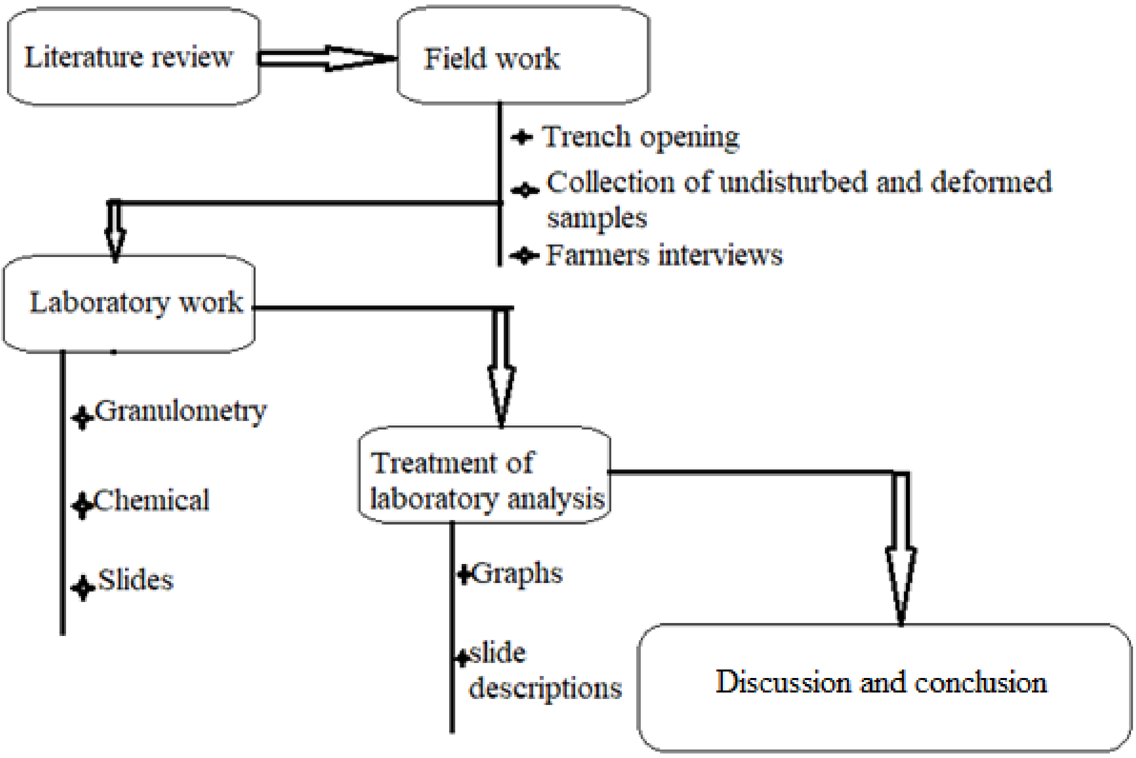


Figure 1. 3: Representative thesis

Chapter 2: Farm survey Huambo

Photo: agricultural field- Angola

2.1-Introduction

In some sub-Saharan African countries, agricultural development has grown less rapidly than the population, agricultural incomes are weak and, in some cases, have fallen (Cleaver, Donovan et al. 1995). Angola has a great agricultural potential, which is the largest economic activity in the country. One of the Angola government goals is to increase the sustainability and productivity of family farming to guarantee food security, fight rural poverty and diversify the economy. However, the percentage of land with agricultural potential used in this activity is low, less 15% (FAO, 2021), 0.2% of the sow surface is irrigated and the rest depend on the weather conditions of the country (MAP, 2017). Among the factors related to the poor land exploitation is the lack of mechanization and technology, lack of finances and inputs, precarious infrastructure (FAO, 2021) and little scientific research on soils for agricultural purposes. A real analysis of the agricultural soil and the problems of family farming must involve the participation of its stakeholders which are the farmers. Their experience and knowledge of land use and management are essential in assessing soil quality.

This chapter addresses the lack of discussion by assessing the relationships between traditional farmers and agricultural soils to evaluate the efficiency of nutrient management. It seeks to determine the agricultural land management behaviours influencing soil nutrient element levels. Based on an interview approach and situational analyses the chapter first classifies the range of land management behaviours, including cultivation practices and nutrient element management within Huambo province Angola.

2.2-Description of local farming systems (land management in Huambo province)

Sustainable land management is the way to achieve success in agricultural activities. In rural communities in Angola, agriculture is dominated by small farming families who practice in so-called traditional agriculture (property management is shared by the family and the food produced there is the main source of income for these people). Agricultural soil preparation requires strict criteria and precise techniques. However, poor agricultural management practices can cause soil degradation (Zingore, Murwira et al. 2007). The pre-existing nutrient element balances in the soil are broken when land is cultivated, and crops are removed. To prevent soil degradation and for an efficient management of the land, the farmers must attend to certain precautions and know the physical and chemical characteristics of the soil that allow the adoption of irrigation processes, soil preparation and adequate fertilization practices.

Irrigation and fertilizations may be undertaken to support plant grow and mechanisation can improve the efficiency of these processes. Irrigation facilities are mostly non-existent in rural areas which makes small farmers dependent on rain and vulnerable to climate change and natural catastrophes.

Soil preparation is done by ordinary tools. Small farmers in Angola cultivate their lands using hoes or machetes, some own animals or rent traction animals (oxen) to assist in soil preparation and with the family as the labour force. Proper soil preparation benefits its natural fertility. However, depending on the soil and its deficiencies, it often needs to be improved with fertilization techniques to ensure greater control of productivity and product quality.

Fertilization, inputs applied to the soil to replace nutrients that res essential for the development of crops is done by Angolan farmers mainly with inorganic products and in a timid way with organics. CAN (Calcium Ammonium Nitrate), NPK (Nitrogen, Phosphorous, Potassium) are the dominant compounds used. However, considering the broader agricultural system, economic and social constraints on use of fertilizers in Angola continue to result from small markets, lack of credit, lack of knowledge in fertilizer use, availability of fertilizer critical times in the agricultural cycle the high price of fertilizers and socially gendered

As an alternative to inorganic fertilisers, the use of organic fertilizers is recent in tropical and Angolan agriculture. The lack of animals that can provide this material and the lack of knowledge on how to work with these materials make this practice still little used in the Southern African region.

Small farmers

Small- scale farmers are defined differently in different countries, but in most cases, they cover households with up to 3ha (Nagayets 2005, Jayne, Mather et al. 2010, Masters, Djurfeldt et al. 2013, Lowder, Skoet et al. 2016). According to the definitive results of the 2014 Census, the population in Angola at the time of the census is illustrated in Table 1. The table shows the population distribution by gender in rural and urban areas.

Angola	*Men*	*Women*
Urban	62.9%	62.4%
Rural	37.1%	37.6%

Table 2. 1: Population in Angola (Census 2014).

Data collected by FAO and African governments report that the majority of Africa's poor live in rural areas and depend on agriculture for survival (Cleaver, Donovan et al. 1995).

2.3-Methodology

When the theme of the project was defined the importance of fieldwork was agreed. Knowledge of the current nutrient status, the lack of laboratories to test soil and, the lack of updates on of the impact of human activities are all factors that made fieldwork imperative. Fieldwork was conceived with the objective of obtaining updated information about the small famer's perception and their land management. In addition, this was supplemented with bibliographic analysis. Quantitative research: application of social surveys by questionnaire to farmers to analyse their practices in land management. Qualitative data: it includes farmers' responses to the open questions that were asked.

Data analysis techniques*:* Qualitative data, were worked on according of the type of answer and then, with the objective of qualitatively evaluating them a framework was created to categorize the information provided by the farmers equivalent to the same topic

2.4-Quantitative research

2.4.1-Field programme

Social survey fieldwork was undertaken based on local farming community interviews (Figure 2.1).

Figure 2. 1: Interview with small farmers-Ngongoinga. Photo: LT, 2018

The interviews were conducted with local farming communities; individual farmers (the ‘head’ of the farm) were interviewed in each of the study areas in Huambo province – Bailundo – 67 farmers, Lepi - 50 farmers, Ngongoinga - 64 farmers and Mungo-61 farmers. The enquiries took place the month of September 2018 (3 weeks), lasting 15-25 min. The survey therefore included the researcher and local agricultural extension groups who had been invited to assist with the interview process. Sobas (traditional entities) from each region have the function of organizing the local farmers for the interviews. The approach for apply the questionnaires was based in collective meetings, which occurred in place such as school’s community centers. The questionnaire consists of closed and open semi structured questions. (Appendix 2.1). The first part is related with local population (farmers), gender, age, marital status, and landholding size. The second part is the land management properly. In addition, we tried to understand the notions about the concept and functions of the soil, management and conservation, the use of management practices by farmers. At the commencement of the interview process a brief explanation was given of the reason for the research and it was an independent University research program. In addition, interviewees were informed that they could answers the questions freely. Responses included those that enabled completion of the questionnaire as well as qualitive 'free text' recorded as part of the conversations.

2.5- Social survey's findings

Subsistence farm 'heads." In rural areas women constitute the foundation of domestic life. In the same way as men, they dedicate themselves to agriculture as what is valuable to them and thus fulfil their role as mother, farmer, woman and responsible for the house.

Figure 2. 2: Women farmers- Huambo. Photo: De Sousa Teixeira, 2018

Of 242 interviews, 40.5% were women (figure 2) and 59.5% are men, both genders with age ranges between 19 and more than 40 years responded to survey. From the survey results there were no gender differences in land management. Both (women and men) have a similar knowledge base, with low level of knowledge of farmers and local leaders about the ways to protect the soil (FAO, 2014). Although the respondents who answered the survey were mostly men, it is know that in Angola it is women who represent the highest percentage in this line of activity (FAO, 2017).

Farm size

A study by Hazel cited by (Masters, Djurfeldt et al. 2013) reports that the average farm size has decreased for the African region as whole as well as in China. The study by (Masters, Djurfeldt et al. 2013) covers the distribution of agricultural land in 14 African countries and, observed that 80% of properties are smaller than 2 ha and operate about 25% of agricultural land. The results of this work show that the extent of the interviewees' individual farm holding ranges from 1 to 3 hectares. Farm 'heads' highlighted that property size means difficulties because of their scale limits the possibility of more efficient agricultural land management practices. These areas are characterized by houses are located on a small property designed Ochumbo, an area usually used for the cultivation vegetables and fruit trees, and Onaka, small wet fields situated near rivers and drainage systems used for growing vegetables, maize, and bananas. 48.8% of respondents said they have properties of less than 1ha and 48.5% answered to have (2-5) ha (Table 2.2).

Area	Responses
less 1 ha	48.76543
2-5 ha	48.45679
more 6ha	2.777778

Table 2. 2: Land size

Land preparation practices

The techniques of soil preparation, cultivation and harvesting originated from experience and passed down from generation to generation. For these farmers, the wisdom of life and work has of excellent value.

Tools: Use of basic cultivation tools was similar across all farms interviewed. These includes hoes, machetes, and shovels, with manual labour (figure 3) tractor (on occasions) and animal traction for land preparation, seeding of the land as well as in the harvest of the product.

Figure 2. 3: Tools used by small farmers- Huambo. Source: LT

Crop residues, burning and ploughing the land

Plant material (crop residues, pruning debris) are used as soil cover, protecting the land, and providing nutrients. In addition, it has an impact on soil pH, influences the availability of nitrogen, phosphorus and in tropical climates protect the soil for plant growth (Turmel, Speratti et al. 2015) and nutrient recycling is beneficial. Besides that, crop residues assist in weed control, helps to maintain, or improve soil fertility and decrease erosion (de Leeuw, 1997; Yaun et al., 2011). Most of the interviewees have the perception of the advantages of covering the ground with crop residues. It was observed that 93.8% of respondents from all regions use the harvest residues as a way to preparing the soil.

Burning of crop residues is a long-established practice in Angola as a form of land treatment and returning nutrient elements quickly to the cultivated soil. Some agriculturists use this to prepare their agricultural land to combat pests and plant diseases. Regarding the practice of burning in the study areas, farmers in the localities of NGongoinga and Bailundo and Lepi do not adopt this practice, and 19.7% in Mungo affirmed use the practice of burning.

Ploughing the land, Figure 2.4 illustrates the responses of small when asked about the way they use to cultivate the soil. 60% of farmers in Bailundo and 47% in Mungo region said they do it manually. Using machinery only 16% of peasants in Bailundo said yes. Animals, 47% and 38% in NGongoinga and Lepi, respectively.

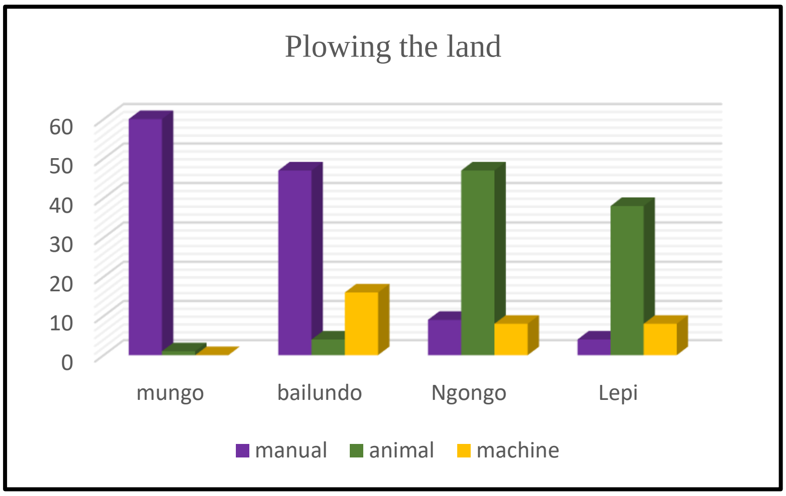


Figure 2. 4: Different ways of preparing the soil- Huambo

Fertilization.

Low use of organic and inorganic fertilizers is one of the biggest factors in increasing agricultural productivity of agricultural systems of West Africa (Bationo, Buerkert et al. 1995).

There are diverse ways to fertilise the land, including inorganic fertilisers and organic fertilisers and these practices are similar across crops. Angola does not produce fertilizers, so the existence of this product on the market depends in part on the support that the state provides to entrepreneurs in this segment (Republic Journal 137, 2020). It was fond in the survey that 75% of farmers use fertilizers when they can. However, the amount (Figure 2.5) and the days (Figure 2.6) of fertilization vary from region to region. The reasons that lead to this behavior and while most of smalholders realize the value of using fertilizers, they rarely apply them at the recommended rates, farmers cannot buy recommended quantities and the appropriate time due to the lack of the product in the market, the lack of credit, delivery delays, the high price and the low economic power of peasants. In addition, there is a lack of soil analyses due to the lack specialized soil laboratories and as result limited supervision and guidance by specialized technicians. Thus, farmers tend to devise their own practices in terms of what quantities to buy and application methods. So, regarding quantities of fertilizer applied, it was notable that more than 60% of respondents use less than 350 kg/ha. 87.5% in NGongoinga, 82% in Lepi, 56.7% in Bailundo and 41.7% in Mungo. Our results agree with those of other authors who report that the use of chemical fertilization in Africa is insufficient and often not affordable (Mwangi 1996, Breman and Debrah 2003, Bostick, Bado et al. 2007). Far from the 50kg/ha target established in the Abuja Declaration (FAO, 2006), only 8.4 Kg/ha of plant nutrients were used by farmers in SSA (Mwangi 1996). On the other hand, these values have doubled between 1990 and 2020 in 2020 from 3.6Mt to 7.1 Mt although the region (SSA) represented 4% of the global total in 2020 (FAO, 2022). Other studies show (Guo et al., 2010) that high rates and inappropriate times of nitrogen application result in the significant soil acidification and, therefore low nitrogen use efficiency and high costs.

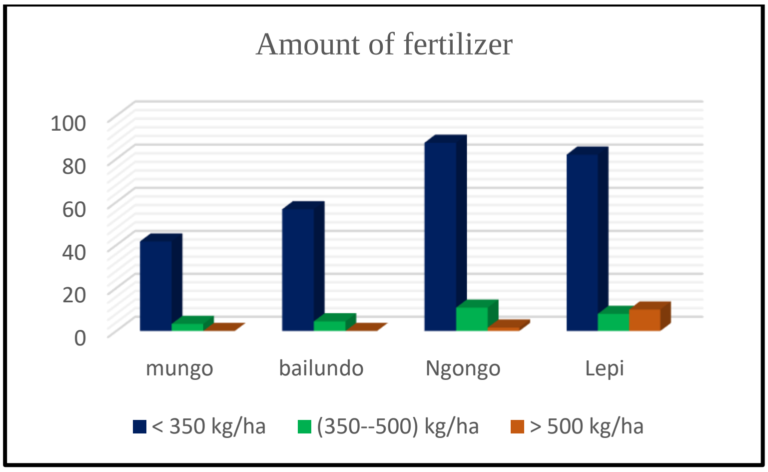


Figure 2. 5: Amount of fertilizer used by farmers in Mungo, Bailundo, NGongoinga and Lepi

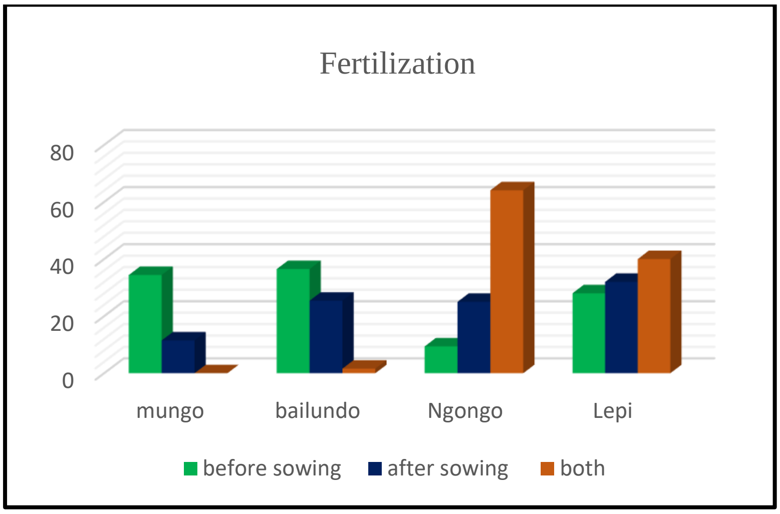


Figure 2. 6: *D*ays of fertilization used by farmers in Mungo, Bailundo, NGongoinga and Lepi

Regarding the amount of fertilizer. According to Table 2.2 it was found that most respondents use quantities less than 350 kg/ha. As mentioned above the number of inputs applied to improve crops depends on whether the product exit on the market and whether the small farmers have money to buy.

Amount fertilizer	**Mungo**		**Bailundo**		**NGongoinga**		**Lepi**	
Kg/ha	Frequency	%	Frequency	%	Frequency	%	Frequency	%
< 350	25	41	38	56.7	56	87.5	82	82
(350-500)	2	3.3	4.5	4.5	7	10.9	8	8
0	33	54.1	38.8	38.8	0	0	0	0
> 500	0	0	0	0	1.6	1.6	10	10

Table 2. 3: Productive inputs in Mungo, Bailundo, NGongoinga, Lepi regions. Source: survey data, 2018

Mineral fertilizers – NPK (Nitrogen, Phosphorous, Potassium) (12% + 24% = 12%) and Urea (Figure 2.7) are the most common mineral fertilizers on the market and used by small farmers in these regions. Related to the NPK, 44.3% of respondents in Mungo, 53.1% in Bailundo, 98.4% in NGongoinga and 50% in Lepi. Followed by ammonia (NH_4), with 54.7% in NGongoinga e 92% in Lepi. Urea is the least used and, when asked about this product, 5% in Mungo, 2% in Lepi and only 1% in Bailundo and NGongoinga of the farmers answered that they use it. These results are like those reported by (Soropa, Nyamangara et al. 2019), which states that the most fertilizer used by farmers in Zimbabwe is NPK. The same author states that nutrient deficiencies in SSA are more evident in smallholder sector, as they apply suboptimal fertilizer rates to their crop due to poverty and other limitations.

Figure 2. 7: NPK and UREA mineral fertilizers used by small farmers- Huambo. Photo: LT, 2018

Liming is another inorganic way of fertilising. Liming improves acidity, increases soil cation exchange capacity, and improves nutrient utilization. In regarding to liming only 5.8% of rural producers in the studied regions reported that they use this technique.

One of the important tools of rural producers are products that act in the prevention control pests. Herbicides and insecticides are used as defensive in pest control during crop development. Asked about the use of these products, only 5.4% of respondents in all regions said they use these tools.

Organic fertilizer. Organic fertilizer contributes to soil enrichment and nutrient supply. In addition, it improves its fertility, affecting the physical and chemical compounds as well as its biological activity. Organic fertilizers can include animal manures, flours, peels, and vegetable remain. Animal manure using cattle, sheep, and chickens (Figure 2.8) is an example of this. It was contacted in the research that only in Lepi some farmers have any animals. The answer to question related with animal manure shows only an exceedingly small proportion of agriculturists in the Lepi (2%) said they use this practice. This practice, although known by some small farmers, is not widely used by farmers because of the lack of animals in sufficient numbers to produce this type of fertilizer and the lack of technical knowledge and added to problem of lack of water that most small farmers suffer. That situation is similar with the study of (Mafongoya, Kuntashula et al. 2006) who reports that the amount of manure depends on several factors such as breed, herd size, management system and seasonal rainfall conditions. Generally, waste is prepared in the agricultural spaces themselves. The use of kitchen waste as organic fertilizer in the areas studied is applied without any preparation or mixture; these residues are dispersed into small fields in some locations. On the other hand, this result is at odds with the behavior of some farmers in Africa where organic fertilization mainly compost and manure are used (Rware, Kansiime et al. 2020).

Figure 2. 8: Animals belonging to the small farmers- Huambo

2.6-Results

The set of graphs illustrated in Figure 2.9 is the representation of land management in the studied areas, based on farmer interviews related to close question in survey. It is noticed that there are some differences in land management practice between these sites. In a similar work carried out by (Jul-Larsen and Bertelsen 2011) in two locations in the southern region of Angola, shows that the differences are related to socio-cultural and socio-political factors.

Although this work does not focus on the comparative study of management practices between the regions, it is possible based on the study conducted by these authors, to withdraw some analyses that perfectly fit the regions focused here.

Another factor are area and technique issues. The size of area owned by most small farmers is an average 2 hectare. In these cases, investments are less in animals, in agricultural machinery and instruments due to weak financial power. Further, the financial capacity of smallholder, the distribution/sale of surplus production, and the earnings as they are shared. In addition, the power of each individual farmer or associations to be able to purchase fertilizers, herbicide, insecticide, or the lack of this product in certain region compared to others and other materials essential to agricultural practice. The use of any type of fertilizer by farmers in all localities is driven by expected yields and fertility of land. Those who use organic fertiliser (most of the time, manure), indicated that it is cheap compared to inorganic fertilizer and the product stays on the land longer.

The socio-political factors refer to the articulation among the communities and the government figure, to the rural extension's groups and deficient articulation between Institutions and small farmers.

Access to education, health, and basic sanitation play a key role that indirectly affect the entire process. In common all studied areas have the climate problems that even this varies from region to region affecting land management. There is a set of aspects that must be considered that led to differences in land management between these regions.

On the other hand, these findings show that are the men are the ones who compared to women have attitudes more focused on good land management, which suggests that there is a gender gap in relation land management. Huyer (2016) already reported the existence of a gender gap in productivity and obtaining resources when dealing with women in agriculture.

Second, currently the challenges associated with climate change, agriculture and food security require a more integrative approach in order to adapt knowledge to action (Vermeulen, Aggarwal et al. 2010) whether they are men or women.

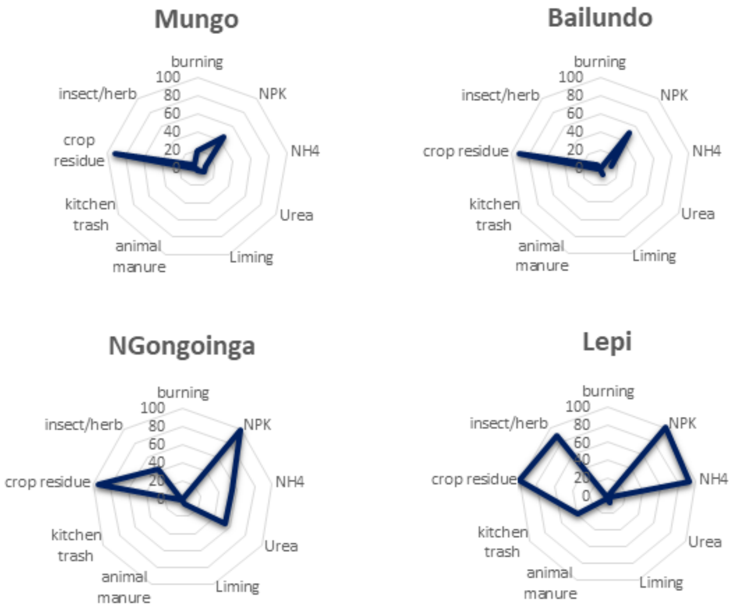
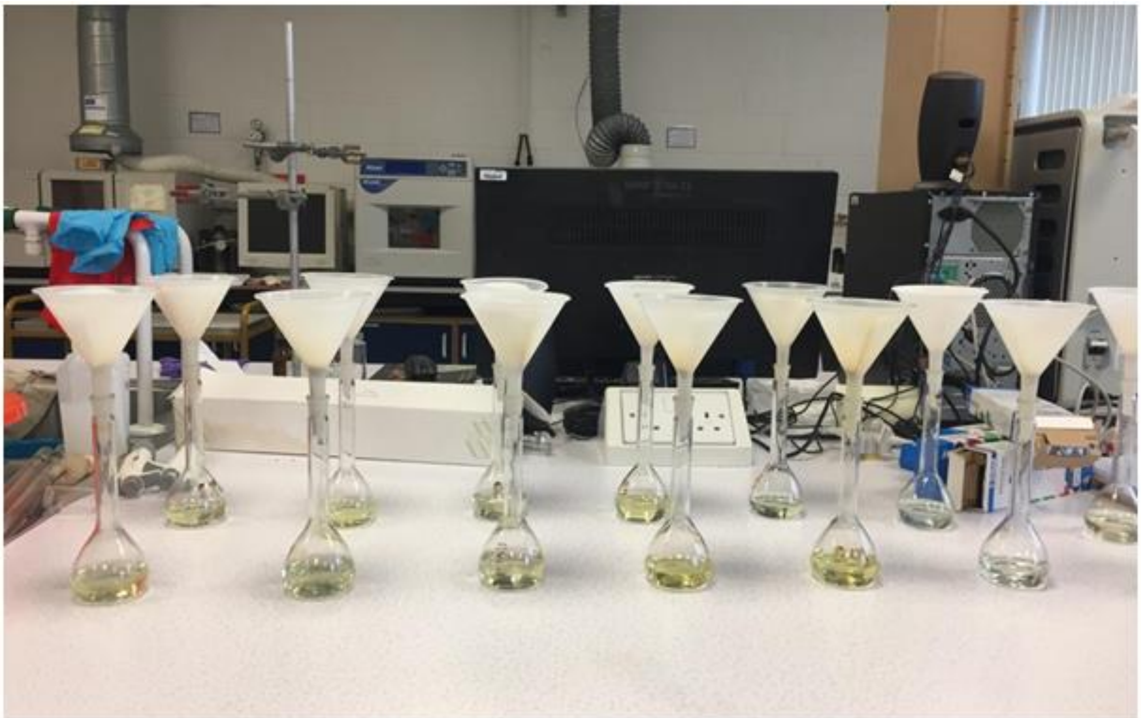


Figure 2. 9: Land management practices in Mungo, Bailundo, NGongoinga, Lepi

Chapter 3: Data collection



Instrument laboratory- University of Stirling, 2019
Source: LT

3.1- Introduction

This chapter sets out the approach and methods used to address the research questions identified in Chapter 1. Field-based work, including sampling approaches, are, followed by a consideration of the laboratory-based analyses required. Analyses include pH, cation exchange capacity (CEC), and particle size as fundamental soil assessments. More advanced analyses include inductively coupled plasma (ICP) to determine nutrient levels in the selected soils. Micromorphology with associated SEM/EDX analyses will assess soil architectures and their relationship nutrient distributions within the soils.

3.2- Research Design

The aim of this research is to evaluate the nutrient element status of representative Angolan agricultural soils, and to explain the identified nutrient concentrations and patterns by assessing the relative contributions of cultural residues, geological weathering, and texture on soil nutrient status.

Two key area (Huambo and Luanda) with undulating topography and vital to the agricultural economy of Angola has been selected for this work, with soil profile locations placed on catena transect lines giving upper, middle, and lower slope locations. The physical and morphological analyses carried out in the field and laboratory included Munsell colour, texture, and structure. Laboratory analyses included granulometric analysis through Counter Coulter equipment, pH, and CEC together with inductively coupled plasma optical emission spectrometry-ICP OES, allowing the simultaneous multi-element analysis of the nutrient concentration as well as heavy metals. Thin section micromorphology integrating polarized light - to assess coarse, organic material, microstructure and pedofeatures - and scanning electron microscopy, with energy dispersive spectroscopy (SEM/EDX), were applied to establish where, what and how elements exist within the soil architecture. An interview-based approach was also developed to work with local farmers and enable assessment of soil management and agricultural practice particularly in relation to the management of nutrients. Together, these approaches and analytical techniques are a ‘tool-kit’ to allow assessment and explanation of the nutrient status of selected Angolan agricultural soils.

3.3-Study area

The Republic of Angola is the third largest country located in southwestern Africa with an area of 1.246.700 km^2, it is bordered on the West by the Atlantic Ocean for a length of 1650 km. The country is divided into eighteen (18) administrative provinces. Two city regions were chosen due to their specific characteristics to be study targets of this work: Huambo, and Luanda.

3.4-Climate

Angola is in the inter-tropical and sub-tropical region of the Southern hemisphere Influenced by the cold Benguela Current and by factors such as the relief and proximity to the sea, make the climate varied. Figure 3.1 show in detail the climatic varieties in the Angolan territory according to the Köppen-Geiger. On the coast the climate is drier and hotter, while on the plateau the climate is more humid and rainier. To the north it is tropical and to the South it is sub-tropical. However, two seasons are noteworthy throughout the territory. The dry season “cacimbo,” dry and cool, runs from June to September and the rainy season, which is hot, runs from October to May.

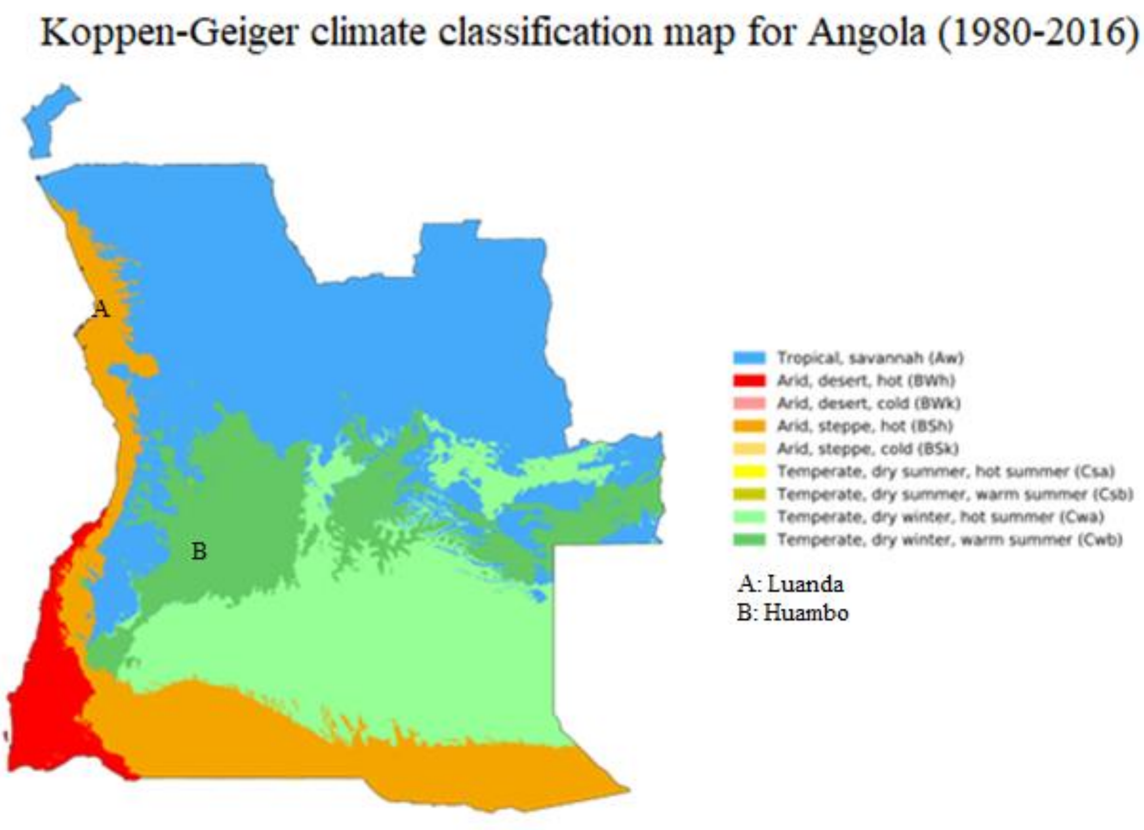


Figure 3. 1: Climate in Angola. Source: Beck et al., 2018

3.5-Vegetation

Angola is located in the Southern part of the tropical prairie (Savanna) defined on the North by the Congo rainforest and on the South by the Kalahari Desert. Its plant formation is varied and grouped according to regions (Figure 3.2). It is estimated that 60 % of the territory is occupied by forest and 33% is occupied by Savanna (Shaw, 1947). In the Southern part of the Luanda-Congo region, there are the species such as thorns (*Acacia),* spurges (*Euphobia)* and agaves *(Vellozia*). On the islands of Luanda, the coconut-palm is the one stands out the most. Even in this region between the rivers Cuango and Loge there is open bush of low trees or shrubs 4-6m of height (Shaw, 1947). Moreover, woody species such as *mufuto (Acacia sieberiana DC) and mubanga (A. welwitchia N.E.Br)* one of the cactiform spurges. In certain areas, on the lands with rocky subsoil the vegetation cover is formed by *mutongue* or *cabenda* twisted trunks covered with the sticky resin which exudes naturally.

In the regions of sub plateau, there is a dense vegetation characterized by the transition from dry bush to the "forest" that covers the West side of the plateau. This plant formation has a size not exceeding 12m, crooked trunks and abundant branches (Shaw, 1947; Dinis 1973). In the Bié plateau region, covering the areas of Huila, Benguela, Huambo and Bié there are shrub communities called "*anharas do ongole*." In these, grasses and other herbaceous plants are rare. There, predominant the species called locally by "*ongole*" scrubs that measure 10-25cm. In the central part of Angola, the shrub is sparse and among the species present there are *Monotes calneurus, Anisophyllea-gossweilleri*, *Protea petiolaris, Upaca nenguelensis* and *Swartzia maddagasccariensis.* In areas of swampy, hydromorphic soils such as prairies the vegetation is herbaceous and the most common genera being *Cyperaceae, Eriocalacea*, *Droseraceae and Lythraccceae* and grasses like as *Loudetia simplex*, *Loudetia superba* and *Saccolepis* species.

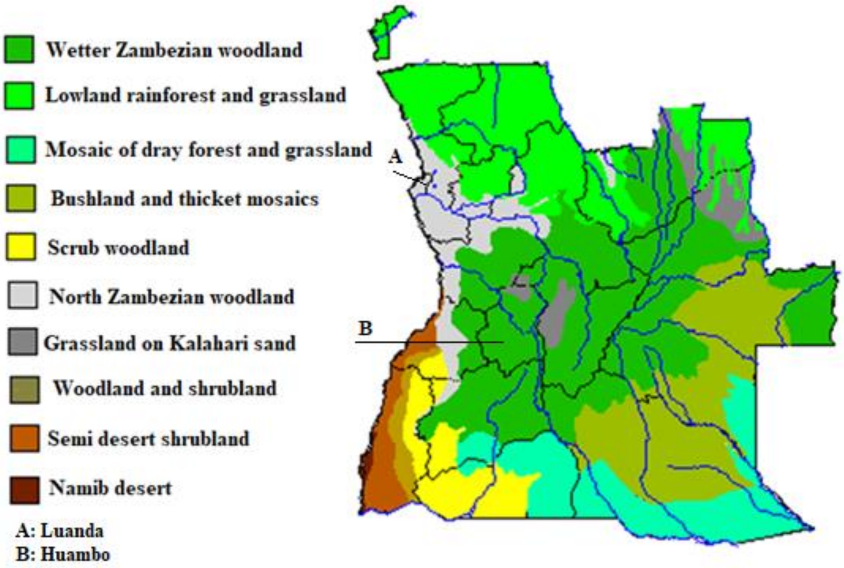


Figure 3. 2: Angola -vegetation cover. Source: FAO

3.6-Land use

The soil of the areas where the samples were collected are mostly used by small farmers as a traditional agriculture. There are also areas with natural vegetation. In NGongoinga site the harvesting area is used as an experimental zone for students from Faculty of Agricultural Sciences- José Eduardo dos Santos (FCA-UJES). In Huambo region they produce corn, beans, and vegetables. In Luanda, the farmers produce vegetables, corn, and same fruit such as banana, mango, and papaya.

3.7-Site selection 1

Huambo

Huambo is a province of Angola, located in the Central Region and is 450km southeast of the capital Luanda. The province is one of the richest agricultural in the country, in recent years (since the end of the civil war) the areas for cultivation are among the fastest growing in the country. Its population lives mainly from agriculture. The main cereal crop is maize and millet/sorghum, following by beans, sweet potatoes, and coffee. Four sites of the Huambo province were chosen to collect samples for this work, Bailundo, Mungo, Ngongoinga and Lepi (Figure 3.3).

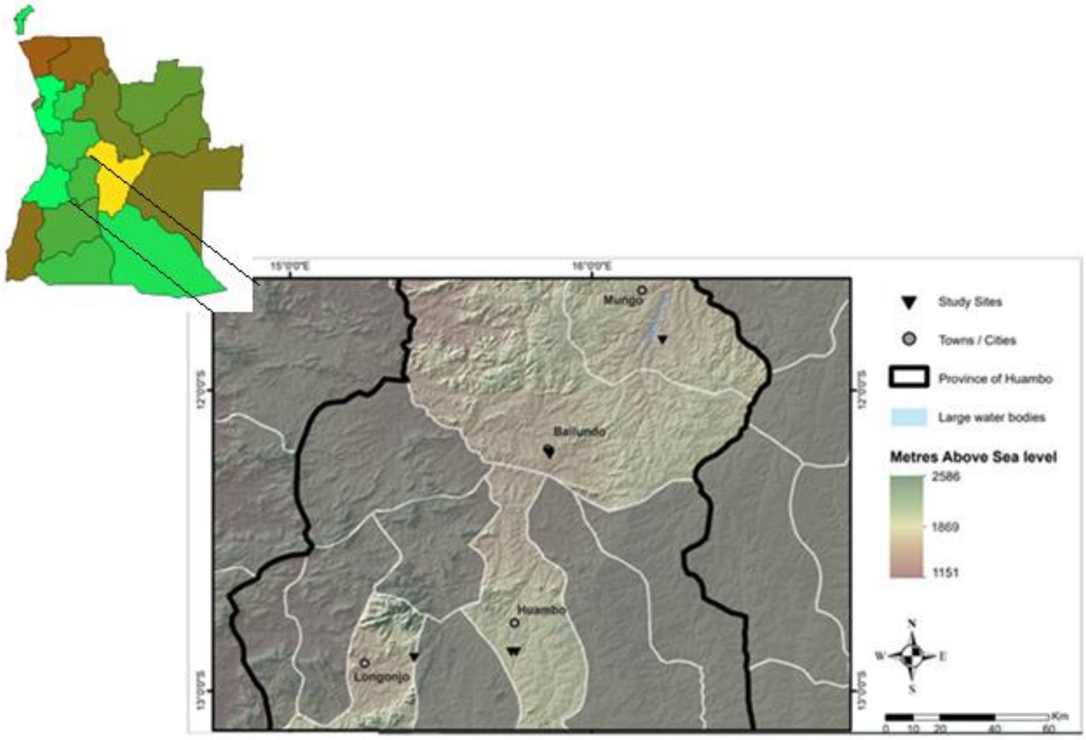


Figure 3. 3: Huambo and studied sites (Bailundo, Lepi (Longonjo), Mungo and Ngongoinga) in Angola context

Site location 2- *Luanda*

Luanda is the capital and largest city in Angola. The province is located on Angola's northern Atlantic coast (Figure x). It is the richest and most developed province in the nation, home to large industrial and commercial services. In agricultural terms, it is the home to one of the largest centres in country (Quiminha). The agricultural activity is based on the production of cassava, bananas, and vegetables. Four regions of Luanda province were chosen to collect soil samples for this work, Talelo, Funda, Bom Jesus and Ramiros (Figure 3.4).

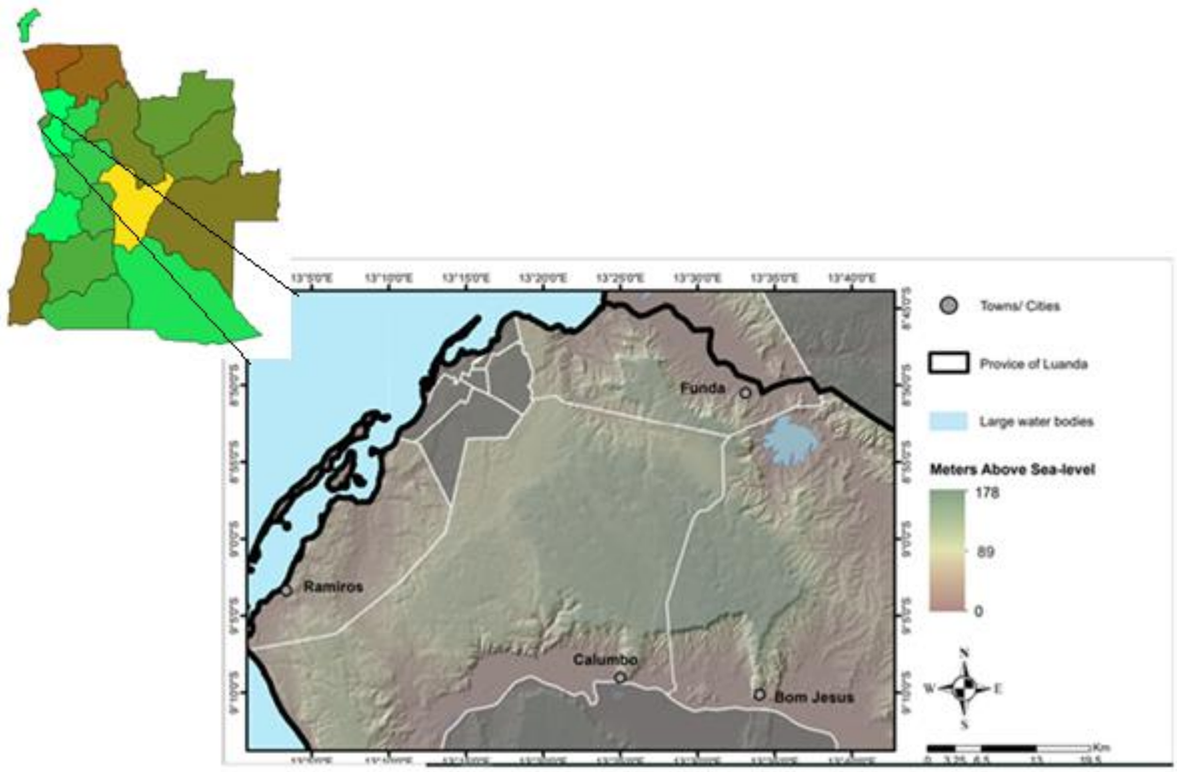


Figure 3. 4: Luanda and studied sites (Bom Jesus, Funda, Ramiro and Talelo (Calumbo) in Angola context

3.8-Sampling

The soils were collected in traditional agricultural areas from three random profiles at each location and covering different forms of relief and vegetation. At all sites profile 1 correspond to the top, profile 2 represents the middle and profile 3 the bottom of the hillslope. In each study area, trenches (100x100 cm) of three soil profiles were opened (Figure 3.5), collecting disturbed samples in the layers (0-100) cm (Figure 3.6a; 3.7a; 3.8a; 3.9b; 3.10a; 3.11a,c; 3.12a,b) (in some areas it was not possible to collect up to 100 cm due to the hardness of the soil and inappropriate tools) making a total of 152 samples being Bailundo (21), Ngongoinga (17), Mungo (19), Lepi (9) and Bom Jesus (19), Funda (22), Talelo (20), Ramiro (25). In addition, intact, undisturbed samples in the layers (25-35) cm were collected for micromorphology analysis using 5 x 7 cm kubiena tins (Figure 3.6c; 3.7b; 3.8b; 3.9c; 3.10b; 3.11b, c). These samples totalled (21), the samples from the Ramiro site when arrived at the University laboratory (Stirling) were considered degraded and, for that reason are not part of the micromorphology analyses (Chapter 4). The samples were examined by light microscopy and scanning electron microscopy energy dispersive X-ray spectroscopy (SEM-EDS), (description in Chapter 4). The samples were packaged and labelled in place bags to be taken to Scotland, and later analysed in Stirling. The disturbed samples were collected for chemical and granulometric analysis and the undisturbed samples were collected for micromorphology and analysis microchemistry.

Figure 3. 5: Trench opening. A-Ngongoinga, B-Bailundo, C-Mungo, D-Ramiro, E-Funda, F-Talelo

Sample collection

Figure 3. 6: a-B3 profile collection area; b-open trench for sample collection; c-undisturbed sample collection site for making slides-Bailundo

Figure 3. 7: a-open trench for sample collection (M2); b-undisturbed sample collection site for making slides (M2); c- open trench for sample collection (M3); d-undisturbed sample collection site for making slides (M3)-Mungo

Figure 3. 8: a-open trench for sample collection (NG1); b-undisturbed sample collection site for making slides (Ng1); c- open trench for sample collection (NG2); d-undisturbed sample collection site for making slides (Ng2)-Ngongoinga

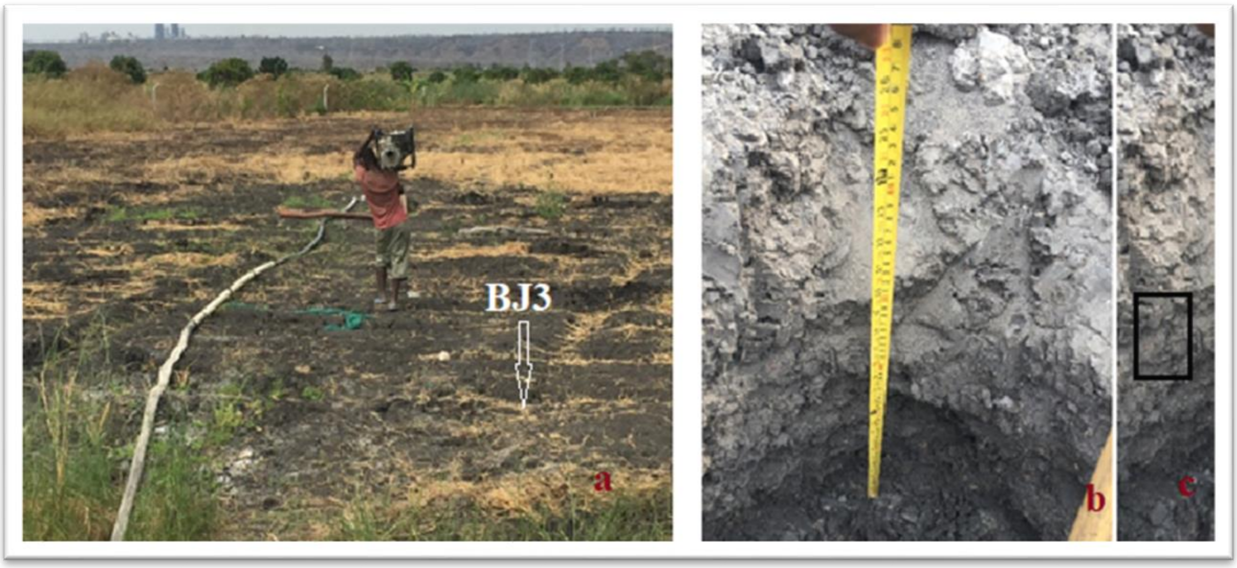


Figure 3. 9: a-profile collection area (BJ3); b- open trench for sample collection (BJ3); c-undisturbed sample collection site for making slides (BJ3)-Bom Jesus

Figure 3. 10: a-profile collection area (F3); b-undisturbed sample collection site for making slides (F3); c sample in plastic bag-Funda

Figure 3. 11: a-profile collection area (T1); b-undisturbed sample collection site for making slides (T1); c-profile collection area (T2); d-undisturbed sample collection site for making slides (T2)- Talelo

Figure 3. 12: a-profile collection area for disturbed sample (R1); b-profile collection area for disturbed sample (R2)-Ramiro

3.9-Laboratory methods

3.9.1-Sample preparation

The samples (disturbed) were prepared and taken diverse types of analysis (Figure 3.13). The sample for granulometric and chemical analysis were dried in an oven (i.e., at 105^0c) and then crushed in a mortar to reduce the fragments followed by removal particles with a 2mm sieve.

Figure 3. 13: a-deformed samples packed; b-undisturbed samples in Kubiena; c-samples ready for drying; d-sample griding; e-sieve sample

3.10-Physical analysis

3.10.1-Granulometric analysis

The granulometric analyses were carried out at the instrumentation laboratory at the University of Stirling. The particle size proposes to quantify the size distribution of individual particles (rock fragments, nodules, individual mineral grains) of soil minerals. After being prepared the samples were subjected granulometric analysis carried out in an apparatus Coulter LS. Samples were weighed and sieved before 10cm (soil mass) of each appropriate vial sample was measured out. Distilled water and sodium hexametaphosphate (Na $(PO_3)_6$) were added and subsequently agitated for 4 hours on a shake table to disperse the sample (Edmund Buhler, model 7400 Tubingen). Then the particle fractions were determined by laser diffraction on a LS Coulter apparatus, brand Beckman Coulter, model LS 230 (Figure 3.14).

Figure 3. 14: Coulter LS (University of Stirling- Laboratories)

3.10.2-Chemical analysis

Macronutrients and micronutrients were analysed using ICP-MS methodology in all samples and expressed in µg/g, the elements carbon and hydrogen expressed in percentage (%), cation exchange capacity (CEC) in (mmol/kg) and base saturation (BS) expressed in percentage (%).

pH

The analysis of soil pH is a fundamental characteristic in the balance and stabilization of soils. pH values influence biological and chemical processes such as soil microbial activity, weathering processes, the mobility of ions in solution, and nutrient availability. In addition, they act in the formation and breaking of the soil structure.

Procedure: The analyses were performed both in water and in $CaCl_2$ (0.125m) solution. Ten g of each sample were weighed and 25 ml of distilled water in an Erlenmeyer flask were added. After shaking with glass rod, followed by a rest of 10 minutes, the pH value was then read in the suspension by means of a pH meter model 292 Pye Unicam (Figure 3.15). The same procedure was used to determine pH in $CaCl_2$ solution.

Figure 3. 15: Material in suspension

3.10.3- ICP-MS

Instrumentation

Inductively Coupled Plasma Mass Spectrometry, or ICP, was introduced commercially in the 1980s. It is an analytical technique used for elemental determination that has been increasingly used in soil laboratories as an element analysis technique (Bortolon, Gianello et al. 2010, Cihacek, Yellajosula et al. 2015) as it allows the simultaneous analysis of metal and trace elements with a wide concentration (Aries, Valladon et al. 2000, Yu, Robinson et al. 2001, Fonseca, Alleoni et al. 2005, Khan, Jeong et al. 2013) This is technique with high elementary analytical capacity, great stability, precision, and high analytical frequency. Moreover, this technique provides elevated levels of detection and can be used for microanalysis (Limbeck et al., 2015) and determination of heavy metals (Moor et al., 2001). Its application level covers several fields such as, biological, metals, geological, environmental, agricultural (Santos 2018) allowing an accurate detection and quantification of elements. *Advantages and disadvantages:* Detection limits for most elements equal to or better than those obtained by Graphite Furnace Atomic Absorption Spectroscopy (GFAAS); higher throughput than GFAAS; the ability to manage both simple and complex matrices with a minimum of matrix interferences due to the high-temperature of the ICP source; superior detection capability to ICP-OES with the same sample throughput; the ability to obtain isotopic information.

Procedure: Each sample (0.25g) was weighed and transferred to PTFE (Polytetrafluoroethylene) vials followed by addition of 2 ml of HNO_3. The flasks were sealed and heated in a Sartorius brand, Mars / CEM model microwave synthesis, and the samples digested using the general soil digestion program to ensure that the sample material was completely dissolved and in solution. After digestion of the sample, the vials were allowed to stand and cool at room temperature for at least 1 hour. The vials were then carefully open inside the fume cupboard and the sample solutions were decanted and transferred to volumetric flasks and made up to the 100ml mark with de-ionized water. Finally, each sample solution, including blanks, was added to the test tube, and placed in the test area on the ICP (iCAP 6000 SERIES) (Figure 3.16).

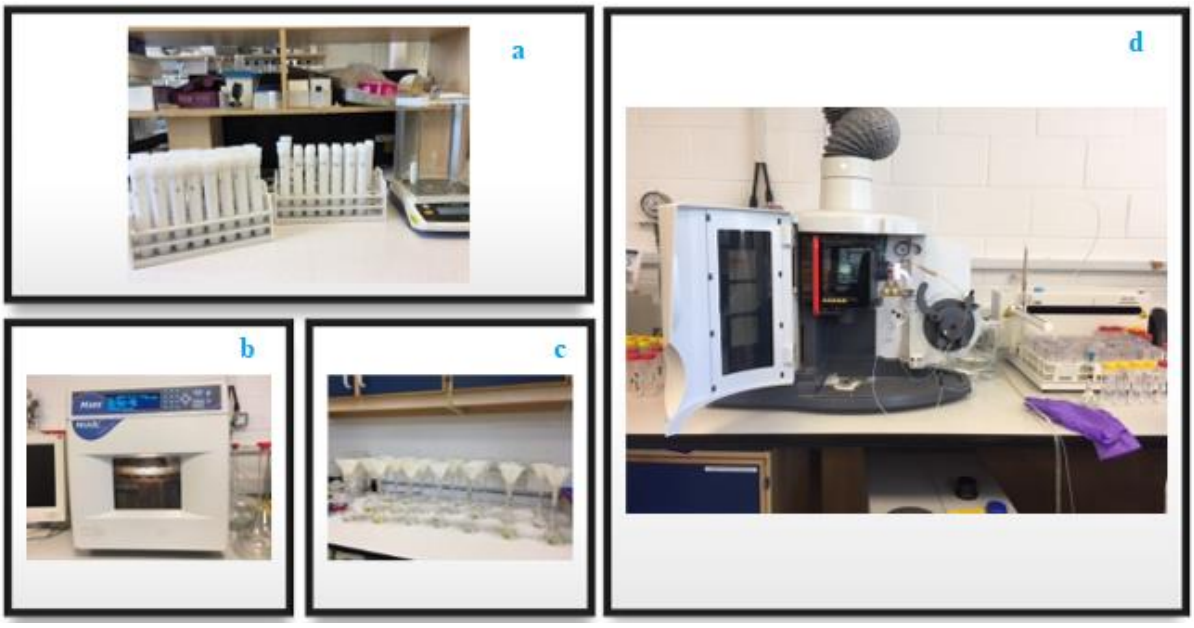


Figure 3. 16: Instrument laboratory (University of Stirling). A) vials; b) sample solution digestion; c) sample solution decanted; d) ICP equipment.

3.10.4-Carbon and Nitrogen determination

The Nitrogen and Carbon contents were analysed using the FlashSmart elemental analyser and the results being expressed as a percentage in each sample. Samples were dried and homogenised before being weighed out in mg to 2 d.p. Samples were combusted at 950^{o}c in the presence of Oxygen and an appropriate catalyst (Platinised Alumina + Cooper Oxide). Sample gas stream was carried through the system using Helium as the Carrier gas. Excess Oxygen was then removed using reduced Copper (at 50^{o}c) to avoid interference peaks in the spectra. A Magnesium perchlorate filter was used to remove water from the sample gas stream. Samples were resolved using a “Multiseparation" column (SS, 2m, 6x5mm. Part # 260 07920) at 50^{o}c.

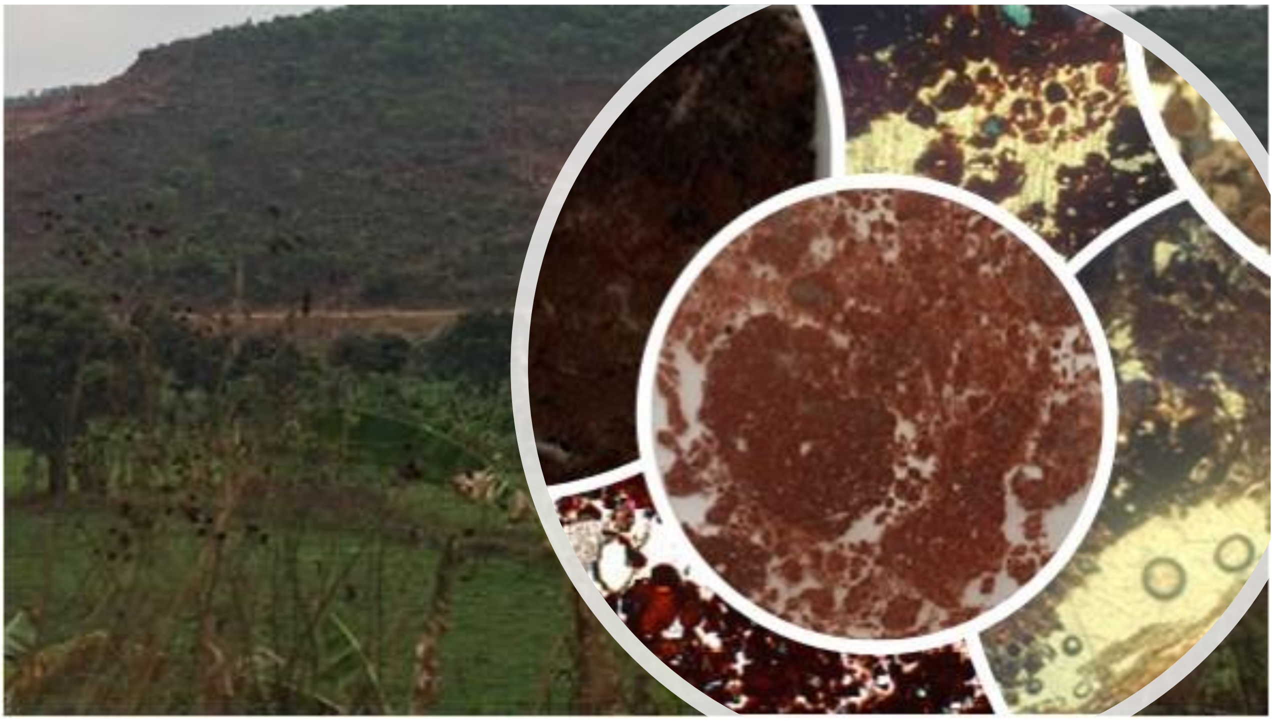
Flow rates for the method were as follow; Carrier = 140ml/min. Oxygen = 250 ml/min. Reference = 100 ml/min.

Oxygen injection was set to 10s, sampling delay was set to 12s and Cycle (run time) was set to 400s. Average K factors for standards that spanned the expected % N. % C range were used set to calculate final percentages. Check standards (run every 12 samples) were required to have % Root Squared Deviation from initial standard of less than 10% or QC fail occurred and samples after this point were re-run.

3.11-Statistical analyses

To perform statistical analysis, was used Jamovi 2.3 software. At first, descriptive statistics from the total amounts of macronutrient and micronutrient were analysed. Second, we will investigate the variation of the elements based on different hypotheses. Thus, hypothesis: the hillslope position, depth, and site. Dependent (Y) variables of element concentrations and independent (X) variables hillslope position, depth, and site. Was used an Ancova test to investigate the effect of categorical variables (i) hillslope position, (ii) site and (iii) depth on nutrient concentration. Third, pairwise correspondences analyses between the groups of different sites were performed using a Tukey test with Boferroni correction. Due to limited degrees of freedom in the sampling design, interaction terms could not be evaluated. Nonetheless, trends in the data by site, hillslope position and soil depth are identified in the following narrative. Statistical test results were assessed at the usual 0.05 significance level.

Chapter 4: Soil physical results



4.1-Introduction

Knowledge and understanding of the physical properties of soils are fundamental for their management. Thus, texture and soil micromorphology are the characteristics to be analysed in this chapter.

Soil texture affects nutrient and water availability and retention in weathered soils (Silver et al., 2000) as well as the susceptible of soils to erosion.

On the other hand, the morphological and mineralogical features of soils in tropical regions are influenced by climate, topography and rock type (Aldeias, Goldberg et al. 2014, Bockheim and Hartemink 2017). Information on morphological and mineralogical soil characteristics is increasingly used in soil fertility assessment and management (Abe, Masunaga et al. 2006, Adderley, Simpson et al. 2006, Stoops and Marcelino 2018). The sustainable use of natural resources and land, in particular, is a matter of national relevance in Angola due to the increase in anthropogenic activities. These alterations that come from human activity have a severe impact on the soil and can intensify both its formation and natural development process, as well as losses, or redistribution, due to erosion and crop harvesting. Furthermore, the analysis of weathering and pedogenesis processes helps to better interpret and clarify the soil, its origin and formation. Research on soil micromorphology, mineralogy to agricultural issues is scarce in Angola.

The aims of the work presented in this chapter were therefore to determine the texture of soils and its relationship with the nutrients, and to analyse the soil micromorphology, determine the minerals present and their relationship with the nutrients.

4.1.2-Particle size distribution across catena, Textural classes

The textural classes in this work were evaluated according to the soil particle size classification system (Table 4.1).

Table 4. 1: Particle size classification

Particle size		**USDA (mm)**	**WRB/FAO (mm)**
clay		<0.002	< 0.002
silt		0.002 – 0.05	0.002 – 0.063
sand	Very Fine	0.05 - 0.10	0.063 – 0.125
	fine	0.10 -0.25	0.125 – 0.20
	Medium	0.25 - 0.50	0.20 – 0.63
	coarse	0.50 -1.00	0.63 – 1.25

USDA: United States Department of Agriculture

WRB: World Reference Base for Soil Resources

Huambo-Bailundo

Soils of this region presented predominantly silt texture (Figure 4.1) with substantial contrast in relation to clay and sand fractions. Silt and sand fractions tend to fluctuate across the catena while, the clay fraction tends to a slight decrease down the catena. Within the profile, it was found that the silt contents are high in the upper layers. On the contrary, the clay fraction showed high values in the lower layers. The sand fraction presented higher contents in the upper layers.

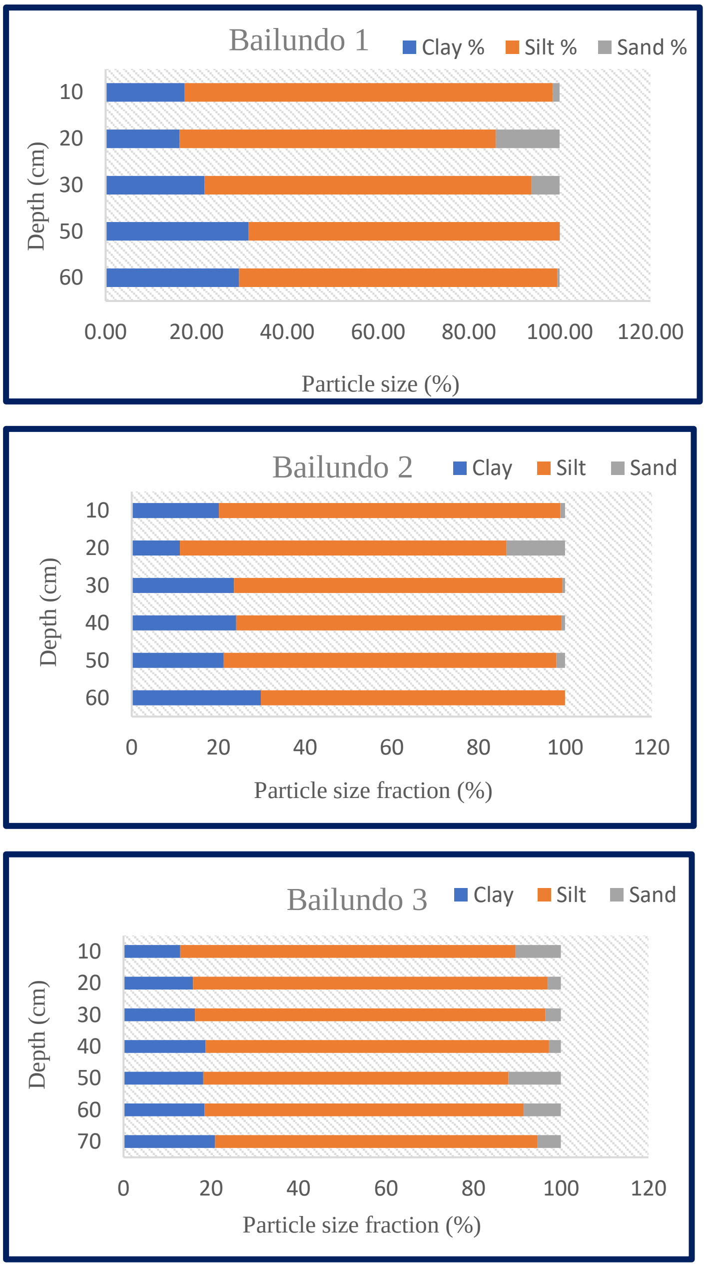


Figure 4. 1: Textural classes of soil, clay, silt and sand, the numbers 1, 2 and 3 refer to the hill-slope position (1 upper, 2 mid, 3 lower)-Bailundo

Huambo-Mungo

In general, the soils have a silt clay texture (Figure 4.2) with a predominance of silt fraction. The silt fraction tends to similar values across catena, while the clay fraction tends to decrease. By contrast, the sand fraction tends to increase across the catena. Within the profile, the silt contents are balanced. Clay observed higher values in the upper layers in M1 and in the lower layers in M2. Sand fraction has higher contents in the upper layer in M2 while, in M1 the higher values are in the lower layers.

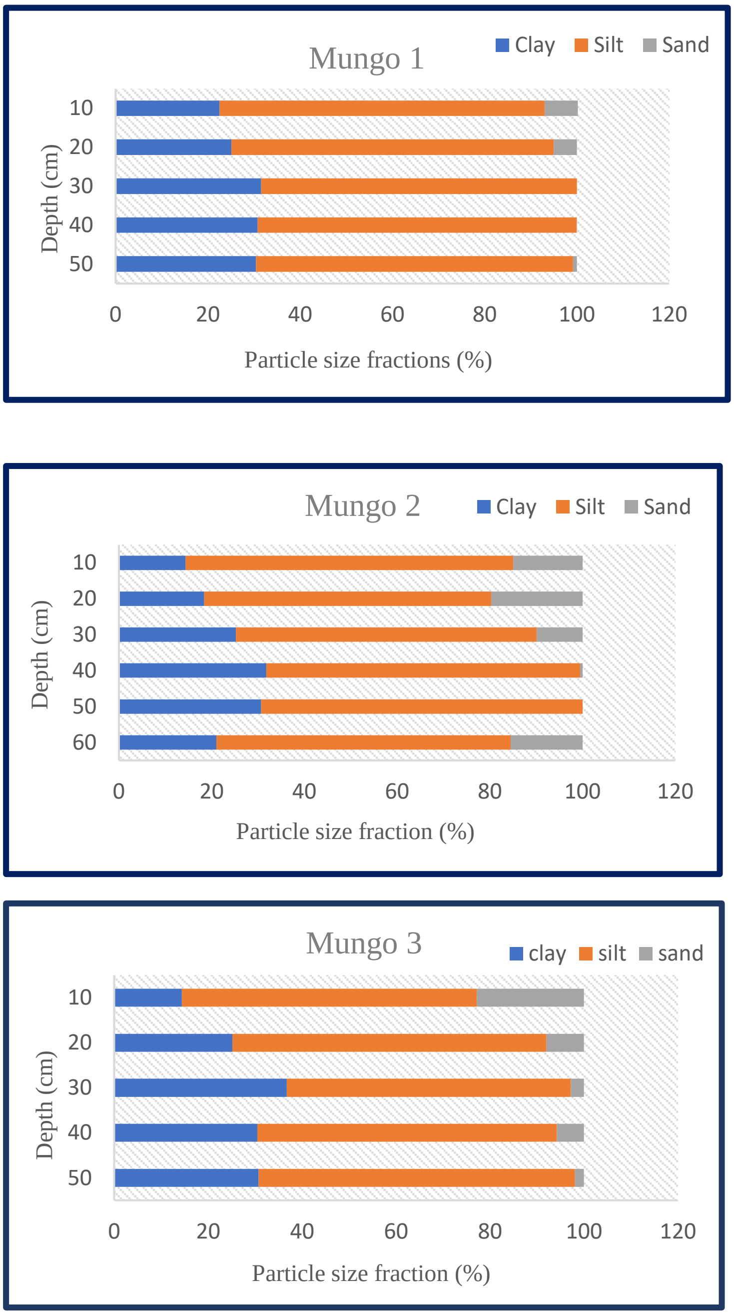


Figure 4. 2: Textural classes of soil, clay, silt and sand, the numbers 1, 2 and 3 refer to the hill-slope position (1 upper, 2 mid, 3 lower)-Mungo

Huambo-Lepi

Soils had a predominantly silt texture (Figure 4.3), followed by clay and sand fractions. Silt and sand fraction tend to decrease slightly across catena while, clay tends to a tad increase. Within the profile the silt has the highest contents in the lower layers in L1 and L3 while, in L2 the silt values are high in the top layers. The clay fraction has highest contents in the lower layers in all hill-slope profiles. On the contrary, the sand fraction presents higher contents in the upper layers.

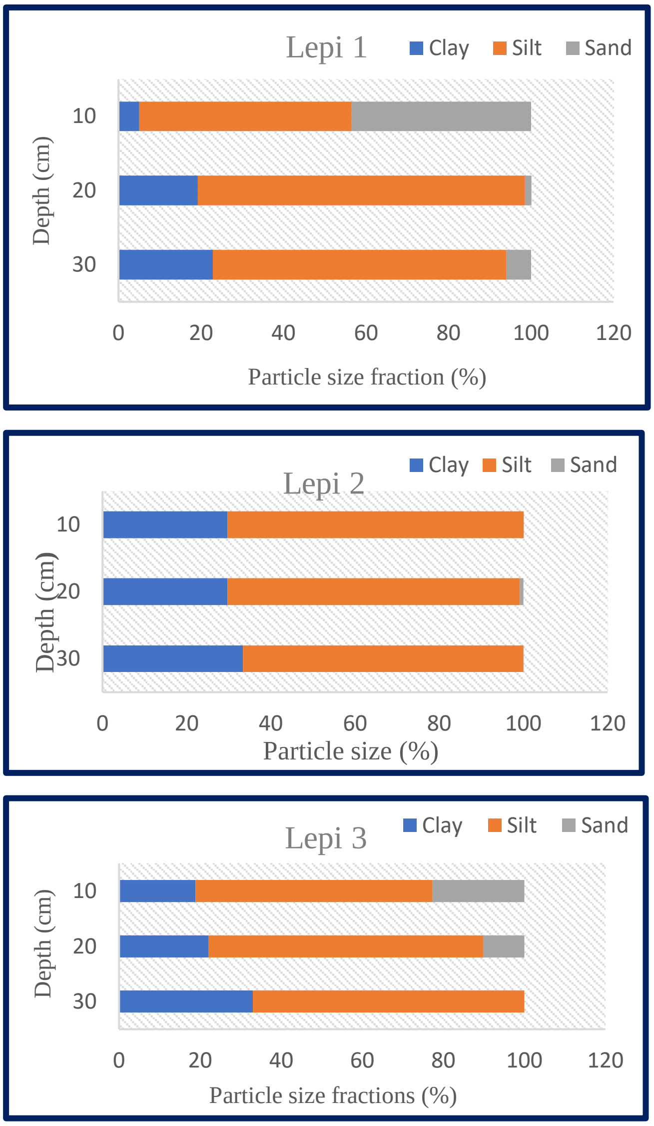


Figure 4. 3: Textural classes of soil, clay, silt and sand, the numbers 1, 2 and 3 refer to the hill-slope position (1 upper, 2 mid, 3 lower)-Lepi

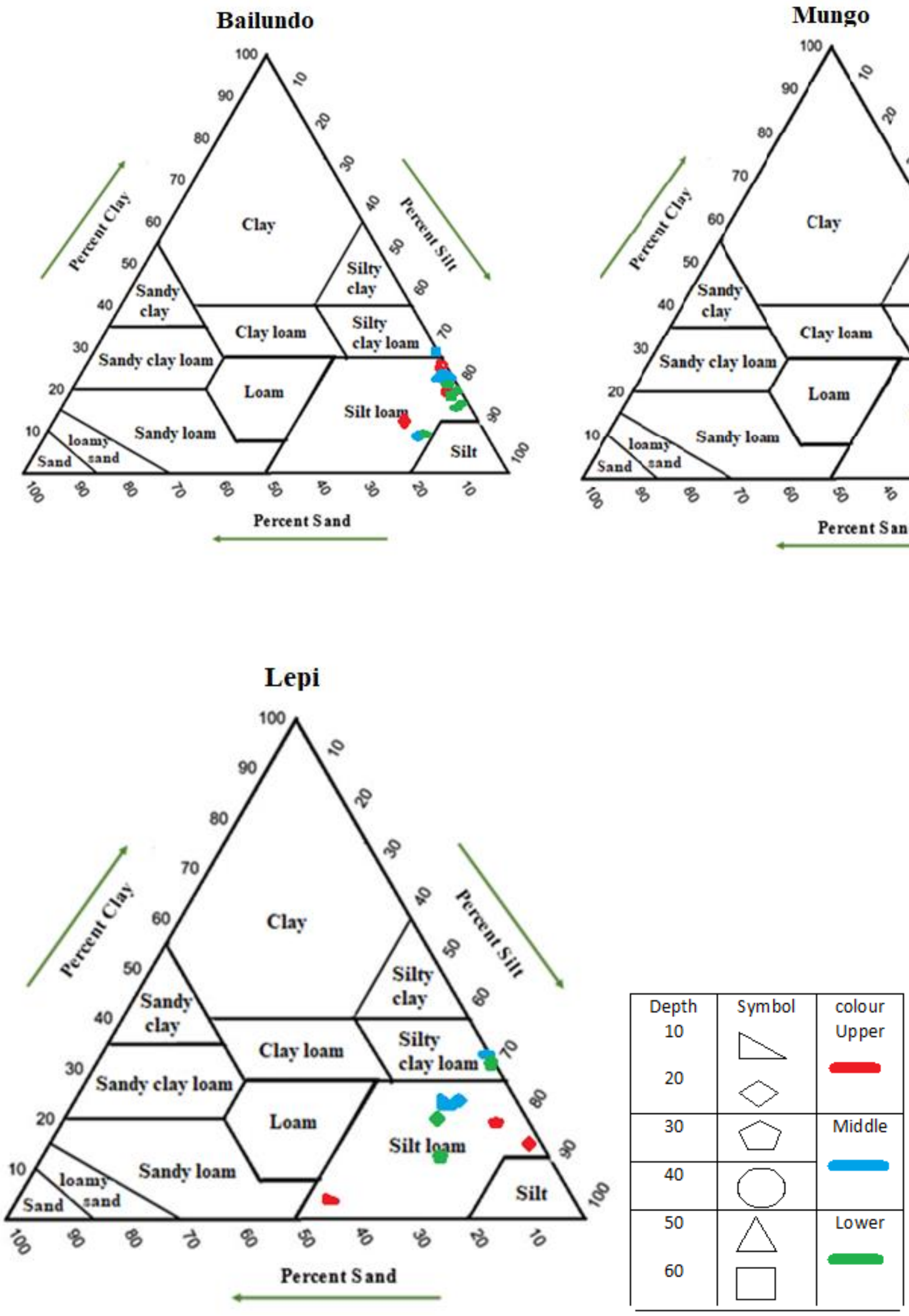


Figure 4. 4: Soil textural classes in Huambo province (Bailundo, Mungo and Lepi)

Luanda-Bom Jesus

It is observed by granulometric analyses (Figure 4.5) that silt is the dominant size fraction along the catena. Obviously, there is predominance of the silt fraction and sand content is negligible. Silt presents a regular value along catena and for clay it is verified that there is a slight increase of this fraction across catena. By contrast, for sand there is only a slight reduction along the catena. The particle distribution shows a silt loam soil along the catena.

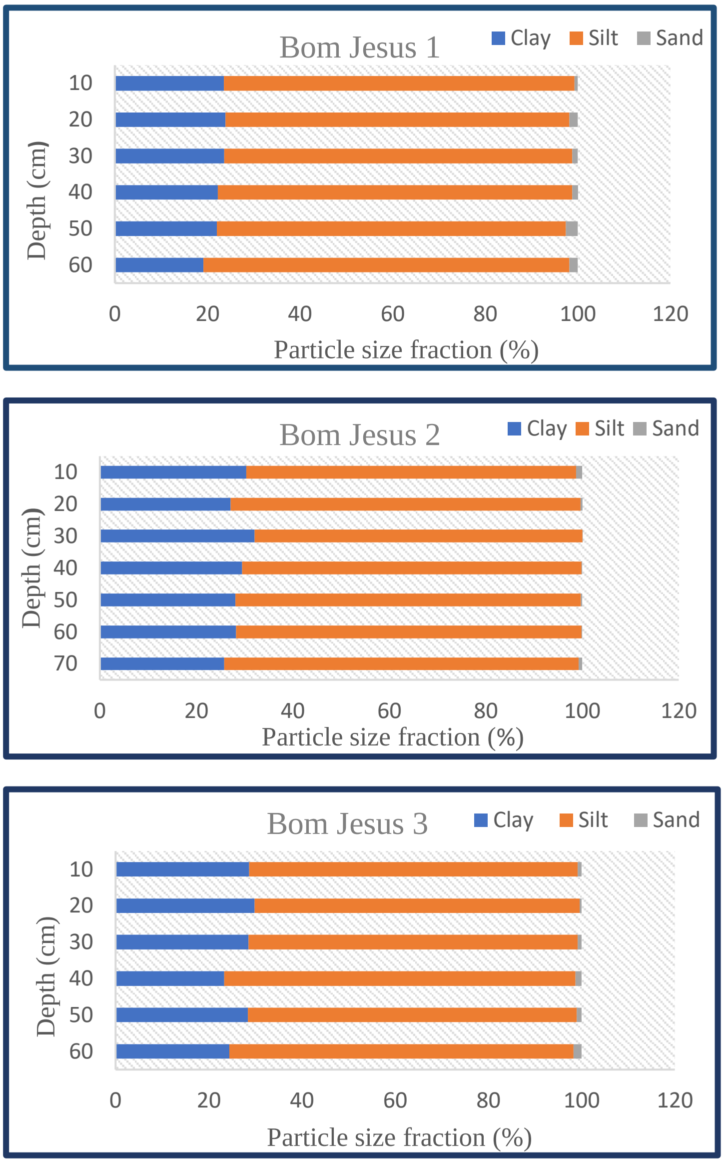


Figure 4. 5: Textural classes of soil, clay, silt and sand, the numbers 1, 2 and 3 refer to the hill-slope position (1 upper, 2 mid, 3 lower -Bom Jesus

Luanda-Funda

Distribution of particles in the Funda region (Figure 4.6) shows a slight variation. The values of clay fraction show a slight change with tendency to decrease across catena. Similarly, contents of the sand and silt fractions tend to decrease along catena. Dominant fraction is silt with low variability in the catena. Due to the characteristics presented, the soil in this area is largely silty and some predominance of clay.

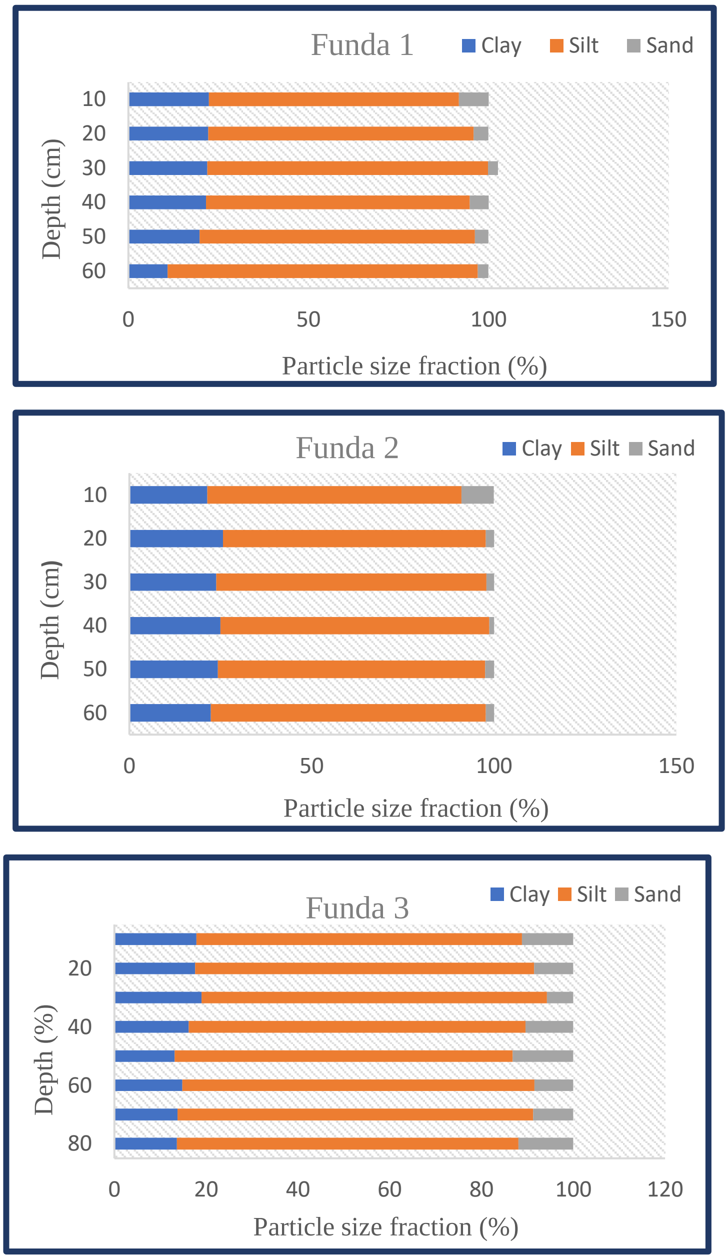
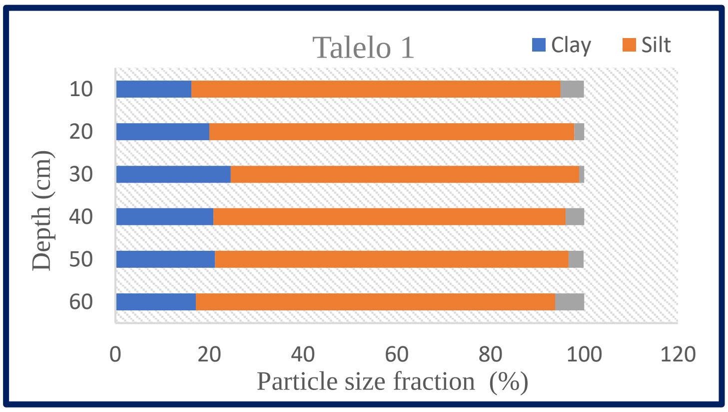
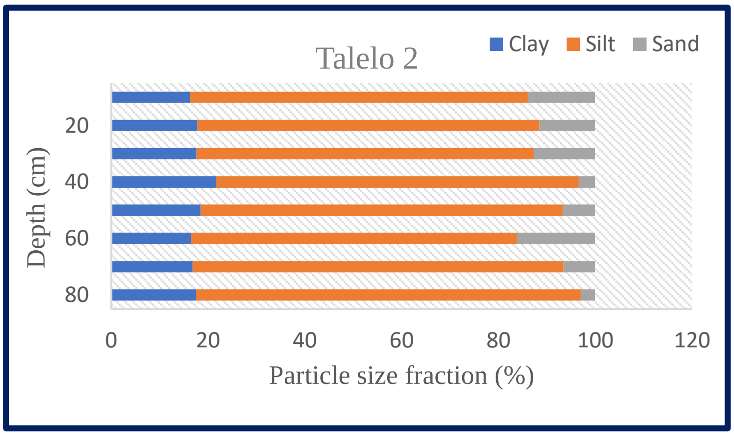


Figure 4. 6: Textural classes of soil, clay, silt and sand, the numbers 1, 2 and 3 refer to the hill-slope position (1 upper, 2 mid, 3 lower)- Funda

Luanda-Talelo

Structural analysis in the Talelo region (Figure 4.7) showed a minor change in the soil fractions. The sand fraction had low variability, tending to increase across catena (from top to the lower profile). Silt fraction tends to decrease in the catena, but its contents are higher in the lower layers of the profiles. Sand fraction oscillating values were observed with a slight tendency to increase across catena. In this area the dominant fraction is silt followed by clay, which gives the soil silt loam characteristics





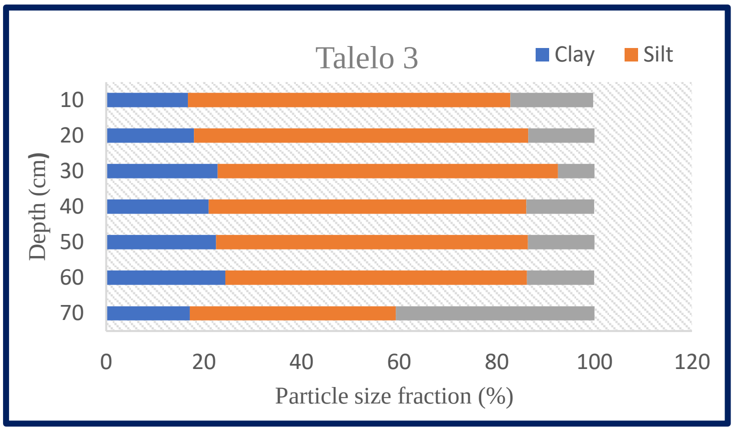
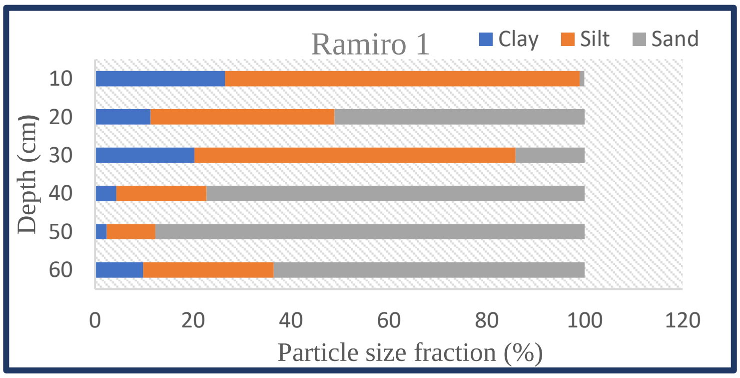


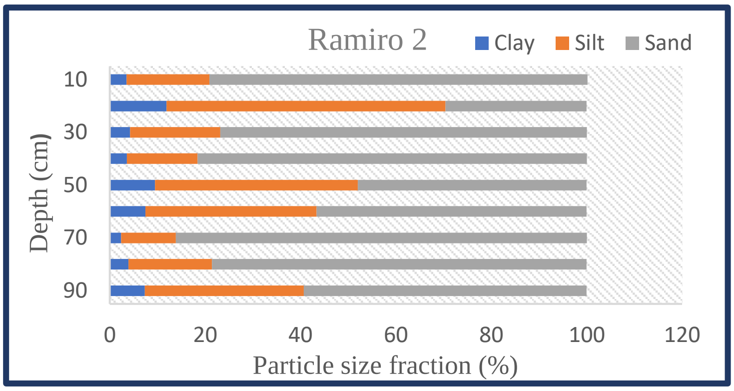
Figure 4. 7: Textural classes of soil, clay, silt and sand, the numbers 1, 2 and 3 refer to the hill-slope position (1 upper, 2 mid, 3 lower)-Talelo

Luanda-Ramiro

The particle size evaluation in this region (Figure 4.8) showed variability along the catena. The silt and clay fractions observe a slight change in their values across the catena with a tendency to decrease. Sand fraction presents regular contents in the catena. The dominate fraction is clearly sand, followed by the silt fraction and finally clay, which gives the soil characteristics of sandy loam. Thus, this soil is potentially erosion and has low nutrient retention.

Soil texture is an essential factor for understanding soil behaviour and management. Figure 4.9 illustrates the textural classes of soils analysed in Luanda province.





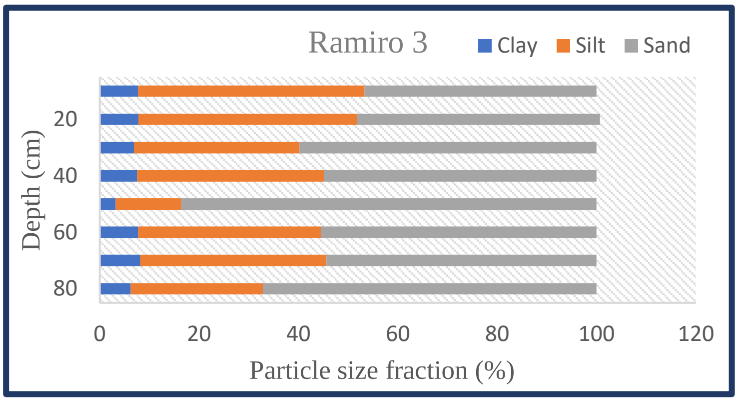
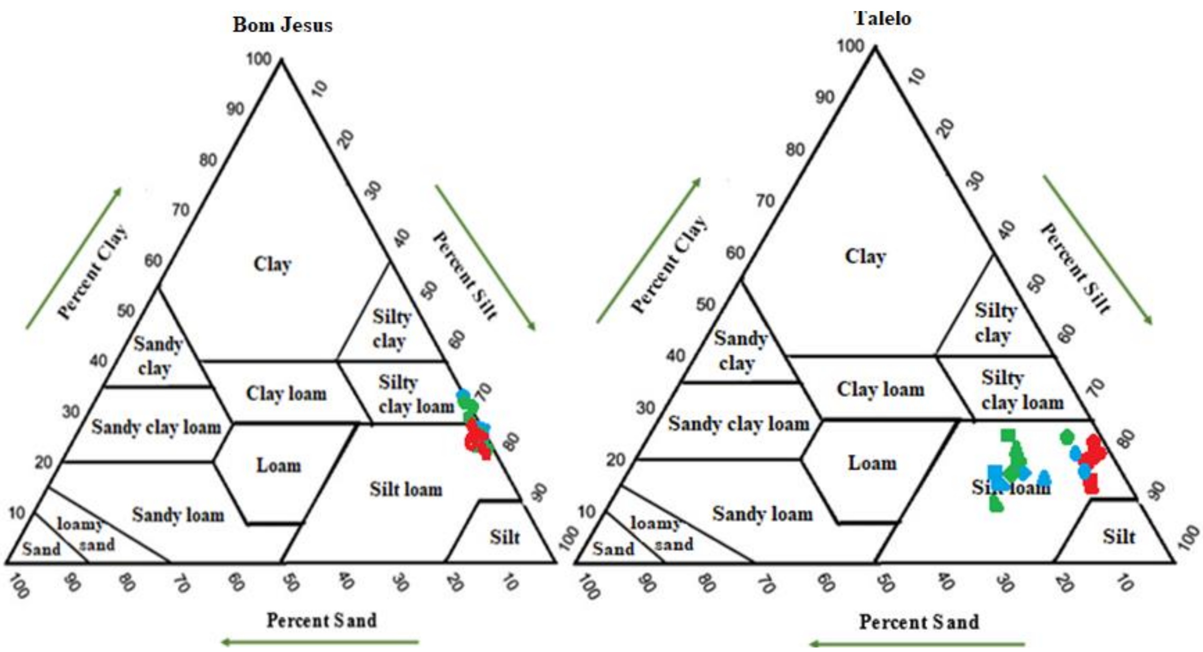


Figure 4. 8: Textural classes of soil, clay, silt and sand, the numbers 1, 2 and 3 refer to the hill-slope position (1 upper, 2 mid, 3 lower)-Talelo



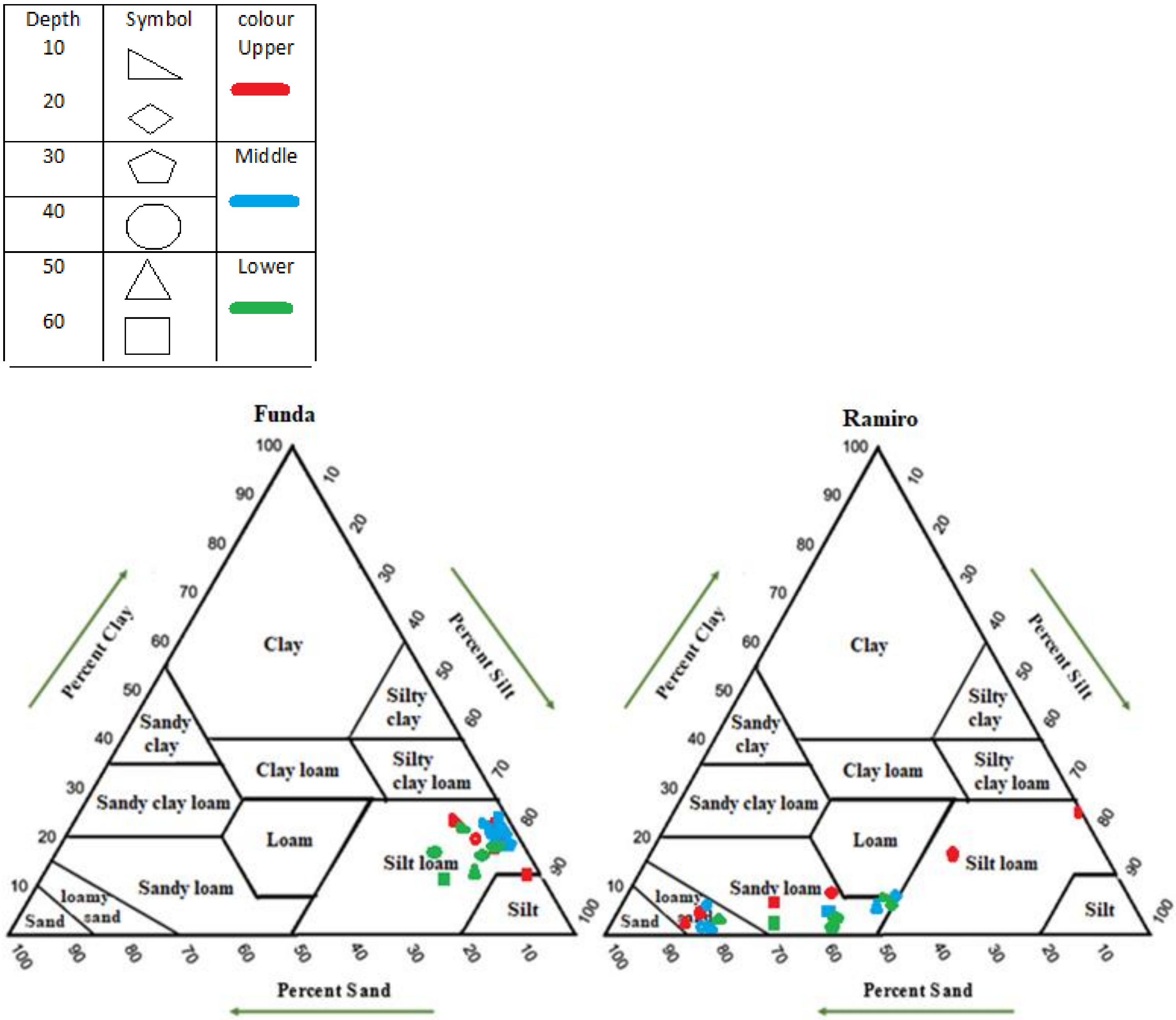


Figure 4. 9: Soil textural classes, Talelo, Bom Jesus, Funda and Ramiro.

4.1.3-Soil textural fraction data

Soils are mostly silt loam with a predominance of the silt fraction, except for Ramiro. Silt fraction with an average of 75% presented the highest frequency among the soil fractions in both provinces. Followed by the clay fraction with much lower contents, the highest average was observed in the Mungo (Huambo) and Bom Jesus (Luanda) region with 26.2% and 26.3% respectively. The sand values are vastly different between regions and the highest content was observed in Ramiro (Luanda) with 53%. Similarly, higher standard deviation was observed in Ramiro region with 26.7% indicating higher variability.

Table 4. 2-Descriptive results from soil fractions, clay, silt, and sand in Bailundo, Lepi and Mungo regions- Huambo province.

site	*mean*	*median*	*St. Devi*	*Skewness*	*kurtosis*	*25%*	*50%*	*75%*
clay								
Bailundo	20.4	19.4	5.61	0.542	-0.138	16.6	70.6	1.11
Lepi	23.8	22.9	8.99	-1.04	1.26	19.2	66.6	1.33
Mungo	26.2	27.8	6.58	-0.55	-0.559	22.2	63.6	2.13
silt								
Bailundo	74.8	75.2	4.15	0.0597	-1.27	19.4	75.2	3.03
Lepi	66.8	67.7	7.91	-0.682	1.27	22.9	67.7	8.1
Mungo	66.6	67.5	3.28	-0.522	-1.09	27.8	67.5	6.51
sand								
Bailundo	5.06	3.03	4.86	0.816	-0.819	23.2	78.1	8.52
Lepi	14.3	8.1	16	0.972	-0.251	29.7	70.3	24.5
Mungo	8.22	6.51	7.4	0.767	-0.539	30.8	69.2	13.7

mean, median, Standard Deviation, skewness, kurtosis, 25, 50 and 75 quartiles

Table 4. 3- Descriptive results from soil fractions, clay, silt, and sand in Bailundo, Lepi and Mungo regions- Luanda province

	mean	*median*	*st Dev*	*skewness*	*25%*	*50%*	*75%*
clay							
Bom Jesus	26.3	27.1	3.45	-0.287	23.6	27.1	28.6
Funda	19.7	21.5	4.36	-0.567	16.5	21.5	22.7
Ramiro	10.2	7.72	7.4	1.28	5.78	7.72	11.3
Talelo	19.3	18	2.76	0.632	17.1	18	21.3
silt							
Bom Jesus	72.8	72.6	2.99	0.242	70.5	72.6	75.3
Funda	74.5	73.8	3.4	1.76	73.3	73.8	75.4
Ramiro	36.8	37.1	19.6	0.556	24.5	37.1	44.4
Talelo	70.4	70.6	8.26	-2.05	67.3	70.6	75.4
sand							
Bom Jesus	0.972	0.85	0.69	0.537	0.37	0.85	1.3
Funda	5.86	4.66	3.78	0.495	2.56	4.66	8.69
Ramiro	53	55.2	26.7	-0.788	48.4	55.2	69.7
Talelo	10.3	7.45	8.64	2.22	3.92	7.45	13.8

mean, median, Standard Deviation, skewness, kurtosis, 25, 50 and 75 quartiles

The soil fractionation measurement revealed significant contrast in the clay and sand contents of among Huambo and Luanda with p=0.019 and p=0.037, respectively Table 5.4.

Table 4. 4- Comparison soil fraction between Luanda and Huambo province

Kruskal-Wallis

	χ^2	**df**	**p**
clay	5.5080	1	***0.019***
silt	0.0733	1	0.787
sand	4.3573	1	***0.037***

4.1.4-Relationship among soil fractions and elements NPK

Huambo

In soils of the regions studied in the Huambo province the NPK elements were not shown to be associated with soil fractions (Table 4.5). However, an exception was observed where phosphorus decreases with increasing silt fraction showing a significant, negative, and weak correlation with silt fraction, r = -0.342.

Table 4. 5- Correlation Matrix soil fractions (clay, silt, sand) and Nitrogen (N), potassium (K) and, phosphorus (P)-Huambo

	N	**P**	**K**	**Clay**	**Silt**	**Sand**
N	-					
P	0.244	-				
K	0.334*	0.452**	-			
Clay	-0.133	0.214	0.104	-		
Silt	0.008	-0.342*	-0.3	-0.393**	-	
Sand	0.185	0.116	0.231	-0.604***	-0.291	-

Note. * p < 0.05, ** p < 0.01, *** p < 0.001

Luanda

Soils analysed in the regions of Luanda province all showed without exception a significant correlation between the elements nitrogen (N), phosphorus (P) and potassium (K) (Table 4.6).

Table 4. 6- Correlation Matrix soil fractions (clay, silt, sand) and Nitrogen (N), potassium (K) and, phosphorus (P)-Luanda

	Clay	Silt	Sand	N	P	K
Clay	-					
Silt	0.321**	-				
Sand	-0.881***	-0.617***	-			
N	0.551***	0.516***	-0.613***	-		
P	0.557***	0.386***	-0.641***	0.603***	-	
K	0.48***	0.473***	-0.524***	0.682***	0.418***	-

Note. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Nitrogen increased with clay and silt fraction with r = 0.551 and r = 0.516 respectively, while the correlation among N and sand fraction was negative and strong, r = -0.617, resulting in a decreasing of N with an increase of the sand fraction.

Phosphorus was correlated with clay and silt fractions, with a significant positive and moderate correlation with clay and silt, r = 0.557 and r = 0.386, respectively. Moreover, P correlated with the sand fraction, showing a significant negative and strong correlation (r = -0.641) between both.

Potassium increased with clay and silt fraction, showing a significant positive and moderate correlation (r = 0.480 and r = 0.473 for clay and silt, respectively), while with the clay fraction, K decreased, showing a significant negative and moderate correlation, r = -0.524.

4.1.5-Nutrient (NPK) predictive analysis (model)

For this analysis, profile, depth, and region were used independent variables, for that we started by doing independent variables: because we have three independent variables, which must sum to 100, a compositional analysis was used:

Log -clay = log $_a$ (clay/silt)

Log -sand = log $_a$ (sand/silt)

Log = (clay/silt); Log = (sand/silt)

A compositional analysis from linear mixed effects model for 5 fixed effects tested random effect (site).

N = Region + site + profile + depth + Log clay + Log silt

The results showed that there is no significant difference between regions on N concentration (Table 4.7). However, was observed that profile has a significant effect on Nitrogen (P< 0.001), and that an increase in the ratio of clay/ silt causes a decrease in Nitrogen (P= 0.0394). For the other elements (P and K), no significant differences were observed between these and the soil fractions, no other significant effects were found.

Table 4. 7- NPK, texture by region, depth, and profile in the studied soils.

	df	***P***
	N	
profile	-4.317	3.48e-05 ***
depth	-0.68	0.4982
clay	-2.085	0.0394 *
sand	0.525	0.6006
	K	
profile	-0.935	0.3519
depth	-1.21	0.229
clay	-0.148	0.8829
sand	-0.244	0.808
	P	
profile	0.198	0.8437
depth	1.92	0.0575.
clay	-1.719	0.0885.
sand	-0.96	0.3391

*Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1*

4.2-Micromophology

The morphological and mineralogical features of soils in tropical regions are influenced by climate, topography and rock type (Aldeias, Goldberg et al. 2014, Bockheim and Hartemink 2017). Information on morphological and mineralogical soil characteristics is increasingly used in soil fertility assessment and management (Abe, Masunaga et al. 2006, Adderley, Simpson et al. 2006, Stoops and Marcelino 2018). The sustainable use of natural resources and land, in particular, is a matter of national relevance in Angola due to the increase in anthropogenic activities. These alterations that come from human activity have a severe impact on the soil and can intensify both its formation and natural development process, as well as losses, or redistribution, due to erosion and crop harvesting. Furthermore, the analysis of weathering and pedogenesis processes helps to better interpret and classify the soil, its origin and formation. Research on soil micromorphology and, mineralogy in relation to agricultural issues, is scarce in Angola.

The aim of this chapter it to build on micromorphological to improve our understanding of soil nutrients status and mineralogy.

4.2.1- General soil micromorphology

Together with other conventional information sources, micromorphology provides data on the evolution, formation and functioning of soils. Micromorphology is the microscopic and ultramicroscopic study of soil organization, that encompasses the detailed study of the constituents of soil horizon aggregates, measurements and interpretations of their constituents and their relationships. Other studies point to the importance of this technique in the interpretation of prehistoric agricultural practices (Macphail, Courty et al. 1990). Figure 4.1, illustrate the major features to be analysed in the slides (see appendix 4) following the descriptive terminology of Stoops, 2021

Information on agricultural weathering or soil formation in Angola is either outdated or non-existent. This study will be a pioneer in addressing this issue in agricultural soils in Angola, including the soils of Bailundo, Ngongoinga, Mungo, Lepi (Huambo province) and Funda, Talelo and Bom Jesus (Luanda/ Bengo province), seeking to contribute to a better understanding of the properties and agricultural potential of soils. Two questions arise: (1) what minerals materials are there in agricultural soils? (2) How important is weathering to nutrient element status in these soils? Thus, the aim of this chapter is to assess the pedogenetic and micromorphological characteristics of these Angolan soils, and their relationship with their nutrient content.

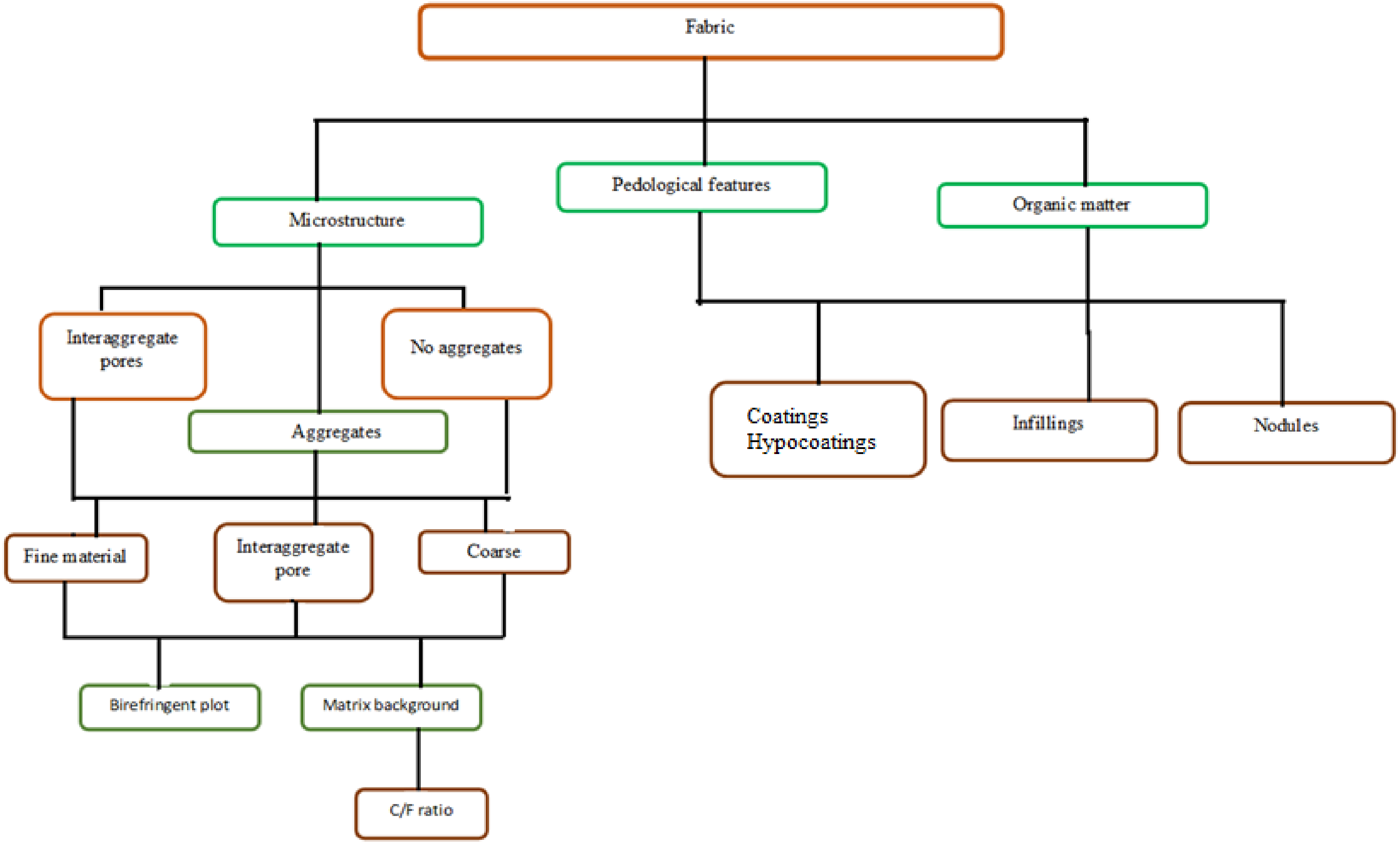


Figure 4. 10: Features analysed in the slide

4.2.2- Preparation of samples (slides)

Thin sections were prepared from the Kubiena samples at the Micromorphology Laboratories of the University of Stirling. They were first left to dry in acetone vapour in a sealed plastic box, and the acetone was changed every 3 days. At the same time, regular measurements were made of the specific gravity of the water and acetone mixture to check the drying progress. After drying, the samples were impregnated with epoxy resin under vacuum to ensure outgassing of the soil and proper penetration of the resin into the soil micro voids. When the resin had cured, blocks were cut with an approximate thickness of 1 cm and the polished face of the block was then bonded to a glass slide. The excess soil block was cut off using a diamond blade saw and the thin section was lapped in 15µm calcined aluminium oxide to a nominal thickness of 40 microns (µm). The thin section was then carefully cleaned and polished using a 3-micron diamond polishing solution. Thin sections were left without cover slips to allow for SEM-EDX analysis.

All slides were analysed in detail in terms of microstructure, their pedological features as well as the recognition of mineral grains. SEM/EDS (scanning electron microscope/ energy dispersive spectroscopy) complemented this analysis.

4.2.3- Micromorphological analysis and chemical microanalyses of thin sections

After preparing the slides, the micromorphological description used Stoops (1987) was performed using an Olympus BX51 optical polarized microscope, with Analysis PRO (analysis Pro is a specific thin section sample analysis software). Different magnification ranges (x20 – x100) and light sources (plane polarized-ppl, cross-polarized-xpl and oblique incident-oil) were used, thus allowing a detailed qualitative and semi-quantitative description of the features present in the slides (soils) and which were recorded in summary tables. Some representative fields of pedological features and alteration phases were selected. In these fields, the mapping was done by element using the dispersive energy characteristic of the chosen elements. A total of 21 slides (Appendix 4.1, 4.2, 4.3, 4.4, 4.5, 4.6 and 4.7) were analysed, being, Bailundo (3), Ngongoinga (3), Mungo (3), Lepi (3), Bom Jesus (3), Funda (3) and, Talelo (3), Ramiro samples were excluded for the reasons already presented (see Chapter 3).

4.2.4- SEM-EDX analysis of thin sections

Minerals grains were analysed using a scanning electron microscope (SEM/EDX), Zeiss EVO/MA15 operating under pressure (60 Pa) to minimise charging and allow analysis without the need for a conductive coating to be added to the slides. 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. The slide surface was positioned at a working distance of 8.5 mm to optimise the EDX detector geometry and point counts were performed with a count time of 20 seconds. Elements were identified automatically using the Zeiss Aztec software (analyse the features present on the soil) and element concentrations (wt %) for each analysis were normalised to 100%.

4.2.5- Statistical analysis

Data was collected, filed, and processed in Excel format. Categorical variables were summarized as median, mean, maximum and minimum. Statistical analysis was performed using Jamovi 2.3.

4.2.6-General micropedology, micromorphology, microchemistry aspects

The terminology used to describe the micromorphology features in thin sections was in accordance with the descriptions (Stoops, 2021)

Table 4. 8- Particle size classes

Micro	Fine	< 2 µm
	Medium	2 – 20 µm
	Coarse	20 – 50 µm

Bullock et al., 1987

B1 (Table 4.9 and Figure 412): soil presents a ratio between coarse material (> 20µm) and fine material (< 2µm) in the order of 2/3 with porphyric relative distribution. The visually estimated porosity is 30% of the slide area.

As for the coarse material random, quartz grains spherical common dominate with varied sizes. The larger (sand) grains are slightly sub-angular, and the small (silt) ones are angular smooth and some others with fissure. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). The presence of very few (<5% slide area) small nodules of iron was observed.

The fine material consists of fine silt and clay forming a reddish yellow speckled birefringent fine material, and clay coating, in some areas, a visibly darker colouring. Microstructure ranges from subangular blocky to granular, with inter-aggregate complex packing voids and bridges. From the SEM images (Figure 4.11) it is possible to observe the granular microstructure. EDX emission maps show low levels of nutrients. (a) shows the presence of Fe nodules within aggregates, with Si rich quartz grains and the clay rich fine material dominated by Al, residual levels of k concentrated in coarse mineral grains. (b) presented Si rich quartz grains, Fe nodules within aggregates, and Ti contents.

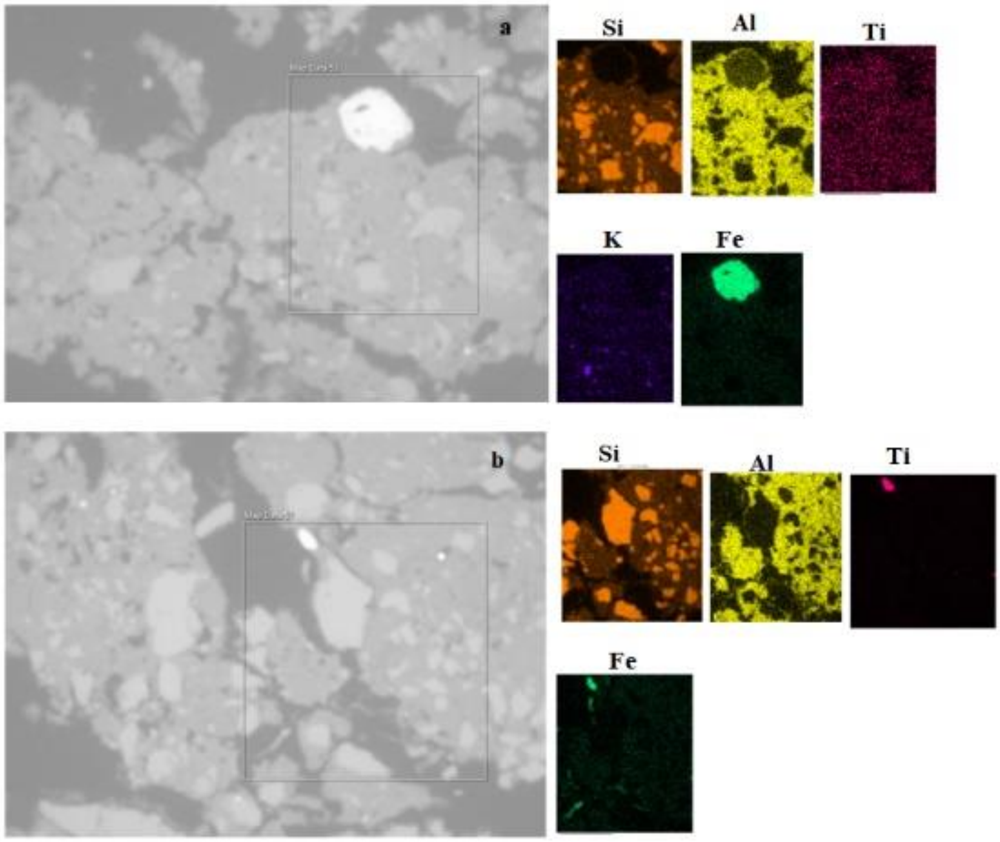


Figure 4. 11: SEM backscattered electron images and EDX emission maps of selected elements- B1 profile

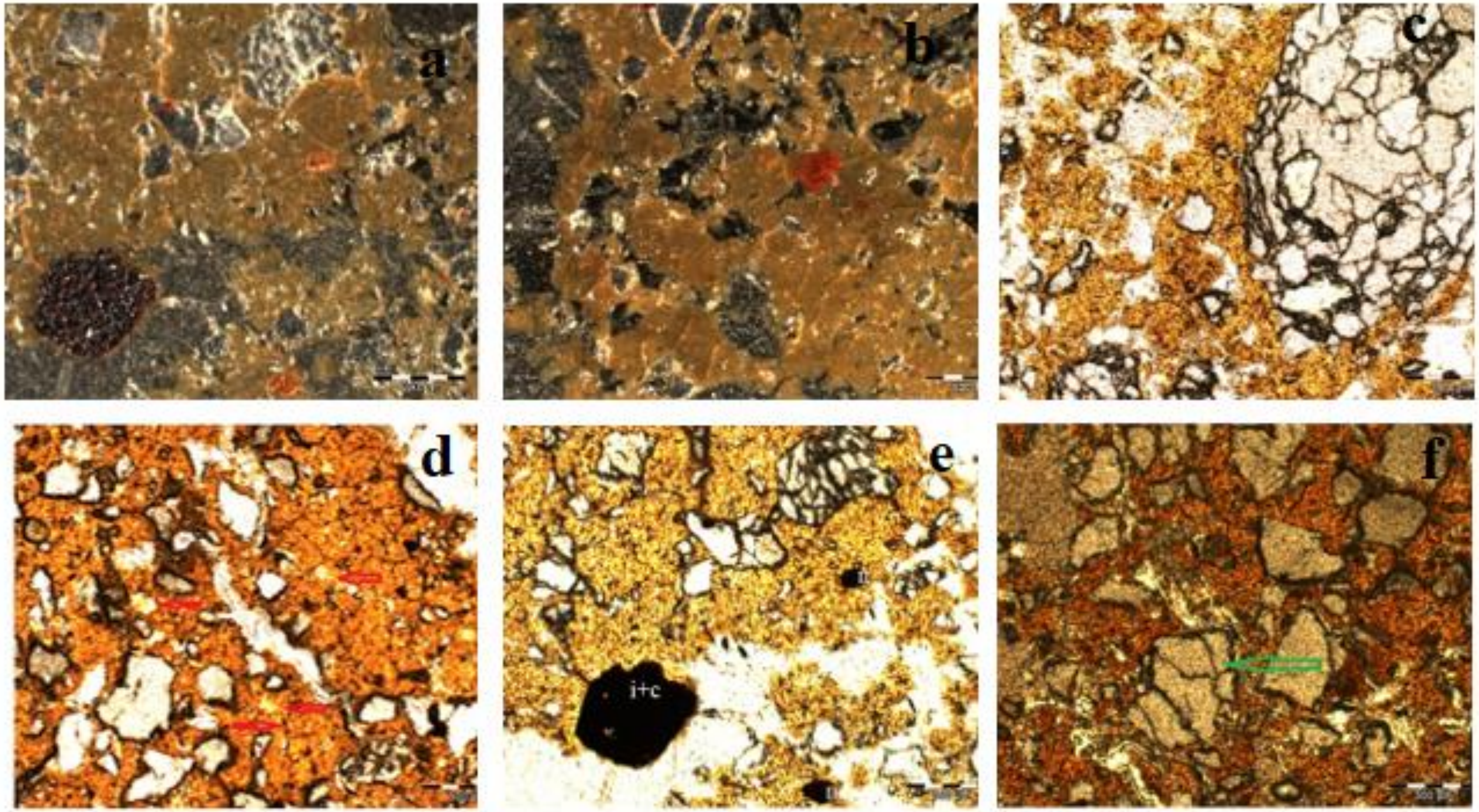
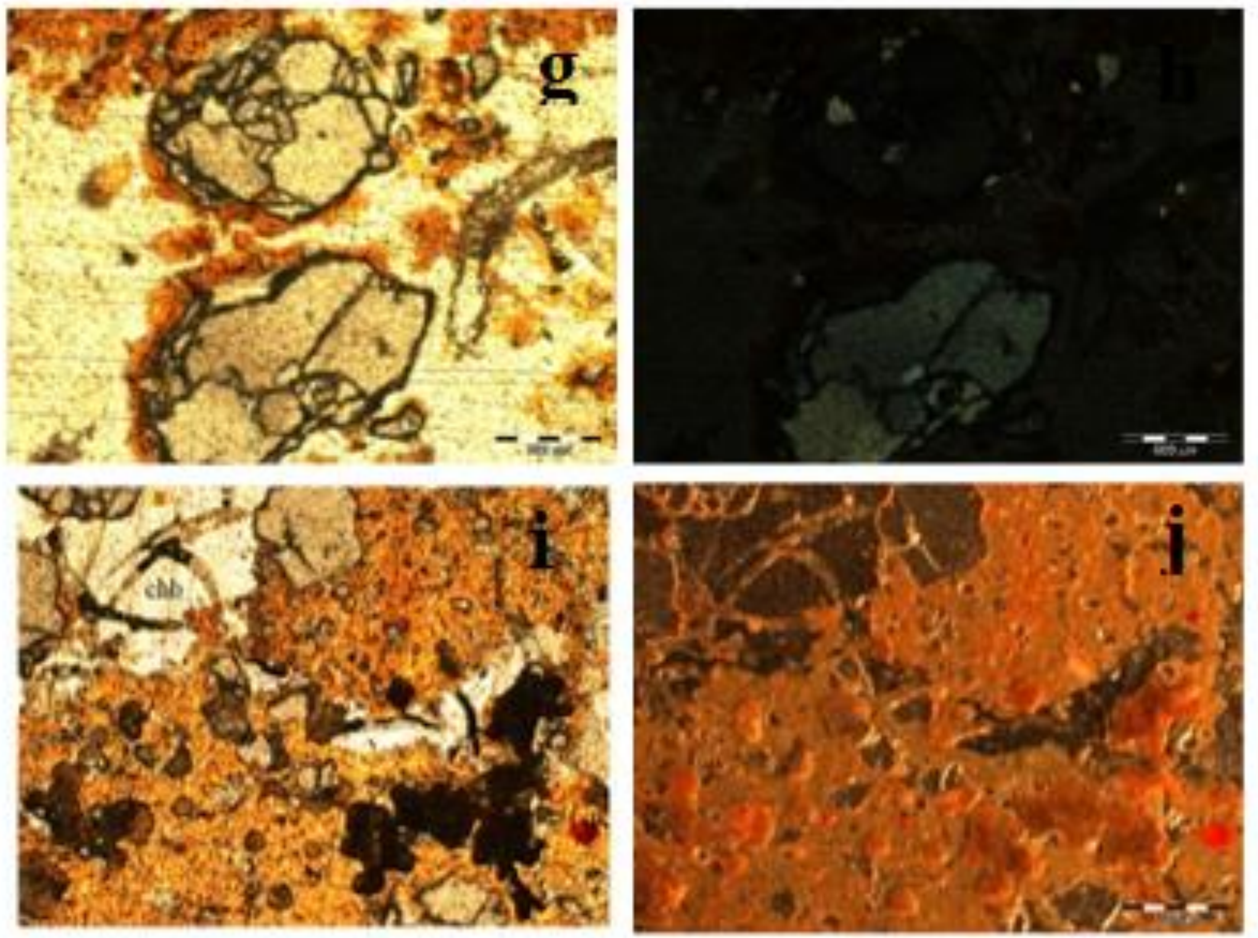


Figure 4. 12: photomicrograph of thin section slide, B1. a-iron nodule, oblique incident light (oil) view; b- iron micronodule, oblique incident light (oil) view; c-fissured quartz grain, bridges clay, plane polarized light (ppl) view; d-clay coatings, plane polarized light (ppl) view; e-same as a, plane polarized light (ppl) view; f-grains with cracks, signal for chemical compaction including convex-concave contacts (arrow)



Cont Figure 4.12: photomicrograph of thin section slide, B1. g- chambers type pores, plane polarized light (ppl) view; h-same as g, cross polarized light (xpl) view; i-chambers, iron nodule, plane polarized light (ppl) view; j- same as I, oblique incident light (oil) view

B2 (Table 4.9 and Figure 4.14): soil presents a ratio between coarse material (> 20µm) and fine material (< 2µm) in the order of 2/3 with porphyric relative distribution. The visually estimated porosity is 30% of the slide area.

The coarse material is randomly sorted, well rounded quartz grains predominate, with the larger grains being subangular, smooth, and fissured. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). Very few (< 5% slide area) iron micronodules are found, together with a quartz grain encrusted with iron. In addition, a subrounded quartz grain evidencing water-mediated erosion, was also present.

The fine material consists of fine silt and clay sized fractions making a reddish yellow speckled birefringent fine material. The main microstructure is a mixture of pellicular and single-grain structures, contain intra-aggregate voids are separated by voids (chambers), the granules contain voids. In the SEM images (Figure 4.13) it is possible to observe the subangular blocky microstructure. Figure 4.10a) shows a Si rich quartz grain (high Si), clay with Al predominance, and presence of Fe micronodules; Figure 4.10b) shows fine minerals dominated by Al, high Si quartz grains, some nodules of Ca concentrated in fine material minerals, and Ti minerals.

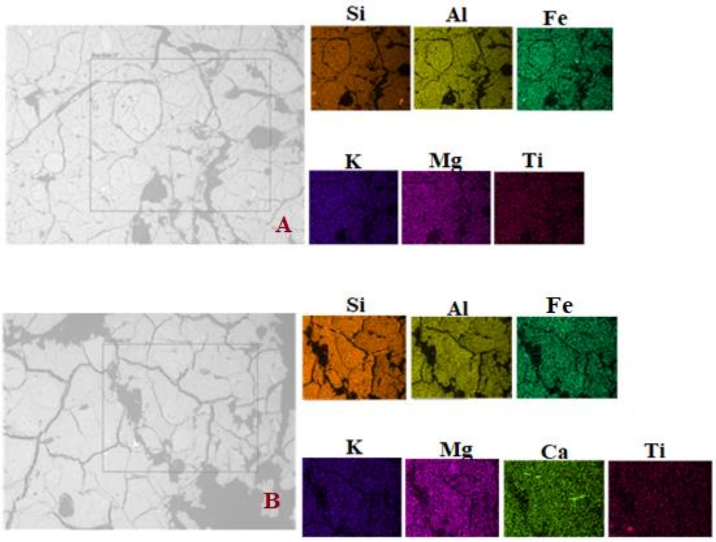


Figure 4. 13: SEM backscattered electron images and x-Ray emission maps of selected elements- B2 profile.

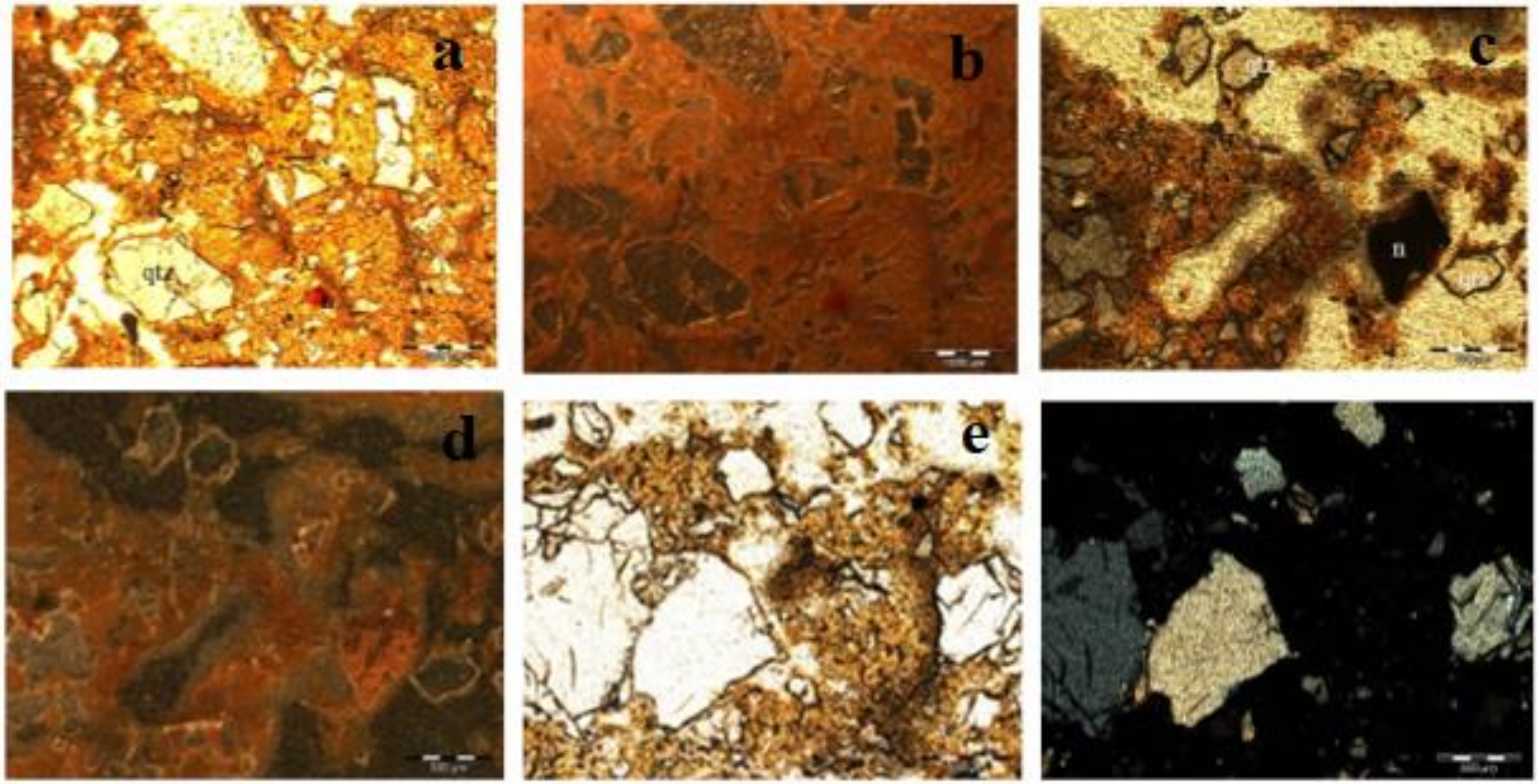
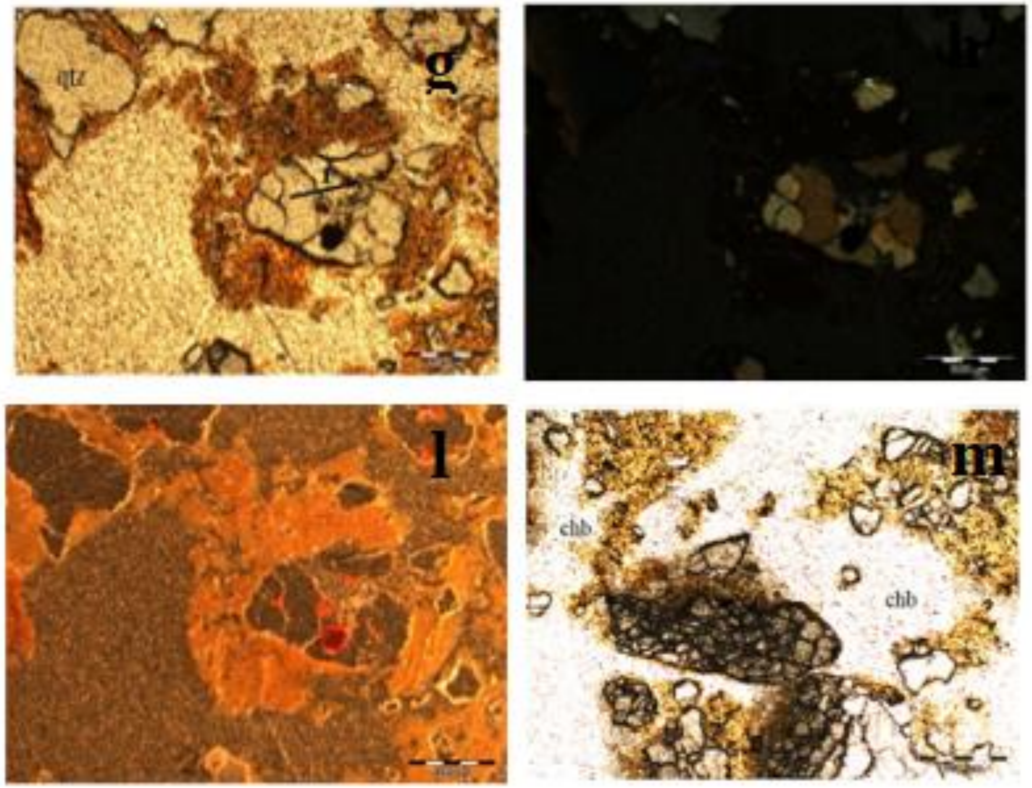


Figure 4. 14: Photomicrograph of thin section slide, B2. A-quartz grains, iron nodule, plane polarized light (ppl) view; b-same as a, oblique incident light (oil) view; c-iron nodule, plane polarized light (ppl) view; d-same as c, oblique incident light (oil) view; e-signal for chemical compaction including convex-concave contacts between quartz grains, plane polarized light (ppl, 4x) view; f-same as e, cross polarized light (xpl, 4x) view.



Cont. Figure 4.14: photomicrograph of thin section slides B2. g-iron nodule enclosed in quartz grain, quartz grains, plane polarized light (ppl, 4x) view; h-same as g, (xpl, 4x) view; l-same as g, (oil, 4x) view; m- chambers, plane polarized light (ppl, 4x) view.

B3 (Table 4.9 and Figure 4.16): Soil presents a ratio between coarse (> 20µm) material and fine material (< 2µm) in the order 2/8 and the visual relative distribution is porphyric. The visually estimated porosity is 30% of the slide area.

The coarse material is formed by few (5-15% slide area) smaller quartz grains, slightly angular smooth and with cracks. The alteration pattern of quartz is type D (dotted) and degree zero (0).

Common (15-30% slide area) pieces of (charcoal) were observed. Iron pedo-features, consisting of few (<5% slide area) nodules, iron matrix impregnations, and void hypocoatings were observed.

The fine material consists of fine to medium silts and clay forming a dark yellow speckled birefringent fine material. In isolated sectors the presence of fine darker material is visible. Hypocoatings around pores suggest that water circulation may be remobilizing iron. The microstructure is complex with channels, voids, and pores (vughs) and intra-aggregates. SEM images (Figure 4.15) show EDX emission maps. Figure 4.15a) presents high Si quartz grains, zones with high Al concentration, and Ca plagioclases. Figure 4.15b) shows the presence high Si quartz grains, Fe nodules enclosed within aggregates, Ti minerals.

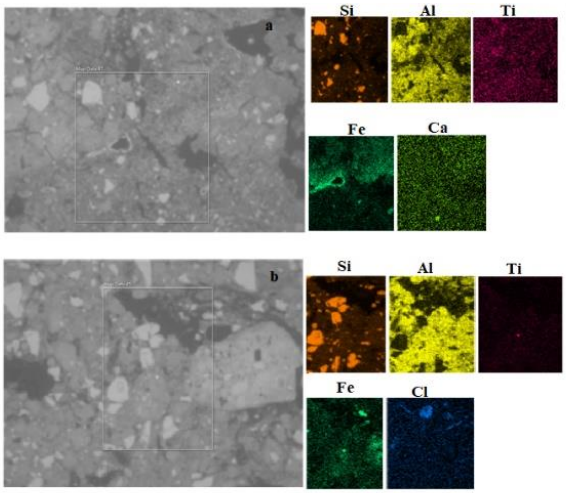


Figure 4. 15: SEM backscattered electron images and EDX emission maps of selected elements- B3 profile.

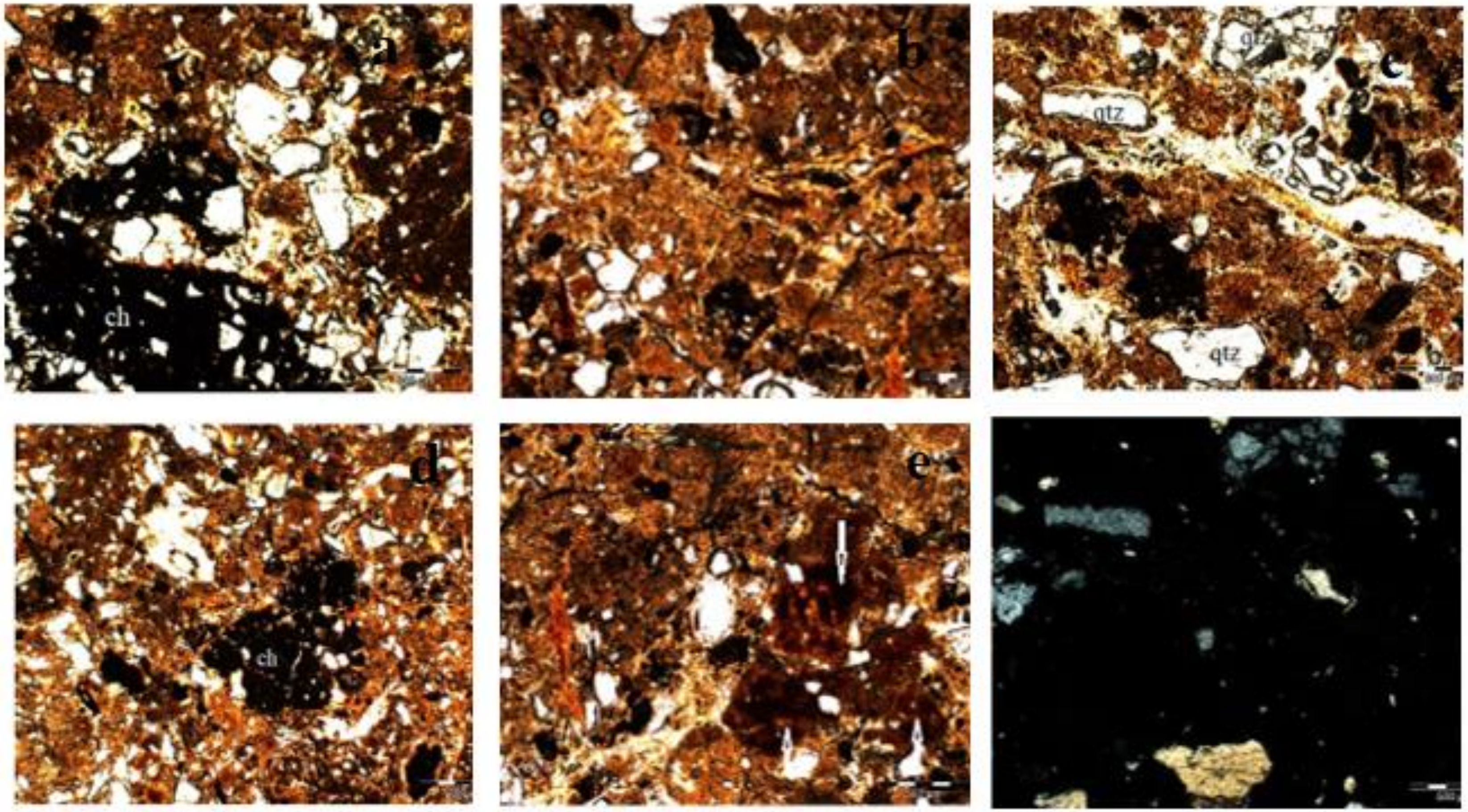
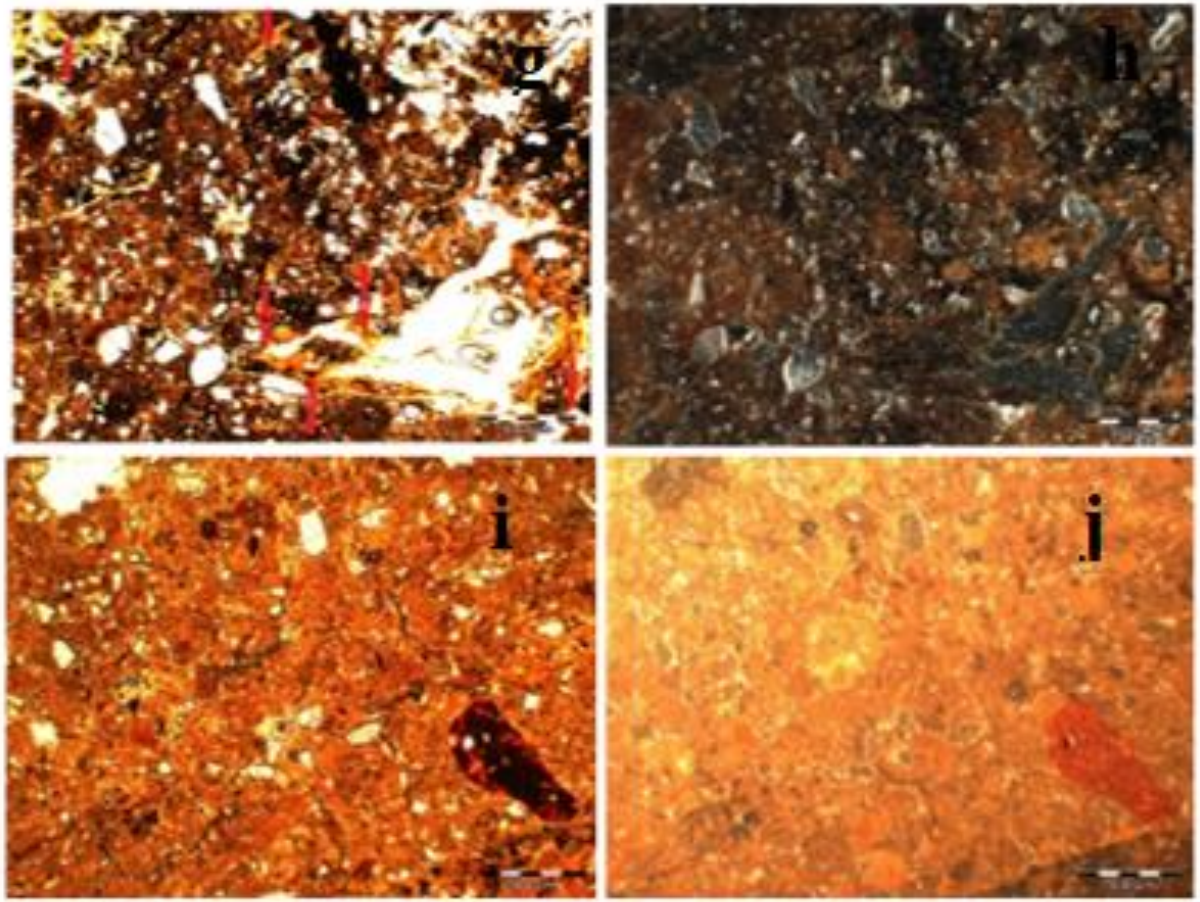


Figure 4. 16**:** Photomicrograph of thin section slide, B3. a- nodule (charcoal) plane polarized light (ppl, 4x) view; b-abundant organic matter (ppl, 4x) view; c-quartz grain (ppl, 4x) view; d-nodule (ppl, 4x) view; e-clay coating/filling fragment (ppl, 4x) view; f-same as c, cross polarized light (xpl, 4x)



Cont. Figure 4.16: photomicrograph of thin section slide, B3. g-clay coating infilling, plane polarized light (ppl, 2x) view; h-same as g (oil, 2x) view; i-sub-rounded iron nodule plane polarized light (xpl, 2x) view; j-same as i (oil, 2x) view.

Table 4. 9- Summaries of soil micromorphology characteristics- Bailundo

Horizon	Coarse mineral Material (>2µm)		Coarse material arrangement	Coarse organic/biological material	Iron Pedo- features			Micro- structure	Fine mineral material	Related distribution	C/F ratio (20 µm)
	Quartz	Feldspar		Charcoal	Fe impregnation (matrix)	Fe hypocoating (poroid)	Fe nodule				
B1	•••	None observed	Random Sorted	None observed	•	•	•	Granular to subangular blocky microstructure; compound packing voids	Reddish Speckled- b fabric	Open porphyric	2/3
B2	•••	None observed	Random Sorted	•	•	•	•	Mixture of pellicular and single grains	Reddish Speckled- b fabric	Open porphyric	2/3
B3	••	None observed	Random Sorted	•••	••	•	••	Complex microstructure, with compound voids (channels and vughs)	Reddish Speckled- b fabric	Open porphyric	2/3
. Very few (<5 % slide area); .. Few (5-15 % slide area); ... Common (15-30 % slide area); .... Frequent (30-50) % slide area); ...... Dominant (50-70 % slide area); b fabric birefringent fabric; G-granular; SB-subangular.											

Ng1 (Table 4.10 and Figure 4.18): Soil presents a ratio between coarse (> 20µm) and fine material (< 2µm) in the order of 1/2 with visual open porphyric relative distribution. The visually estimated porosity is 30% of the slide area.

The nature of the coarse material is essentially randomly sorted quartz, with grains of varied sizes, the largest being rounded, the smallest being rounded and spherical, all grains have smooth roughness and cracks. The alteration pattern of quartz is type D (dotted) and degree zero (0). Iron pedo-features consist of few (< 5% slide area) iron nodules.

The fine material consists of fine to medium silt and clay making a yellow speckled birefringent fine material. The microstructure is composed by subangular blocky and granular in complex packing of channels, vughs, and voids. Figure 4.17 shows the SEM images together with SEM-EDX mapping of the elements in this soil. Figure 4.17a) illustrate the High Si quartz grains, Al embedded quartz grains, areas with slight Ti and K concentration.

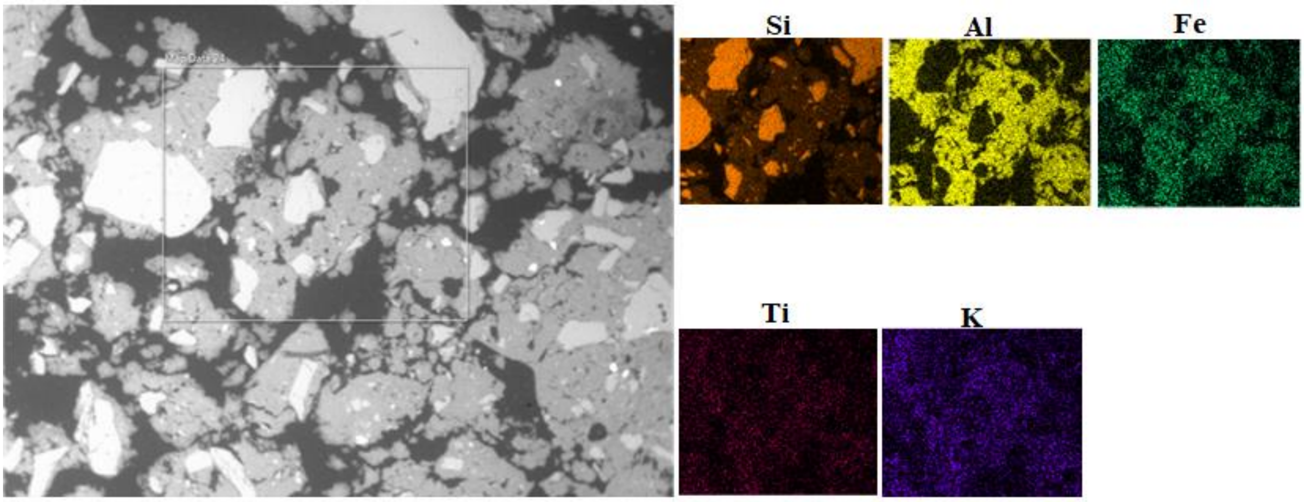


Figure 4. 17: SEM backscattered electron images and EDX emission maps of selected elements- Ng1 profile

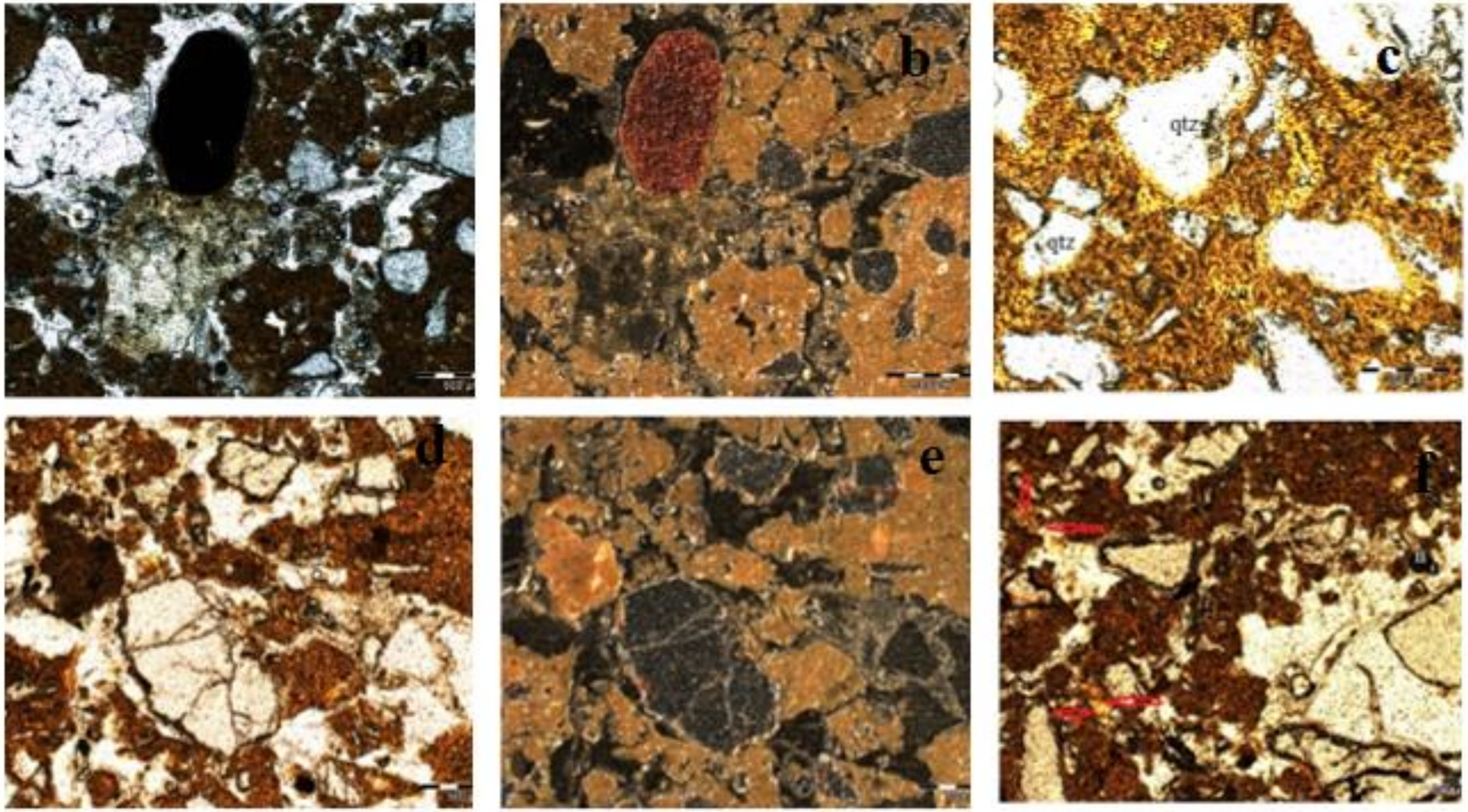


Figure 4. 18: Photomicrograph of thin section slide, Ng1. a- sub-rounded iron nodule, cross polarized light (xpl, 4x) view; b-same as a, oblique incident light (oil, 4x) view; c-rounded to sub-angular quartz grain, plane polarized light (ppl, 4x) view; d-quartz grain with cracks, plane polarized light (ppl, 4x) view; e-same as d, oblique incident light (oil, 4x) view; f-clay coating (arrows) plane polarized light (ppl, 4x) view.

Ng2 (Table 4.10 and Figure 4.20): Soil presents a ratio between coarse material and fine material in the order 1/2 with an open porphyric relative distribution. The visually estimated porosity is 30% of the slide area consisting of interaggregate channel and packing voids and intra-aggregate vughs.

The coarse material is predominantly randomly sorted sub-rounded to rounded quartz grains minerals smooth with different sizes, some of them with cracks and all with roughness. The alteration pattern of quartz is type D (dotted) and degree zero (0). Iron pedo-features, includes very few (< 5% slide area) iron nodules, few (< 5% slide area) iron matrix impregnation was visible. The presence of small angular and non-spherical organic biological material (charcoal) was observed.

The fine material consists of fine to medium silt and clay forming a yellow speckled birefringent fine material. The microstructure is a mixture of subangular blocky and granular where the aggregates are separated by channels and, packing voids Figure 4.19 shows the SEM images together with EDX mapping of selected elements. Figure 4.19a) shows the presence of Fe nodules, with Si rich quartz grains, Figure 4.19b) shows the high Si quartz grains, as well as an Al/Fe nodule.

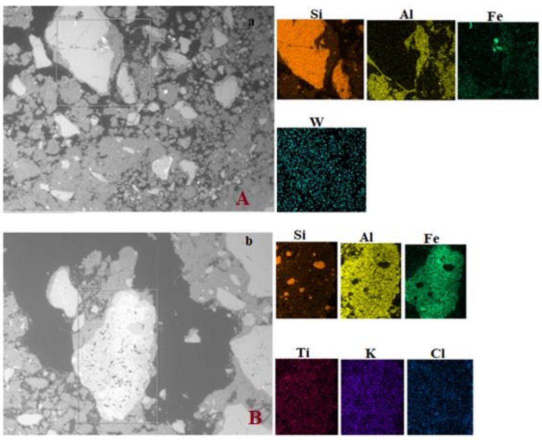


Figure 4. 19: SEM backscattered electron images and EDX emission maps of selected elements- Ng2 profile.

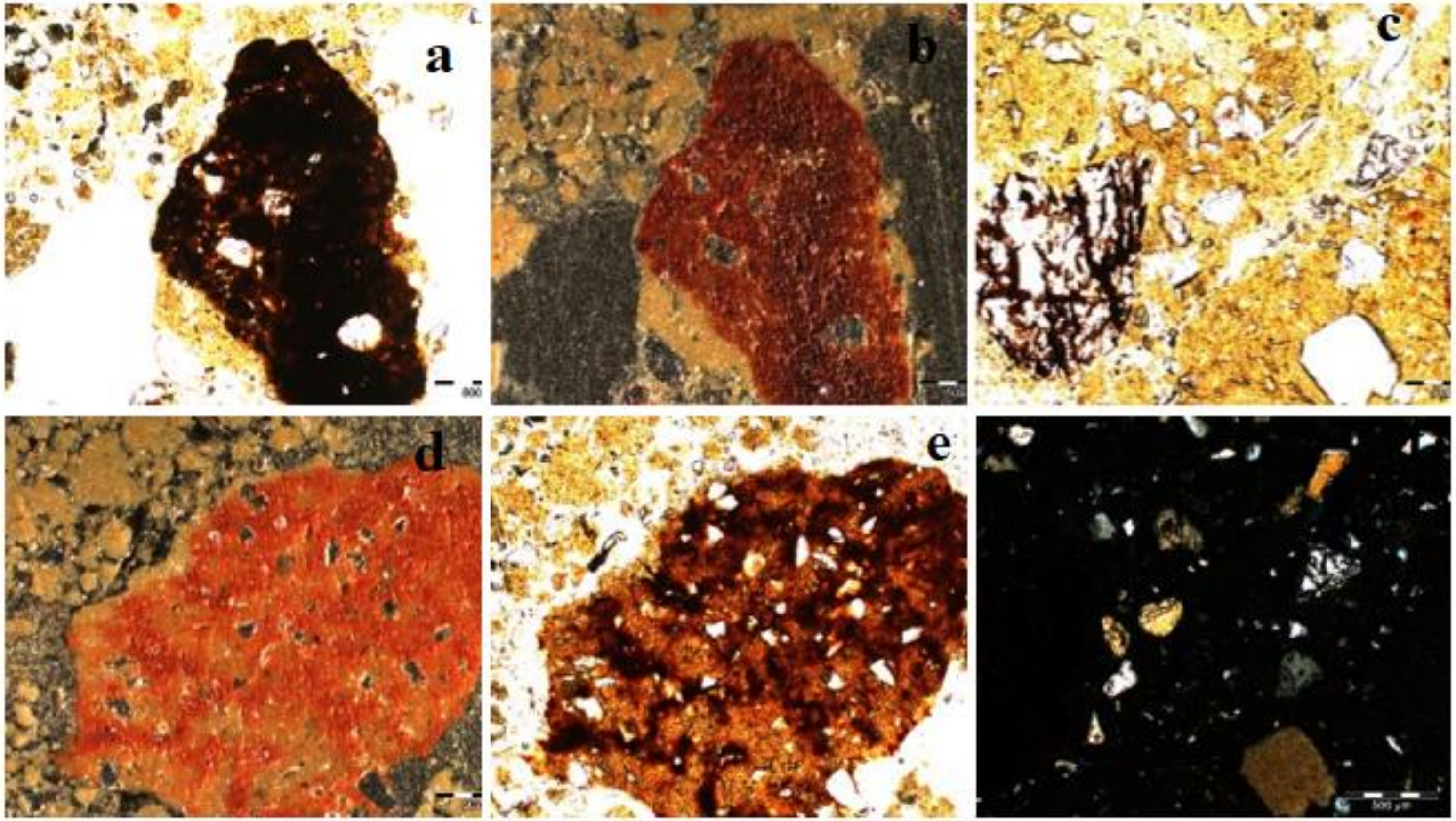
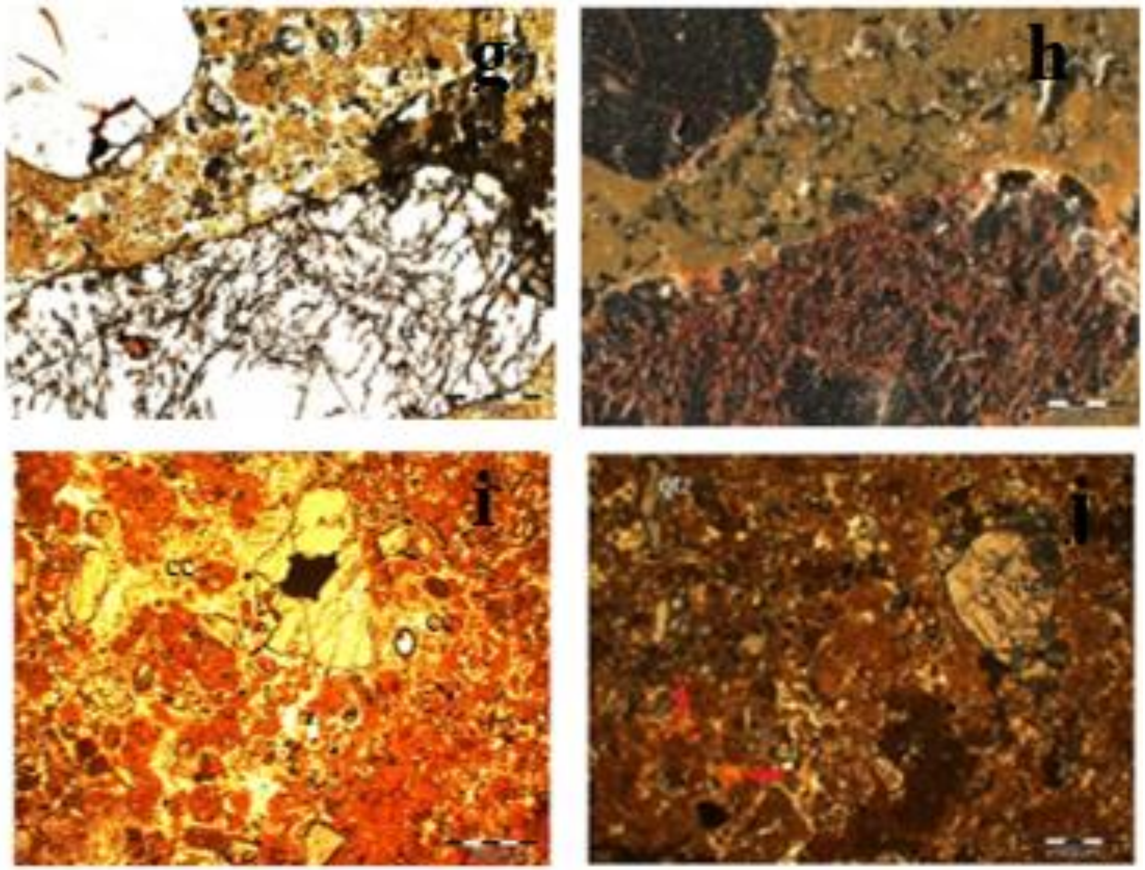


Figure 4. 20: Photomicrograph of thin section slide, Ng2. a-sub-rounded iron nodule, plane polarized light (ppl, 4x) view; b-same as a, oblique incident light (oil, 4x) view; c-iron infilling in the grain cracks, plane polarized light (ppl, ex) view; d-filled bioturbation, (oil, 4x) view; e-same as d (ppl, 4x); f-same as c (xpl, 4x) view



Cont. Figure 4.20: photomicrograph of thin section slide, Ng2. a- sub-rounded grain with iron infilling, plane polarized light (ppl, 4x) view; h-same as g (oil, 4x), nodule enclosed in grain, plane polarized light (ppl, 2x) view; j-clay coating (arrows), plane polarized light (ppl, 2x) view.

Ng3 (Table 4.10 and Figure 4.22): Soil presents a ratio between coarse (> 20µm) and fine material in the order 2/3 with open porphyric relative distribution. The visually estimated porosity is 20% of the slide area.

The coarse material is dominated by rounded and subangular quartz grains with diverse sizes, the larger grains tend to angular to subangular and small (silt) grains rounded, all grains smooth and fissured, and some quartz grains are surrounded by clay. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). Iron-pedofeatures are composed of few (5 - 15 %) iron nodules, and iron impregnate to quartz grains. The presence of small and non-spherical charcoal was also observed

The fine material consists of fine to medium silts and clay forming a yellow speckled birefringent fine material. Subangular to angular blocky micro-aggregates separated by inter-aggregate, channels for of the microstructure. Figure 4.21 shows the SEM together with EDX mapping of selected elements in this soil can be observed. Figure 4.21a) shows the presence of Fe nodules enclosed in aggregates, with high Si quartz grains, Ti minerals

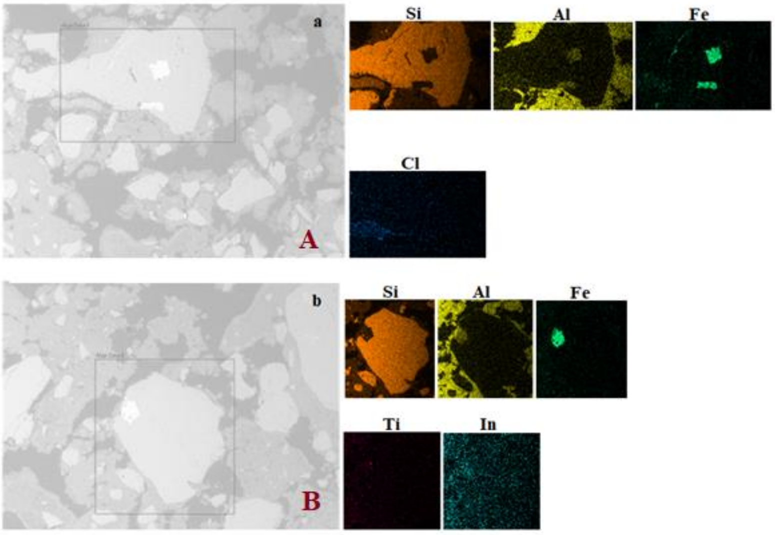


Figure 4. 21: SEM backscattered electron images and EDX emission maps of selected elements- Ng3 profile.

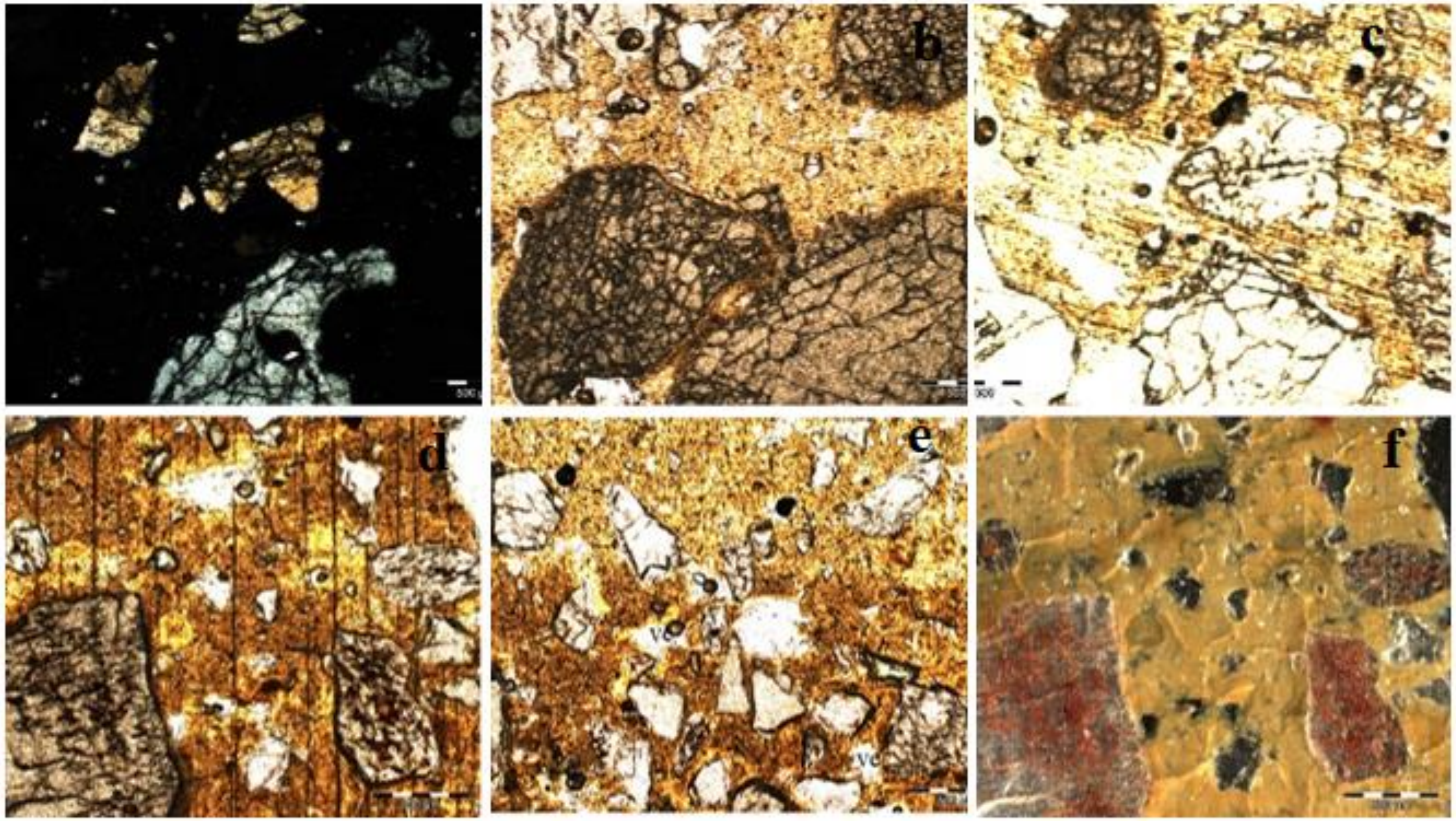
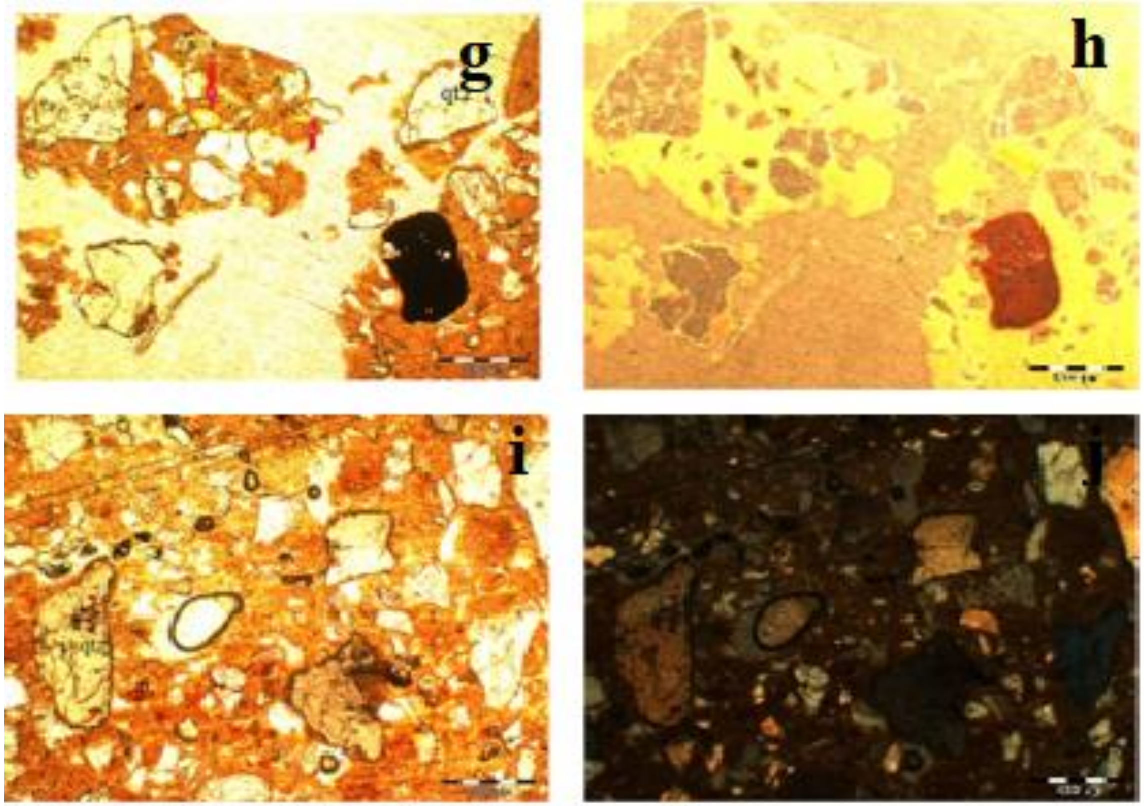


Figure 4. 22: Photomicrograph of thin section slide, Ng3. a- quartz grains with cracks, cross polarized light (xpl, 4x) view; b-same as a (ppl, 4x) view; c-micronodules, plane polarized light (ppl, 4c); c- cracked and iron-filled grains, plane polarized light (ppl, 4x) view; e-clay coating and nodules, plane polarized light (ppl, 4x); f-same as d (oil) view.



Cont. Figure 4.20: photomicrograph of thin section slide, Ng3-g-iron nodule, and clay coating (arrows), plane polarized light (ppl, 2x) view; h-same as g (oil) view; i-quartz grains and micronodules, plane polarized light (ppl, 2x) view; j-same as I (xpl, 2x) view.

Table 4. 10- Summaries of soil micromorphology characteristics- Ngongoinga

Horizon	**Coarse mineral Material (>2µm)**		**Coarse material arrangement**	**Coarse organic/biological material**	**Iron Pedo- features**			**Micro- structure**	**Fine mineral material**	**Related distribution**	**C/F ratio (20 µm)**
	Quartz	Feldspar		Charcoal	Fe impregnation (matrix)	Fe hypocoating (poroid)	Fe nodule				
Ng1	•••	None observed	Random Sorted	None observed	•	•	•	subangular blocky and granular microstructure; compound packing voids	Yellow Speckled- b fabric	Open porphyric	1/2
Ng2	•••	None observed	Random Sorted	•	•	•	•	As above	Yellow Speckled- b fabric	Open porphyric	1/2
Ng3	••	None observed	Random Sorted	•••	••	•	••	Granular to subangular blocky microstructure; compound packing voids	Yellow Speckled- b fabric	Open porphyric	2/3
. Very few (<5 % slide area); .. Few (5-15 % slide area); … Common (15-30 % slide area); …. Frequent (30-50) % slide area); …... Dominant (50-70 % slide area); b fabric birefringent fabric; G-granular; SB-subangular.											

M1 (Table 4.11 and Figure 4.24): Soil presents a ratio between coarse (> 20μm) and fine material in the order 2/3 with an open and closed porphyric relative distribution. The visually estimated porosity is 40% of the slide area. The relative distribution is open porphyric and close porphyric.

The coarse material is randomly sorted, predominates the sub-rounded to rounded quartz grains, with larger slightly angular to subangular and small grains, all grains with smooth roughhouses and some of them fissured. The alteration pattern of quartz is type D (dotted) and degree zero (0). Iron pedo-features, consisting of very few (< 5% slide area) iron nodules and very few (< 5% slide area) iron impregnation (matrix).

The fine material consists of fine to medium silts and clay making a reddish speckled birefringent fine material. In isolated sectors there is a darker colour in contrast to the general colour. The microstructure is complex a mixture of crumb structure, granular and pellicular grain structure with a packing of voids (vughs) and channels. Figure 4.23 shows the SEM together with EDX images where mapping of selected. Figure 4.23a) illustrate the presence of Fe nodules, with high Si quartz grains, the clay fine material dominated by Al, contents of Cl concentrated in grains and Ca contents concentrated in grain Ti minerals

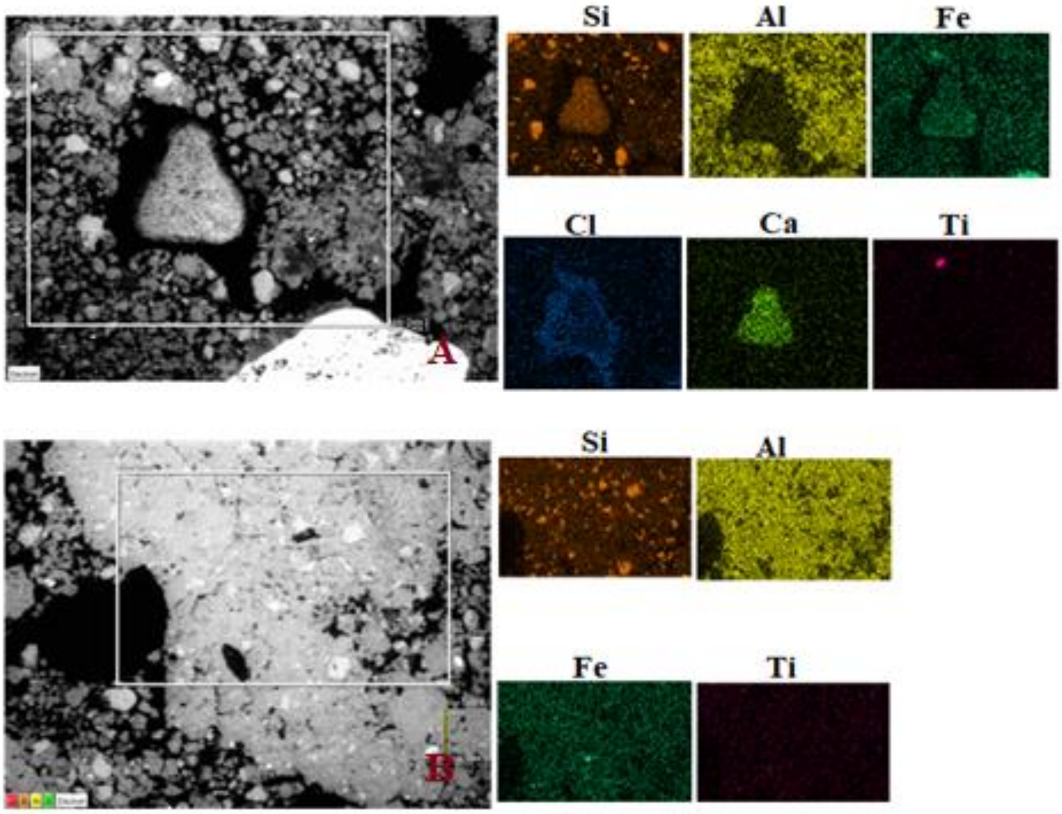


Figure 4. 23: SEM backscattered electron images and x-Ray emission maps of selected elements- M1

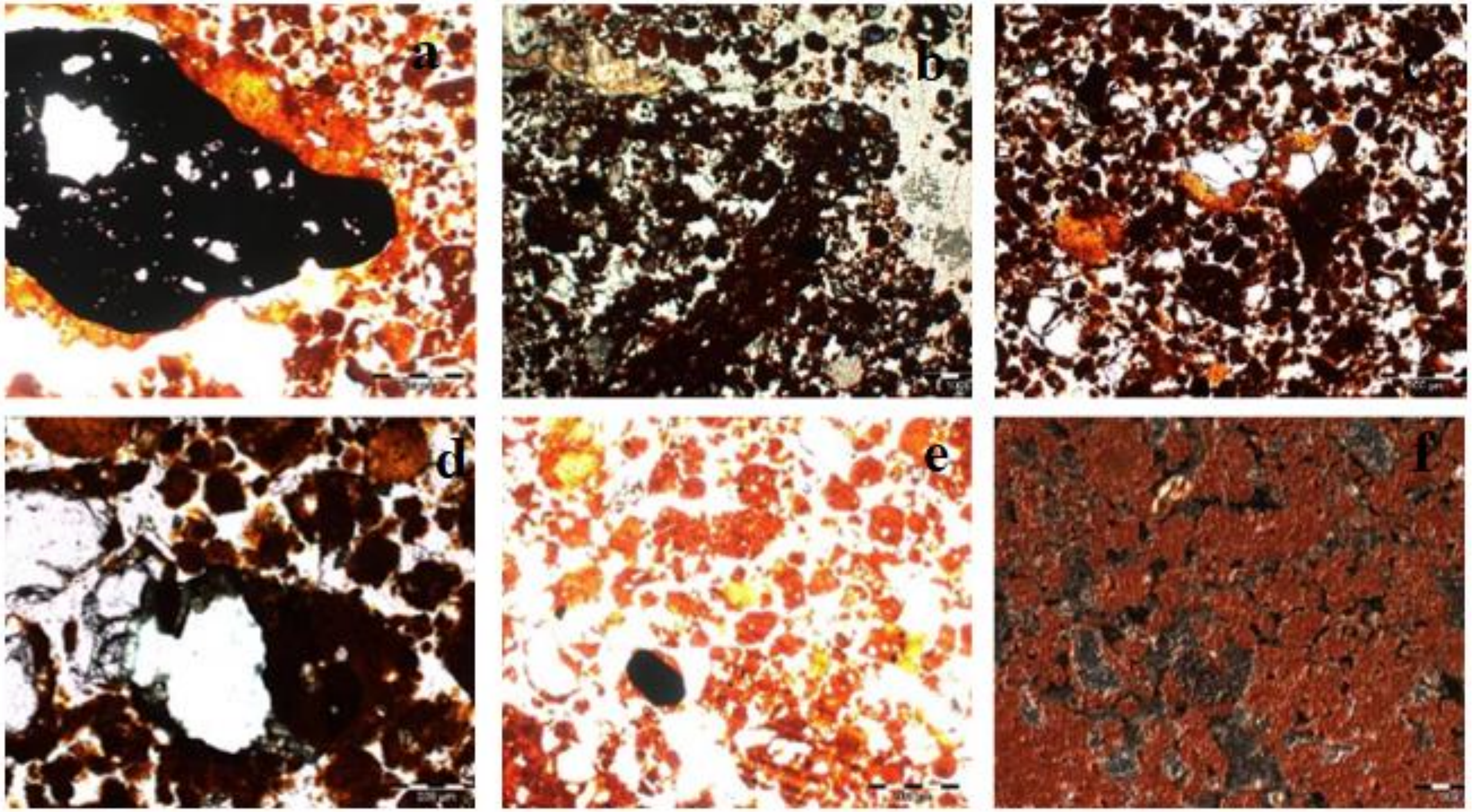


Figure 4. 24: Photomicrograph of thin section slide, M1-a-charcoal, plane polarized light (ppl, 4x) view; b-clay coating, plane polarized light (ppl, 4x) view; c-quartz grains surrounded by clay, plane polarized light (ppl, 4x) view; d-dark aggregates with dispersed clay interaggregate and quartz grain, plane polarized light (ppl, 10x); charcoal, plane polarized light (ppl, 4x) view; f-same as e (oil) view.

M2 (Table 4.11 and Figure 4.26): Soil presents a ratio between coarse (> 20 μm) and fine material in the order 2/3 with open porphyric and close porphyric relative distribution. The visually estimated porosity is 40% of the slide area.

The coarse material is predominantly randomly sub-rounded to rounded quartz grains with different sizes, some of them with fissures. The alteration pattern of quartz is type D (dotted) and degree zero (0). Iron pedo-features, consisting of few (5 - 15% slide area) iron nodules. The presence of small non-spherical charcoal was also observed.

The fine material consists of fine to medium silts and clay forming a reddish speckled birefringent fine material. The microstructure is complex subangular blocky, and granular with a packing of voids, channels, and vughs. In some sectors the presence of fine darker material is visible. Figure 4.25 shows the SEM images together with EDX the mapping of selected elements. Figure 4.25a) shows the presence of Fe micronodules, with Si rich quartz grains, organic channels (semi-circular shape); Figure 4.25b) illustrate the presence of Fe nodule enclosed in aggregates, the clay fine material dominated by Al, contents of Ti concentrated in fine material and grains.

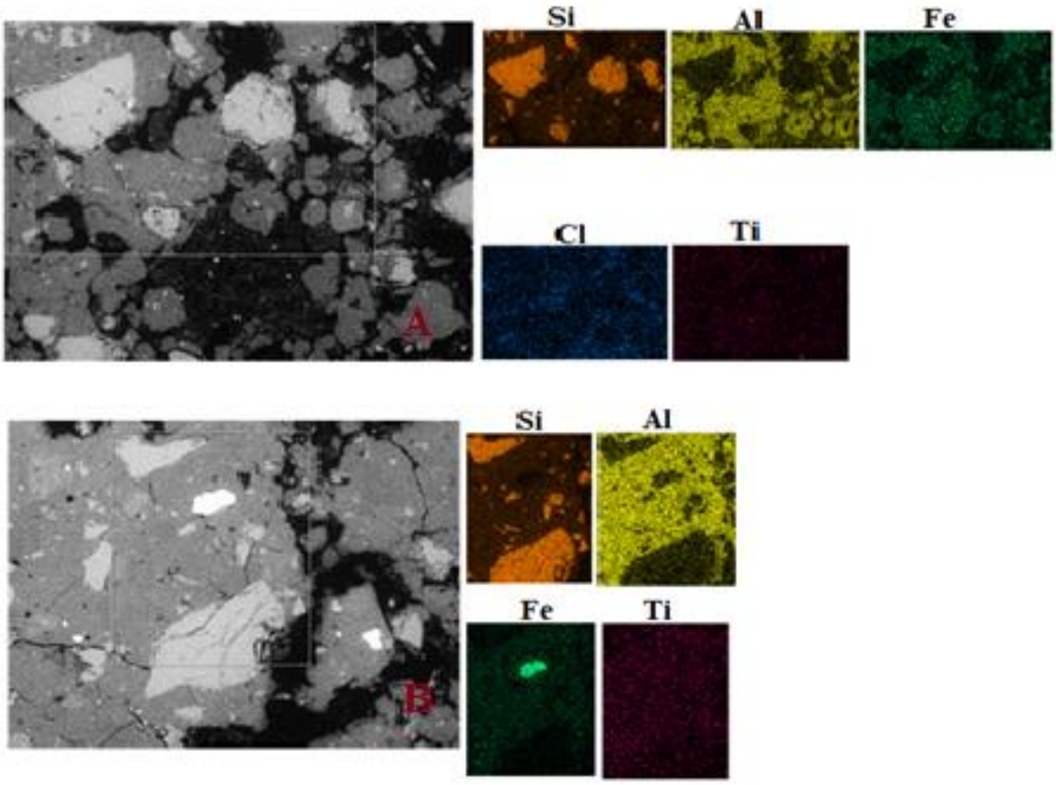


Figure 4. 25: SEM backscattered electron images and x-Ray emission maps of selected elements- M2

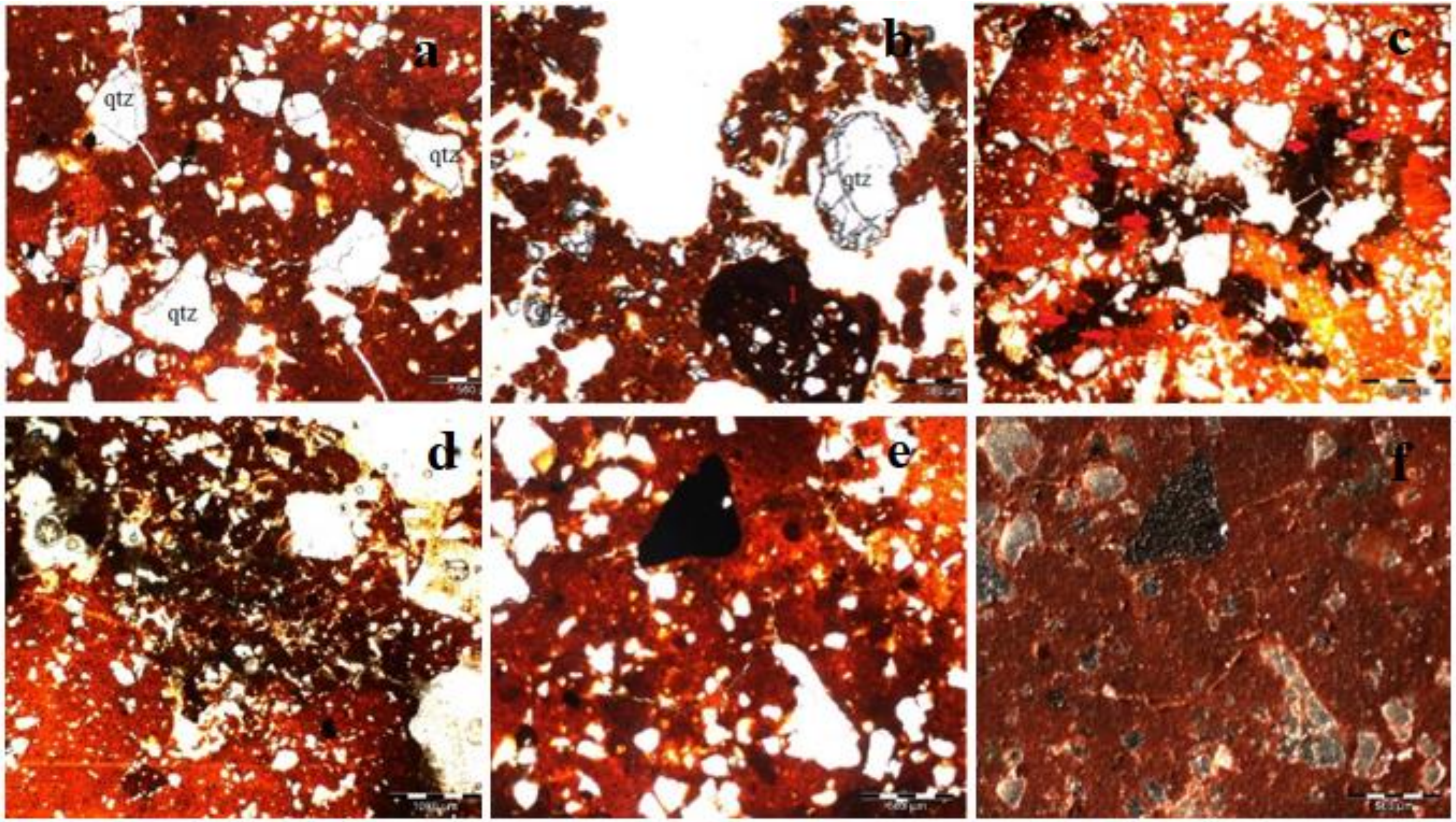


Figure 4. 26: Photomicrograph of thin section slide, M2-a- sub-rounded quartz grains, plane polarized light (ppl, 4x) view; quartz grain with cracks, plane polarized light (ppl, 4x) view; c-clay coating (arrows), plane polarized light (ppl, 2x) view; d-granular microstructure with 2 types of aggregates dark red and light red, plane polarized light (ppl, 2x) view; e-charcoal, plane polarized light (ppl, 4x) view; f-same as e (oil) view.

M3 (Table 4.11 and Figure 4.28): Soil presents a ratio between coarse (> 20µm) and fine material in the order 2/3 with open porphyric and chitonic relative distribution. The visually estimated porosity is 40% of the slide area.

The coarse material is mostly randomly sorted quartz grains, with diverse sizes, the larger grains slightly angular and some of them with cracks, and small grains are slightly spherical. The alteration pattern of quartz is type D (dotted) and degree zero (0). Iron pedo-features, consisting of few (5 - 1 5% slide area) iron nodules. Common charcoal was also observed, and a big conglomerate of organic biological material has been identified.

The fine material consists of fine to medium silts and clay forming a dark red speckled birefringent fine material. In some isolated sectors it is visible the presence of fine and clear material in contrast to general colour. The microstructure is composed by mixture of crumbs, granular structure with a packing of voids, channels, and vughs. Figure 4.27 shows the SEM together with EDX images mapping of selected elements. Figure 4.27a) shows the presence of high Si quartz grains, Al/Fe nodules, K-feldspar, Ti minerals. Figure 4.27b) shows the presence of Fe micronodules, with Si rich quartz grains, K grains, contents of Cl and K concentrate in fine material.

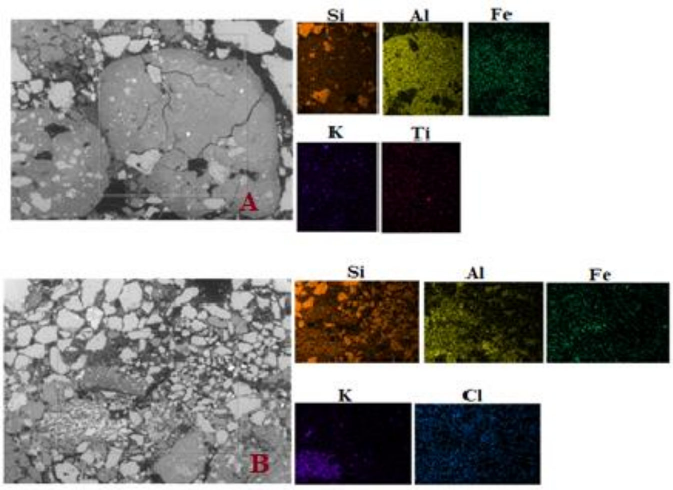


Figure 4. 27: SEM backscattered electron images and EDX emission maps of selected elements- M3

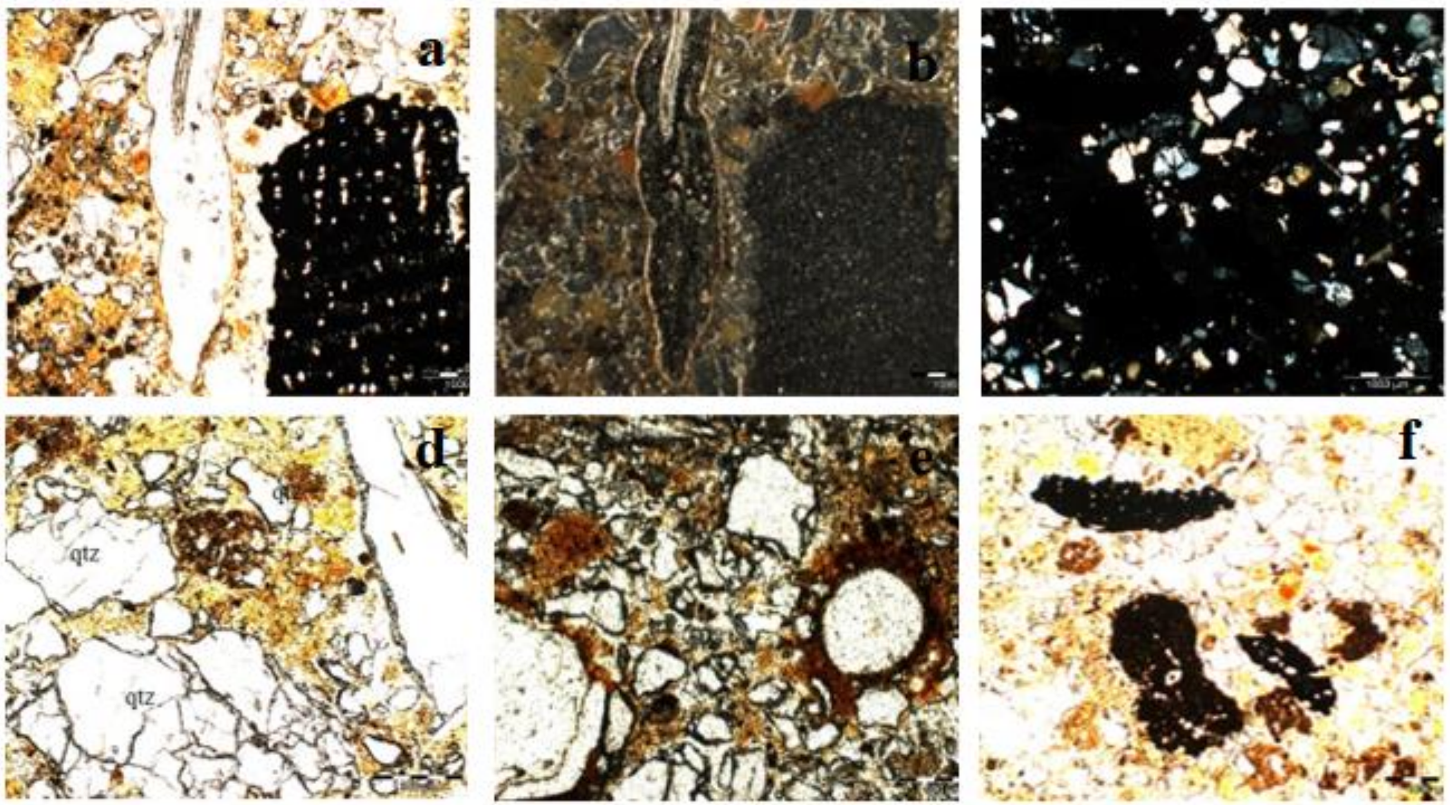
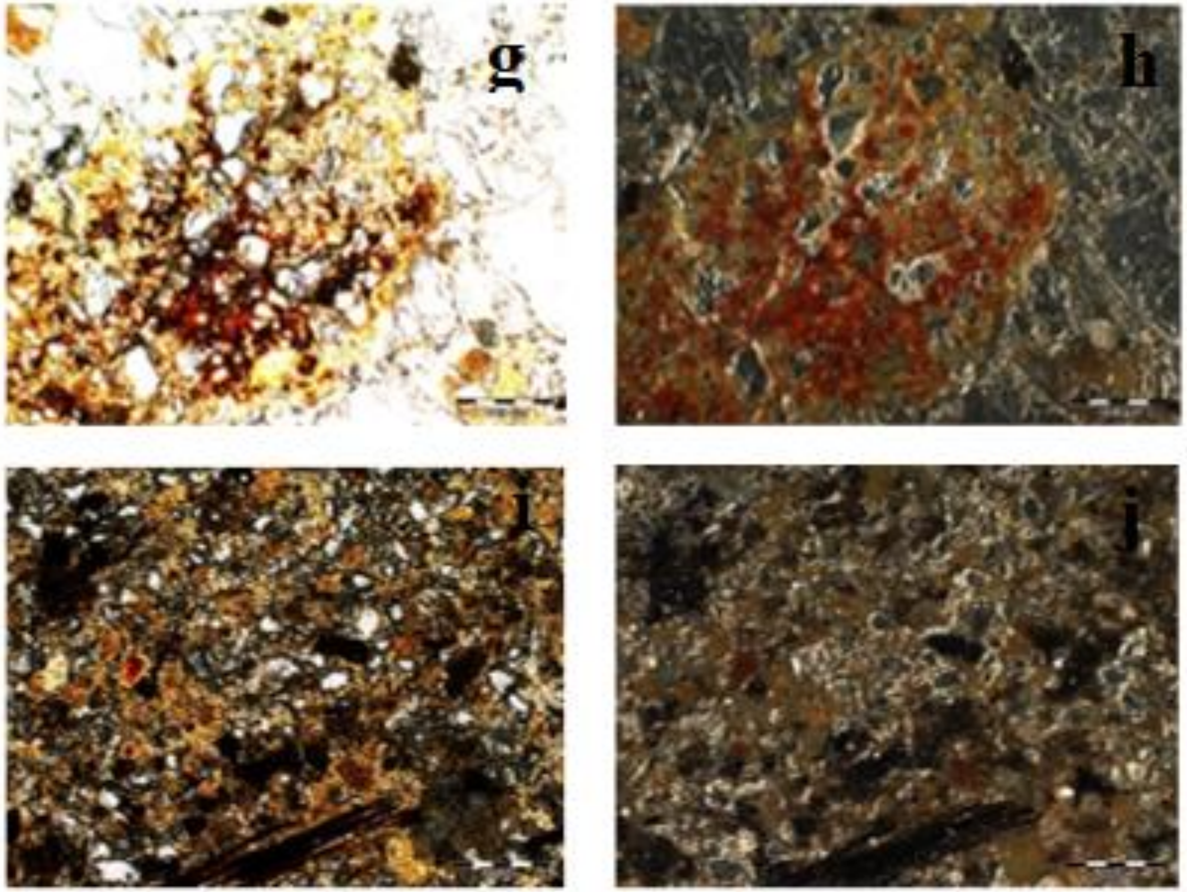


Figure 4. 28: Photomicrograph of thin section slide, M3. a-charcoal with light clay with fine clay coatings in the cavities, plane polarized light (ppl, 2x) view; b-same as a (oil) view; c-same as f (xpl, 2x) view; d-quartz grains, plane polarized light (ppl, 4x); e- grains surrounded by clay, plane polarized light (ppl, 4x) view; f-charcoal and iron nodule, plane polarized light (ppl, 2x) view.



Cont. Figure 4.28: photomicrograph of thin section slide, M3. G-evidence of bioturbation, plane polarized light (ppl, 2x) view; h-same as g (oil) view; i-iron nodule and organic waste, plane polarized light (ppl, 4x) view; j-same as I (oil) view.

Table 4. 11-Summaries of soil micromorphology characteristics- Mungo

Horizon	**Coarse mineral Material (>2µm)**		**Coarse material arrangement**	**Coarse organic/biological material**	**Iron Pedo- features**			**Micro- structure**	**Fine mineral material**	**Related distribution**	**C/F ratio (20 µm)**
	Quartz	Feldspar		Charcoal	Fe impregnation (matrix)	Fe hypocoating (poroid)	Fe nodule				
M1	•••	None observed	Random Sorted	None observed	•	•	•	Complex microstructure: mixture of granular, crumbs and pellicular grain, compound packing voids	Reddish Speckled- b fabric	Open and close porphyric	2/3
M2	•••	None observed	Random Sorted	•	•	•	•	Subangular blocky and granular	Reddish Speckled- b fabric	Open and close porphyric	2/3
M3	••	None observed	Random Sorted	•••	••	•	••	Complex microstructure, crumbs, and granular, simple packing voids	Reddish Speckled- b fabric	Chitonic and Open porphyric	2/3

. Very few (<5 % slide area); .. Few (5-15 % slide area); … Common (15-30 % slide area); …. Frequent (30-50) % slide area); …... Dominant (50-70 % slide area); b fabric birefringent fabric; G-granular; SB-subangular.

L1 (Table 4.12 and Figure 4.30): Soil presents a ratio between coarse (> 20μm) and fine material in the order 2/3 with open and close porphyric relative distribution. The visually estimated porosity is 40% of the slide area

The coarse material moderately selected, rounded, and spherical quartz grains predominate. The larger grains being angular to subangular and small grains spherical, all grains with smooth roughness. The alteration pattern of quartz is type D (dotted) and degree zero (0). Iron pedo-features, consisting of very few (< 5% slide area) iron nodules and very few (< 5% slide area) organic material with roughness.

The fine material consists of fine to medium silts and clay forming a yellow speckled birefringent fine material. The main microstructure is composed by strongly developed complex structure, crumbs and granular with vughs and channels. Figure 4.29 shows the SEM images mapping of the elements in this soil. Figure 4.29a) illustrate the presence of high Si quartz grains, Fe nodules, Ti minerals. Figure 4.29b) shows the presence of Fe nodules, with Si rich quartz grains, the clay fine material dominated by Al, Ti minerals.

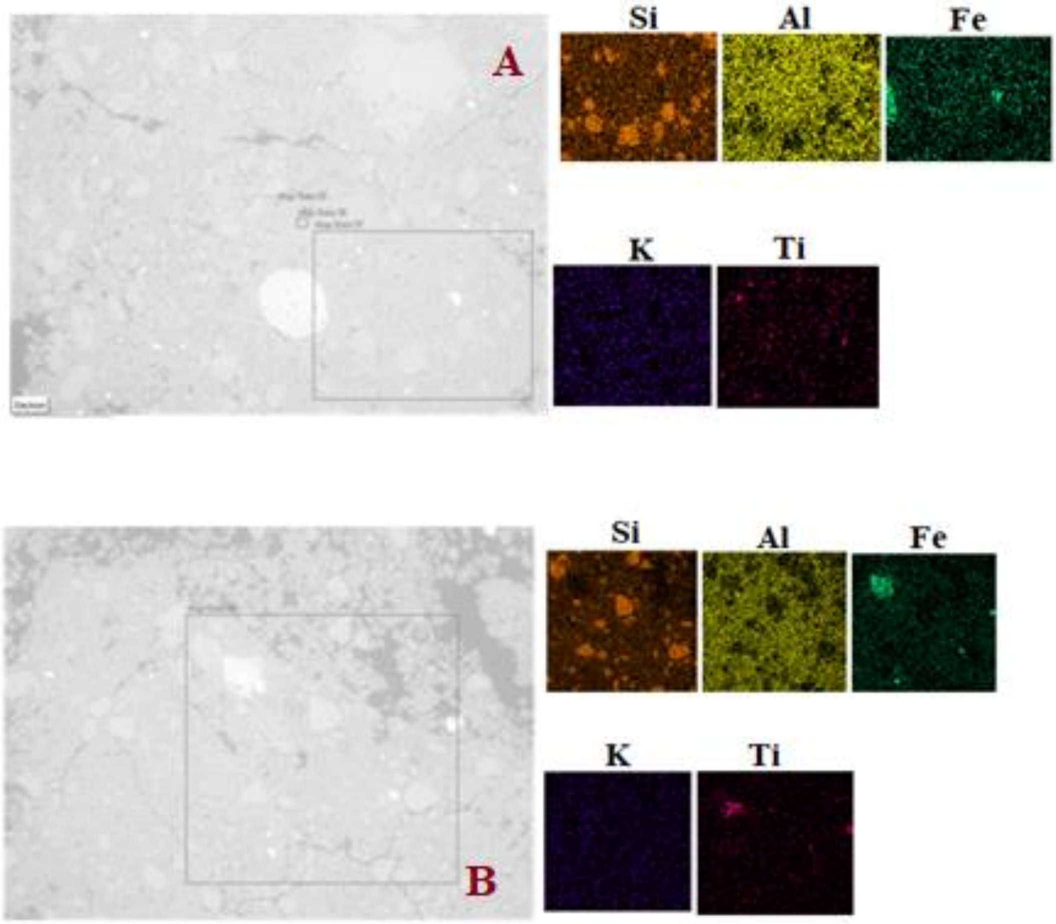


Figure 4. 29: SEM backscattered electron images and x-Ray emission maps of selected elements- L1

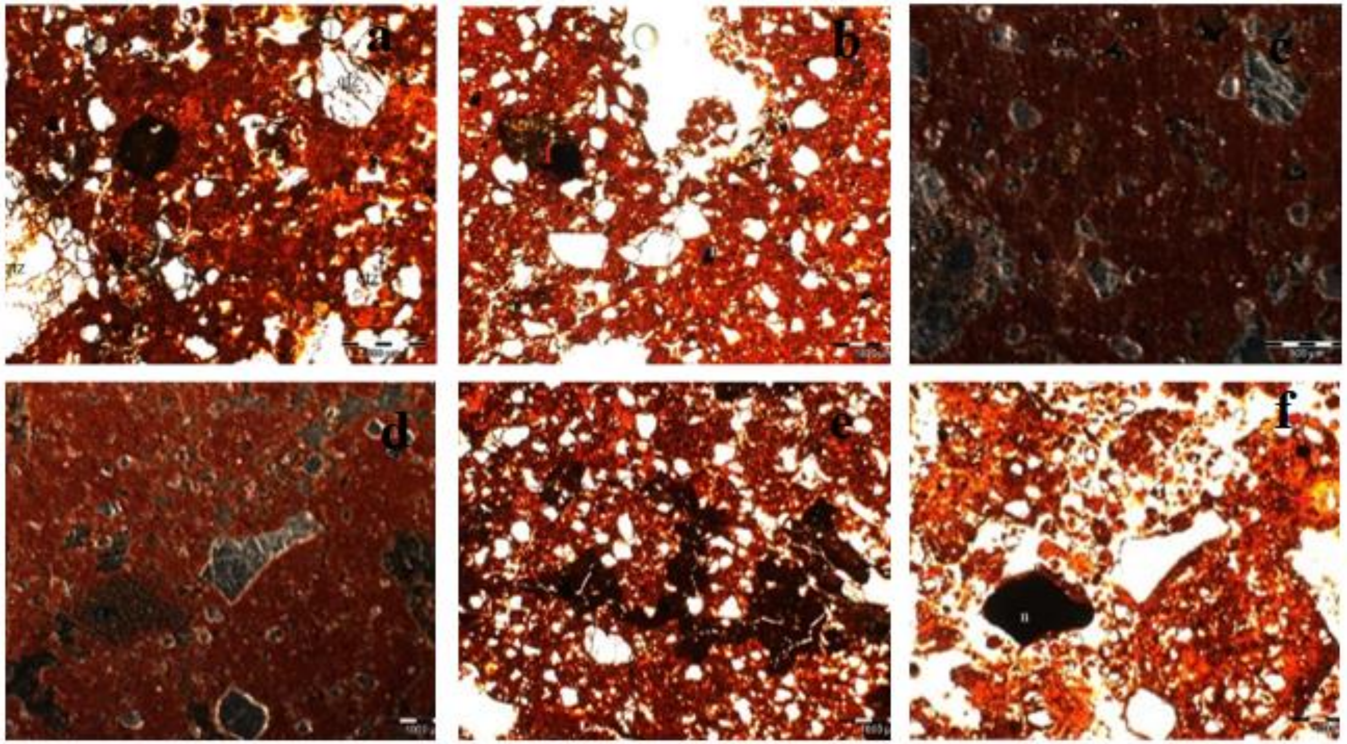
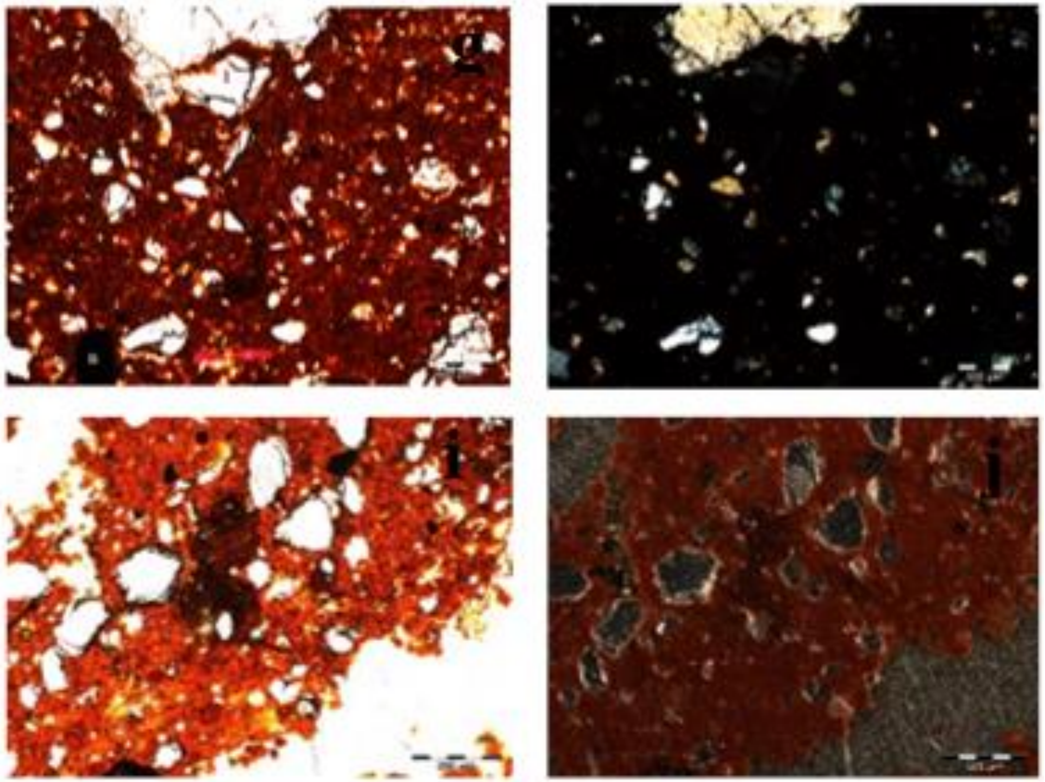


Figure 4. 30: Photomicrograph of thin section slide, L1. a- quartz grains with cracks, plane polarized light (ppl, 4x) view; b-micronodules (ppl, 4x) view; c-same as a (oil) view; (d and f)-nodule and clay coating, (oil and ppl, 2x) views; clay fill fragment, (ppl, 2x) views.



Cont. Figure 4.30: photomicrograph of thin section slide, L1. g- nodule, clay coating fill (arrows), plane polarized light (ppl, 4x); h-same as g (xpl, 4x); i-clay fill, plane polarized light (ppl, 4x) views, j-same as I (oil) views.

L2 (Table 4.12 and Figure 4.32): Soil presents a ratio between coarse (> 20μm) and fine material in the order 2/3 with open and close porphyric relative distribution. The visually estimated porosity is 40% of the slide area.

The coarse material is randomly sorted, quartz grains predominate, with the larger grains being subangular and slightly spherical, with cracks and smooth. The alteration pattern of quartz is type D (dotted) and degree zero (0). Iron-pedofeatures is constituted by the presence of very few (<5% slide area) iron nodules, small rounded rough charcoal.

The fine material consists of fine to medium silts and clay forming in a dark red speckled birefringent fine material. The microstructure is composed complex granular and crumbs with a packing vugh, and channels. Figure 4.31 shows the SEM images together with EDX mapping of elements. Figure 4.31a) shows Si rich quartz grains, with presence of Fe nodules, Ti/Fe grains, Ti minerals; Figure 4.31b) shows Si rich quartz grain, the clay fine material dominated by Al and K grains.

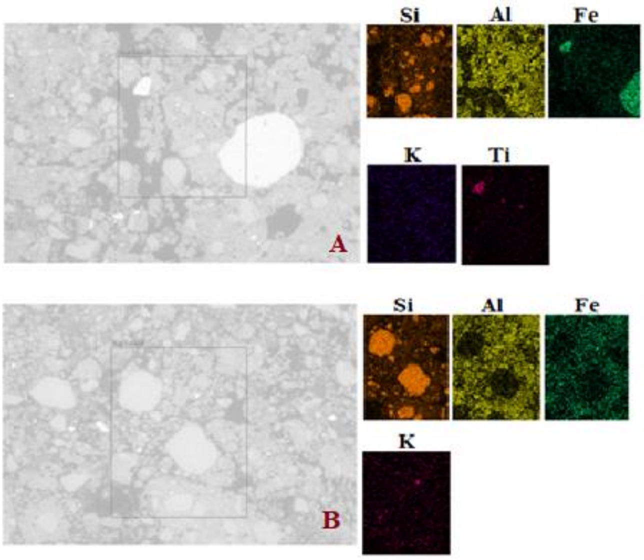


Figure 4. 31: SEM backscattered electron images and EDX emission maps of selected elements- L2

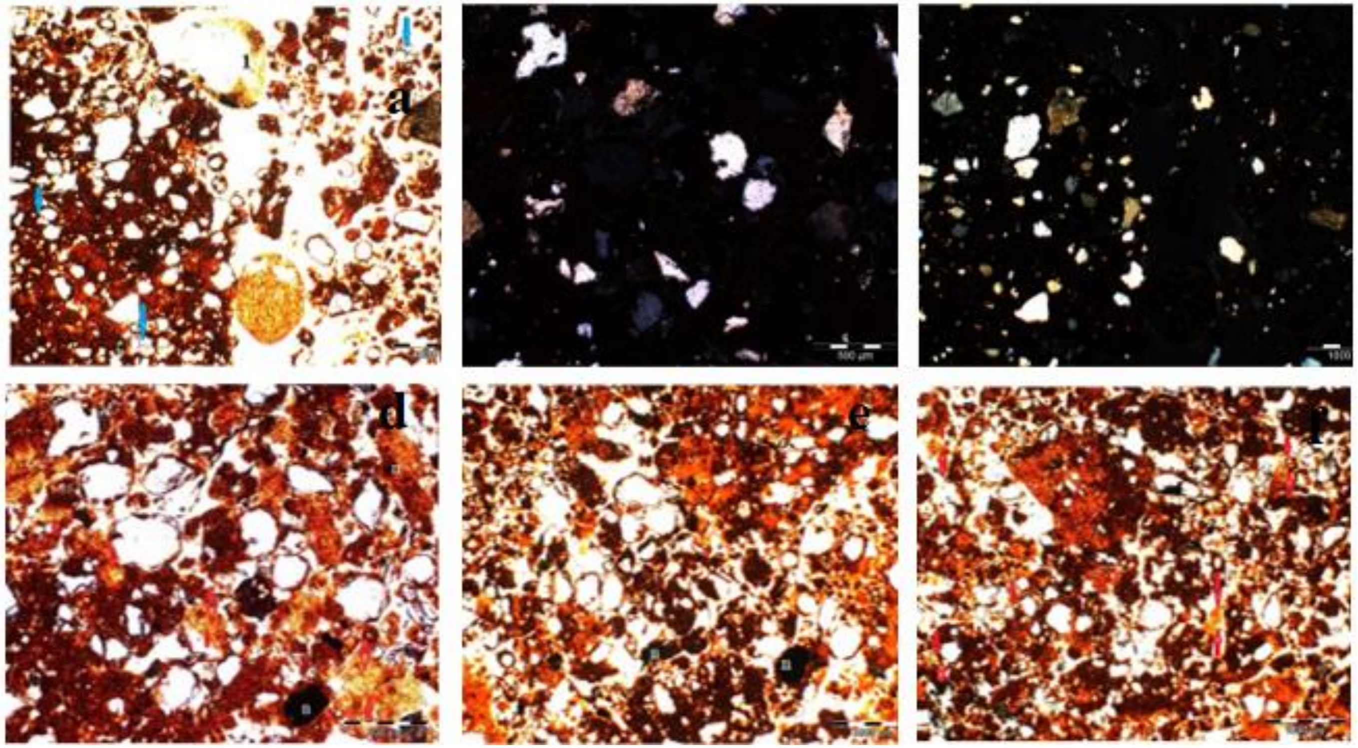
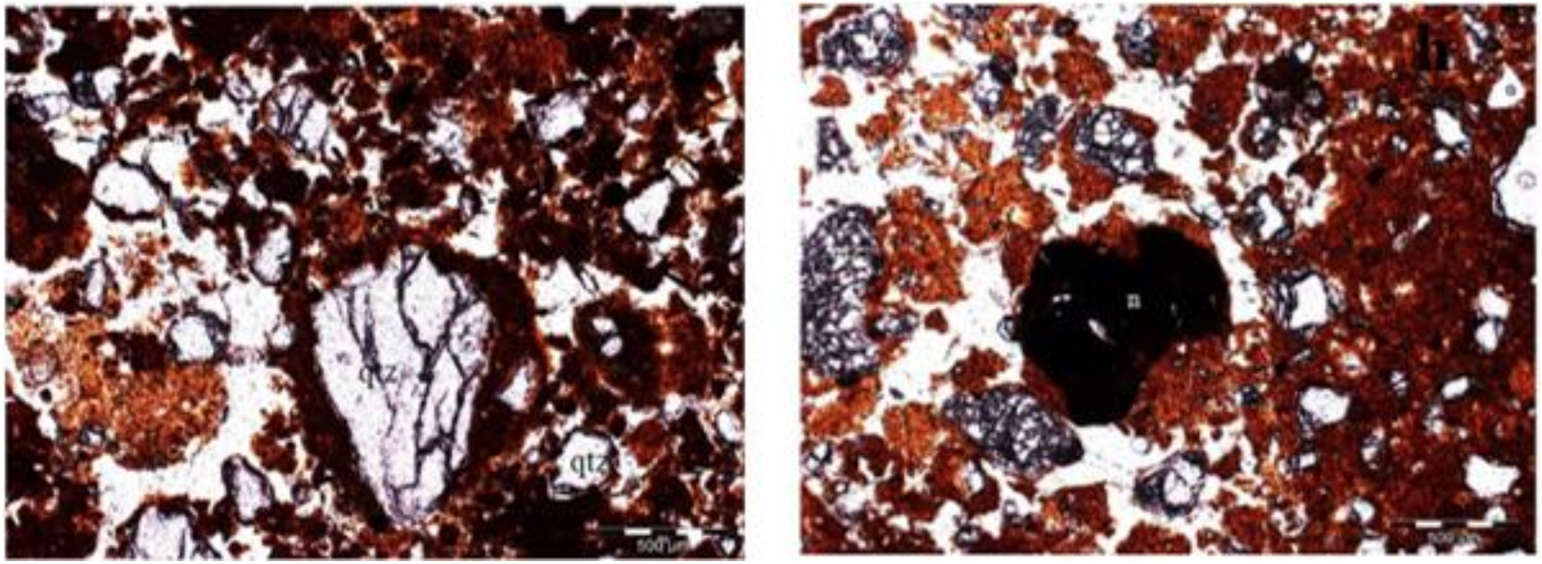


Figure 4. 32: Photomicrograph of thin section slide, L2. a-convex-concave grain (arrows) and high porosity, plane polarized light (ppl, 2x); c-same as a (xpl, 2x); c- granular microstructure, cross polarized light (xpl, 4x) views; d-quartz grains and nodules, plane polarized light) ppl, 4x); e-2 types of aggregates, dark red and light red, plane polarized light (ppl, 4x); f-clay coating (arrows) and micronodules, plane polarized light (ppl, 4x) views.



Cont. Figure 4.32: photomicrograph of thin section slide, L2. g-abundant quartz grains, some of grains are fissured, plane polarized light (ppl, 4x) views; h-nodule, with high porosity, plane polarized light (ppl, 4x) views.

L3 (Table 4.12 and Figure 4.33): Soil presents a ratio between coarse (> 20µm) and fine material in the order 2/3 with open porphyric relative distribution. The visually estimated porosity is 40% of the slide area.

The coarse material random sorted quartz grains predominate sub-rounded to rounded. The alteration pattern of quartz is type D (dotted) and degree zero (0). Iron pedo-features, consisting of few (5-15% slide area) iron nodules and few (5-15% slide area) iron hypocoating and, and some quantities of charcoal.

The fine material consists of fine to medium silts and clay making a yellow speckled birefringent fine material. The microstructure is composed complex structure granular and crumbs with a packing complex vugh and channels. Figure 4.33 shows the SEM images together with EDX mapping of selected elements present. Figure 4.33a) illustrate the presence of Fe nodules, high Si quartz grains, K-feldspar, Ti minerals. Similarly, Figure 4.33b) shows the presence of Fe nodules, with rich Si quartz grains, Fe nodule, K concentrated in grains and the clay fine material dominated by Al.

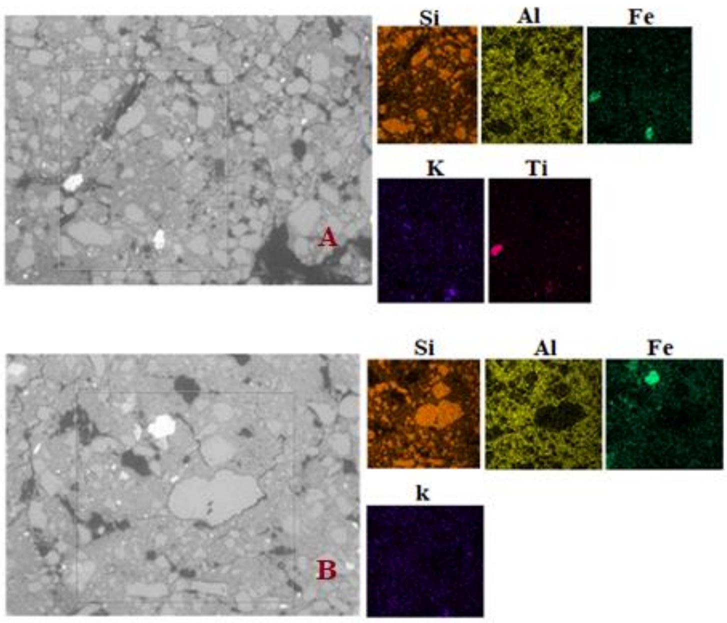


Figure 4. 33: SEM backscattered electron images and EDX emission maps of selected elements- L2

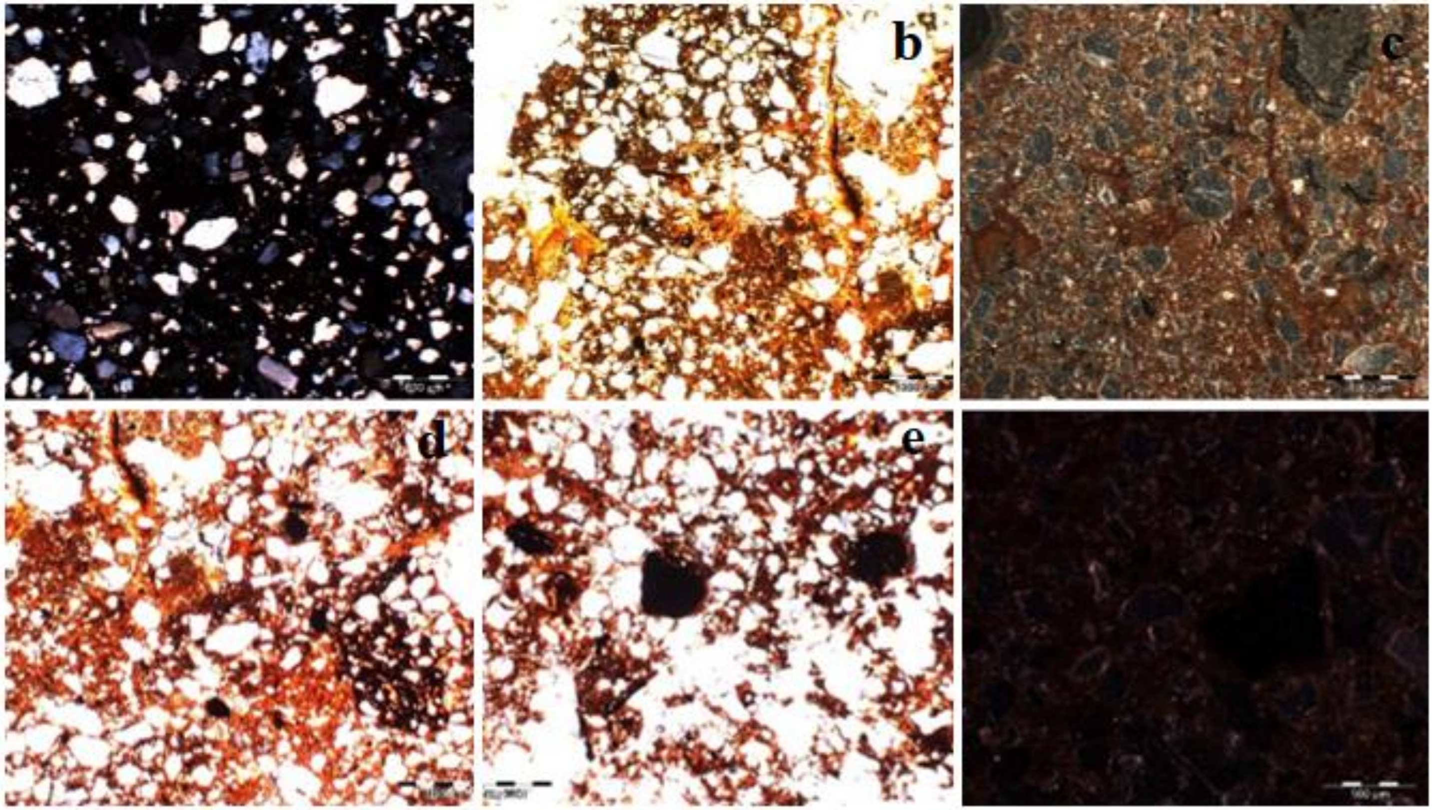
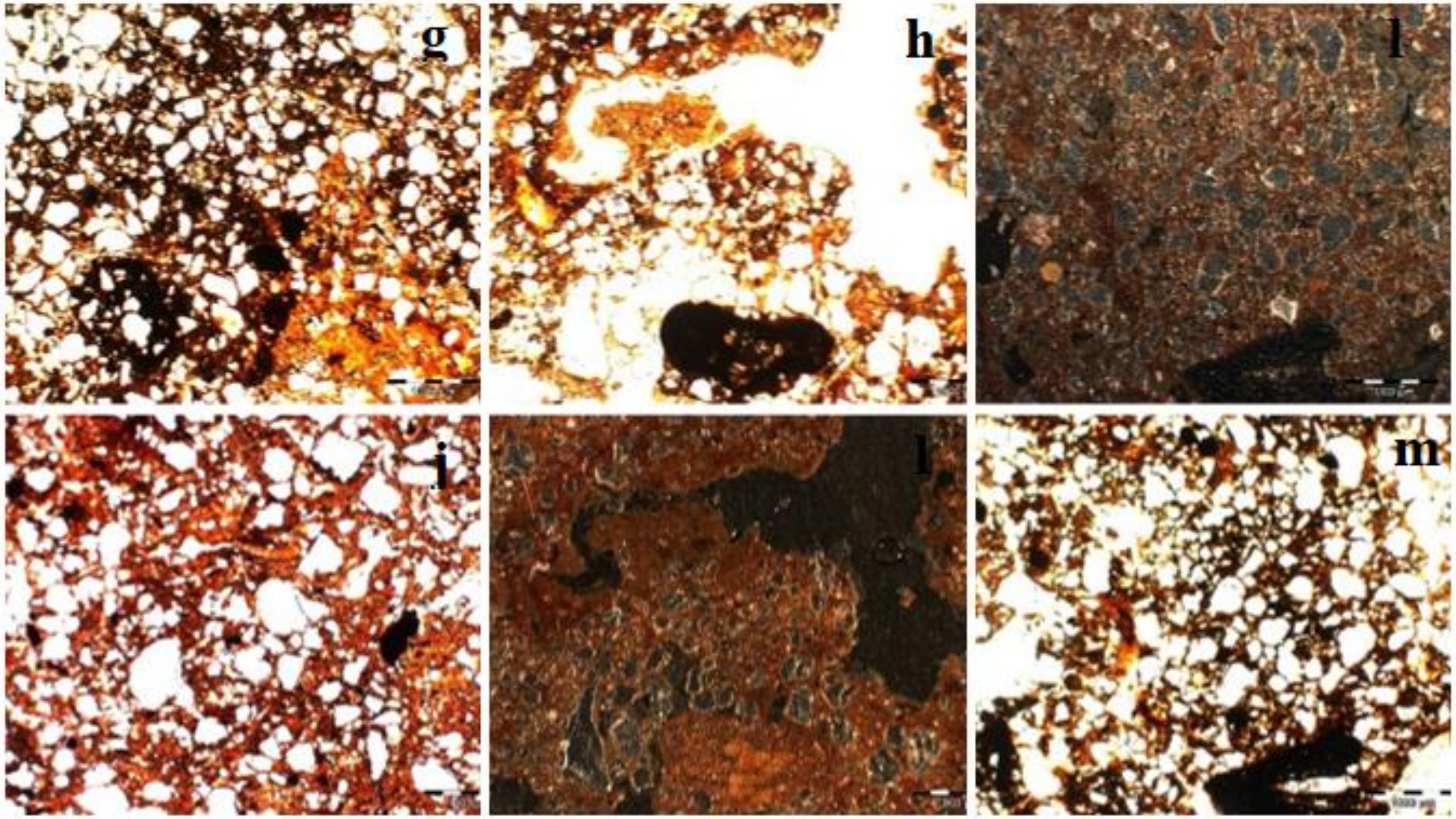


Figure 4. 34: Photomicrograph of thin section slide, L3. a- granular microstructure, cross polarized light (xpl, 2x) views; b-clay fill, plane polarized light (ppl, 4x) views; c-same as b (oil) views; d-abundant quartz grains, plane polarized light (ppl, 4x); e-charcoal, plane polarized light (ppl, 2x) views; f- same as e (oil) views.



Cont. Figure 4.34: photomicrograph of thin section slide, L3. g-abundant quartz grains and nodule, plane polarized light (ppl, 2x) views; h- nodule, and chambers, plane polarized light (ppl, 2x) views; i-same as m (oil) view; j-clay fill and nodule, plane polarized light (ppl, 2x) views; l-same as h (oil) views; m-sub-angular nodule (charcoal), plane polarized light (ppl, 2x) views.

Table 4. 12- Summaries of soil micromorphology characteristics- Lepi

Horizon	Coarse mineral Material (>2µm)		Coarse material arrangement	Coarse organic/biological material	Iron Pedo- features			Micro- structure	Fine mineral material	Related distribution	C/F ratio (20 µm)
	Quartz	Feldspar		Charcoal	Fe impregnation (matrix)	Fe hypocoating (poroid)	Fe nodule				
L1	•••	None observed	Random Sorted	None observed	•	•	•	Complex microstructure: mixture of granular and crumbs; compound packing voids	Reddish Speckled- b fabric	Open and close porphyric	2/3
L2	•••	None observed	Random Sorted	•	•	•	•	As above	Reddish Speckled- b fabric	Open and close porphyric	2/3
L3	••	None observed	Random Sorted	•••	••	•	••	Complex microstructure, mixture granular, subangular blocky; simple packing voids	Reddish Speckled- b fabric	Chitonic and Open porphyric	2/3
. Very few (<5 % slide area); .. Few (5-15 % slide area); … Common (15-30 % slide area); …. Frequent (30-50) % slide area); …... Dominant (50-70 % slide area); b fabric birefringent fabric; G-granular; SB-subangular.											

4.4.1.2-Luanda- Bom Jesus

BJ1 (Table 4.13 and Figure 4.36): Soil presents a ratio between coarse (> 20µm) material and fine material in the order of 1/10 with open porphyric relative distribution. The visually estimated porosity is 30% of the slide area.

The coarse material is poorly selected, rounded, and spherical very few (< 5% slide area) smaller quartz grains being slightly angular and slightly spherical, smooth. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). The presence of few (5-15% slide area) small angular and non-spherical organic biological material (charcoal) was observed. Few (5 – 15% slide area) iron nodules were observed, some of them coat in quartz grains. In some isolated sectors it is visible the presence of fine and dark material.

The fine material consists of fine to medium silts and clay sized forming a deep brown speckled birefringent fine material. Subangular blocky composed by channels and pores inter-aggregates are part of the microstructure. Figure 4.35 shows the SEM images together with EDX mapping of elements presents. Figure 4.35a) shows the clay rich fine material dominated by Al, contents of K concentration, Mg, and Ca concentrated in fine material. Similarly, Figure 4.35b) illustrate presence of Fe nodules, with Si rich quartz grains, as well contents of K, Mg and Ca concentrated in fine material.

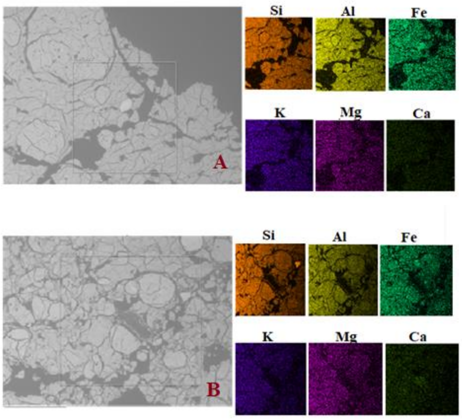


Figure 4. 35: SEM backscattered electron images and EDX emission maps of selected elements- BJ1 profile.

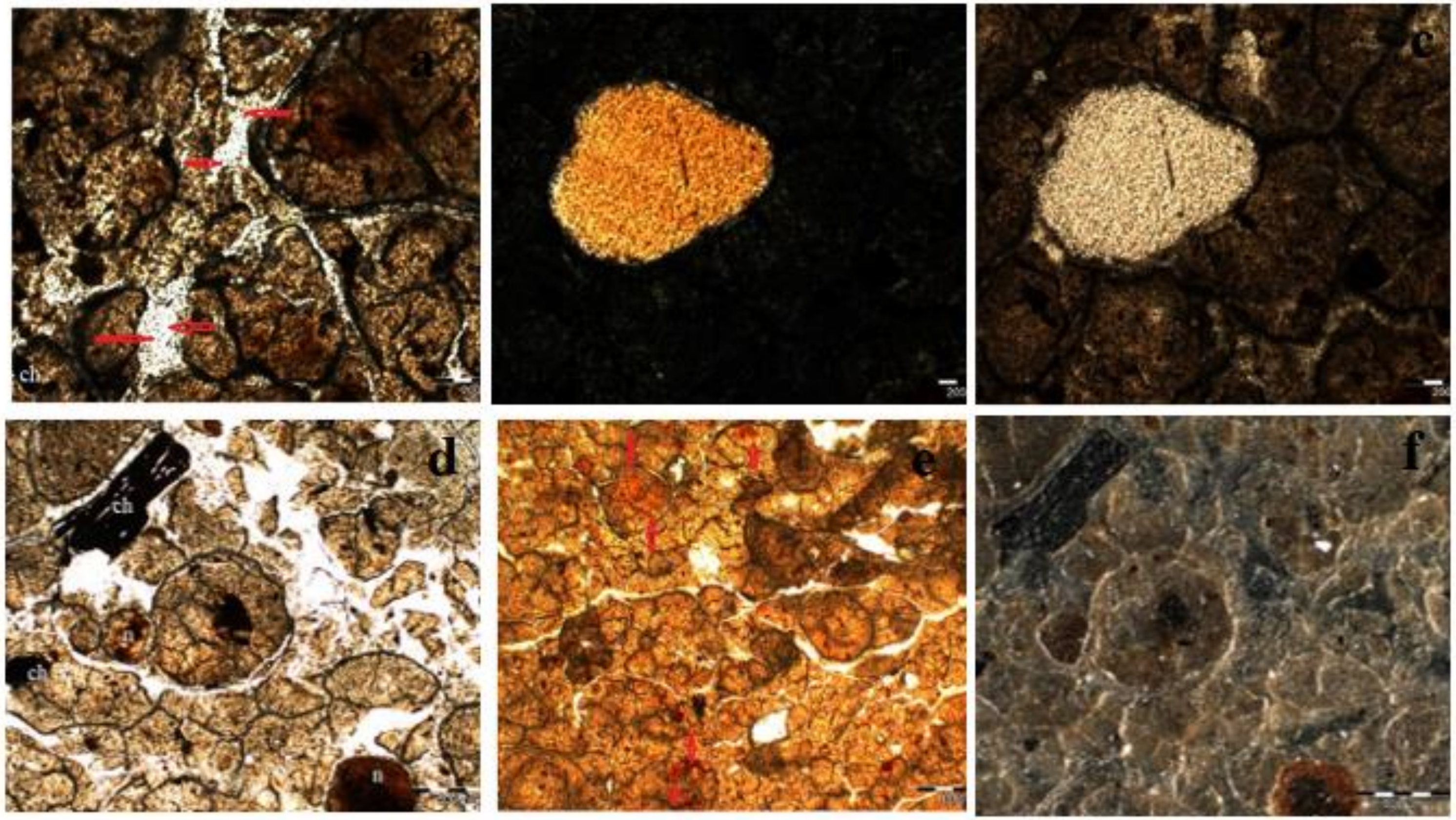
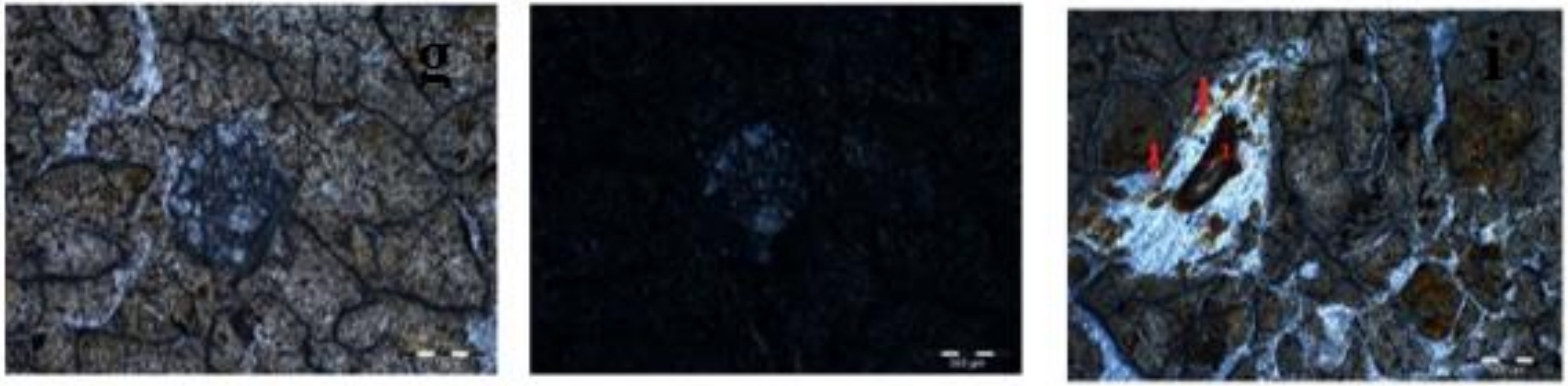


Figure 4. 36: Photomicrograph of thin section slide, BJ1. a- pores type chambers, plane polarized view (ppl, 10x) views; b-individual quartz grain, cross polarized light (ppl, 10x) views; c-same as b (ppl, 10x) views; c- charcoal and nodules, plane polarized light (ppl, 4x) views; e- clay coating (arrows), plane polarized light (ppl, 2x) views; f-same as d, oblique incident light (oil, 4x) views.



Cont. Figure 4.36: photomicrograph of thin section slide, BJ1. g- individual quartz grains fissured, plane polarized light (ppl, 10x) views; h- same as g (xpl, 10x) views; i-clay fill, and pores type chambers, plane polarized light (ppl, 4x) views.

BJ2 (Table 4.13 and Figure 4.38): Soil presents a ratio between coarse (> 20µm) material and fine material is in the order 1/10 with open porphyric relative distribution. The visually estimated porosity is 30% of the slide area.

The coarse material is poorly selected, characterized by non- spherical very few (<5% slide area) small quartz angular and smooth. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). The presence of few small angular and non-spherical charcoal was observed. Few (5-15% of slide area) iron nodules were also observed.

The fine material consists of fine to medium silts and clay sized forming a deep brown speckled birefringent fine material. Subangular blocky composed by channels and pores inter-aggregates are part of the microstructure. Figure 4.37 shows the SEM images together with EDX mapping of elements presents. Figure 4.37a) show presence of Fe nodules, with Si rich quartz grains and clay rich fine mineral dominated by Al, and Ca concentration. Figure 4.37b) shows the presence of Fe rich nodules, the clay rich fine material dominated by Al, and Ti minerals.

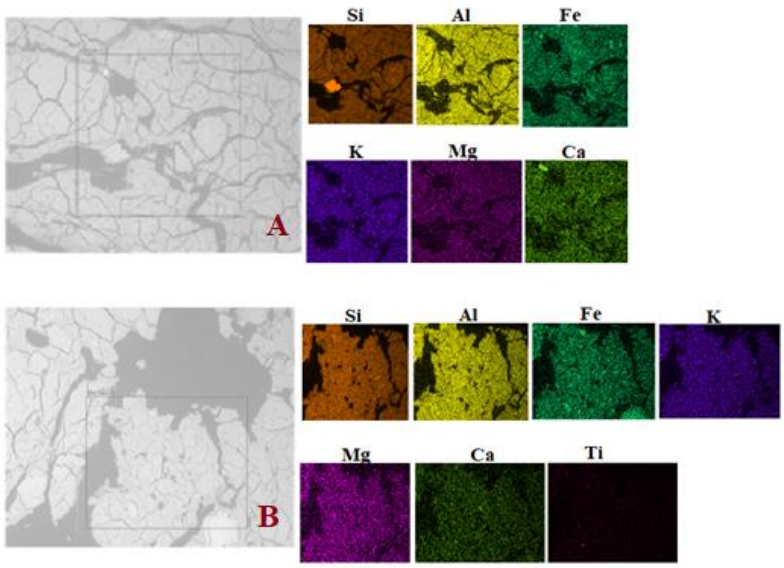


Figure 4. 37: SEM backscattered electron images and EDX emission maps of selected elements- BJ1 profile

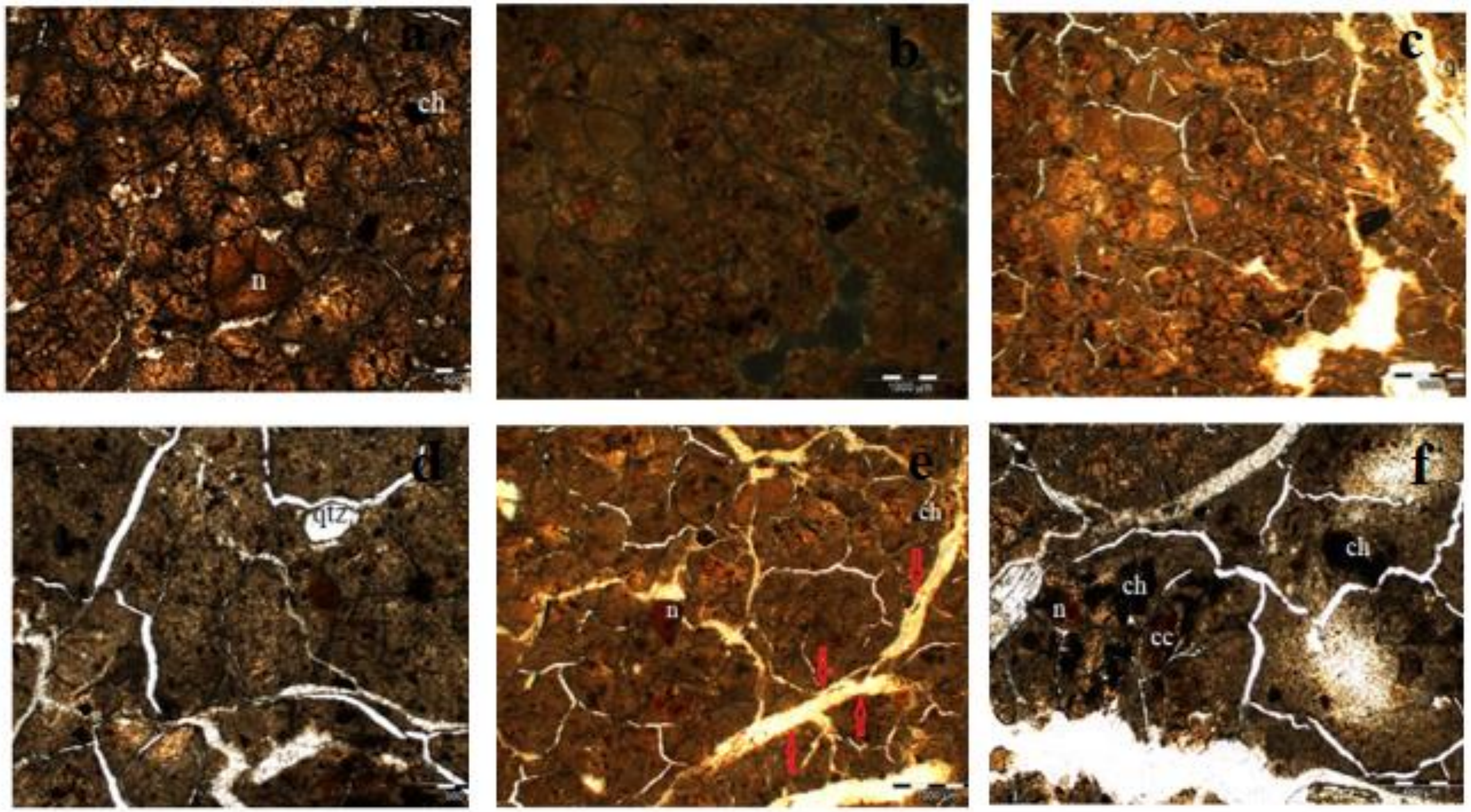
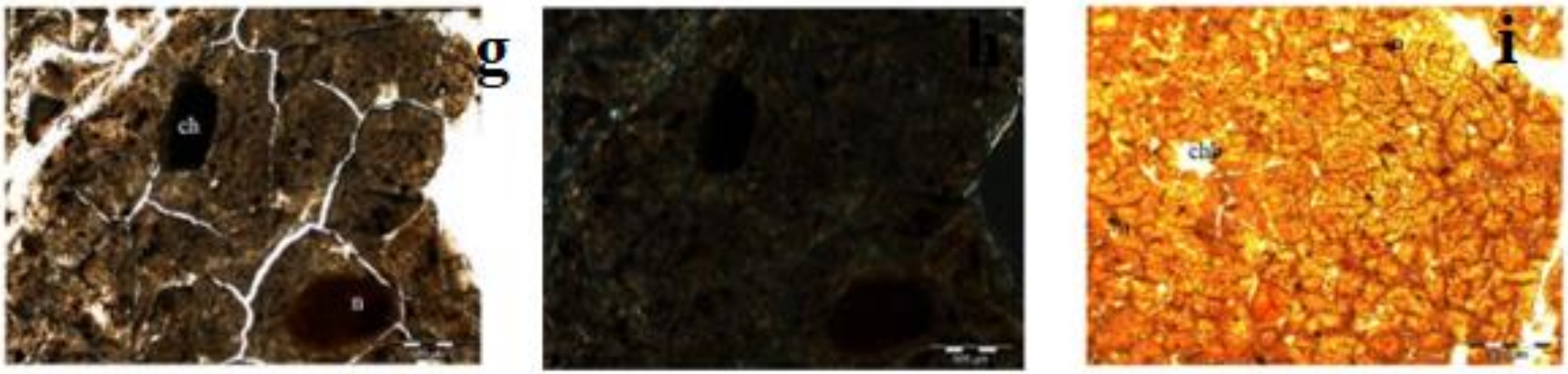


Figure 4. 38: Photomicrograph of thin section slide, BJ2.a-charcoal and iron nodules, plane polarized light (ppl, 4x) views; b-channels and chambers, oblique incident light (oil) views; c-same as b (ppl, 2x) views; c- rounded single quartz grains, plane polarized light (ppl, 4x) views; e-iron micronodule, micronodule (charcoal) and clay infilling, plane polarized light (ppl, 4x) views; f-clay coating (cc), charcoal (ch) and channels, plane polarized light (ppl, 4x) views.



Cont. Figure 4.38: photomicrograph of thin section slide, BJ2. g- iron nodule (n) and charcoal (ch), plane polarized light (ppl, 4x) views; h-same as g (xpl) views; i-massive microstructure with micronodules and fissure, plane polarized light (ppl, 2x) views.

BJ3 (Table 4.13 and Figure 4.40): Soil presents a ratio between coarse (> 20μm) and fine material in the order 1/10 with open porphyric relative distribution. The visually estimated porosity is 30% of the slide area.

The coarse material is poorly sorted, very few (< 5% slide area) quartz spherical, smooth, and fissured. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). The presence of few small angular and non-spherical organic biological material (charcoal) was observed. Few (5 – 15% of slide area) iron nodules were observed, and iron impregnate within quartz grains.

The fine material consists of fine to medium silts and clay forming in a deep brown speckled birefringent fine material. Subangular blocky and fissure structure composed by packing of planar voids (channels) and pores inter-aggregates are part of the microstructure. Figure 4.39 shows the SEM images together with EDX mapping of the elements observed. Figure 4.39a) shows the presence of Fe rich nodules within aggregates, with Si rich quartz grains and the clay rich fine material dominated by Al, Ti minerals and Ca. Similarly, Figure 4.39b) show the presence of Fe nodules, with Si rich quartz grains and the clay rich fine material dominated by Al, Mg.

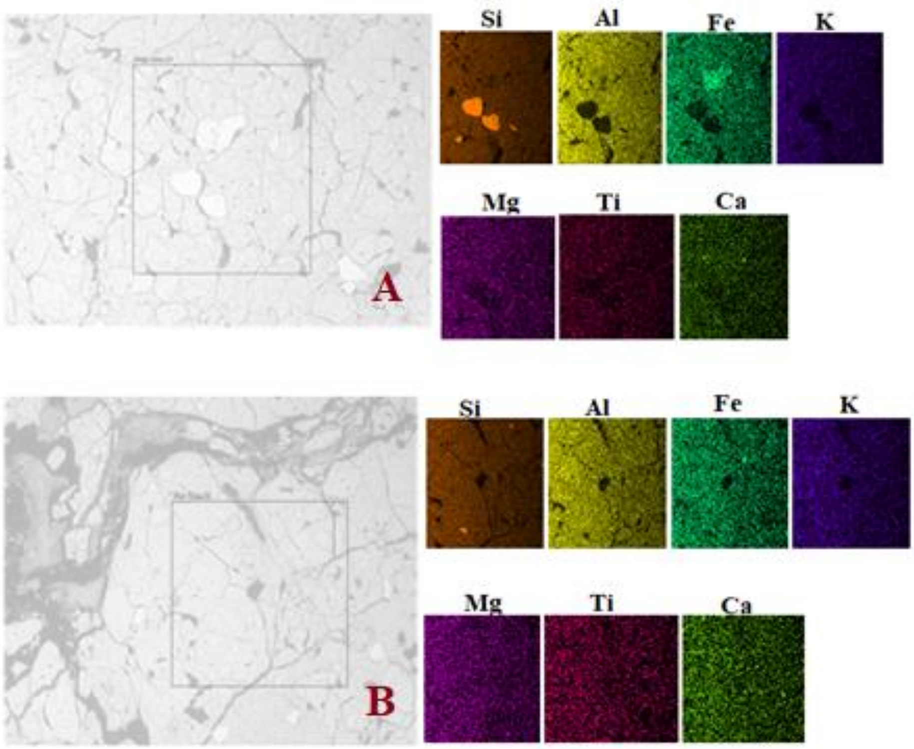


Figure 4. 39: SEM backscattered electron images and EDX emission maps of selected elements- BJ3 profile.

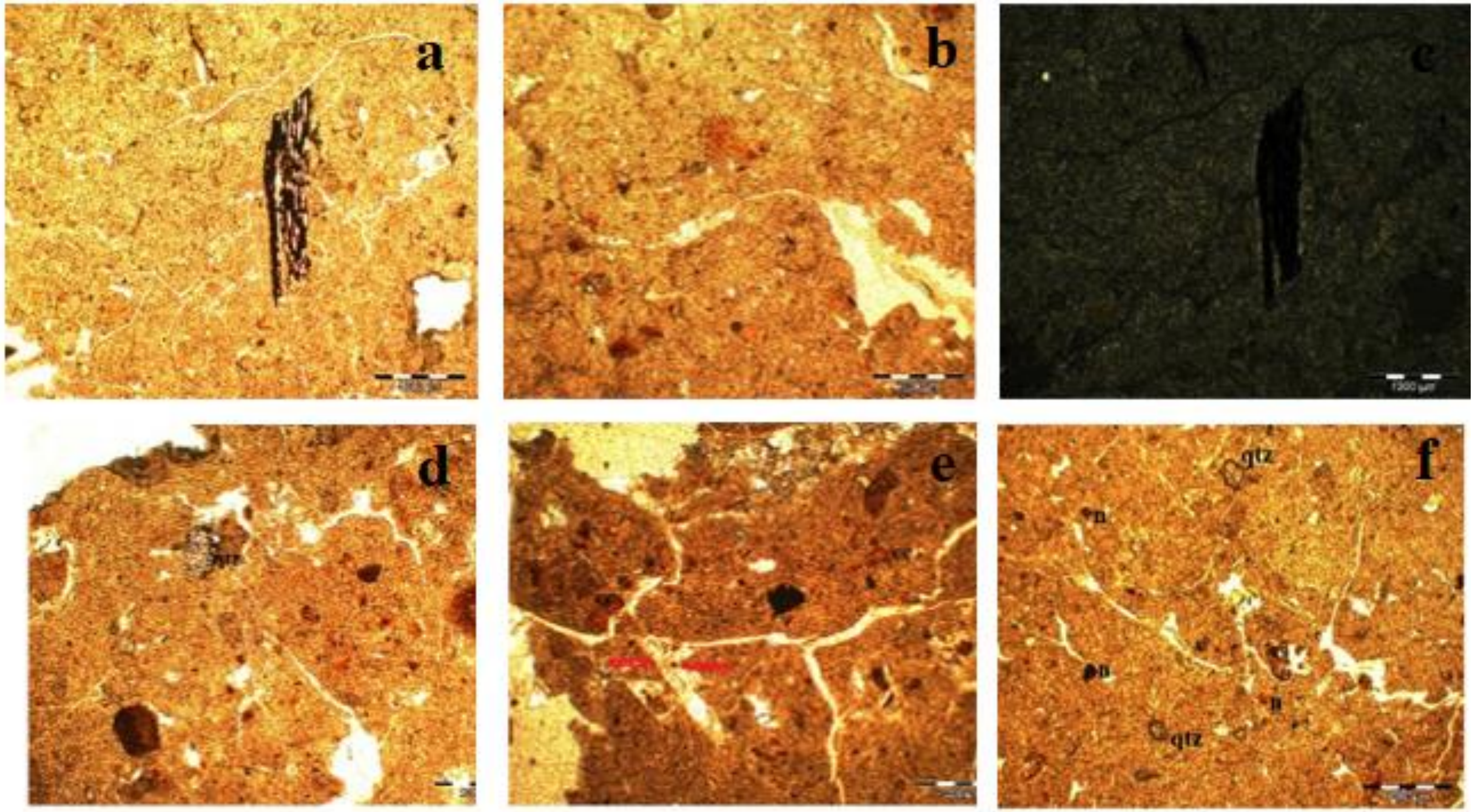


Figure 4. 40: Photomicrograph of thin section slide, BJ3. a- sub-angular organic material (charcoal), plane polarized light (ppl, 2x) views; b-pores type chambers and channels, plane polarized light (ppl, 2x) views; c-same as a (xpl, 2x); d-quartz grain showing strong corrosion, plane polarized light (ppl, 2x) views; e-clay coating infilling (arrows), plane polarized light (ppl, 4x) views; f-small quartz grains, and iron nodule, plane polarized light (ppl, 2x) views.

Bom Jesus

Table 4. 13- Summaries of soil micromorphology characteristics- Bom Jesus

Horizon	**Coarse mineral Material (>2µm)**		**Coarse material arrangement**	**Coarse organic/biological material**	**Iron Pedo- features**			**Micro- structure**	**Fine mineral material**	**Related distribution**	**C/F ratio (20 µm)**
	Quartz	Feldspar		Charcoal	Fe impregnation (matrix)	Fe hypocoating (poroid)	Fe nodule				
BJ1	•	None observed	Poorly Sorted	••	••	•	••	Well-developed subangular blocky; simple packing voids	Deep brown Speckled- b fabric	Open porphyric	1/10
BJ2	•	None observed	Poorly Sorted	••	••	•	••	As above	Deep brown Speckled- b fabric	Open porphyric	1/10
BJ3	•	None observed	Poorly Sorted	•	••	•	••	Subangular blocky; simple packing voids	Deep brown Speckled- b fabric	Open porphyric	1/10

. Very few (<5 % slide area); .. Few (5-15 % slide area); ... Common (15-30 % slide area); .... Frequent (30-50) % slide area); …... Dominant (50-70 % slide area); b fabric birefringent fabric; G-granular; SB-subangular.

F1 (Table 4.14 and Figure 4.42): Soil presents a ratio between coarse (> 20µm) and fine material is in the order 1/10 with visual porphyric relative distribution. The visually estimated porosity is 30% of the slide area.

The coarse material is poorly rounded, very few (< 5% slide area) quartz predominate, angular and slightly spherical, and smooth. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). The presence of few (5 – 15% slide area) small charcoal was observed. Very few (<5% slide area) iron nodules were also observed.

The fine material consists of fine to medium silts and clay sized forming a brown speckled birefringent fine material. Subangular blocky aggregates with vughs and planar channels. Figure 4.41 shows the SEM images together with EDX mapping of selected elements presents. Figure 4.41a) illustrate the clay rich fine material dominated by Al, Ca, Mg grains. Figure 4.41b) shows Si rich quartz grains, the clay rich fine material dominated by Al, small grains of K and Ca.

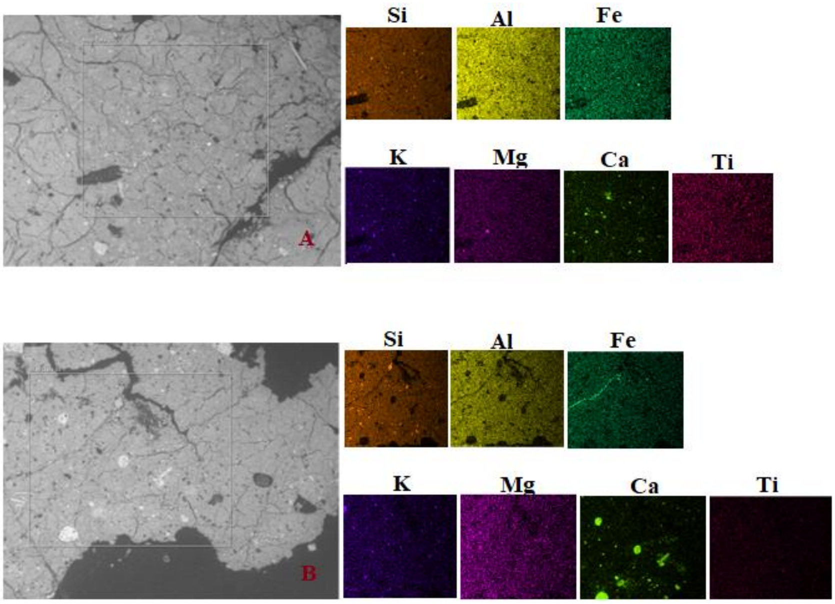


Figure 4. 41: SEM backscattered electron images and EDX emission maps of selected elements- F1 profile.

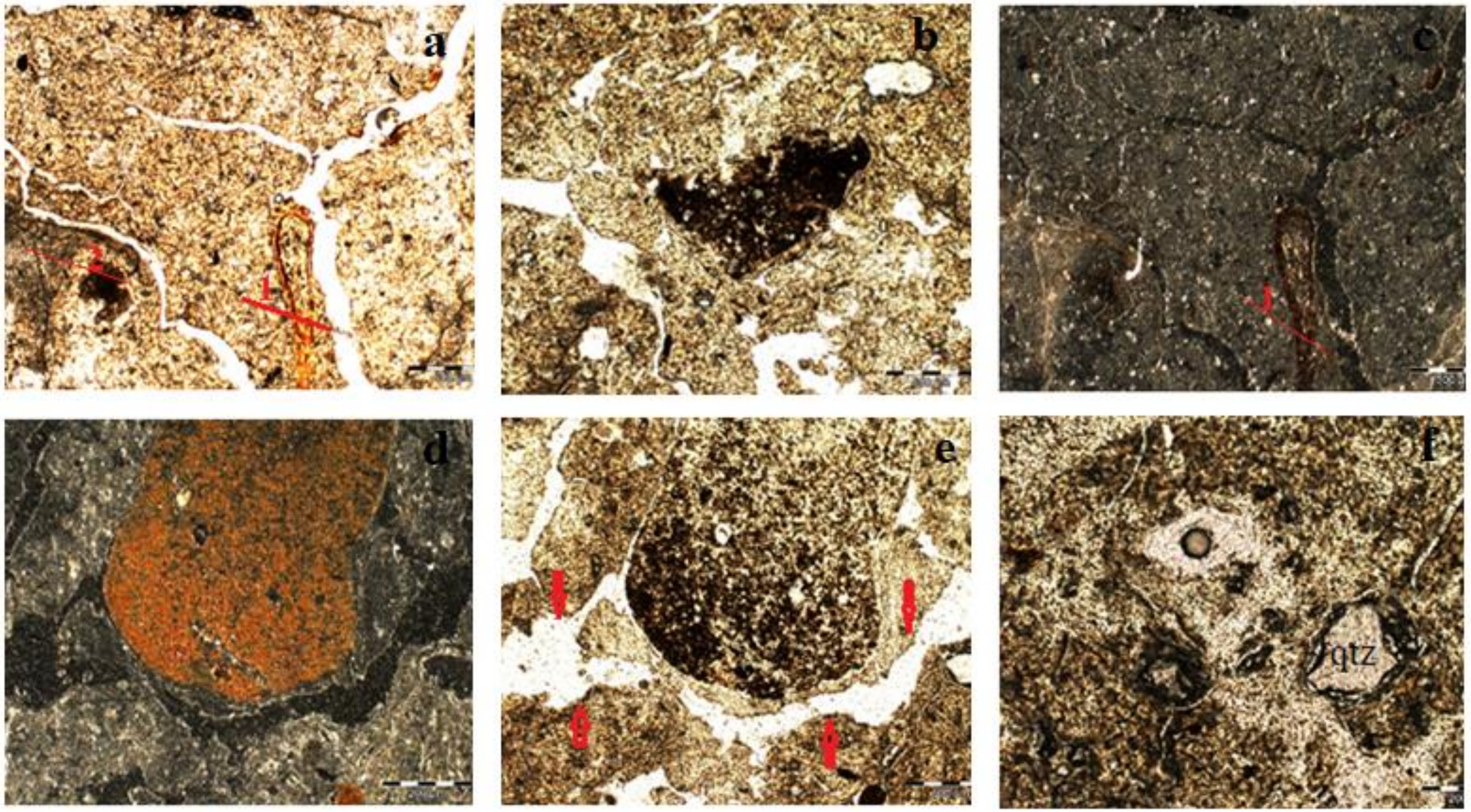
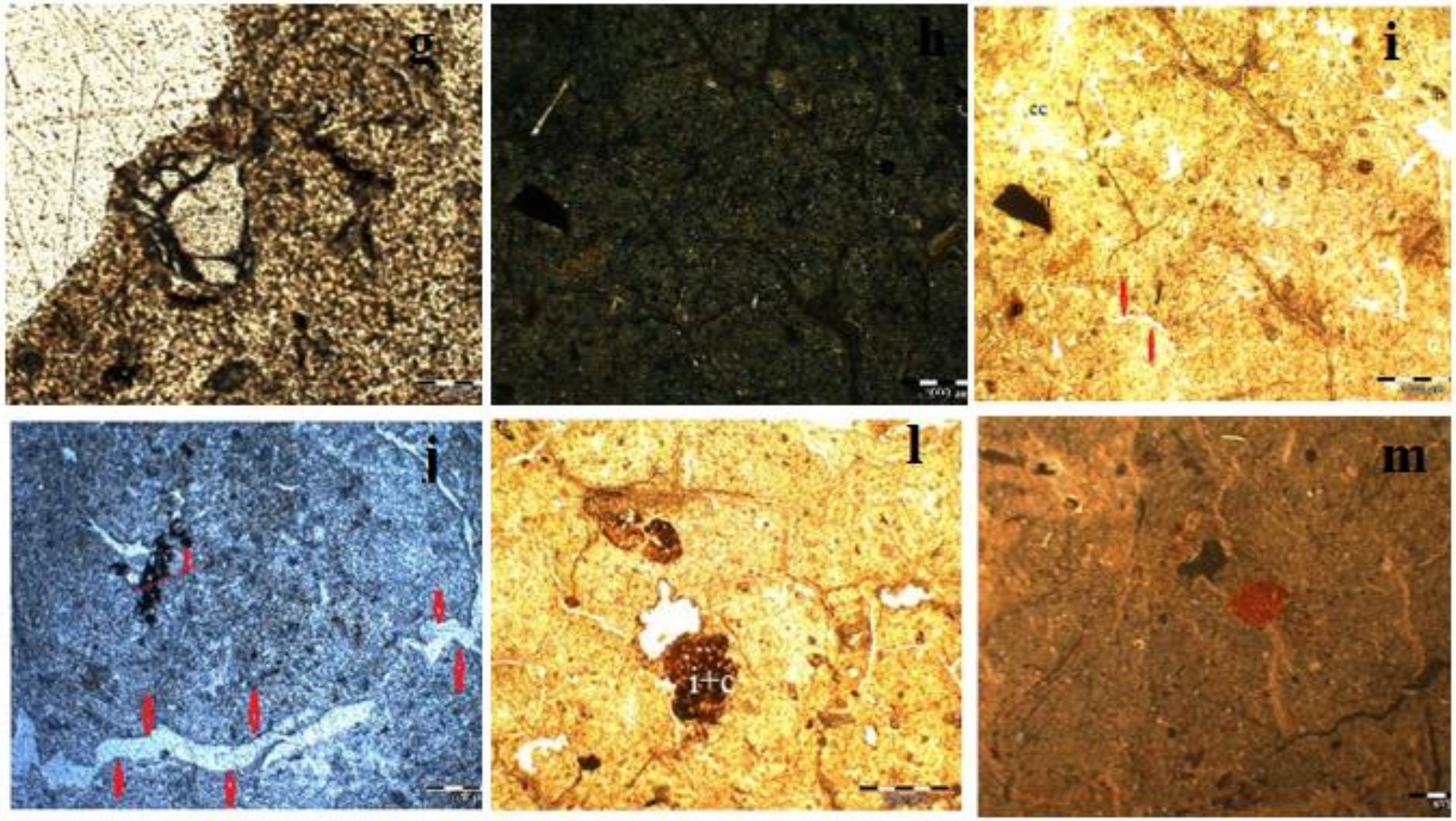


Figure 4. 42: Photomicrograph of thin section slide, F1.a- iron matrix (1), charcoal (2), plane polarized light (ppl,4x) views; b-iron enclosed in grain, plane polarized light (ppl, 4x) views; c-same as a, (oil) views; d and e- iron enclosed in aggregate, oblique incident light and plane polarized light respectively, 4x; f- quartz grain, plane polarized light (ppl, 10x) views.



Cont. Figure 4.42: photomicrograph of thin section slide F1.g-quartz grain with cracks, plane polarized light (ppl, 10x); h- and i- iron nodule and clay infilling (arrows), oblique incident light (oil, h) and plane polarized light (ppl, i), 2x. j-channels (arrows) and charcoal (1), plane polarized light (ppl, 4x); l- iron enclosed in grain, plane polarized light (ppl, 2x) views; m- charcoal and iron nodule, oblique incident light (oil, 2x) views.

F2 (Table 4.14 and Figure 4.44): Soil presents a ratio between coarse (> 20µm) and fine material in the order 1/10 with open porphyric relative distribution. The visually estimated porosity is 30% of the slide area.

As for the coarse material, random selected rounded and spherical smaller quartz are dominant. The larger grains are angular, smooth, and fissured. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). The presence of few small non-spherical charcoals was observed. Very few (<5% slide area) iron nodules were observed, and iron nodules impregnate the quartz grains.

The fine material consists of fine to medium silts and clay sized mineral grains in a dark brown speckled birefringent fine material. Subangular blocky and crack structure composed by channels and inter-aggregates complex packing voids are part of the microstructure. Figure 4.43 shows the SEM images together with EDX mapping of selected elements presents. Figure 4.43a) shows Si rich quartz grains and the clay fine material dominated by Al, and Mg. Similarly, Figure 4.43b) illustrate the clay fine material dominated by Al, with Si rich quartz grain.

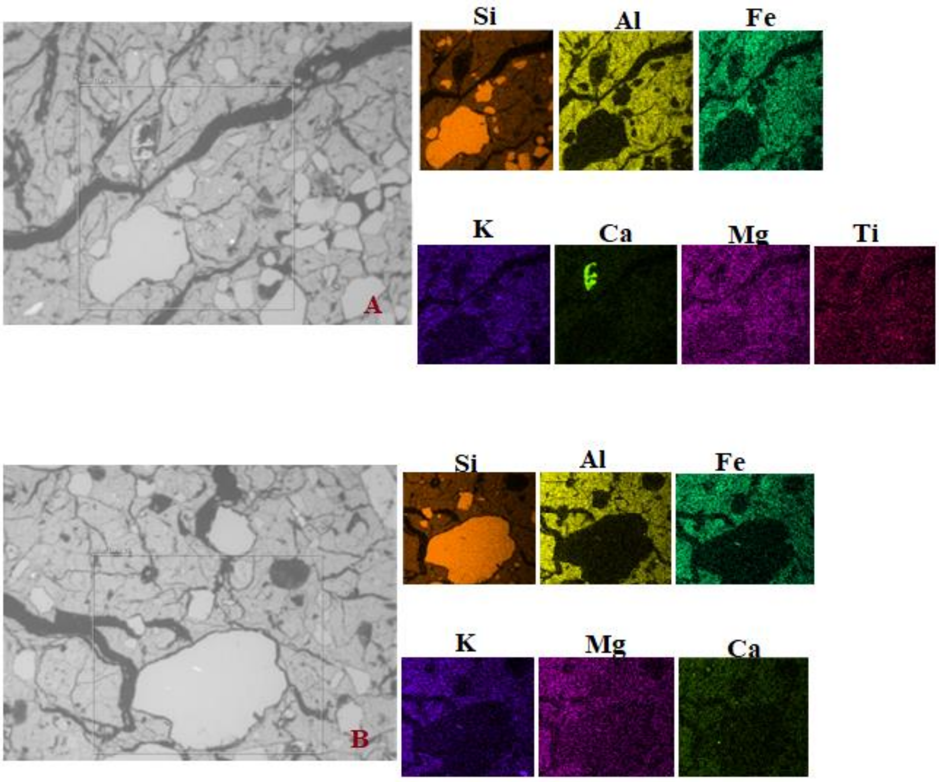


Figure 4. 43: SEM backscattered electron images and EDX emission maps of selected elements- F2 profile.

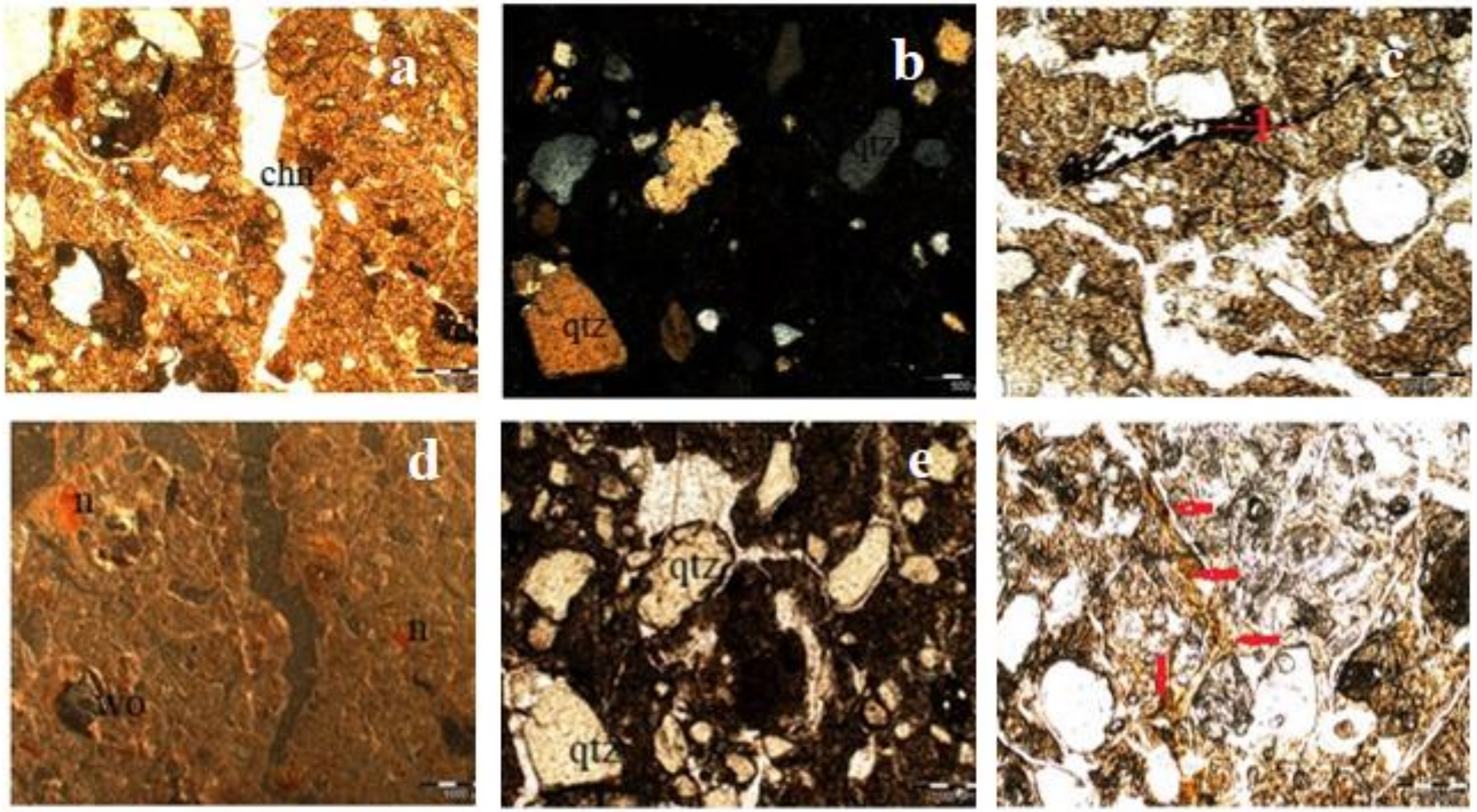
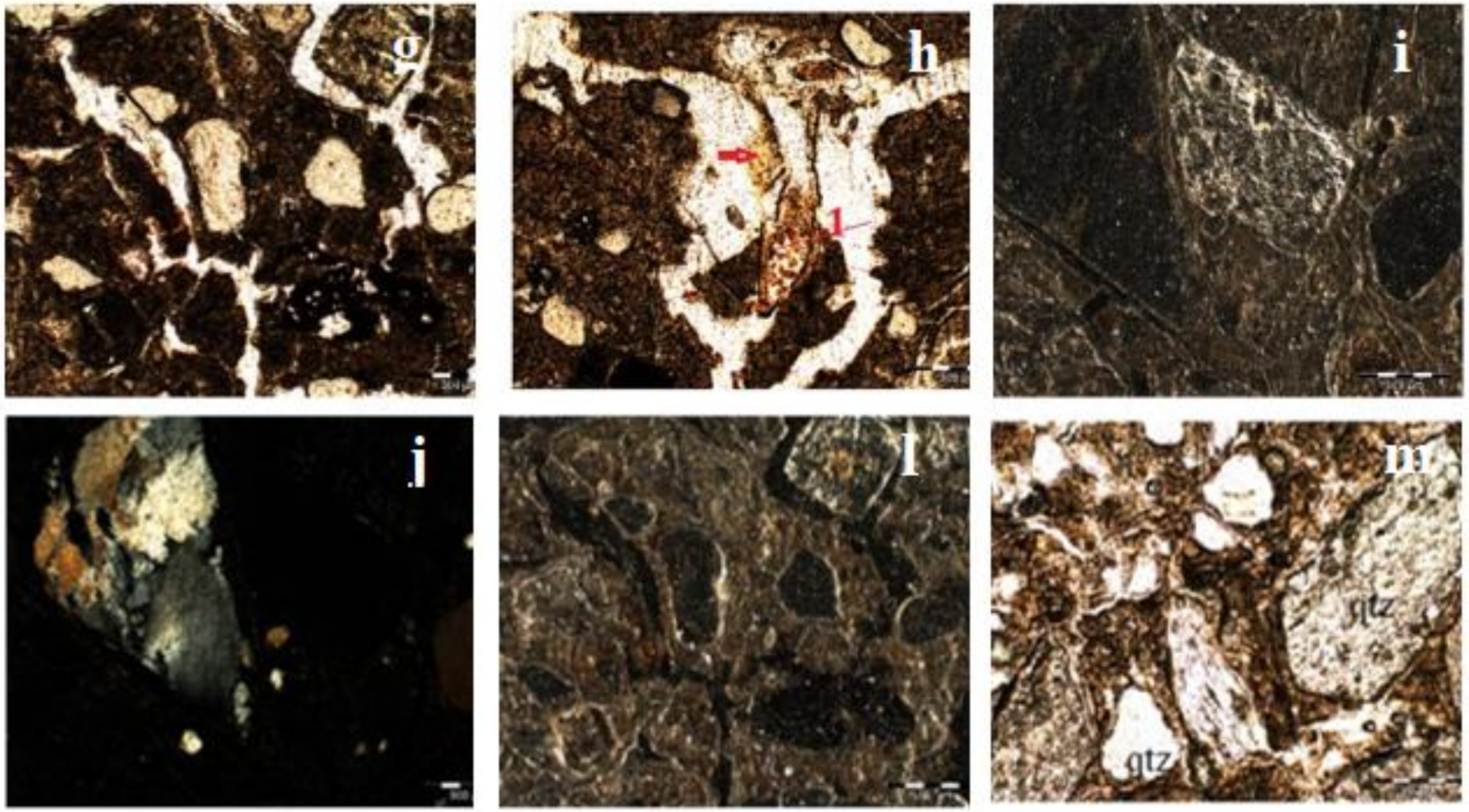


Figure 4. 44: Photomicrograph of thin section slide, F2. a- chambers, plane polarized light (ppl, 4x) views; b-sub-angular and rounded quartz grains, cross polarized light (xpl, 4x) views; c-organic material (1), plane polarized light (ppl, 4x) views; d-same as a, oblique incident light (oil, 4x) views; e-same as b, plane polarized light (ppl, 4x) views; f-clay coating infilling, plane polarized light (ppl, 4x) views.



Cont. Figure 4.44: photomicrograph of thin section slide, F2. g-pores type channels and fissure, plane polarized light (ppl, 4x) views; h-clay coating (arrows) and iron matrix (1), plane polarized light (ppl, 4x) views; i-charcoal and mineral grains, oblique incident light (oil); j-same as I, (xpl, 4x); l-same as g (oil) views; m- quartz grains, plane polarized light (ppl, 4x) views.

F3 (Table 4.14 and Figure 4.46): Soil presents a ratio between coarse (> 20µm) and fine material in the order 1/10 with open porphyric relative distribution. The visually estimated porosity is 30% of the slide area.

The coarse material poorly selected, rounded very few (<5% slide area) smaller quartz grains were observed, with smooth. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). The presence of small angular charcoal was observed. A non-angular and non-spherical iron and quartz conglomerate were observed and very few (< 5%) small iron nodules as well. In some isolated sectors it is visible the presence of fine and dark material.

The fine material consists of fine to medium silts and clay sized forming a dark brown speckled birefringent fine material. Subangular blocky and crack structure composed by channels and pores inter-aggregates are part of the microstructure. Figure 4.45 shows the SEM images together with EDX mapping of selected elements presents. Figure 4.45a) shows the presence of Fe rich nodules within aggregates, with Si rich quartz grains and the clay fine material dominated by Al, K grains is also observed.

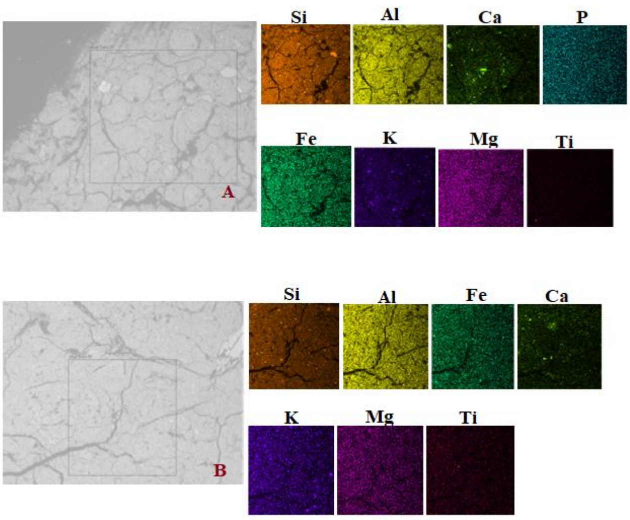


Figure 4. 45: SEM backscattered electron images and EDX emission maps of selected elements- F3 profile.

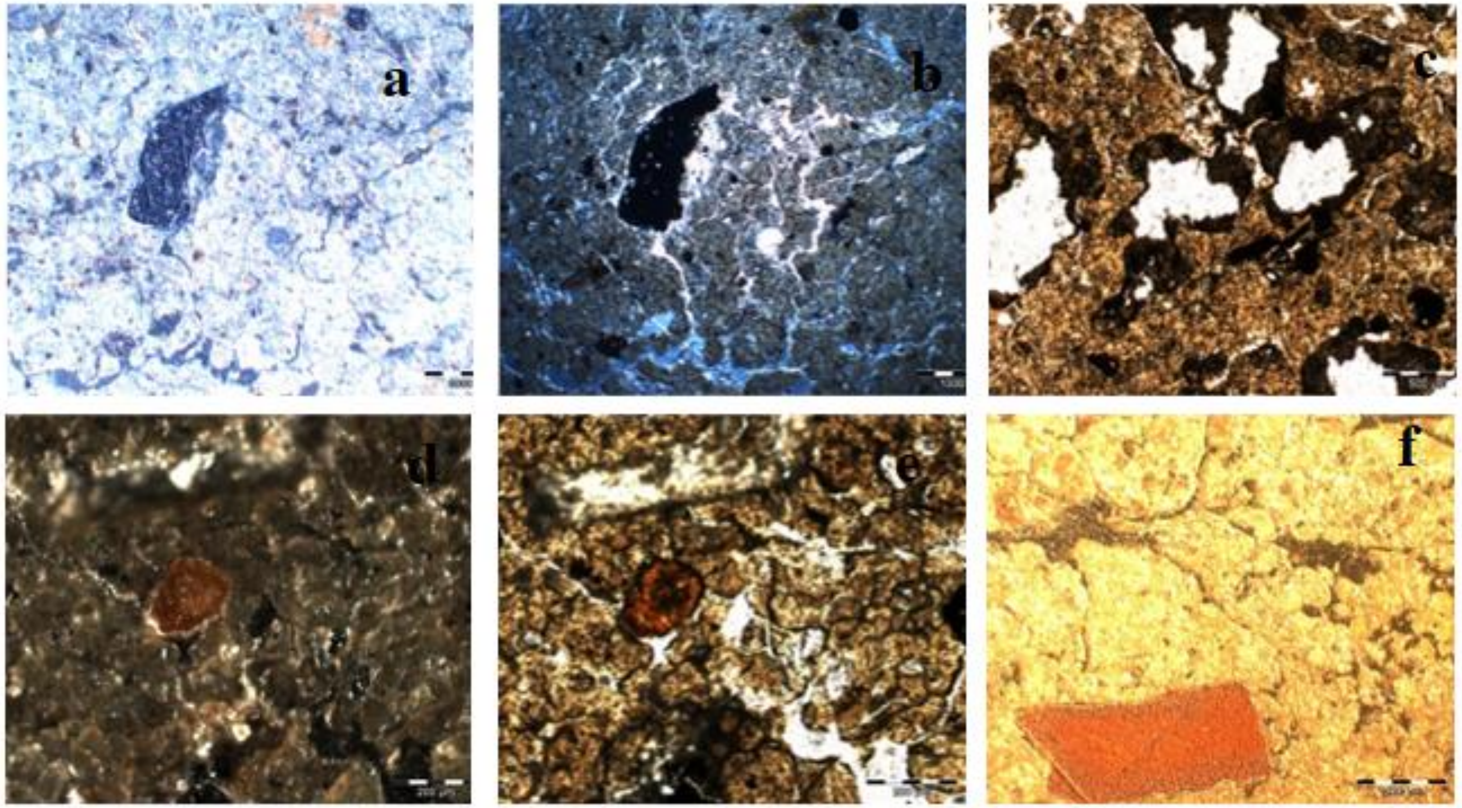
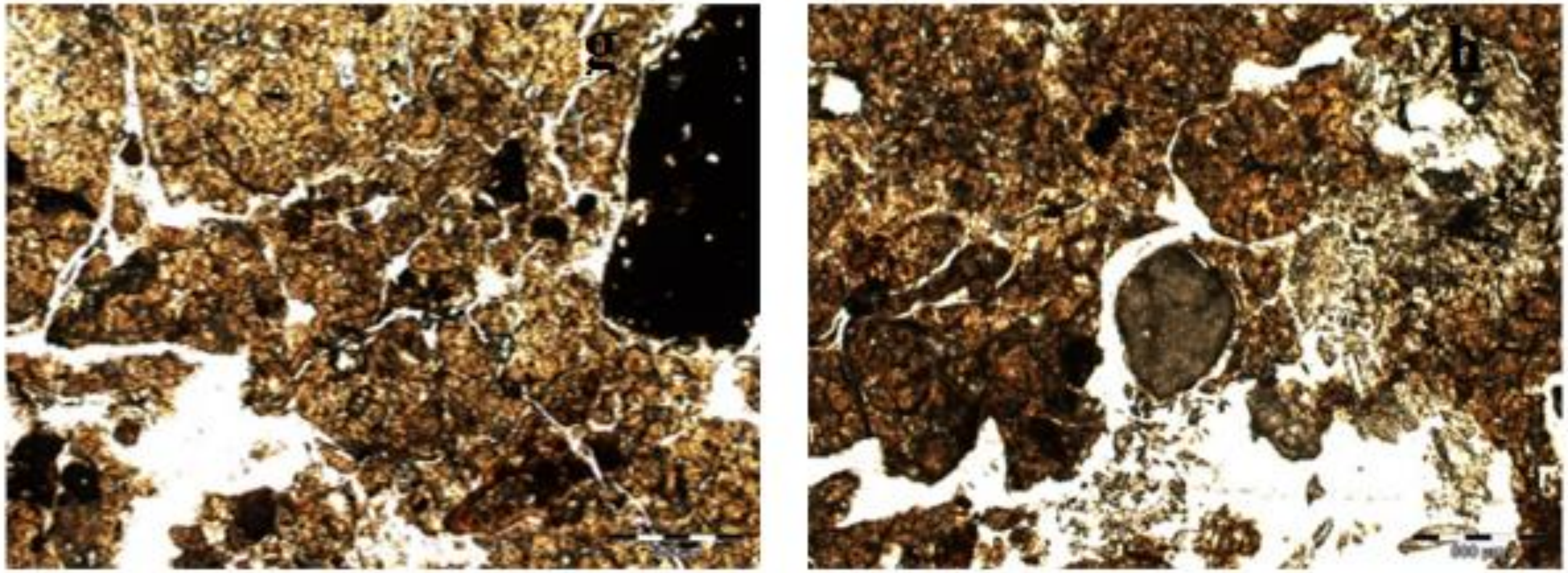


Figure 4. 46: Photomicrograph of thin section slide, F3. a-charcoal grain, oblique incident light (oil, 2x) views; b-same as a plane polarized light (ppl, 2x) views; c-charcoal, plane polarized light (ppl, 4x) views; d-iron nodule, oblique incident light (oil) view; e-same as d, (ppl, 10x); sub-angular iron grain, oblique incident light (oil,2x) views.



Cont. Figure 4.46: photomicrograph of thin section slide, F3. g- abundant organic matter, chambers, plane polarized light (ppl, 4x) views; h- quartz grain, plane polarized light (ppl,4x) views.

Table 4. 14- Summaries of soil micromorphology characteristics- Funda

Horizon	Coarse mineral Material (>2µm)		Coarse material arrangement	Coarse organic/biological material	Iron Pedo- features			Micro- structure	Fine mineral material	Related distribution	C/F ratio (20 µm)
	Quartz	Feldspar		Charcoal	Fe impregnation (matrix)	Fe hypocoating (poroid)	Fe nodule				
F1	•	None observed	Poorly Sorted	None observed	•	•	•	Crack microstructure; simple packing voids	Dark brown Speckled- b fabric	Open porphyric	1/10
F2	•	None observed	Poorly Sorted	None observed	•	•	•	Subangular blocky microstructure; simple packing voids	Dark brown Speckled- b fabric	Open porphyric	1/10
F3	•	None observed	Poorly Sorted	•	•	•	•	Subangular blocky microstructure; simple packing voids	Dark brown Speckled- b fabric	Open porphyric	1/10
. Very few (<5 % slide area); .. Few (5-15 % slide area); ... Common (15-30 % slide area); .... Frequent (30-50) % slide area); ...... Dominant (50-70 % slide area); b fabric birefringent fabric; G-granular; SB-subangular.											

T1 (Table 4.15 and Figure 4.48): Soil presents a ratio between coarse (> 20µm) and fine material in the order 2/3 with porphyric relative distribution. The visually estimated porosity is 40% of the slide area.

The coarse material is randomly sorted, smaller quartz grains predominate, with larger grains minerals being angular to subangular and small grains slightly spherical to subangular, all of them smooth and with cracks. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). Few (< 5% slide area) irons impregnation (matrix) was observed in quartz grains. Very few (<5% slide area) small grains of feldspar were observed

The fine material consists of fine to medium silts and clay sized constituting a dark yellow speckled birefringent fine material. In some isolated sectors it is visible the presence of fine and clear material and clay coating infillings. Subangular blocky and granular separated by compound complex packing voids (vughs and channels) and inter-aggregates voids are part of the microstructure. Figure 4.47 shows the SEM images together with EDX mapping of selected elements. Figure 4.47a) shows the presence of Fe rich nodules within aggregates, with Si rich quartz grains, and Ca, Na, and Mg grains. Similarly, Figure 4.47b) illustrates Si rich quartz grains, the presence of Fe rich nodules and K, and Ca grains and Ti minerals.

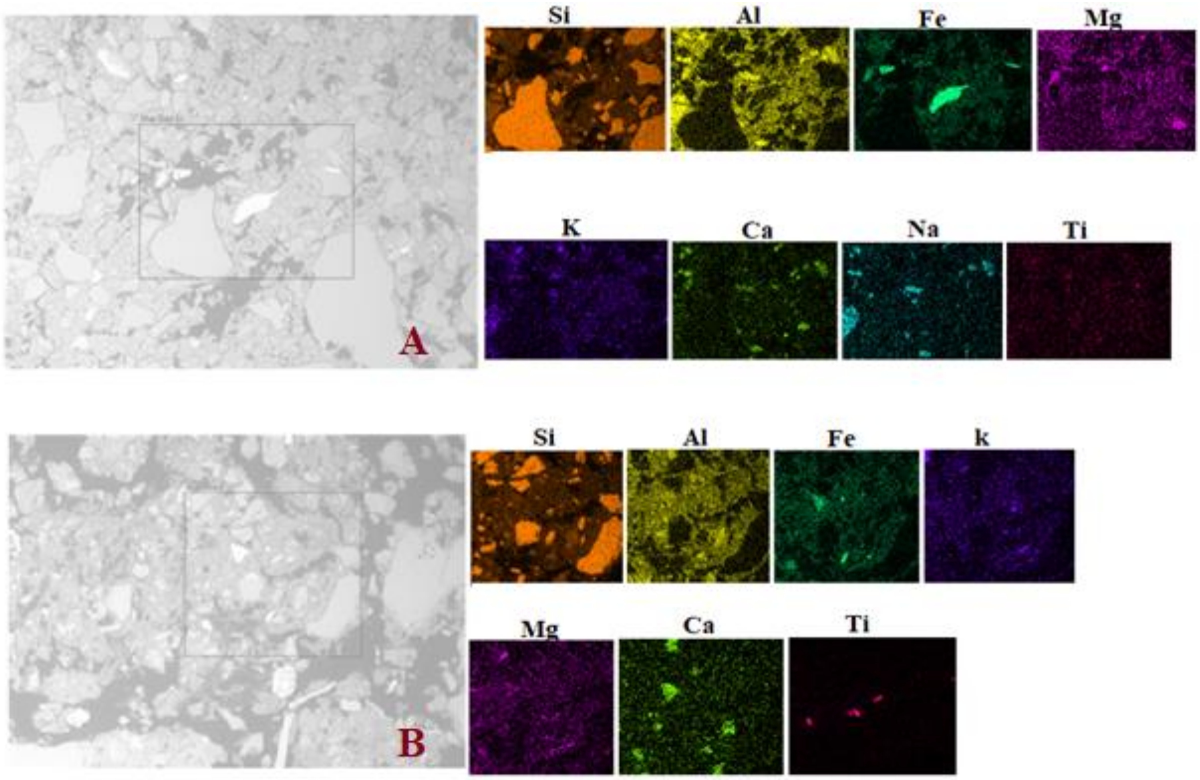


Figure 4. 47: SEM backscattered electron images and EDX emission maps of selected elements- T1 profile.

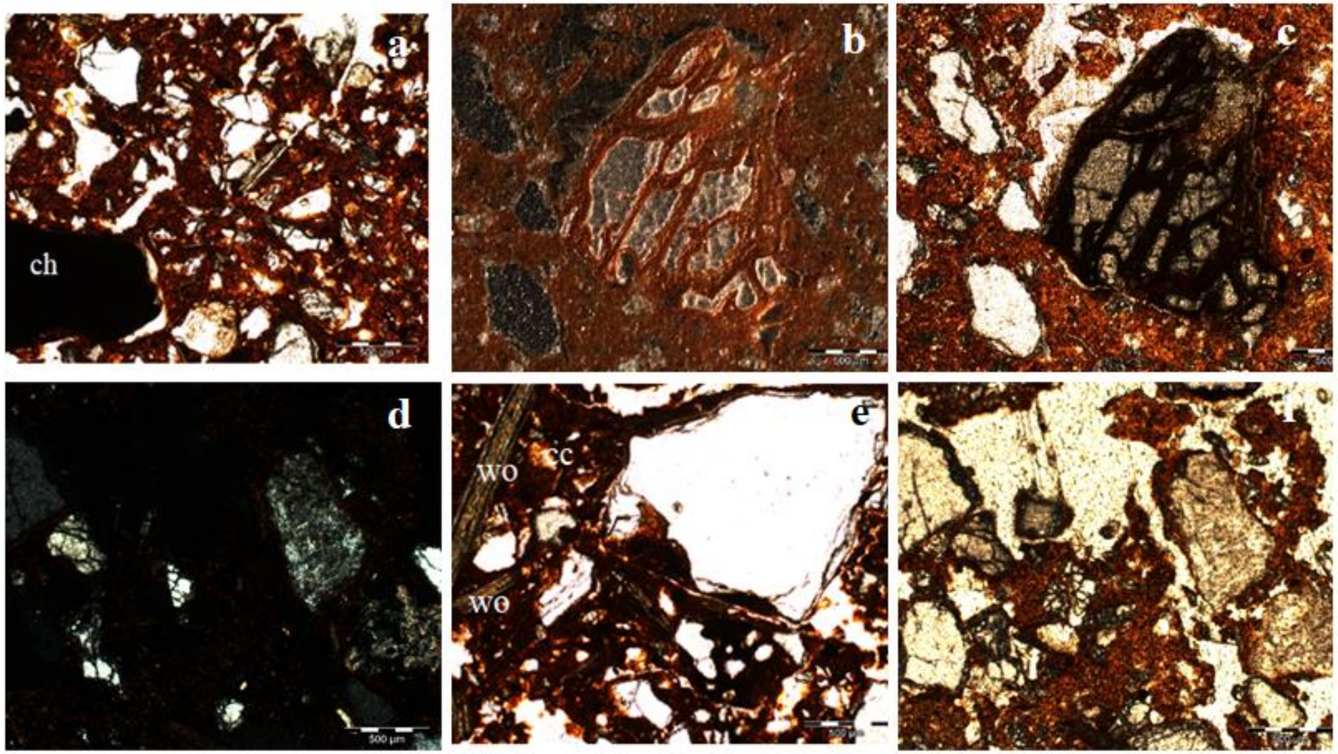
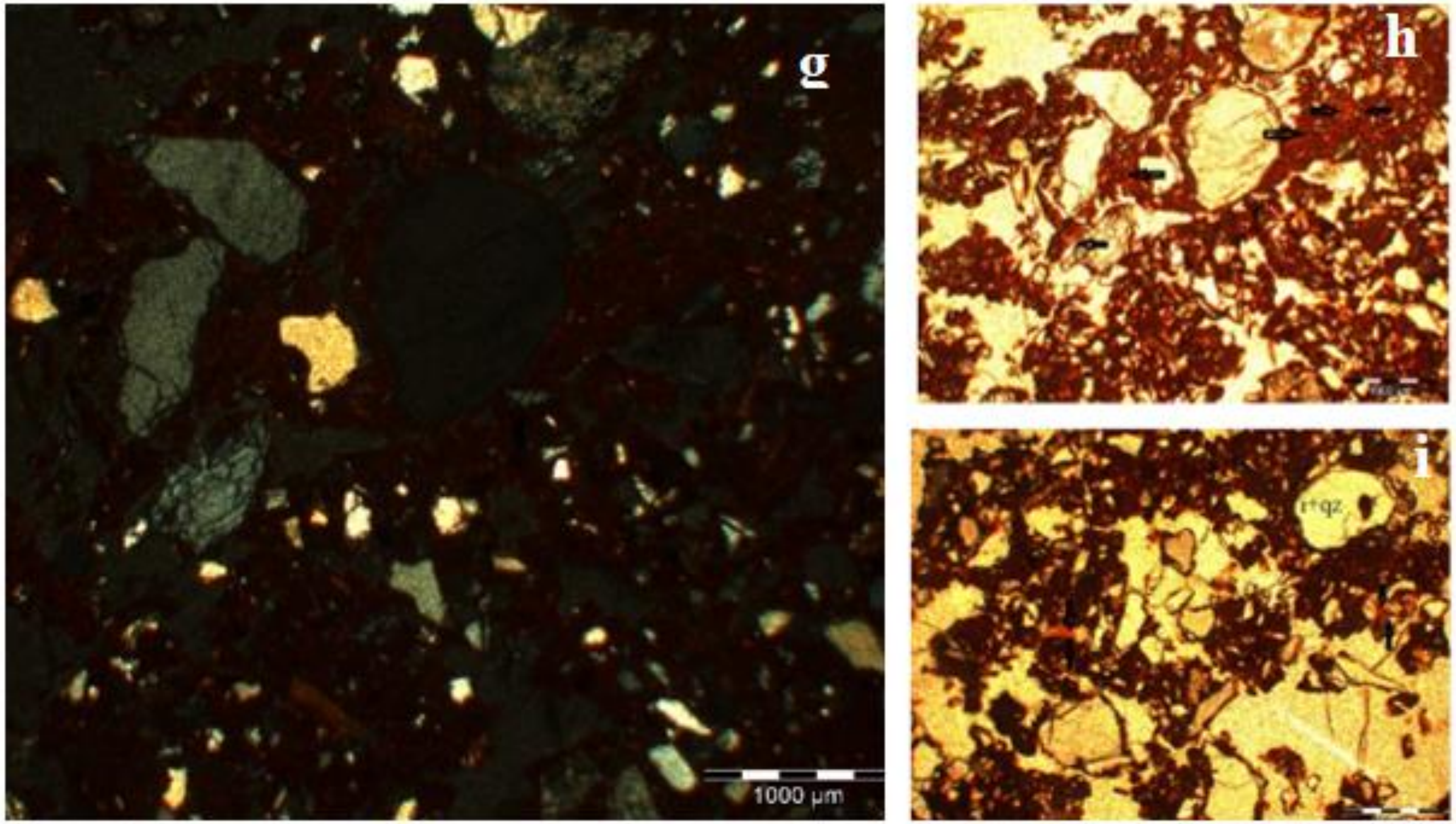


Figure 4. 48: Photomicrograph of thin section slide, T1. a- charcoal, plane polarized light (ppl, 4x) views; b- iron filling in the grain cracks, oblique incident light (oil, 4x) views; c-same as b (ppl, 4x) views; d- same as f (xpl, 4x); e- organic waste and clay coating, plane polarized light (ppl, 4x) views; f- quartz grain smooth and fissured, plane polarized light (ppl, 4x) views.



Cont. Figure 4.48: photomicrograph of thin section slide, T1. G abundant quartz grains, cross polarized grains (xpl, 2x) views; h- clay coating infilling (arrows), plane polarized view (ppl, 2x) views; i- iron enclosed in quartz, abundant pores, plane polarized light (ppl, 4x) views.

T2 (Table 4.15 and Figure 4.50): Soil presents a ratio between coarse and fine material in the order 2/3 with porphyric relative distribution. The visually estimated porosity is 40% of the slide area.

The coarse material is randomly sorted, dominated by quartz grains, with different sizes, the small ones rounded and large angular to subangular, smooth, or fissured. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). The presence of few (< 5% slide area) small non-spherical material charcoal was observed. Few (5-15% slide area) iron impregnation matrix and few (5 – 15% slide area) small iron nodules were observed. Moreover, very few (< 5% slide area) angular grains of feldspar were identified.

The fine material involves of fine to medium silts and clay forming a dark brown speckled birefringent fine material. Subangular blocky to granular structure comprised of channels and inter-aggregate voids, are part of the microstructure. Figure 4.49 shows the SEM images together with EDX mapping of selected elements. Figure 4.49a) shows the presence of Fe nodules within aggregates, with Si rich quartz grains, residual k and Mg contents concentrated in grains. Figure 4.49b) illustrates Si rich quartz grins, presence of Fe nodules, Mg, Ca and Na grains, Ti minerals.

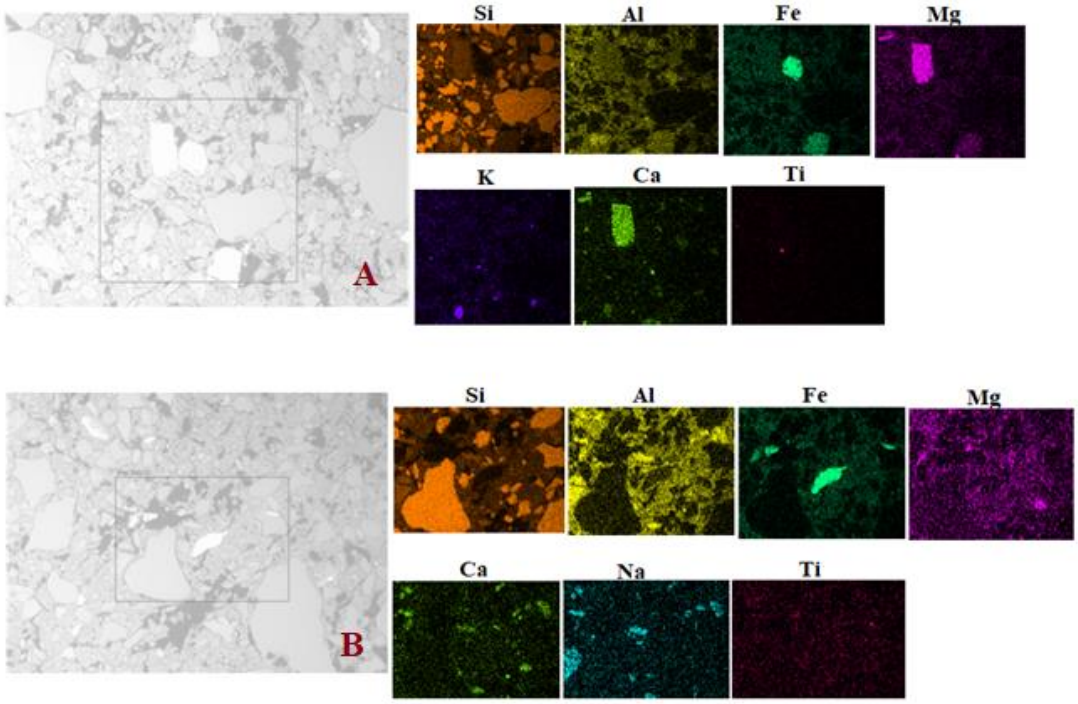


Figure 4. 49: SEM backscattered electron images and x-Ray emission maps of selected elements- T2 profile.

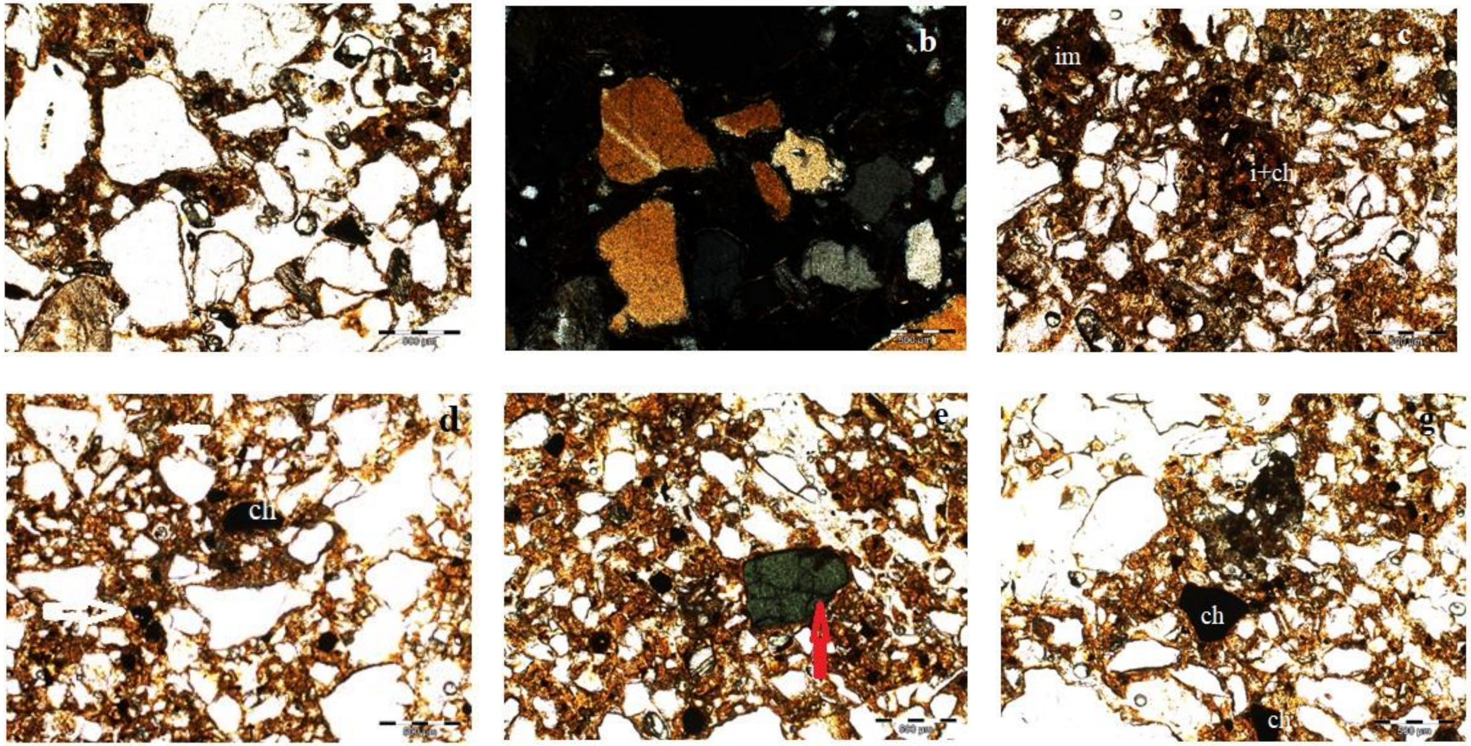
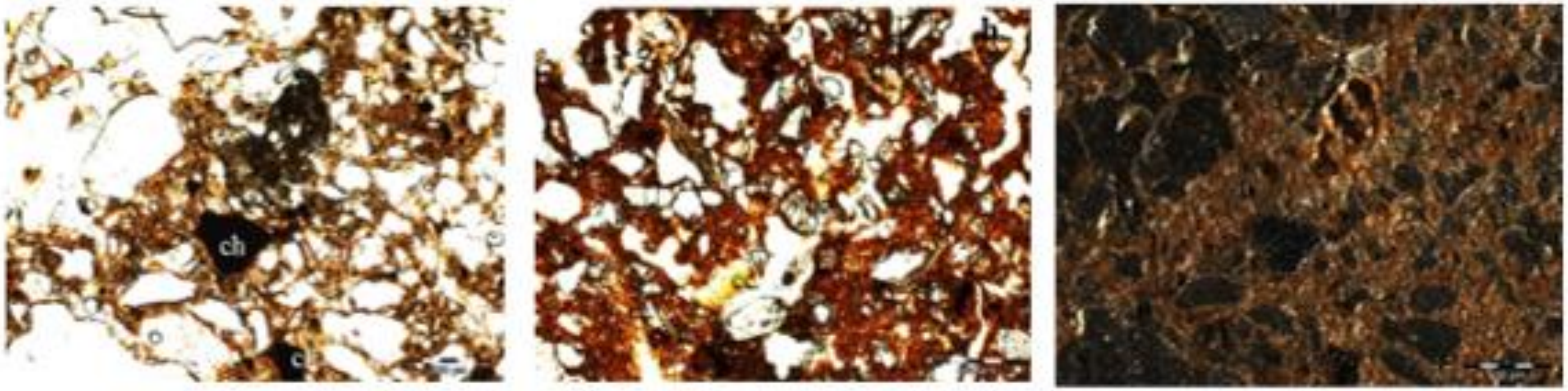


Figure 4. 50: Photomicrograph of thin section slide, T2. a- abundant quartz grains, plane polarizes light (ppl, 4x) views; b- same as a cross polarized light (xpl, 4x) views; c- iron enclosed in grain, plane polarized light (ppl, 4x) views; d- charcoal and iron nodules, plane polarized light (ppl, 4x) views; e-mineral grain, plane polarized light (ppl, 4x) views; f-charcoal, plane polarized light (ppl, 4x) views.



Cont. Figure 4.50: photomicrograph of thin section slide, T2. g-evidence for chemical compaction including convex-concave contacts, plane polarized light (ppl, 4x) views; h- clay coating, plane polarized light (ppl, 4x); i-same as g (oil) views.

T3 (Table 4.15 and Figure 4.52): Soil presents a ratio between coarse (> 20µm) and fine material in the order 2/3 with porphyric relative distribution. The visually estimated porosity is 40% of the slide area.

As for the coarse material, random sorted different sizes of quartz grains predominate, some of them (grains) being angular and others spherical, with cracks and smooth. The alteration pattern of quartz is type D (dotted) and degree zero (0) and one (1). Iron-pedofeatures is constituted by the presence of few small angular and non-spherical charcoal, and organic waste. Very few (<5% slide area) iron nodules with roughness were observed. In some isolated sectors it is visible the presence of fine and clear material. Very few (< 5% slide area) small grains of feldspar were observed.

The fine material involves of fine to medium silts and clay creating a brown speckled birefringent fine material. Complex mixture composed by subangular blocky and granular structure, with channels and inter-aggregates complex packing voids are part of the microstructure. Figure 4.51 shows the SEM images together with EDX mapping of selected elements present. Figure 4.51a) shows the presence of Fe nodule within aggregates, with high Si quartz grains, residual Ca and K concentrated in grains and, Ti minerals. Similarly, Figure 4.51b) shows the presence of Fe nodules, residual K, Ca, and Mg concentrated in grains and fine material, Ti minerals.

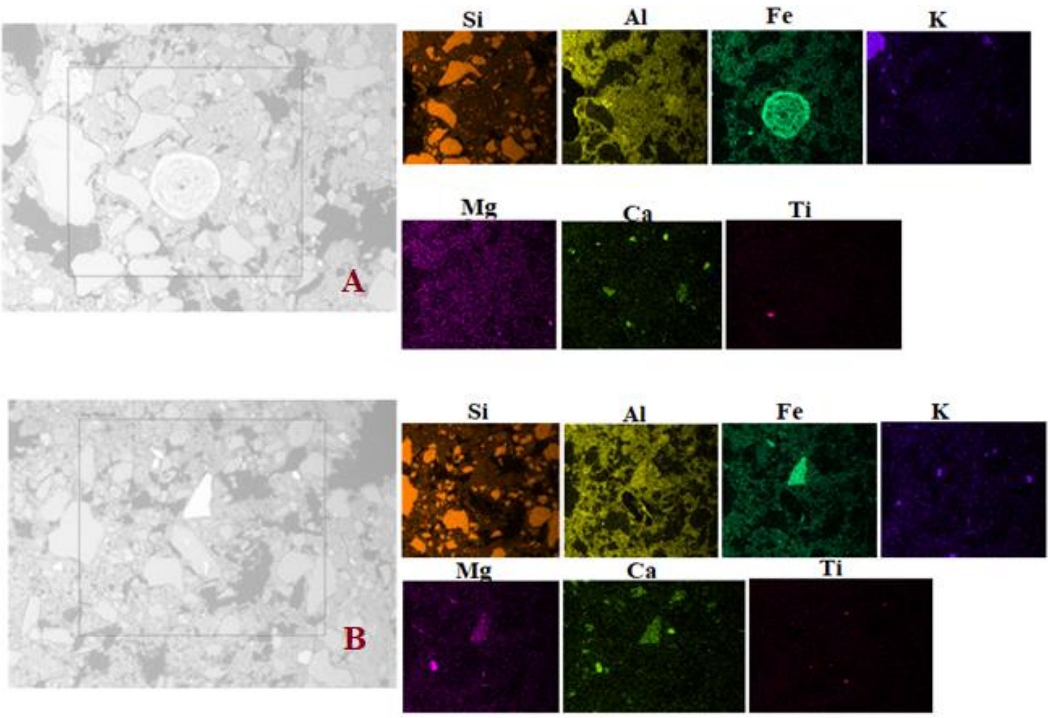


Figure 4. 51: SEM backscattered electron images and EDX emission maps of selected elements- T3 profile

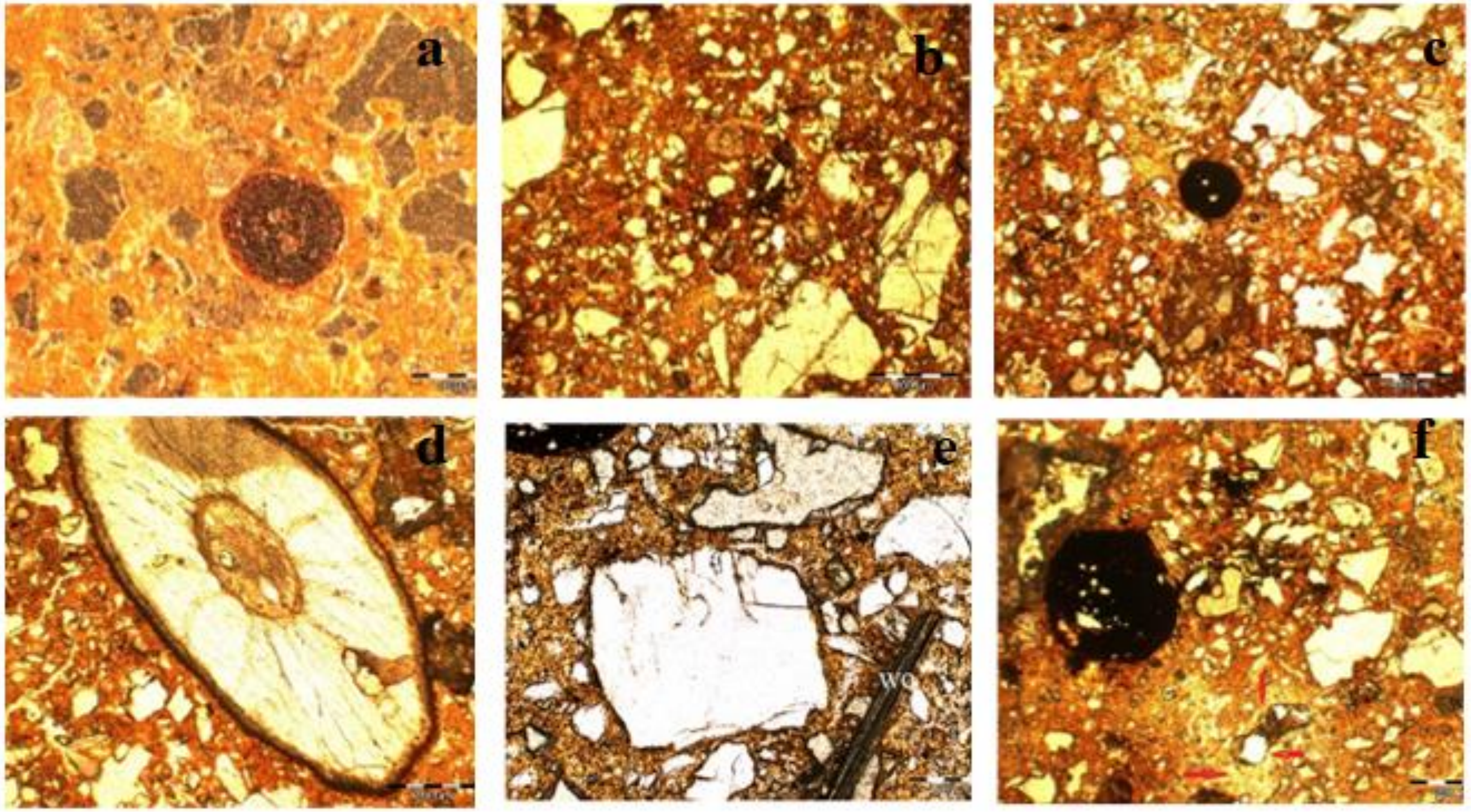
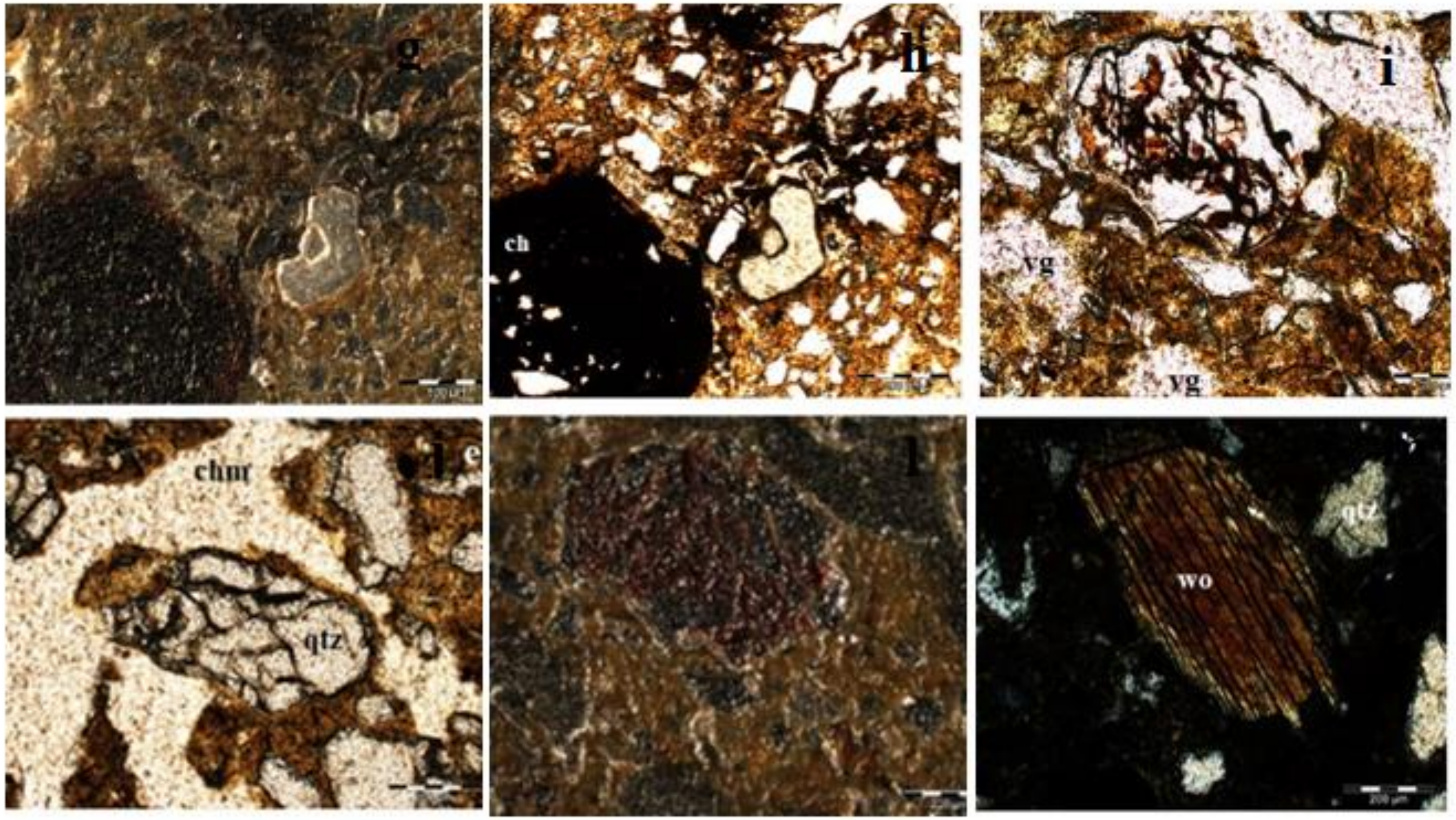


Figure 4. 52: Photomicrograph of thin section slide, T3. a-iron nodule, oblique incident light (oil, 2x); b-abundant quartz grains, plane polarized light (ppl, 2x) views; c-same as a, (ppl, 2x) views; c roots, plane polarized light (ppl, 4x) views; e- organic waste, plane polarized light (ppl, 4x) views; - clat coating (arrows), plane polarized light (ppl, 4x) views.



Cont. Figure 4.52: photomicrograph of thin section slide, T3. G-charcoal, oblique incident light (oil, 4x) views; b-same as g (ppl, 4x) views; i-pores type vughs, plane polarized light (ppl, 4x) views; j- rounded quartz grain with cracks and chambers, (plane polarized light (ppl, 4x) views; l- same as I, (oil) view; m- organic waste, plane polarized light (ppl, 4x) views.

Table 4. 15- Summaries of soil micromorphology characteristics- Talelo

Horizon	Coarse mineral Material (>2µm)		Coarse material arrangement	Coarse organic/biological material	Iron Pedo- features			Micro- structure	Fine mineral material	Related distribution	C/F ratio (20 µm)
	Quartz	Feldspar		Charcoal	Fe impregnation (matrix)	Fe hypocoating (poroid)	Fe nodule				
T1	•••	•	Random Sorted	None observed	••	•	•	Complex microstructure; mixture sub-angular blocky and granular; compound packing voids	Dark brown Speckled- b fabric	Open porphyric	2/3
T2	•••	•	Random Sorted	•	•	•	•	As above	Dark brown Speckled- b fabric	Open porphyric	2/3
T3	••	•	Random Sorted	•	•	•	•	Complex microstructure; mixture sub-angular blocky and granular; compound packing voids	Dark brown Speckled- b fabric	Open porphyric	2/3
. Very few (<5 % slide area); .. Few (5-15 % slide area); … Common (15-30 % slide area); …. Frequent (30-50) % slide area); ….. Dominant (50-70 % slide area); b fabric birefringent fabric; G-granular; SB-subangular.											

4.3- EDX (Energy dispersive X-ray spectroscopy) microscopy Chemical composition

4.3.1- Chemical composition in fine material

Overall, the silica and aluminium contents are higher (compared with grains) in the composition of the fine material in the studied soils of the two provinces and there were higher contents of the silica in relation to aluminium. Silica showed a decreasing trend with increasing depth in the profiles of Ngongoinga and Bailundo regions (Ng1- Ng3 and B1- B3, Table 4.8), while in Mungo and Lepi Si tend to increase. Al showed an increasing trend moving from top hill-slope profile to low hill-slope profile in Ngongoinga and Mungo region. The opposite was observed in Lepi and Bailundo. Fe showed lower contents compared to Al and Si, with a decreasing trend in all hill-slope profiles. This fact may be an indication of the destruction of clays according to Schaefer (2002) who verified comparable results in soils from Minas Gerais (Brazil).

Similarly, to Huambo, in Luanda the contents of Si were higher than those of Al. silica tends to increase from the top to the bottom hill-slope profile in Bom Jesus and Lepi, while in Funda region it decreases. Al tends to decrease in all hill-slope profiles studied (Table 4.17, 4.18, 4.19 and 4.20). Fe showed lower contents than Si and Al and a decreasing trend in Funda and Talelo region.

Fine material- Huambo

Table 4. 16- contents of some elements obtained through EDS analysis in fine material- Huambo province

	Na	*Mg*	*Al*	*Si*	*P*	*S*	*Cl*	*K*	*Ca*	*Ti*	*Cr*	*Fe*	*W*	*Mn*	*Si/Al*	*total*
B1	0.02	0.01	10.6	13	0.02	0.02	0.0182	0.216	0.0255	0.27	0.01	2.23	0.02	0.02	1.24	27.7797
B2	0.02	0.01	9.45	13.3	0.02	0.02	0.11	0.157	0.0228	0.281	0.01	1.38	0.02	0.02	1.46	26.3408
B3	0.02	0.01	8.05	11.2	0.02	0.02	0.0344	0.02	0.171	0.491	0.01	1.05	0.02	0.02	2.15	23.3464
	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe	W	Mn	Si/Al	total
Ng1	0.02	0.01	7.96	17.1	0.02	0.02	0.207	0.384	0.0168	0.366	0.01	1.95	0.02	0.02	10.2	38.3638
Ng2	0.02	0.01	9.44	10.1	0.02	0.0194	0.146	0.349	0.01	0.528	0.01	1.72	0.02	0.02	1.09	23.5624
Ng3	0.02	0.01	9.6	10.7	0.02	0.01	0.0225	0.304	0.0194	0.533	0.01	1.43	0.02	0.02	1.11	23.8689
	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe	W	Mn	Si/Al	total
M1	0.04	0.01	8.59	7.92	0.02	0.03	0.0428	0.02	0.02	1.15	0.01	4.39	0.03	0.02	1.2	23.5628
M2	0.053	0.017	10.2	9.13	0.03	0.04	0.0451	0.0324	0.0154	0.582	0.629	4.6	0.02	0.013	1.06	26.528
M3	0.02	0.02	8.77	12.6	0.02	0.03	0.01	0.428	0.0193	0.26	0.046	1.66	0.02	0.01	1.56	25.5633
	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe	W	Mn	Si/Al	total
L1	0.01	0.03	9.05	10.6	0.02	0.03	0.04	0.388	0.03	0.347	0.02	4.42	0.0178	0.04	1.18	26.3028
L2	0.02	0.01	7.3	10.9	0.02	0.02	0.03	0.345	0.01	0.514	0.261	3.62	0.03	0.0295	1.75	24.9895
L3	0.02	0.106	8.73	13.7	0.02	0.03	0.024	0.688	0.026	0.457	0.01	4.22	0.03	0.02	1.58	29.771

The data report the mean of all samples (slides) in each region.

Fine material- Luanda

Table 4. 17: contents of some elements obtained through EDS analysis in fine material- Luanda province

	Na	*Mg*	*Al*	*Si*	*P*	*S*	*Cl*	*K*	*Ca*	*Ti*	*Cr*	*Fe*	*W*	*Mn*	*Si/Al*	*total*
BJ1	0.0704	0.49	6.79	11.4	0.0163	0.017	0.0337	0.753	0.443	0.279	0.0119	2.89	0.02	0.02	1.7	24.9943
Bj2	0.01	0.521	6.41	15.3	0.0114	0.07	0.0186	0.853	0.554	0.299	0.01	3.16	0.02	0.02	5.01	32.327
Bj3	0.01	0.492	6.51	13.6	0.02	0.01	0.463	0.555	0.372	0.317	0.01	3.01	0.02	0.02	2.72	28.2123
	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe	W	Mn	Si/Al	total
F1	9.5	0.678	6.92	14.2	0.0424	0.02	0.166	0.75	1.6	0.332	0.01	3.24	0.02	0.02	2.05	39.6284
F2	0.01	2.59	9.04	9.81	0.0391	0.0552	0.26	0.691	0.537	0.02	0.797	2.53	0.02	0.02	2.42	28.9193
F3	0.01	0.422	5.48	12.4	0.01	0.898	0.06	0.497	2.77	0.364	0.01	2.72	0.0155	0.0155	2.82	28.8635
	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Cr	Fe	W	Mn	Si/Al	total
T1	0.149	0.864	5.81	11.1	0.01	0.02	0.132	1.1	0.192	0.01	0.563	4.92	0.01	0.01	5.41	30.3894
T2	0.213	0.629	3.76	16.3	0.01	0.02	0.177	0.829	0.454	0.01	0.33	3.7	0.01	0.324	9.05	35.876
T3	0.285	0.429	4.54	16.4	0.01	0.02	0.102	0.624	0.187	0.01	0.373	3.35	0.015	0.122	5.96	32.487

The data report the mean of all samples (slides) in each region.

Grains- Huambo

Table 4. 18: contents of some elements obtained through EDS analysis in grains- Huambo province

	Na	*Mg*	*Al*	*Si*	*S*	*P*	*Cl*	*K*	*Ti*	*Ca*	*Cr*	*Fe*
B1	0.01	0.01	1.73	27.6	0.01	0.0308	0.0173	0.234	0.01	0.0488	1.69	0.01
B2	0.155	0.0452	1.84	26.3	0.01	0.016	0.0212	0.841	0.124	0.0176	0.637	0.01
B3	0.01	0.01	3.52	19.7	0.01	0.01	0.0163	0.184	0.0311	0.01	0.801	0.01
	Na	Mg	Al	Si	S	P	Cl	K	Ti	Ca	Cr	Fe
Ng1	0.01	0.01	1.5	30.5	0.01	0.01	0.0255	0.0214	0.01	0.01	0.655	0.01
Ng2	0.01	0.01	1.66	28.6	0.01	0.01	0.0224	0.0841	0.01	0.01	0.391	0.01
Ng3	0.01	0.01	1.39	30.2	0.01	0.01	0.0272	0.0672	0.01	0.01	0.424	0.01
M1	0.02	0.02	3.79	15.6	0.0303	0.0249	0.0338	0.328	0.0172	0.0903	6.29	0.01
M2	0.185	0.12	3.35	22.5	0.0341	0.0149	0.0341	0.755	0.164	0.0716	2.77	0.0154
M3	0.144	0.012	2.73	26	0.026	0.0165	0.024	0.227	0.341	0.0135	0.37	0.0217
L1	0.0236	0.015	2.8	23.1	0.0254	0.02	0.04	0.513	0.0246	0.0393	3	0.0104
L2	0.02	0.01	1.81	26.4	0.0295	0.0395	0.0205	0.187	0.02	0.0124	2.24	0.01
L3	0.02	0.414	1.78	28.4	0.03	0.0618	0.04	0.0591	0.0673	0.0973	5.66	0.0436

The data report the mean of all samples (slides) in each region.

Grains- Luanda

Table 4. 19*:* contents of some elements obtained through EDS analysis in grains- Luanda province

	Na	*Mg*	*Al*	*Si*	*S*	*P*	*Cl*	*K*	*Ti*	*Ca*	*Cr*	*Fe*	*Ba*
BJ1	0.0222	0.49	5.9	16.2	0.01	0.0574	0.0522	0.291	0.46	0.01	4.44	0.0478	0.01
BJ2	1.3	3.2	8.21	8.76	0.01	0.02	0.147	0.326	1.26	0.01	11.5	0.02	0.01
BJ3	0.263	0.899	6.17	14.7	0.01	0.02	0.111	0.552	0.356	0.01	3.49	0.479	0.01
F1	0.548	0.43	3.27	8.72	0.0467	0.0222	0.586	0.179	1.29	0.01	1.86	0.01	0.01
F2	0.029	0.0534	1.15	17.9	2.73	3.34	0.0748	0.0593	3.52	0.0131	0.749	0.0379	0.01
F3	0.0679	0.325	4.82	11	2.92	0.01	0.0207	0.229	5.1	0.02	2.58	0.02	0.0221
T1	0.68	0.621	3.26	20.8	0.01	0.0209	0.0277	2.13	0.632	0.01	3.77	0.01	0.01
T2	0.882	0.701	5.23	22.4	0.01	0.01	0.05	0.274	1.76	0.0164	3.34	0.0524	0.01
T3	0.285	0.429	4.54	16.4	0.01	0.01	0.101	0.373	0.187	0.01	3.35	0.02	0.01

The data report the mean of all samples (slides) in each region.

Chapter 5: Soil nutrient results

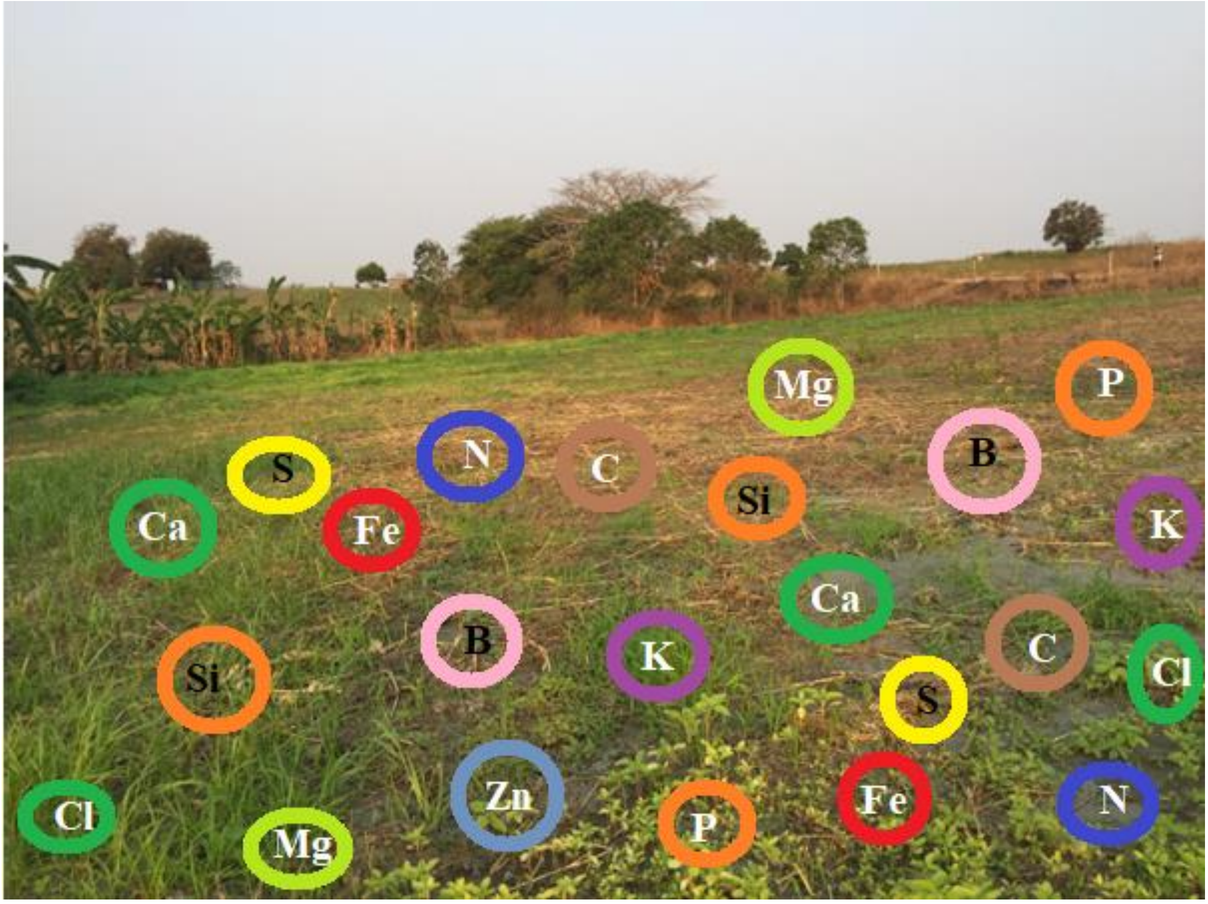


Photo: LT

5.1-Introduction

Knowledge of the nutrient status in the soil is essential for the assessment of soil quality, for its maximization as well as for the practice of sustainable agriculture. Furthermore, nutrients influence human, animal, and soil health as they are present in plants consumed as food and in seeds (Kihara, Bolo et al. 2020). Satisfying basic food needs in Angolan society involves development policies in the agricultural sector and, consequently, a better understanding of the patterns and dynamics of nutrient variation in these soils. Soils are an essential natural resource with a strong contribution to human well-being, providing important ecosystem services, vital nutrients for the environment (Smith, Woodruff et al. 2009, Towett, Shepherd et al. 2013) and plant growth. Plants need nutrients and depending on their chemical form these nutrients can be absorbed by the roots of plants. The nutrients and their chemical and biological interactions in the soil form the basis for the development and yield of agricultural crops. Determining the amount and availability of nutrients in soil generates information about their fertility, depending on the management conditions and their chemical characteristics. In developing countries in sub-Saharan Africa, the knowledge of soil nutrient status is a tool in land assessment (Towett, Shepherd et al. 2015) and is extremely important to increase the success and profitability of crop production.

The aim of the research in this chapter: a) to create new knowledge of the status of nutrient elements in Angolan agro-ecosystem soils, with emphasis on macronutrient and micronutrients; b) to identify the behaviour among soil nutrients, and acidity. An evaluation of the nutrients in the studied areas will be made allowing a better understanding of its excess or deficiency, thus allowing correction in terms of fertilization.

Thus, the sequence of the analyses in this chapter will be: first, the statistical summary of the soil nutrient contents (N, Ca, K, Mg, P, S, Fe, Mn, Zn, Cu, Mo, Al, and pH (H_2O)) measured in the laboratory will be presented. Second, will analyse the variation of nutrient contents along the hillslope profile, site, and depth. Third, an analysis of the behaviour of nutrients between sites will be conducted. In other words, the questions will be investigated:

Does nutrient status change with depth? With Profile? With Sites?

5.2- Total nutrient status of the soils studied

The results of the status of elements concentrations in soils are strongly varied in different regions (Table 5.1). Soil macronutrient and micronutrient concentrations and their phyto-availability are intrinsically linked to soil fertility (Butler, Palarea-Albaladejo et al. 2020). Differences in soil fertility status between fields within a farm may be associated with the properties of the soil itself and underlying landscape (Vanlauwe, Wendt et al. 2001). This variation in African soils can also be explained by distinct reasons. Furthermore, Angolan soils are mostly classified as ferralsols, and the soils samples for this work were collected in areas with contrasting land use, parent material, vegetation, and climate. These and other factors are responsible for the variety of pH values and macro- and micro-nutrients observed in the studied soils.

pH of the soils analysed ranges from very acidic to weakly alkaline. These values may be due to the composition of parent rock, landscape position where the soil is located (i.e., topographic position of the site), how the land is managed and microclimatic conditions (Solomon et al., 2001). Similar results (acidic to weakly alkaline soils) were reported by Lego et al (2016) in the study of agricultural soils in Ethiopia. Soils with lower pH and CEC (cation exchangeable capacity) need more protection and consequently nutrient levels for these soils will be affected.

Like pH, the observed concentrations of macronutrients and micronutrients were variable. The values for nitrogen (N) in this study are below (see Table 5.2) ranging between 0-7842 ppm, with 3 sites showing the lowest value and Mungo the highest value (Table 5.1). According to (Aranibar, Anderson et al. 2008), N contents may be related to the activity of microorganisms in areas where there is grazing. In deeper profiles with less influence of shorter-term weather, there may be changes in nitrogen forms as a result of water movement within the profile (Gupta and Rorison 1975). Furthermore, a study by (Boyer, Motti et al. 1971) reports that tropical soils generally have low N contents.

Calcium (Ca) and magnesium (Mg) concentration values ranged between 0-224403 ppm, with the highest value registered in Funda region and the smallest value observed in Bailundo, Ngongoinga, Ramiro and Talelo regions. Contents of these element in soils are related to soil acidity (Cavichiolo 2005); low levels of Ca and Mg are a consequence of very acidic soils.

Potassium (K) values vary from 0-23968 ppm, with the lowest concentrations in Lepi and Talelo (Table 5.1) The origin of K is from weathering of parent material. The results for this nutrient are above those predicted for this region, and one of the reasons for this fact may be the drought conditions to which the soils are subject, resulting in a decrease in limited downwards leaching of K through the profile. In addition, the availability of K and its uptake by plants are associated with the cations Ca^{2+} and Mg^{2+} (Oliveira, Carmello et al. 2001). On the other hand, low K concentration may be associated with soils with high aluminium and iron concentrations (Towett et al., 2015).

Again, the origin of phosphorus (P) depends on the parent material. Our results for this macronutrient ranged from 0-2257 ppm and showed the highest concentration in Bom Jesus (Table 5.1), values that are below those predict for this region of Africa. Phosphorus variation in soils may be due to the addition of fertilizers and correctives. Regardless of the soils, P is a relatively little leached element. According to (Boyer, Motti et al. 1971) in ferralsols soils, however, the very weak leaching of P for hundreds of thousands of years is nonetheless, one of the causes of the low level of P in those soils. On the other hand, all forms of P can exist in all soils, but P bound by Al and Fe is abundant in highly weathered acidic soils (Melese, Gebrekidan et al. 2015).

Iron (Fe) this macronutrient is a major element in soils called ferralsols and its origin depends on parent material. The results here showed Fe values ranged from 0.04-82.212ppm, with the lowest concentration being observed in Talelo and the highest concentration in the Talelo site (Table 5.1), exceeding values predicted for this area according Towett, 2015.

Manganese (Mn) this element showed values between 0-15632 ppm, the smallest and highest concentration verified in Talelo locality (Table 5.1). However, the mean value of this element exceeds those predicted for that regional area in Africa.

Similarly, Zinc (Zn) showed values varied from 0-49260 ppm with lowest concentration verified in Bailundo, Funda, Lepi, NGongoinga, Ramiro and Talelo regions and the highest concentration in Funda site (Table 5.1) and, Cupper (Cu) 0-48744 ppm, the lowest values in three regions and the highest in the Bom Jesus region (Table 5.1). For both of these, the concentrations are above those predicted (see Table 5.2), a fact that can be attributed to the weathering process (Vendrame, Brito et al. 2007).

Table 5. 1: Summary statistics of the mean, median, Standard deviation, minimum, maximum and percentiles of the nitrogen, calcium in all region's studies.

			N									Ca					
	Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min		Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min
Bailundo	463	365	407	166	365	718	1493	36.6		653	615	332	388	615	906	1215	104
Lepi	1245	388	1943	224	388	1425	7842	21.1		1112	591	1337	469	591	1096	5303	155
Mungo	1008	601	1022	310	601	1435	3451	113		7674	571	11529	296	571	10432	34758	25.5
Ngongoinga	449	281	388	237	281	539	1327	78.2		925	831	537	383	831	1312	1822	305
Talelo	501	451	340	266	451	707	1314	0.03		2651	2412	1302	1919	2412	3832	5368	0.02
Ramiro	36.7	35.1	23.9	17.5	35.1	50.3	92.9	0.03		209	141	231	81.7	141	210	835	0.03
Funda	640	519	367	408	519	787	1777	204		79236	75555	48482	46547	75555	103715	224403	4.44
Bom Jesus	4386	764	5723	645	764	10666	16975	495		19865	20810	11023	9341	20810	31921	36045	6888

Cont. Table 5.1: summary statistics of the mean, median, Standard deviation, minimum, maximum and percentiles of potassium, and magnesium in all region's studies.

			K									Mg					
	Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min		Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min
Bailundo	327	317	161	217	317	386	756	104		127	129	38.1	94.9	129	157	205	61.4
Lepi	570	525	310	383	525	679	1372	125		340	300	217	193	300	451	844	102
Mungo	450	407	230	292	407	593	909	151		121	96.7	90.4	76.5	96.7	142	413	0.03
Ngongoinga	386	447	191	233	447	524	562	0.02		170	173	58.9	151	173	217	242	46.6
Talelo	14678	14482	6257	9854	14482	19113	23968	0.02		9388	11182	4449	5194	11182	13063	14967	0.02
Ramiro	970	977	277	810	977	1079	1930	556		214	200	68.2	161	200	256	424	94.7
Funda	9223	9401	3159	8497	9401	10423	14931	0.82		7231	7937	4998	4912	7937	8617	26063	0.03
Bom Jesus	13275	11546	3514	10734	11546	16320	19914	9858		7062	6421	1566	6049	6421	8070	9983	5525

Cont. Table 5.1: Summary statistics of the mean, median, Standard deviation, minimum, maximum and percentiles of phosphorus, and sulphur in all region's studies

			P										S					
	Mean	Median	St. Dev	25th perct	50th perct		75th perct	Max	Min		Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min
Bailundo	49	22.2	56.6	14.1	22.2		72.5	189	0.07		33.6	25.3	25.7	15.6	25.3	39.9	96.6	6.46
Lepi	329	313	98.5	276	313		377	537	159		156	80.6	185	58.7	80.6	168	736	24.9
Mungo	64	31.4	65.5	1.02	31.4		130	155	0.03		42.7	37.8	32.9	13.2	37.8	74.6	101	3.52
Ngongoinga	83.6	6.01	121	0.03	6.01		213	270	0.03		42	37.3	24.6	27.8	37.3	60.6	82.7	11
Talelo	217	179	214	147	179		198	1112	0.02		167	190	74.5	115	190	206	310	0.02
Ramiro	116	92.4	109	46.2	92.4		129	502	0.03		62	58.4	23.9	47.8	58.4	71.5	132	25.2
Funda	521	489	251	457	489		609	1366	0.05		1061	1100	299	1014	1100	1249	1375	0.11
Bom Jesus	1559	1741	544	1007	1741		2032	2257	827		365	281	130	273	281	467	698	268

Cont. Table 5.1: Summary statistics of the mean, median, Standard deviation, minimum, maximum and percentiles of iron, and manganese in all region's studies.

	Fe									Mn							
	Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min		Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min
Bailundo	1704	922	2005	739	922	1296	8882	635		106	99.1	61.1	63.7	99.1	139	205	10
Lepi	45788	59274	24126	15682	59274	63541	69029	12287		195	198	122	85.7	198	295	408	22.8
Mungo	4909	978	6810	646	978	5524	21520	407		115	92.2	126	23.7	92.2	145	502	6.53
Ngongoinga	8569	3298	15906	1883	3298	5837	50583	478		301	231	178	202	231	448	540	2.75
Talelo	48709	54500	19084	37214	54500	60601	81212	0.04		9573	9445	4081	6427	9445	12466	15632	0.04
Ramiro	2320	2258	664	1946	2258	2539	4405	1302		632	637	180	529	637	704	1259	363
Funda	32337	35190	9110	30466	35190	37782	39682	3.63		6016	6131	2060	5542	6131	6798	9738	0.53
Bom Jesus	24052	32925	19432	38.6	32925	38153	47186	35.7		9533	9933	2306	7444	9933	11475	12988	6429

Cont. Table 5.1: Summary statistics of the mean, median, Standard deviation, minimum, maximum and percentiles of zinc, and copper in all region's studies.

		Zn									Cu							
		Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min		Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min
Bailundo		8.2	5.63	7.31	2.39	5.63	11.6	23.2	0.1		3.23	1.66	5.28	0.635	1.66	3.63	21.9	0.03
Lepi		22.3	21.4	8.21	17.4	21.4	28.6	36.9	10		43.9	27.4	73	22.3	27.4	32.7	326	9.51
Mungo		3.74	3.03	2.9	1.15	3.03	5.78	8.72	0.02		4.52	4.21	3.83	1.28	4.21	6.92	12.2	0.02
Ngongoinga		6.9	4.87	6.13	2.57	4.87	13.7	15.8	0.03		6.17	6.37	4.56	3.77	6.37	7.1	16.2	0.52
Talelo		179	153	82.3	130	153	210	353	0.04		37.6	40	17.5	25.2	40	53.3	64.6	0.04
Ramiro		25.9	16.3	39.1	9.8	16.3	22.3	191	1.89		5.66	3.37	7.24	1.61	3.37	6.7	31.1	0.41
Funda		12484	2264	17228	1114	2264	22638	49260	0.1		37.1	38.6	11.2	36	38.6	43.6	50.2	0.04
Bom Jesus		7023	1663	8925	763	1663	11513	27134	687		16577	41.2	22449	28.1	41.2	43764	48744	25.6

Cont. Table 5.1: Summary statistics of the mean, median, Standard deviation, minimum, maximum and percentiles of molybdenum, and aluminium in all region's studies.

	Mo									Al							
	Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min		Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min
Bailundo	0.0317	0.03	0.00786	0.03	0.03	0.04	0.04	0.02		8047	7378	4048	5831	7378	8040	20366	4188
Lepi	0.0265	0.03	0.00493	0.02	0.03	0.03	0.03	0.02		0.0282	0.02	0.0101	0.02	0.02	0.04	0.04	0.02
Mungo	0.0218	0.02	0.00393	0.02	0.02	0.02	0.03	0.02		21384	17646	13322	11228	17646	28404	51993	6691
Ngongoinga	0.03	0.03	0	0.03	0.03	0.03	0.03	0.03		13885	9546	11293	8248	9546	14227	43108	7706
Talelo	9336	11121	4425	5166	11121	12992	14885	0.04		76407	81495	22893	72791	81495	88956	106278	0.03
Ramiro	213	199	67.9	160	199	254	422	94.2		7268	8356	3086	5564	8356	9295	12182	0.02
Funda	7191	7894	4971	4885	7894	8570	25921	0.03		94743	102425	30777	87048	102425	110572	134294	8.64
Bom Jesus	7871	7945	1664	6285	7945	9516	9928	5495		108860	110106	26982	89630	110106	127396	153770	59901

Cont. Table 5.1: Summary statistics of the mean, median, Standard deviation, minimum, maximum and percentiles of pH in all region's studies.

			pH (H_2O)					
	Mean	Median	St. Dev	25th perct	50th perct	75th perct	Max	Min
Bailundo	5.84	6	0.322	5.62	6	6	6.2	5
Lepi	6.09	6.2	0.343	5.7	6.2	6.3	6.5	5.5
Mungo	5.39	5.6	0.718	4.6	5.6	6.1	6.4	4.4
Ngongoinga	6.11	6.3	0.369	5.7	6.3	6.4	6.6	5.6
Talelo	6.72	6.6	0.339	6.5	6.6	6.7	7.6	6.4
Ramiro	6.56	6.5	0.86	5.7	6.5	7.1	8	5.4
Funda	7.01	7	0.136	7	7	7.1	7.2	6.7
Bom Jesus	6.31	6.3	0.163	6.2	6.3	6.35	6.8	6.1

Parent material also acts on the availability of nutrients in the soil (Blackmore, Mentis et al. 1990, Bern, Townsend et al. 2005, Rawlins, McGrath et al. 2012, Augusto, Achat et al. 2017). A study prepared by Towett et al. (2015) reports the importance of the parent material, climate and land management influencing the concentrations of elements in the soils of countries in the Sub-Saharan region. Furthermore, vegetation also plays a substantial role in the nutrient status of soils (Olatunji, Ogunkunle et al. 2007, Towett, Shepherd et al. 2015).

5.3-Mean soil element Status

The studied soils showed a wide range of extractable and total element contents. Table 5.2 shows the mean extractable concentration values of macronutrients and micronutrients and the mean of nitrogen and aluminium content.

N: the mean nitrogen contents in the Mungo and Bom Jesus regions observed higher values than the mean predicted for the Angola region reported by (Hengl, Leenaars et al. 2017).

Ca: the mean concentrations obtained in the Bom Jesus, Funda and Talelo sites were higher than those for the Sub-Saharan Africa region in the study by (Towett, Shepherd et al. 2015) and, the predicted mean values for the Angola region (Table 5.2).

K: the mean values of potassium from this study exceed the mean values reported by Towett, 2015 and Hengl, 2017 comparative authors presented in this work (Table 5.2).

Mg: only the mean values of Bailundo, Ngongoinga and Lepi sites are within the predicted mean ranges for the same zone of Africa reported by (Hengl, Leenaars et al. 2017), while for the other sites, Mungo, Bom Jesus, Talelo and Ramiro showed mean values of Mg that are higher than those reported for Angola by the same author.

P: except for Bailundo and Funda site, which present mean values of phosphorus concentration higher than those mentioned in study for Angola by (Hengl, Leenaars et al. 2017), other localities - Ngongoinga, Mungo, Lepi, Talelo and Ramiro - showed mean concentration values of phosphorus below those reported by the previous author. On the other hand, the study made by Towett (2015) showed mean P values higher than those observed in this work in Bailundo, Ngongoinga and Lepi sites but lower than those in the Mungo, Bom Jesus, Talelo and Ramiro sites.

Fe: the mean Fe contents observed in this study were higher than the predicted values for the Angola region (Table 5.2) in all soils the subject of this work. In another comparative study (Towett et al., 2015), the mean values of iron were higher than the mean Fe concentration in Mungo and Talelo sites.

Mn: this element showed mean values that exceed those predicted for this area of Africa Hengl, (2017) in all sites of this work except for the Bailundo site.

Zn: Talelo, Bom Jesus and Funda observed mean values of zinc concentration higher than mean worldwide values reported by Kabata-Pendias and Mukherejee, (2007), while in Bailundo, NGongoinga, Lepi and Ramiro the average contents are below than those of the same author. On the other hand, are higher than the mean predicted by (Hengl, Leenaars et al. 2017).

Cu: Bom Jesus, Funda, Mungo and Talelo showed mean values of cupper higher than the average of all other comparative studies of this thesis (Table 5.2), while in the Bailundo, Mungo, Ngongoinga and Lepi the mean of Cu concentration found are lower than the mean reported for Sub-Saharan Africa region (Towett et al., 2017).

Mo: the mean value for this element is much lower than presented by Kabata-Pendias and Mukherejee (2007) in Bailundo, Ngongoinga, Mungo and Lepi sites (Mo values were below the analytical detection limit in these areas). By contrast, the soils in Bom Jesus, Funda, Talelo and Ramiro presented mean Mo concentration that exceed those reported by the same author.

Al: the mean of aluminium concentration exceeds the mean reported by all comparative studies in this work (Table 5.2).

Overall, having the study of Towett (2015) as a reference, (this study reporting findings of nutrients from the Sub-Saharan African region), our findings in two provinces (Luanda and Huambo) presented results with high and low contents (Table 5.2). Ramiro site (Luanda province) showed low contents in terms of macro- and micronutrients, except for Al and Mn. For the remaining localities, high contents of macronutrients (P, K and Ca) were found in the Lepi, Bom Jesus, Funda and Talelo sites. By contrary, micronutrients (Fe, Mn, Zn and Cu) in the soils of all localities of the Huambo province presented contents below the reference (Towett, 2015), while those of the Luanda province showed values above the reference. Aluminium (Al) in both provinces observed contents above the reference.

Table 5. 2**:** Mean values of the total element concentrations (ppm) from soils studied here, and published concentrations (and ranges) of element contents in Africa and in world soils.

Element	**Bailundo**	**Ngongoinga**	**Mungo**	**Lepi**	**Bom Jesus**	**Funda**	**Talelo**	**Ramiro**	**A**	**B**	**C**	**D**
	ppm											
N	463	449	1008	1245	4386	640	501	36.7	-	-	-	981
Ca	653	925	7674	1112	19865	79236	2651	209	9600	-	9780	330-1820
K	327	386	450	570	13275	9223	14678	970	16	-	10893	62-180
Mg	127	170	121	340	7062	7231	9388	214	-	-	-	60-170
P	49	83.6	64	329	1559	521	217	116	900	-	143	480
S	33.6	42	42.7	156	365	1061	167	62	-	-	-	-
Fe	1704	8569	4909	45788	24052	32337	48709	2320	57	0.57	27954	120-200
Mn	106	301	115	195	9533	6016	9573	632	1400	437	466	117
Zn	8.2	6.9	3.74	22.3	7023	12484	179	25.9		64	29	5
Cu	3.23	6.17	4.52	43.9	16577	37.1	37.6	5.66	--	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	78.4	(1-4) %	33.927	900-998

A: Towett et al., (2013); B: worldwide mean contents by Kabata-Pendias and Mukherjee (2007); C: Sub-Saharan Africa mean contents by Towett et al (2015); D: soil nutrient maps of Sub-Saharan Africa by Hengl et al (2017).

5.3.1-Nutrient & sites

All elements showed a statistically significant difference in relation to the sites. For nitrogen (N) there was a statistically significant difference in sites with $p < 0.001$ (Table 5.3). The highest contents are obviously in the regions of Bom Jesus (Figure 5.1). The comparison among sites and N (Appendix 5) showed a statistically significant difference between Bailundo and Bom Jesus with $p < 0.001$. Moreover, Bom Jesus and Funda, Lepi, Mungo, NGongoinga, Ramiro and Talelo all with $p < 0.001$.

The macronutrients all revealed a statistically significant difference related to site, with $p < 0.001$ (Table 5.3). Thus, Ca showed the highest value in the Funda and Bom Jesus sites (Figure 5.1). The comparison among the locations showed a significant difference between Bailundo and Funda with $p < 0.001$. Moreover, Bom Jesus and Funda with $p < 0.001$, while the difference between Bom Jesus and Ramiro significant at $p= 0.02$ (Appendix 5.10). In addition, there was a statistically significant difference among Funda and the sites Lepi, Mungo, NGongoinga, Ramiro and Talelo, with $p < 0.001$ (Appendix 5.10).

Potassium (K) observed a high value in the regions of Bom Jesus, Funda and Talelo (Figure 5.1). The comparison among the locations showed that there is a statistically significant difference between Bailundo and regions Lepi, Mungo, NGongoinga and Ramiro, all showing $p < 0.001$. Moreover, the pairwise comparisons for the following were all significant at $p < 0.001$: Mungo and Talelo, NGongoinga and Talelo, Lepi and Talelo, Mungo and Talelo, Ngongoinga and Talelo, and Ramiro and Talelo (Appendix 5.11).

For magnesium (Mg), the highest concentrations were found in the sites of Bom Jesus and Talelo (Figure 5.1). The comparison among the regions showed that there is a statistically significant difference among the sites Bailundo and Bom Jesus, and Bailundo and Funda, with $p < 0.001$. Furthermore, a statistically significant difference was verified among the regions Bom Jesus and Lepi, Mungo, Ngongoinga and Ramiro with $p < 0.001$ (Appendix 5.12). In addition, between the regions of Funda and Lepi, Mungo, Ngongoinga and Ramiro presenting a statistically significant difference $p < 0.001$ (Appendix 5.12). Lepi and Talelo with $p < 0.001$; and between Mungo and Talelo, Ngongoinga and Talelo, Ramiro and Talelo, all with $p < 0.001$ (Appendix 5.12).

Phosphorus (P) showed the highest value in the regions of Bom Jesus, Funda and Mungo (Figure 5.2). The comparison among sites there was a statistically significant difference among Bailundo and Bom Jesus regions, with $p < 0.001$, while between Bom Jesus and Funda, Lepi, NGongoinga, Ramiro and Talelo regions these pairwise comparisons were also significant with $p < 0.001$ (Appendix 5.13). Moreover, comparisons between Funda and Lepi, and Funda and Talelo were significant at $p< 0.002$, while Funda and NGongoinga, and Funda and Ramiro were significant at $p < 0.001$ (Appendix 5.13). The comparison between Mungo and Ngongoinga was significant at $p = 0.02$.

Sulphur (S) presented highest values in the localities of Funda and Bom Jesus (Figure 5.2). The comparison among sites showed a statistically significant difference between Bailundo and Bom Jesus and Bailundo and Lepi with $p < 0.001$ (Appendix 5.14). In addition, among the sites of BJ and Lepi, Funda, Mungo, Ngongoinga, Ramiro and Talelo all with $p < 0.001$ (Appendix 5.14). Similarly, a statistically significant difference was observed among the regions of Funda and Lepi, Mungo, Ngongoinga, Ramiro and Talelo with $p < 0.001$ (Appendix 5.14).

Table 5. 3: Comparison between elements within sites, profiles, and depths attention to p value for elements, put in italics when p <0.05-Luanda

	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*

	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

	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

	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*

	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

	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*

	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*

	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

	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*

	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*

Cont. table 5.3: Comparison between elements within sites, profiles, and depths attention to p value for elements, put in italics when p <0.05-Luanda

	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*

Like macronutrients, there were statistically significant differences between sites in the micronutrients (Table 5.3 and 5.4). Thus, Iron (Fe) observed higher values in the Funda, Mungo and Talelo regions (Figure 5.2) (5.1). The comparison between sites shows that there is, a statistically significant difference among Bailundo and the regions of BJ, Funda, Mungo and Talelo (p <0.001) (Appendix 5.15). Moreover, between the sites of Bom Jesus and Mungo, Ramiro and Talelo shows that there is a statistically significant difference (p <0.001) (Appendix 3.15). Similarly, between the regions of Funda and Ngongoinga, and Funda and Ramiro (p < 0.001), observed a statistically significant difference, while the pairwise comparison between Funda and Talelo was significant at p = 0.005 (Appendix 5.15). Lepi and Talelo, Mungo and Ramiro, and Mungo and Ngongoinga were all significantly different in pairwise comparisons (p < 0.001).

Manganese (Mn) presented the highest values in Bom Jesus, Funda and Talelo (Figure 5.2). Comparatively, the regions showed a statistically significant difference among Bailundo and

BJ, and Bailundo and Funda with p < 0.001 (Appendix 5.16). Similarly, among BJ and Funda, Lepi, Mungo, Ngongoinga and Ramiro all presenting p < 0.001 (Appendix 3.16). In addition, Mungo and Talelo, Ngongoinga and Talelo, and Ramiro and Talelo were all significant pairwise comparisons (p < 0.001) (Appendix 5.16).

Zinc (Zn) showed higher value in the localities of Bom Jesus and Funda (Figure 5.3). The comparison among sites showed a statistically significant difference between the regions of Bailundo and Funda (p < 0.001) (Appendix 5.17), Bom Jesus and Ramiro (p = 0.0033), and Funda and Lepi (p = 0.004) while, Funda and Mungo, Ngongoinga, Ramiro and Talelo were all significant pairwise comparisons (p < 0.001) (Appendix 5.17).

For copper (Cu), the highest values were in the site of Bom Jesus (Figure 5.3). The comparison between sites observed a statistically significant difference in the regions of Bailundo and Bom Jesus (p <0.001). In addition, Bom Jesus was statistically significantly different from the regions of Funda, Lepi, Mungo, Ngongoinga, Ramiro and Talelo (p < 0.001) (Appendix 5.18).

For molybdenum (Mo) the highest values were found in the sites of BJ, Funda and Talelo (Figure 5.3). Comparatively, the sites show a statistically significant difference among the areas of Bailundo and BJ, Bailundo and Funda (p < 0.001). Moreover, among Funda and the sites of Lepi, Mungo, Ngongoinga and Ramiro (p < 0.001), Lepi and Talelo (p <0.001), NGongoinga and Talelo and Ramiro and Talelo all with p < 0.001 (Appendix 5.19).

Aluminium (Al) showed high values in the localities of Bom Jesus, Funda and Talelo (Figure 5.3). Comparatively, the regions show a statistically significant difference between Bailundo and BJ, Bailundo and Funda (p <0.001) and Bailundo and Talelo (p < 0.001). In addition, comparisons among Bom Jesus and the sites of Lepi, Mungo, Ngongoinga, Ramiro and Talelo were all significant at p < 0.001. Lepi and Talelo were significantly different at p <

0.001. Similarly, Funda and Lepi, Mungo, Ngongoinga and Ramiro were all significant at $p < 0.001$, while Funda and Talelo were significant at $p = 0.043$. Moreover, the following pairwise comparisons were all significant: Lepi and Talelo ($p < 0.001$), Mungo and Ngongoinga ($p = 0.029$), Mungo and Talelo ($p < 0.001$), Ngongoinga and Talelo and Ramiro and Talelo ($p < 0.001$) (Appendix 5.20).

Table 5. 4: Comparison between elements within sites, profiles, and depths attention to p value for elements, put in italics when p <0.05-Huambo

	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

Cont. Table 5.4: Comparison between elements within sites, profiles, and depths attention to p value for elements, put in italics when p < 0.05-Huambo

	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***

H1: Bailundo, H2: Mungo; H3: NGongoinga; H4: Lepi; L1: Talelo; L2: Ramiro; L3: Funda; L4: Bom Jesus

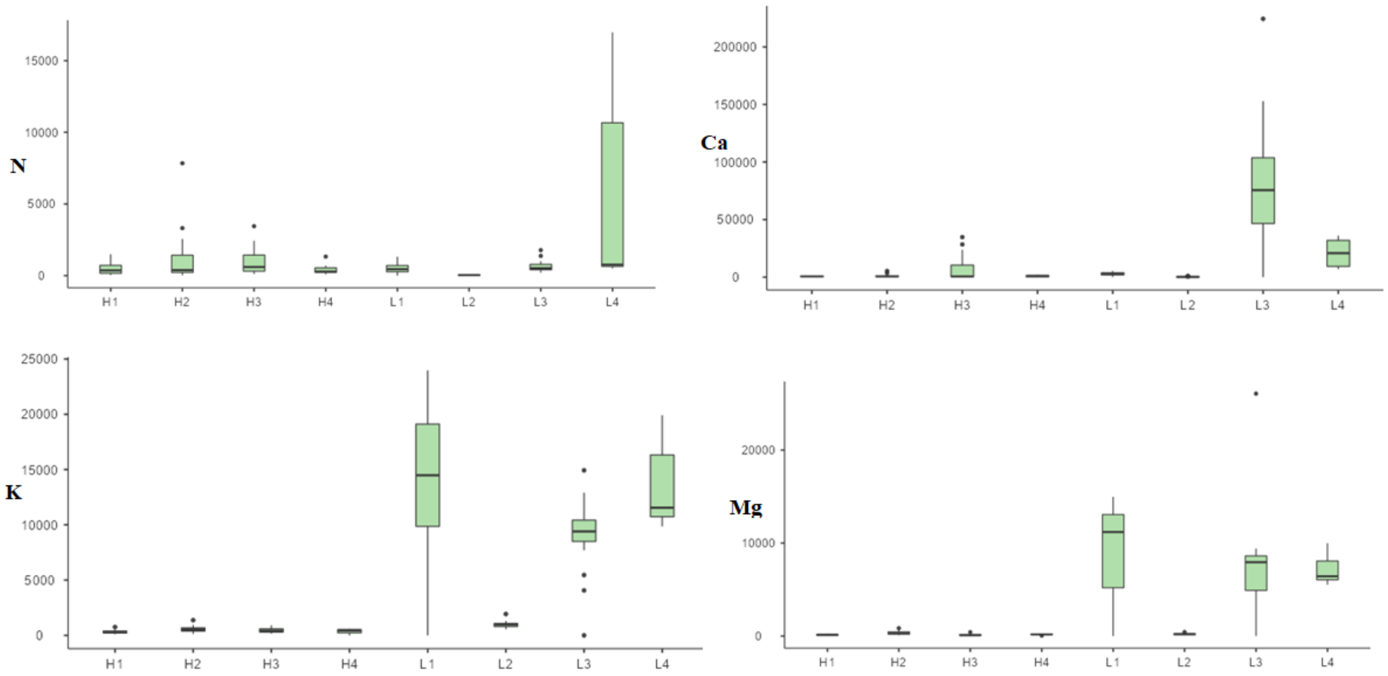


Figure 5. 1: Box plots of variation of nutrient concentration among the soils of the studied regions, potassium (K), magnesium (Mg), calcium (Ca), phosphorus (P). (see Appendix 5.1)

H1: Bailundo, H2: Mungo, H3: Ngongoinga, H4: Lepi, L1: Talelo, L2: Ramiro, L3: Funda and L4: Bom Jesus

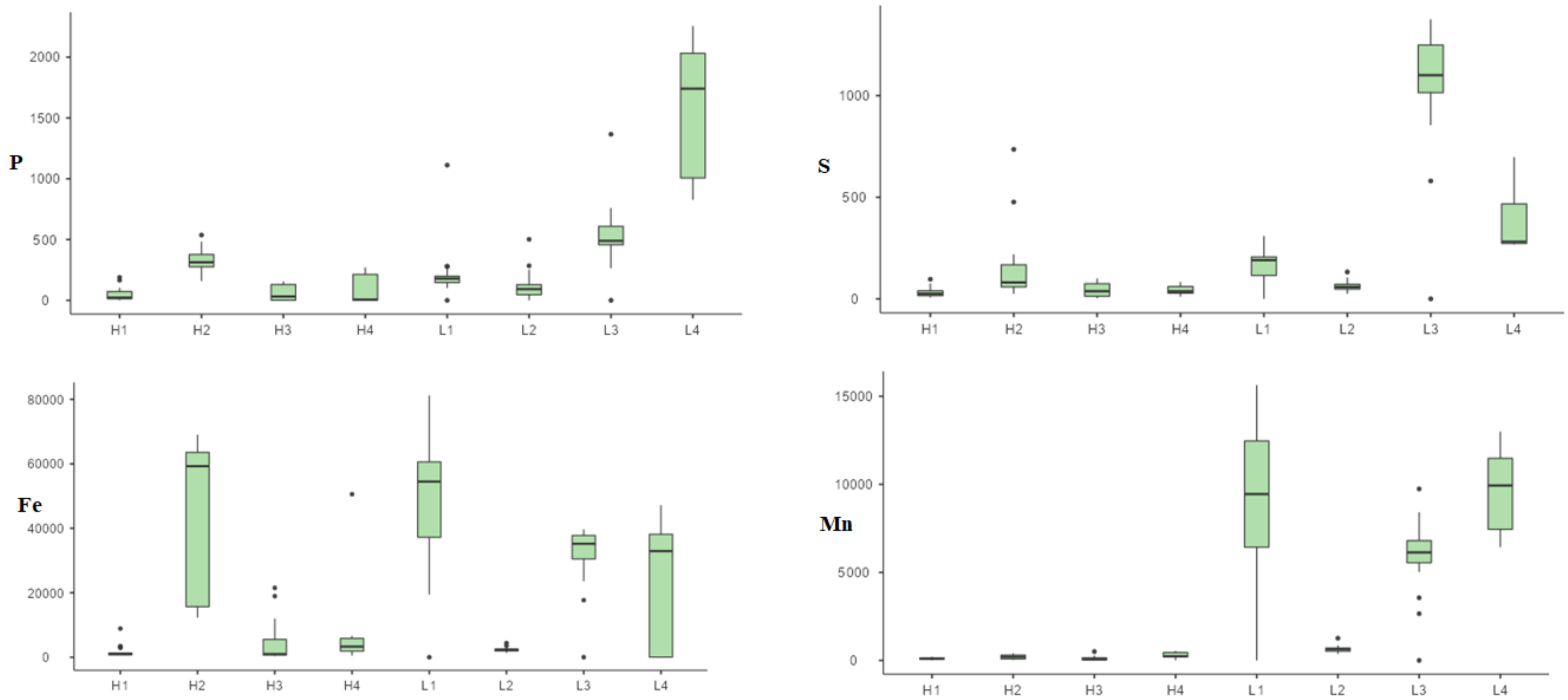


Figure 5. 2: Box plots of variation of nutrient concentration among the soils of the studied regions, phosphorus (P), Sulphur (S), Iron (Fe) and Manganese (Mn) (see Appendix 5.1)

H1: Bailundo, H2: Mungo, H3: Ngongoinga, H4: Lepi, L1: Talelo, L2: Ramiro, L3: Funda and L4: Bom Jesus

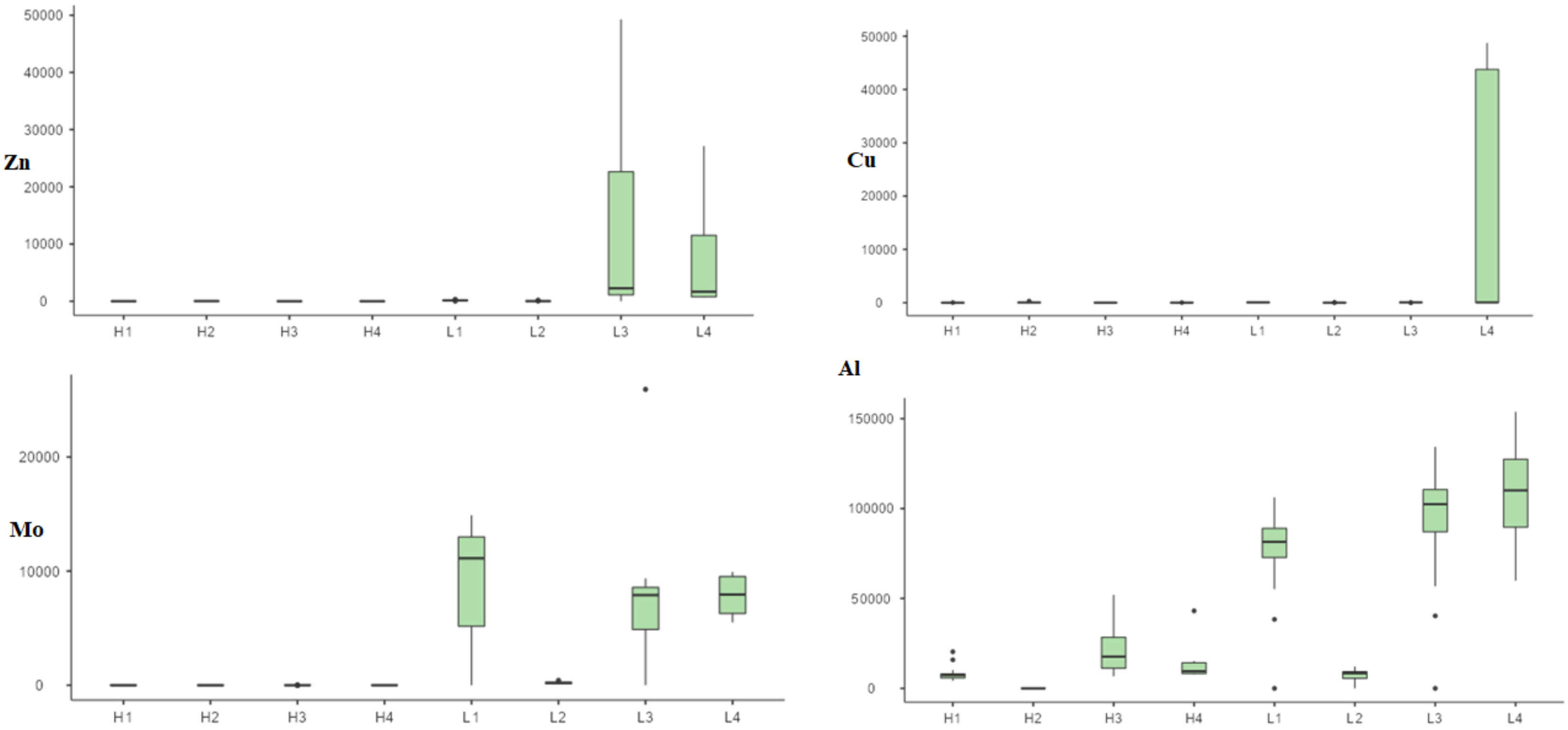


Figure 5. 3: Box plots of variation of nutrient concentration among the soils of the studied regions, Zinc9Zn), Copper (Cu), Molybdenum (Mo) and Aluminium (Al) (see Appendix 5.1)

H1: Bailundo, H2: Mungo, H3: Ngongoinga, H4: Lepi, L1: Talelo, L2: Ramiro, L3: Funda and L4: Bom Jesus

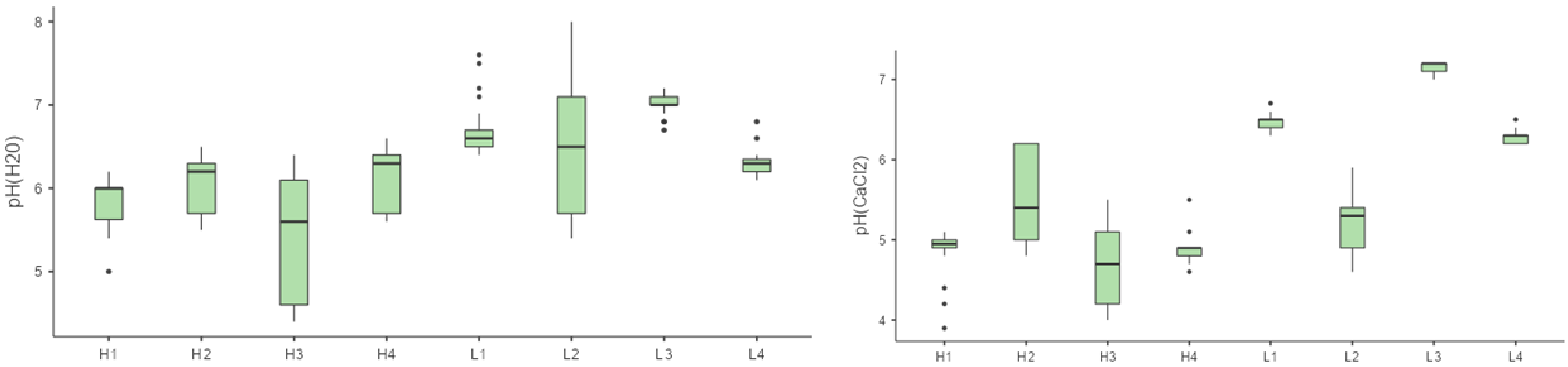


Figure 5. 4: Box plots of variation of nutrient concentration among the soils of the studied regions, pH (H_2O) AND pH ($CaCl_2$) (see Appendix 5.1)

5.3.2-Nutrients & hill-slope position (profile)

Most elements showed a statistically significant difference in relation to hill-slope position. For nitrogen (N) there was a statistically significant difference among N and profile ($p < 0.001$) (Table 5.3) in both provinces. Although the values are slightly similar in the profiles, it was found to be slightly higher in the mid hillslope (Huambo) and upper hill-slope position (Luanda) (Figure 5.6) The comparative analysis among the positions in hillslope showed that there is a statistically significant difference in N between upper- and mid-profiles ($p = 0.015$) and between upper- and low-profiles ($p = 0.016$) (Appendix 5.25).

The analysis of macronutrients revealed that, Mg, S showed a statistically significant difference in relation to the hill-slope position (profile). Magnesium (Mg) observed a statistically significant difference in profile ($p = 0.007$) (Table 5.3) in Luanda. The mean concentration of this macronutrient was higher in the mid profile (Figure 5.9).

There was a statistically significant difference among hillslope profile for S ($p = 0.003$) (Table 5.3) in Luanda. Its highest value was observed in the low profile (Figure 5.11).

In the analysis of micronutrients, two elements presented a significant difference in the hillslope profile: Fe (both provinces) (Table 5.3 and 5.4 respectively). Iron (Fe) observed a statistically significant difference with $p = 0.001$ in Luanda (Table 5.3) and $p<0.001$ in Huambo (Table 5.4). The highest value was in the mid profile (Figure 5.12).

Manganese (Mn) no significant differences were observed in the profile for manganese in both provinces

pH (H_2O) observed a statistically significant difference at contrasting positions along the hillslope profile ($p < 0.001$) (Table 5.3 and 5.4) in both provinces. The highest value was in the upper profile of the hillslope in Luanda (Figure 5.18). The comparison in hillslope profiles presented a statistically significant difference between profiles upper-mid ($p = 0.04$), upper-low ($p < 0.002$) and mid-low ($p = 0.026$) (Appendix 5.37).

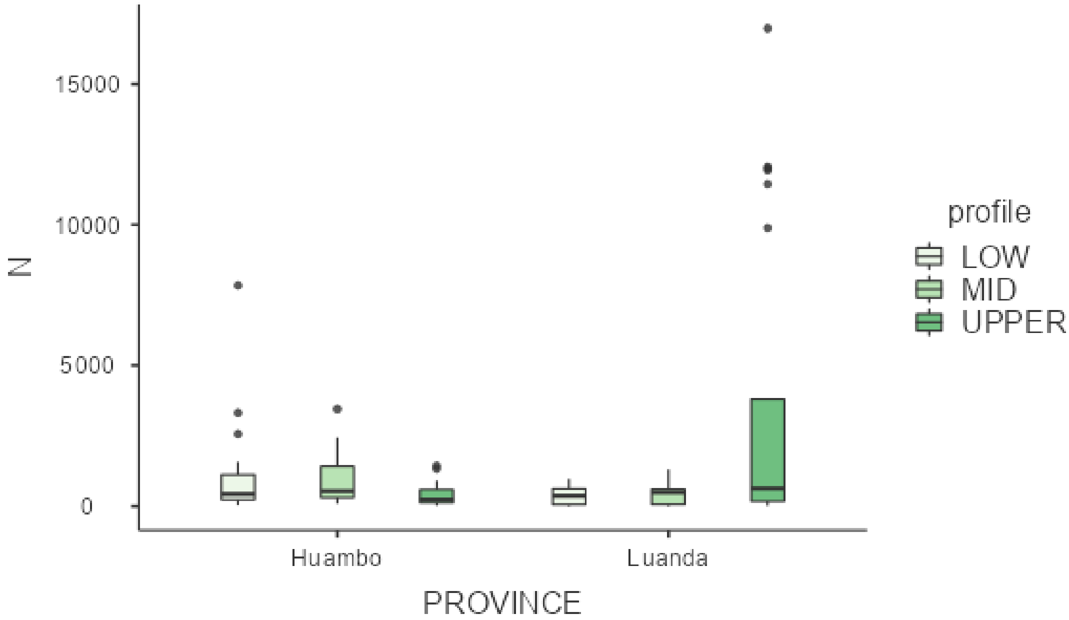


Figure 5. 5: Boxplots of nutrient concentration along hillslope profile: nitrogen (N)

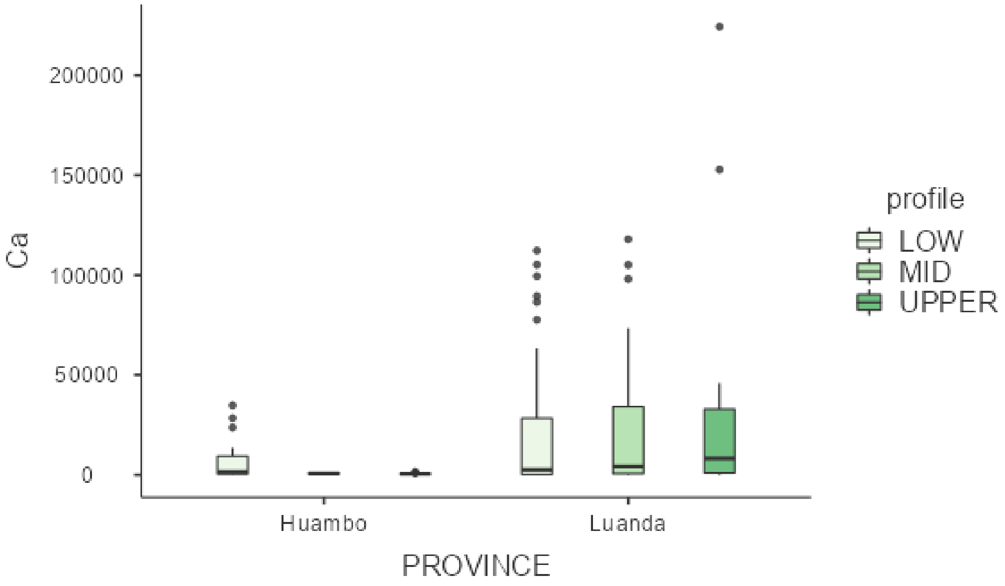


Figure 5. 6: Boxplots of nutrient concentration along hillslope profile: calcium (Ca)

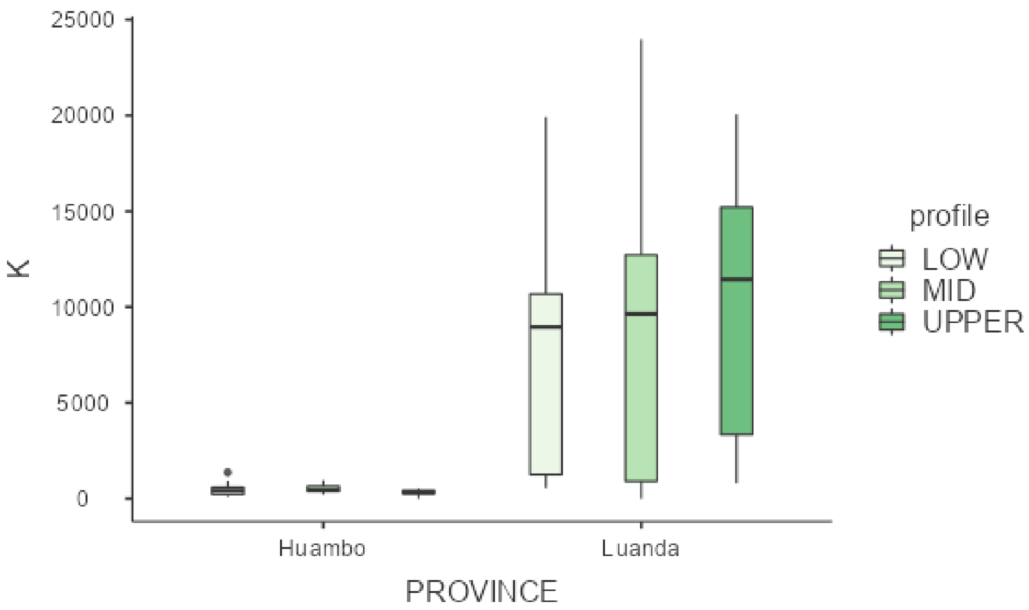


Figure 5. 7: Boxplots of nutrient concentration along hillslope profile: potassium (K)

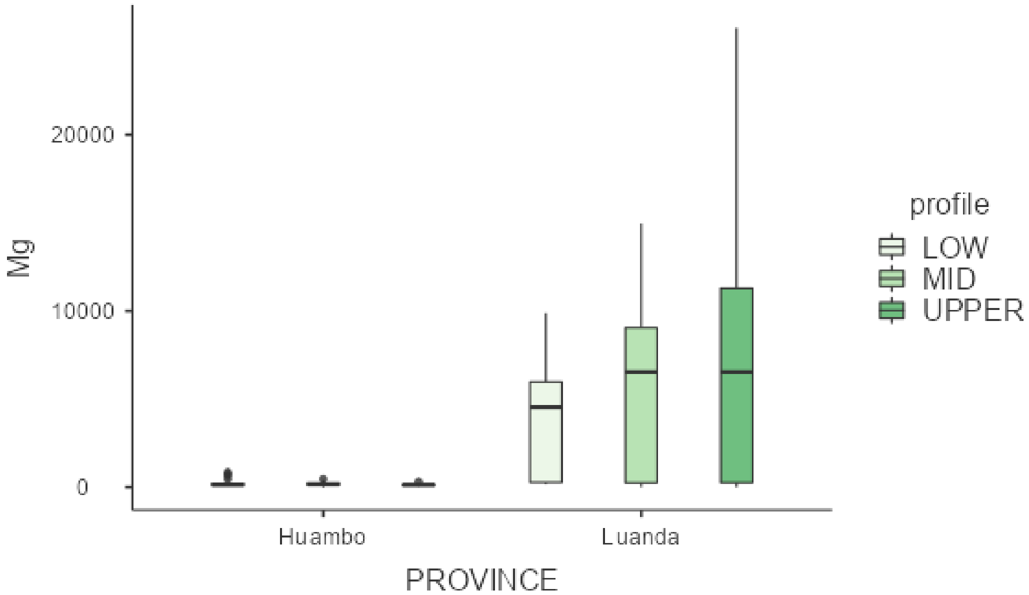


Figure 5. 8: Boxplots of nutrient concentration along hillslope profile: magnesium (Mg)

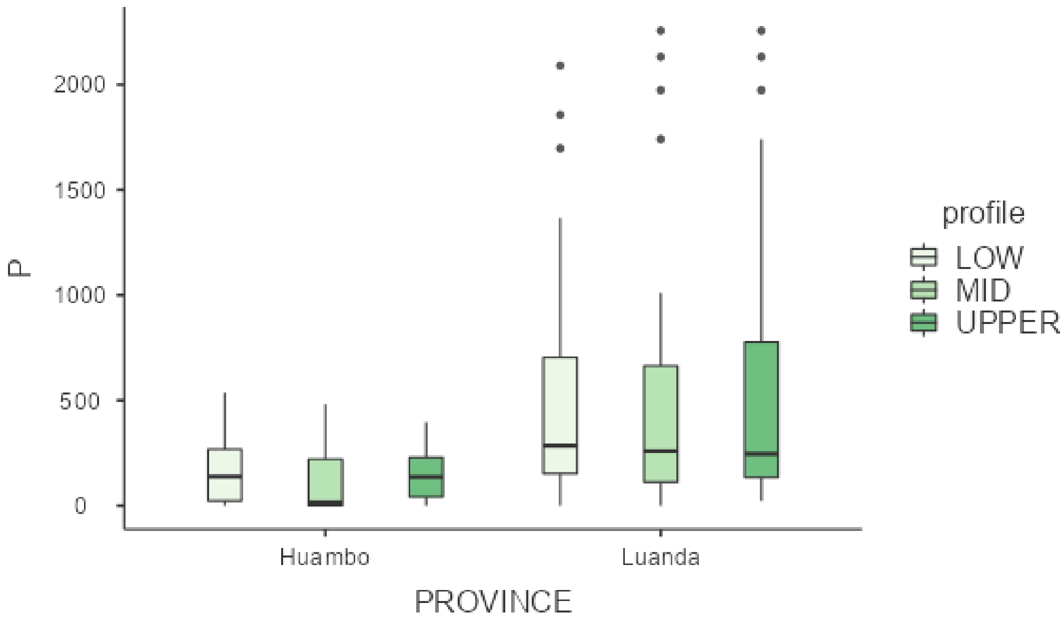


Figure 5. 9: Boxplots of nutrient concentration along hillslope profile: phosphorus (P)

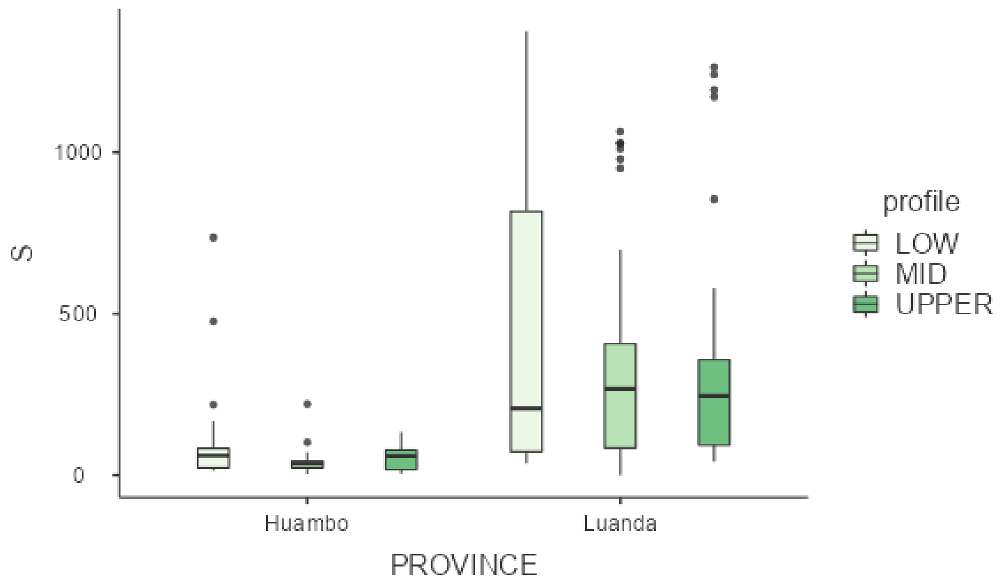


Figure 5. 10: Boxplots of nutrient concentration along hillslope profile: sulphur (S)

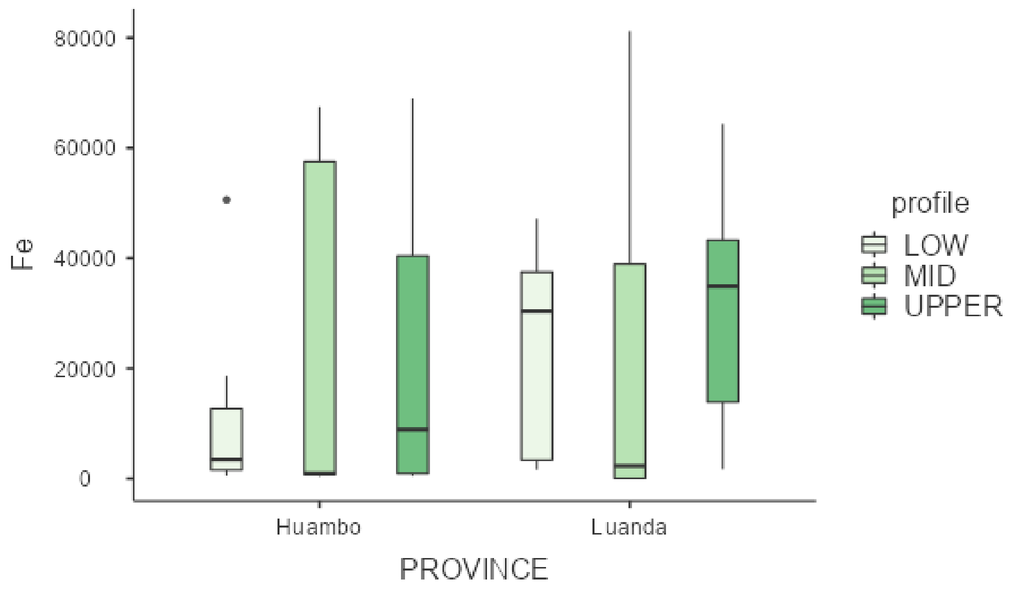


Figure 5. 11: Boxplots of nutrient concentration along hillslope profile: iron (Fe)

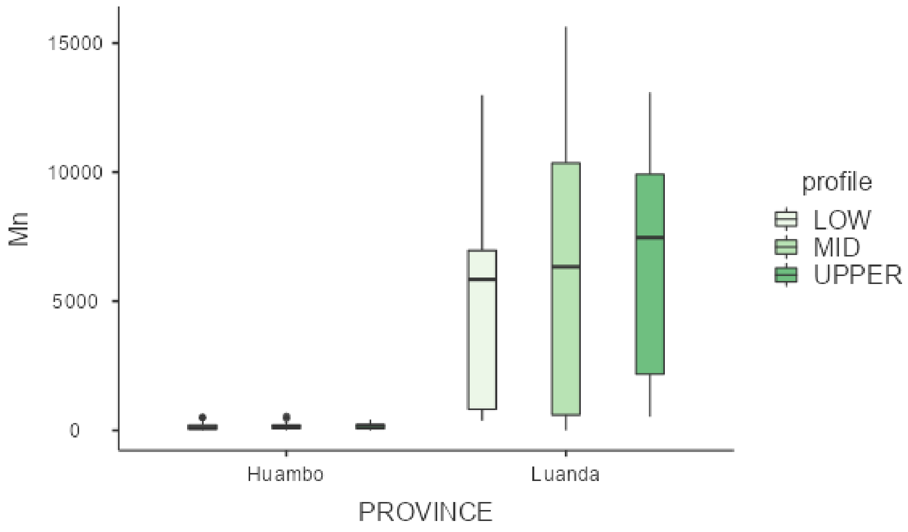


Figure 5. 12: Boxplots of nutrient concentration along hillslope profile: manganese (Mn)

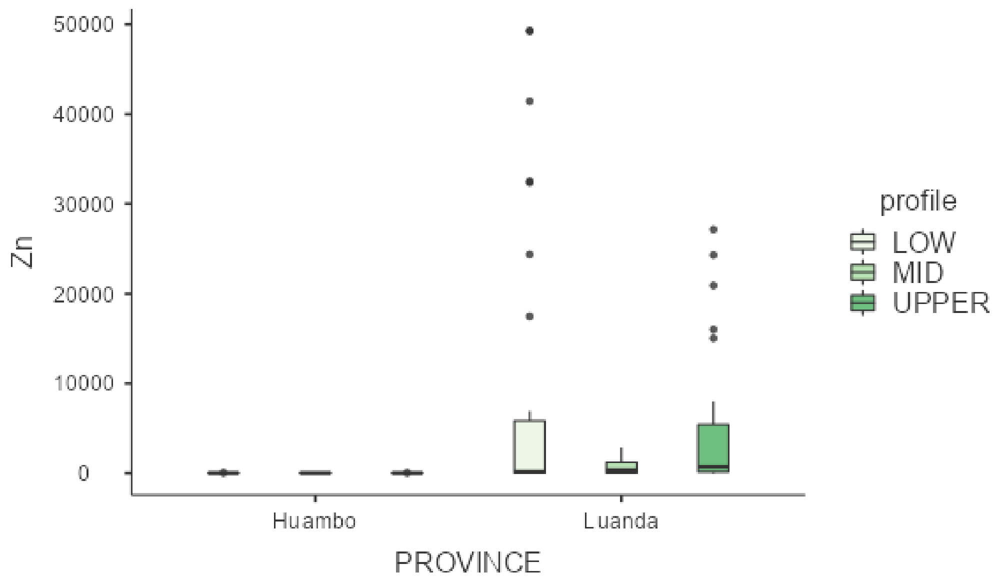


Figure 5. 13: Boxplots of nutrient concentration along hillslope profile: zinc (Zn)

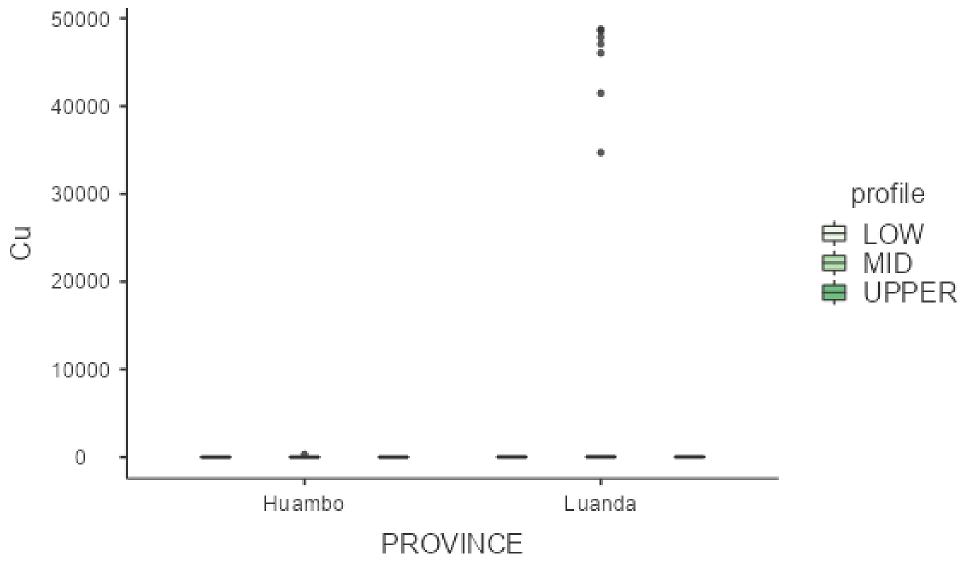


Figure 5. 14: Boxplots of nutrient concentration along hillslope profile: copper (Cu)

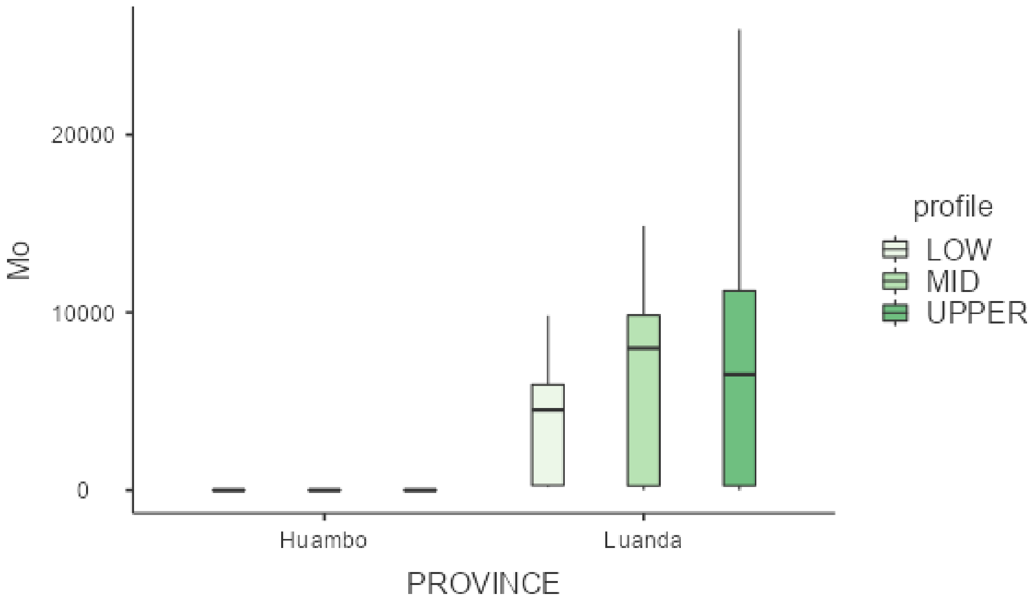


Figure 5. 15: Boxplots of nutrient concentration along hillslope profile: molybdenum (Mo)

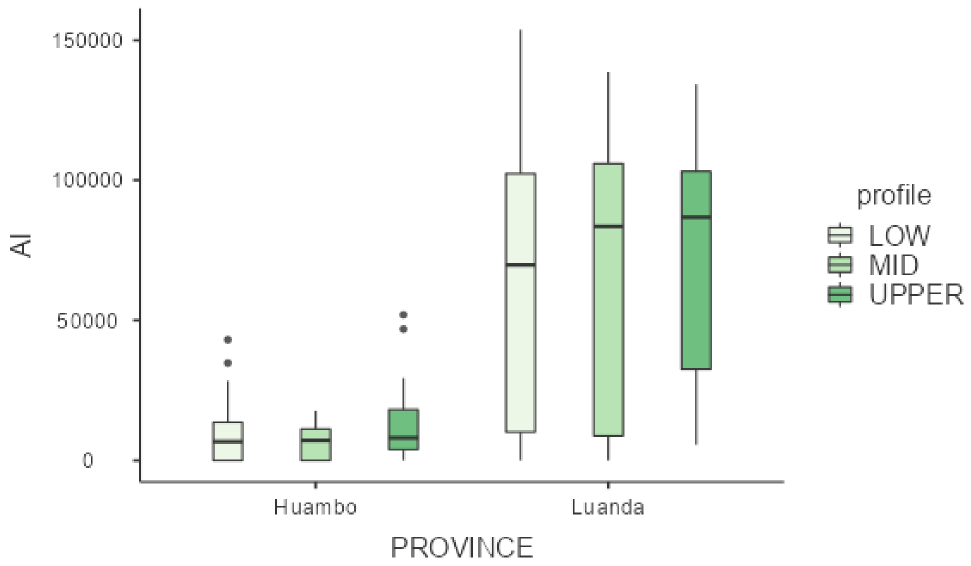


Figure 5. 16: Boxplots of nutrient concentration along hillslope profile: aluminium (Al)

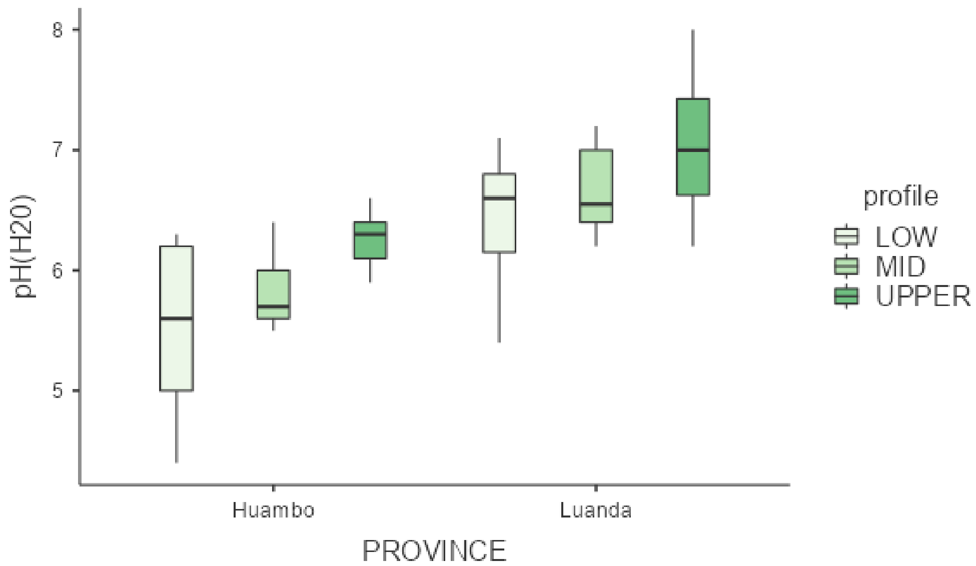


Figure 5. 17: Boxplots of nutrient concentration along hillslope profile: pH (H_2O)

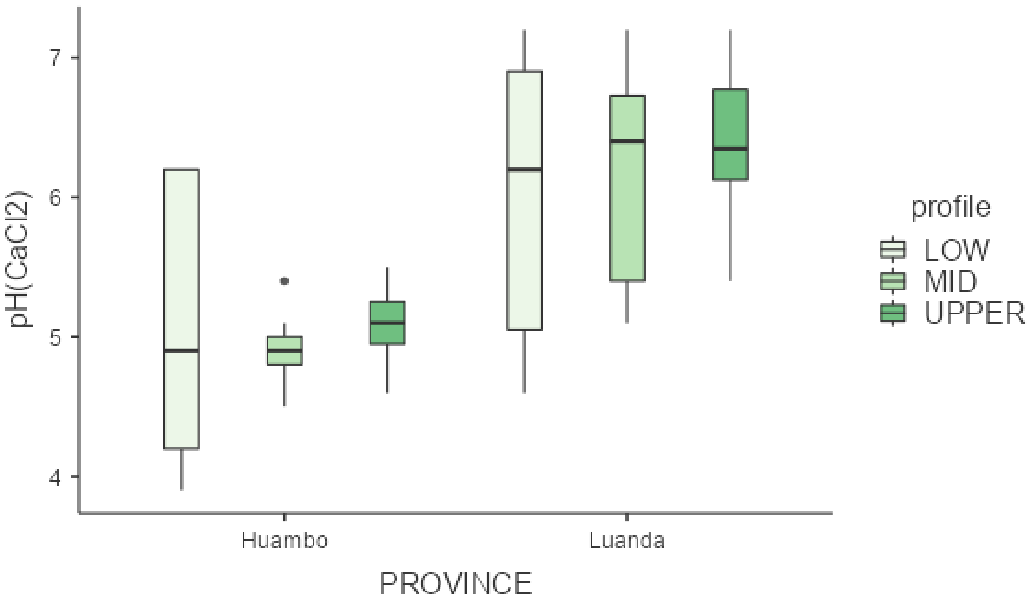


Figure 5. 18: Boxplots of nutrient concentration along hillslope profile: pH ($CaCl_2$)

5.3.3-NPK Relationship within profiles

Huambo

No significant correlations were observed between the NPK elements in Huambo province, except for one locality (Figure 5.20). As observed in the table below, in the Mungo region, a significant positive and strong correlation was observed among nitrogen and potassium (r=0.603) similarly, there was a significant positive and strong correlation between phosphorus and nitrogen elements (r=0.706).

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

Figure 5. 19: relationship between NPK elements- Huambo province

Luanda

In Luanda province only a significant correlation was verified in the Talelo site. Thus, the significant positive and strong correlation between nitrogen and potassium (r=0.721) (Figure 5.20). In Soils of the remaining localities (Ramiro, Bom Jesus and Funda), there were no significant correlations among NPK.

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

Figure 5. 20: relationship between NPK elements- Luanda province

The correlation among NPK elements maybe due to natural soil conditions. Studies show that depending on the type, climatic, conditions and other factors, soils often lack nitrogen and phosphorus in greater amount and potassium in lesser degree (Bojovic and Marckovic, 2009). The same authors state that it also may be due to fertilization, since soils where agriculture is more intensive, substantial amounts of N and P derived from mineral fertilization are used.

5.4-Chemical composition in soils and its variation within profile and across catena

The results of the analysis of the chemical composition (macronutrients and micronutrients, pH, CEC, Base saturation) in the soils analysed in Luanda and Huambo regions are shown in the tables below. In general, there was wide variation in the value of concentration in all regions between macronutrients (calcium-Ca; potassium-K; magnesium-Mg; phosphorous-P; sulphur-S) and micronutrients (copper-Cu; iron-Fe; manganese-Mn; molybdenum-Mo; zinc-Zn). The other elements, presented as content are nitrogen- N and carbon-C, Aluminium-Al, pH, CEC, and base saturation.

Huambo

The chemical results of the soils in Huambo provinces are presented in Appendix 5.1, 5.2, 5.3, and 5.4. Nitrogen and carbon show a decreasing trend from top to bottom on the profile, while in the catena these elements do not show a pattern.

Macronutrients: calcium, potassium, magnesium and phosphorous presented a decreasing trend from top to bottom on the profile, while in the catena there was no pattern. Sulphur shows a decreasing trend from top on the profile in most soils analysed in this province.

Micronutrients: it was observed that iron does not show a pattern except for Bailundo where the concentrations tend to decrease down the profile. Manganese, zinc, and copper showed a decreasing trend in their concentration from top to bottom on the profile, while in the catena the concentrations were very variable. Aluminium concentration showed no pattern, neither down the profile nor the catena.

The pH values are acidic ranging from weakly acidic (6.1) to strongly acidic (4.0)

Luanda

It was observed (Appendix 5.5, 5.6, 5.7, and 5.8) that nitrogen tends to decrease down profile, from top to bottom, while in the catena it does not show a pattern. Carbon presents variable concentrations along the profile and catena.

Macronutrients: It was found that the elements calcium and potassium have oscillating values along the profile and in the catena. Magnesium, phosphorus, and sulphur tend to increase their concentration from top to the bottom on the profile and, the same was observed in the catena.

Micronutrients: the elements iron, zinc, and copper show an increasing trend from top to bottom on the profile, and similar behaviour along the catena. On the contrary, aluminium did not show a pattern, its concentrations were oscillating on the profile and catena.

The pH values range from weakly acidic (6) to alkaline (8).

5.5-Discussion

The results of the two provinces showed different nutrient status in a wide range of concentration. This fact leads us to question whether some of the regions are more suitable for agriculture or, in other words, which soil will be better for such activity. There are many opinions about what constitutes an ideal soil for agriculture. For some it will be a soil that must produce food is a sustainable way, and for others it would be that must maintain and improve human health, be self-sufficient and regenerative, and produce enough food to a growing world population (Higa and Parr 1994). On the other hand, soil health depends on complex biophysical and biochemical processes that interact in space and time (Abbott and Manning 2015). The same author also mentions that microorganisms and soil fauna participate, in the short or long term, in the transformation of geological minerals and release of essential nutrients for plant growth. Furthermore, the nutritional status of elements in soils is related to several factors. According to a study by (Solomon, Lehmann et al. 2016) native soil management practices can transform infertile, carbon-poor, humid tropical soils into durable, fertile, rich and productive soils that can support agriculture ecologically and in a socially sustainable way.

The nutrient status of the target soils of this study are like those typical of tropical soils. The ferralsols have high level of iron and aluminium oxides; hence the high contents of these elements present in the soils of these regions.

On the other hand, the findings of this study are at odds with some studies of the nutritional status of African soils, which show high rates of nutrients depletion resulting from high population density, continuous cultivation, rugged and mountainous terrain, (Bekunda, Nkonya et al. 2002). For the element nitrogen, the results of this work show values were highly variable, ranging from 36.7 to 4386 ppm, although this brackets the value given for Asian tropical soils (0.13 g/kg, or 130 ppm) in a study carried out by Kawaguchi and Kyuma (1997) cited by

(Yanai, Omoto et al. 2014).

Chapter 6: Discussion

This chapter will first discuss the results presented in the chapters related to physical and nutrient status. Next, the limitations we faced in this study will be identified and considered.

6.1-Discussion

6.1.1-Relationship among land management and nutrient status

As previously described in Chapter 2, this study synthesized quantitative and qualitative signals of land management by farmers in the regions studied in Huambo province. Land use leads to soil alteration which can lead to loss of nutrients and changes soil proprieties (Smith, House et al. 2016). The results of survey revealed that land management is almost rudimentary, mostly done manually and its outputs are mainly for subsistence. Mineral fertilization is the most common (NPK) compared to organic (manure, compost) of the former, however, over 60% of farmers use less than 350 kg/ha of fertilizer.

6.1.2-Relationship among soil textural classes and nutrient status

Vegetation cover and both slope angle and shape (e.g., convex, concave) can provide some indication of the potential for erosion. The presence of vegetation is important in wind erosion as it reduces the wind speed at the soil surface. Several studies have reported a positive effect of vegetation on reducing soil erosion (Sterk 2003, Nunes, De Almeida et al. 2011, Guuroh, Ruppert et al. 2018). Reitkerk cited by Guuroh (2018) in study a conducted in African savannas reported that perennial plants are fundamental in controlling erosion due to reduced runoff. Another study mentions that areas with dense vegetation cover have lower denudation rates compared to those with lower values of vegetation cover (Acosta, Schildgen et al. 2015). In addition, woody vegetation, although it can negatively affect crop yields, has positive effects in protecting fields against wind erosion (Sinare and Gordon 2015).

The textural results of the analysed soils reveal that they are mostly silt loam and silt clay loam. Particles size ranging from (0.10-0.25) mm was shown to be most susceptible to erosion. By contrast particles less than 0.05 mm were least erosive; thus, finer fractions of eroded soil were found to comprise higher values of organic matter, N, P and K (Gupta, Aggarwal et al. 1981). Clay and silt particles show relative erosion resistance as a result of their relative adhesion strengths compared to sand particles which are more easily removed (Langston and Neuman 2005, Shahabinejad, Mahmoodabadi et al. 2019). Moreover, clay particles bring greater resistance to wind erosion (Zamani and Mahmoodabadi 2013). The same authors stated that soils with a high sand content tend to be more susceptible to wind shedding. On the other hand, Toy et al. (2002) cited by Parwada (2017) states that soils with a higher proportion of sand and silt than clay in the surface layer promote surface runoff and, therefore are erodible. The exception was Ramiro site that its textural class is sand. This difference could result from the fact that Ramiro geographically is near to the sea compared to the other sites (Funda, Bom Jesus and Talelo) in same province and as well parent material, on the other hand, Ramiro soils are different (see chapter 1). Sandy soils are largely prone to development of slaking and sieving crust but, this can reduce infiltrations rates causing surface runoff and increase the chance of rill and gully erosion (Huang and Hartemink 2020). The same author argues that nutrient leaching is higher in sandy soils unless the soils are compacted or exist a textural discontinuity.

In the current study, the lack of clear empirical information on erosion, and its relationship with both vegetation cover and with landscape position, means that discussion of erosion processes is speculative at this stage. Further work is required both to quantify erosion, at landscape scale, and to understand the processes involved, and their implications.

In addition to soil texture, soil structure has a major influence on soil properties (for example water retention and infiltration, and ease of root penetration), and is influenced by clay mineral composition, organic matter content, soil animal activity and tillage, among other factors. In the current study, it was not possible to analyse macro-structure of the soils, but the thin-section analyses (Chapter 4) provide detailed information on soil micro-structure and element composition, complementing Chapters 2 and 5, and providing unique insight on the degree of weathering of the soils, including of quartz grains.

The results of correlation in this work are diverse and, revealed a clearer relationship between soil fractions and NPK elements in Luanda province compared with Huambo province. This fact can be due to the diversity of soils, sites studied and the different handling of the soil. A study by Wele (2014) reported a correlation between potassium and clayey soils due to the residual effect of previous potassium fertilization.

Phosphorous contents are influenced by soil texture, fertilization, land use and management (Leinweber, Meissner et al. 1999). Findings were reported by (Boke, Beyene et al. 2016) who declared a negative and significant association among sand content and organic P fractions in the study of the evaluation of the effects of texture on phosphorus. The same author citing Hesse (1994) reports that P contents are higher in soils where clay values are equally high. In addition, direct relationship between Potassium and clay fraction are supported by the fact that clay rich soils (micas and vermiculite) are sources of K (Sinha and Biswas 2003, Shakeri and Abtahi 2018). According to (Adeniyan, Ojo et al. 2011) NPK fertilizer positively affects soil nutrient availability and cation exchange capacity substantially in acid soil. Under these conditions the soils of the Luanda province are more prone to better agricultural practices than the soils of the Huambo province.

The predictive analysis showed the impact of profile in nitrogen (N) contents. Nitrogen has the function of nourishing the plant and ensuring that it has a solider and more sustainable development. In general tropical soils have a high abundance of nitrogen (Nardoto, Ometto et al. 2008, Figueiredo 2016). In agricultural context, the N enters in the soil through the addition of mineral or organic fertilizers and the mineralization of organic matter. Furthermore, the way in which the land is management affects nutrient status. In the case of N, it is necessary to balance its supply with the soil reserves according to the needs of the crop (Spiertz 2009).

6.1.3-Relationship among micromorphology &pedogenesis and nutrient status

The micromorphological, mineralogical and micropedological features of the soils analysed in this study are differentiated into three (3) types according to colour and structure.

The red soils (L1, L2, M1, M2, T1) have a complex microstructure that varies from granular structure to crumbs with a packing pores. The yellow soils (T2, T3, L3, M3, B1, B2, B3, NG1, NG2 and NG3) present a complex microstructure being a mixed of granular with subangular blocky structure with local intergrain microaggregates. The brown soils (F1, F2, F3, BJ1, BJ2 and BJ3) shows a subangular blocky structure. Some soils presented some red dots in their microstructure, similar to the study by (de Avila 2009) in the analysis of pedological coverage in toposequence. Moreover, the microstructure has a clay fraction in its constitution and in some soils, clay associated with oxide and silt fraction; this is similar to the work presented by (Ahmad, Lopulisa et al. 2019) and, high porosity.

Porosity is categorized by pores of elongated, circular or arched section (L1, L2, L3, M1, M2, M3, T1, T2 and T3), planar voids that appear in aggregates of more developed volumes (F1, F2, F3 and BJ1, BJ2 and BJ3) or packing voids. The high porosity of soils is indicative of biological activity (Delvigne 1998, Albuquerque Filho, Muggler et al. 2008). Voids are also a consequence of aggregation, and this is related to the degree of weathering. Aggregates are spheroidal, granular, rounded (Lepi, Talelo, Mungo) or blocky aggregates (Bailundo, Funda, Bom Jesus).

Typical nodules and micronodules that were observed in these soils are iron oxides, and this fact may be due the solubilization and precipitation of these iron oxides (Cardoso 1995) or by oxidation-reduction cycles (Scarciglia, Pulice et al. 2006) (Mujinya, Mees et al. 2013); Sousa et al., 2010), and the variability of their diameter evidences the weathering process and that they are in the degradation phase (Rodrigo et al., 2014). In some soils (B3, L3, T2 and T3) hypocoatings were observed in the wall of pores, which may be related to iron precipitation reactions.

Coarse grains are made up of quartz, and are present in most soils, and also by biological organic material (charcoal). In addition, some feldspar (Talelo) grains were observed. SEM/EDX examination of soils showed the same mineral (feldspar) in other localities (Mungo, Lepi, Bom Jesus). Quartz grains have an angular to subangular shape, some of them are partially corroded, presenting fissures infilled by iron and others with grains showing smooth roughness.

Quartz is the dominant mineral in the studied soils and are in agreement with what was found in studeis made (the relevance of quartz is that the minerals have an impact on the concentration levels of elements on soil). The presence of high residual contents of quartz is a fundamental characteristic of soils with high weathering (Eze, 2016; (Schaefer, Ker et al. 2002, Simas, Schaefer et al. 2005, Thanachit, Suddhiprakarn et al. 2010, Oliveira, Brossard et al. 2013) a fundamental characteristic of soils with high weathering. Moreover, quartz grains filled with limpid red clay called “runi-quartz” were observed. These results are similar to what was reported by (Thanachit, Suddhiprakarn et al. 2010, Eze, Knight et al. 2016). The microchemical analysis (grain and fine material) detected high levels of SiO_2, which presupposes this element present in quartz grains minerals. The fractures observed in most quartz grains are evidence of weathering of this material, where silica is removed, and kaolinite is formed. This observation agrees with the concept of ferralitic soils in which kaolinite predominates (Fritsch, Morin et al. 2005, Ramaroson, Becquer et al. 2018). In agreement with this fact, we emphasize that the mineral contents in the clay fraction observed in this study-Kaolinite-, is similar to what was reported by (Schaefer, Ker et al. 2002, Fritsch, Morin et al. 2005, Albuquerque Filho, Muggler et al. 2008, Vendrame, Marchão et al. 2012) to the studies carried out for the other ferralitic soils. Although this study did not carry out a specific mineralogical analysis, the results of the micropedological, micromorphology and chemical analysis help to support the claim that among the minerals present in these soils is hematite (evidence given by reddish colour of the soils), a mineral resulting from the high degree of weathering in tropical and subtropical regions (de Avila 2009).

Regarding to the clay coatings present in the analysed soils, they are of limpid clay with hues ranging from yellow to red or from brownish yellow to yellow originated from translocation processes (Horvath, Varga et al. 2000, Wilson, Simpson et al. 2002) and that are eventually linked to the conditions of the soil itself; that is, its cycles of wetting and drying, Horvat (2016), citing (Stoops 1983).

Although there are slight differences in some of the morphological attributes among the soils of the two provinces, there is no strong distinction in mineralogy.

The mineral present in the soils analysed in this study in the clay fraction is predominantly kaolinite. Among the iron oxides and hydroxides present in the clay fraction, goethite and hematite are the present. In the coarse faction (sand + silt), quartz was the predominant mineral. The quartz grains have assorted sizes, some of which are fractured, indicating a high degree of weathering of the soils.

Insightful information on the content and mineralogy of the clay fraction, on the ratio of coarse to fine sand, are valuable support to a detailed soil classification system. In addition, these factors help for a zoning that allows conservation actions and management of soil fertility and maps of their agricultural potential (Donagemma, Freitas et al. 2016).

6.2-Limitations-discussion of study limitations and challenges

One of the limitations of this research is related with the lockdown due to COVID-19. That situation greatly affected the field work, and as result, no interviews could be carried out with farmers in Luanda province.

Another limitation was the impossibilty of interviewing those responsible for the areas where the samples were collected. On the other hand, it was not possible to collect soil samples in areas of large producers, in the same way that interviews with large producers were not carried out.

Due to the soils being very hard and dry (with the exception of the Ramiro site)it was a challenge to sample beyond 50 cm deep.

Another limitation was the lack of vailable and reliable data with objectives relevant to those of this study. This fact, limited in terms of literature review and comparision of results.

Chapter 7: Conclusion

In this concluding chapter a synthesis and the main conclusions is presented, as well as suggestions for future directions.

7.1-Summary

Appropriate and sustainable soil management, together with diversification of the economy, are essential to address the nutritional and economic challenges facing the population of Angola. As an integral component of agriculture, quantifying and understanding the nutritional status and management of soil resource is essential. That assessment includes the production of knowledge about chemical fertility, underpinning recommendations for the application of correctives and fertilizers. This research therefore aimed to gain knowledge of the nutritional status of Agro ecosystems in some of regions of Austral Africa, and to understand the factors that impact the nutritional status.

Nutrient element status, micromorphology (weathering and pedogenic), textural classes and land management are the topics addressed in the chapters of this thesis. Soils from two provinces were sampled and submitted for chemical and micromorphological analysis to better understand aspects of their genesis, chemistry, and mineralogy. First, Huambo is one of the provinces that, in the past (before the independence of Angola), was one of the most important regions in agricultural terms, with the oldest Faculty of Agricultural Sciences. Second, Luanda province is the capital of the country, encompasses one of the country's agricultural centres and is an area with a strong market for agricultural products. Furthermore, comparative analysis among the profile, site (regions) and soil depth, revealed broad and significant differences in the nutrient status and profile characteristics between the sites.

7.2-Conclusion in relation to study aim

The findings of this research (Chapter 5) illustrate the current nutritional element status of two provinces of Angola. The results for the two provinces showed contrasting nutrient status and a wide range of element contents, and all soils showing higher concentrations levels of macronutrients than micronutrients. The pH analysis showed that the soils of both provinces present acid character, which is slightly more pronounced in Huambo province.

Factors such as land management, soil texture and micromorphology and pedogenesis were shown to be related to nutrient status at various levels (Figure 7.1).

Although not statistically analysed, land management in terms of fertilization proved to be scarce and possibly its impact on nutrient status could be extremely low.

Textural analysis showed soils with silty loam and silty clay loam characteristics in the Huambo province and, silty clay in the Luanda province. NPK elements are impacted on clay and silt fractions. However, in the predictive analyse it was found that the profile had a significant impact on Nitrogen, an increase in the clay/silt ratio origins a decrease in Nitrogen.

Micromorphological and pedogenesis analysis showed that the main elements on these soils are aluminium and silicon.

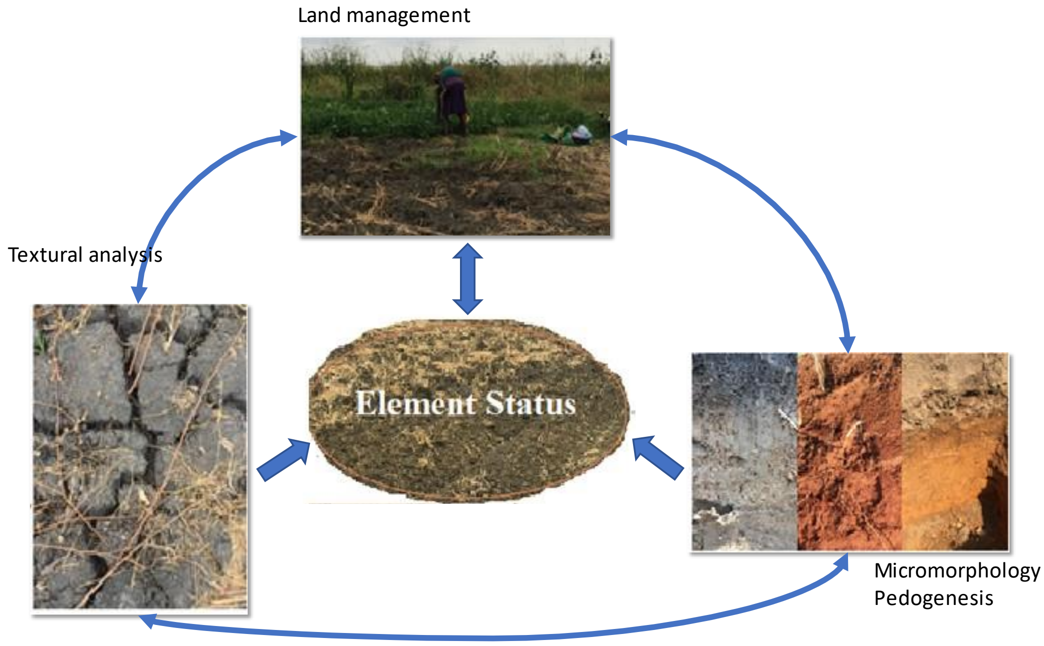


Figure 7. 1: Relationship of element status between land management, soil textural classes and micromorphology and pedogenesis.

7.3-Future research

In this last section, suggestions are made future research at the level of agricultural soils where science can be developed, in dialogue with farmers, to enhance both productivity and sustainability. The main objective of this research has been to provide improved baseline knowledge of the nutritional status of agricultural Angola soils and to make a preliminary investigation into smallholders' understanding of soils and adopted management practices. Until this study, there were no recent, reliable, and accurate works on the status of agricultural soils in Angola.

The main recommendation is that this study could be applied not only to all agricultural regions of these two provinces but also to all agricultural regions of the country. Therefore, widespread analysis (chemical and physical) is recommended to assess the nutrient status and the need for the use of fertilizers, thus contributing to increased productivity. Additionally, studies should be carried out on the current fertilizer recommendations for different type of soils, crops, and land management, thus contributing to a more sustainable cultivation and increased productivity with reduced waste. By this means, chemical mapping of agricultural regions would be carried out serving as a useful tool for small farmers to manage the land. In addition, it would help to create a database for other future studies.

This study could be conducted jointly with other areas (Minister of Environment of Angola) expanding a better knowledge of the soils, the impact that they suffer from distinct parts (human, nature) to create better policies for more sustainable management of soil.

This thesis identified some factors that could be related to the nutrient status of soils in terms of land management. More precise studies are needed to determine the relationship among land management by smallholders and the nutrient status of soils.

This study highlights the role of thin section analysis (micromorphology and pedogenesis) and the contribution of this analysis to a deeper understanding of the soil characteristics. Based on this, and as it is a field where there is a huge scientific gap in Angola, future studies in this area are recommended.

Angola is a country with enormous agricultural potential (good climate, abundant rivers, arable lands). However, articulated actions between different organizations such as Ministries of Science and Technology, Environment; Agriculture, universities, farmer's associations, NGOs, entrepreneurs, and stakeholders are needed so that scientific research on soils will be more systematically implemented and applied.

References

Abbott, L. K. and D. A. Manning (2015). "Soil health and related ecosystem services in organic agriculture." Sustainable Agriculture Research **4**(526-2016-37946).

Abe, S. S., et al. (2006). "Comprehensive assessment of the clay mineralogical composition of lowland soils in West Africa." Soil Science & Plant Nutrition **52**(4): 479-488.

Acosta, V. T., et al. (2015). "Effect of vegetation cover on millennial-scale landscape denudation rates in East Africa." Lithosphere **7**(4): 408-420.

Adderley, W. P., et al. (2006). "Historic landscape management: a validation of quantitative soil thin-section analyses." Journal of archaeological science **33**(3): 320-334.

Adeniyan, O., et al. (2011). "Comparative study of different organic manures and NPK fertilizer for improvement of soil chemical properties and dry matter yield of maize in two different soils." Journal of Soil Science and Environmental Management **2**(1): 9-13.

Ahmad, A., et al. (2019). Mineralogy and micromorphology of soil from gneissic rock in East Luwu, South Sulawesi. IOP Conference Series: Earth and Environmental Science, IOP Publishing.

Albuquerque Filho, M. R. d., et al. (2008). "Solos com morfologia latossólica e caráter câmbico na região de Governador Valadares, Médio Rio Doce, Minas Gerais: gênese e micromorfologia." Revista Brasileira de Ciência do Solo **32**(1): 259-270.

Aldeias, V., et al. (2014). "Deciphering site formation processes through soil micromorphology at Contrebandiers Cave, Morocco." Journal of human evolution **69**: 8-30.

Almeida, A. F. F. d. (2015). O pequeno agricultor africano: problemas que enfrenta e perspetivas sobre o seu futuro.

Altieri, M. A. (2004). "Linking ecologists and traditional farmers in the search for sustainable agriculture." Frontiers in Ecology and the Environment **2**(1): 35-42.

Ananda, J. and G. Herath (2003). "Soil erosion in developing countries: a socio-economic appraisal." Journal of environmental Management **68**(4): 343-353.

Aranibar, J. N., et al. (2008). "Nitrogen isotope composition of soils, C3 and C4 plants along land use gradients in southern Africa." Journal of Arid Environments **72**(4): 326-337.

Aries, S., et al. (2000). "A routine method for oxide and hydroxide interference corrections in ICP-MS chemical analysis of environmental and geological samples." Geostandards Newsletter **24**(1): 19-31.

Augusto, L., et al. (2017). "Soil parent material—a major driver of plant nutrient limitations in terrestrial ecosystems." Global change biology **23**(9): 3808-3824.

Bationo, A., et al. (1995). A critical review of crop-residue use as soil amendment in the West African semi-arid tropics. International Conference on Livestock and Sustainable Nutrient Cycling in Mixed Farming Systems of Sub-Saharan Africa. Addis Ababa (Ethiopia). 22-26 Nov 1993.

Bekunda, M., et al. (2002). "Soil fertility status, management, and research in East Africa." East African Journal of Rural Development **20**(1): 94-112.

Belnap, J., et al. (2007). "Wind erodibility of soils at Fort Irwin, California (Mojave Desert), USA, before and after trampling disturbance: implications for land management." Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group **32**(1): 75-84.

Bern, C. R., et al. (2005). "Unexpected dominance of parent-material strontium in a tropical forest on highly weathered soils." Ecology **86**(3): 626-632.

Blackmore, A., et al. (1990). "The origin and extent of nutrient-enriched patches within a nutrient-poor savanna in South Africa." Journal of biogeography: 463-470.

Blanco-Canqui, H. and C. Wortmann (2017). "Crop residue removal and soil erosion by wind." Journal of Soil and Water Conservation **72**(5): 97A-104A.

Bockheim, J. G. and A. E. Hartemink (2017). The soils of Wisconsin, Springer.

Boke, S., et al. (2016). "Soil phosphorus fractions as influenced by different cropping systems: Direct and indirect effects of soil properties on different P pools of nitisols of Wolayta, Ethiopia." Asia Pacific Journal of Energy and Environment **3**(1): 17-24.

Bortolon, L., et al. (2010). "Phosphorus availability to corn and soybean evaluated by three soil-test methods for southern Brazilian soils." Communications in Soil Science and Plant Analysis **42**(1): 39-49.

Bostick, W. M., et al. (2007). "Soil carbon dynamics and crop residue yields of cropping systems in the Northern Guinea Savanna of Burkina Faso." Soil and Tillage Research **93**(1): 138-151.

Boyer, J., et al. (1971). "Propriedades dos solos e fertilidade."

Breman, H. and S. K. Debrah (2003). "Improving African food security." SAIS Review (1989-2003) **23**(1): 153-170.

Bullock, P.; Stoops G.; Fedoroff, N.; Soops, G.; Jongerius, A.; Tursina T.: Handbook for Soil Thin Section Description. Waine Research, 1987

Butler, B. M., et al. (2020). "Mineral–nutrient relationships in African soils assessed using cluster analysis of X-ray powder diffraction patterns and compositional methods." Geoderma **375**: 114474.

Cardoso, F. B. d. F. (1995). "Análise química, mineralógica e micromorfológica de solos tropicais colapsíveis e o estudo da dinâmica do colapso."

Carranza, F., et al. (2014). Land, Territorial Development and Family Farming in Angola: A Holistic Approach to Community-based Natural Resource Governanance, Food and Agriculture Organization of the United Nations.

Cavichiolo, S. R. (2005). "Perdas de solo e nutrientes por erosão hídrica em diferentes métodos de preparo do solo em plantio de Pinus taeda." UFPR, Curitiba.

Champion, A. M. (1933). "Soil erosion in Africa." The Geographical Journal **82**(2): 130-139.

Chianu, J. N., et al. (2012). "Mineral fertilizers in the farming systems of sub-Saharan Africa. A review." Agronomy for sustainable development **32**(2): 545-566.

Cihacek, L., et al. (2015). "Comparison of seven SO4-S extraction methods for analysis by turbidimetry or ICP spectrometry." Communications in Soil Science and Plant Analysis **46**(20): 2649-2659.

Cleaver, K. M., et al. (1995). Agriculture, poverty, and policy reform in Sub-Saharan Africa, World Bank Washington, DC.

de Avila, F. F. (2009). "Análise da cobertura pedológica em uma Topossequência na bacia do Córrego dos Pereiras-Depressão de Gouveia/MG."

Decreto presidencial n 227/20; Republic journal 137, 2020: [retrieved in 29/05]; http://www.extwprlegs1.fao.org/docs/pdf/ang197596.pdf

De Jager, A., et al. (1998). "Monitoring nutrient flows and economic performance in African farming systems (NUTMON): I. Concepts and methodologies." Agriculture, ecosystems & environment **71**(1-3): 37-48.

Deepthy, R. and S. Balakrishnan (2005). "Climatic control on clay mineral formation: Evidence from weathering profiles developed on either side of the Western Ghats." Journal of Earth System Science **114**(5): 545-556.

Delvigne, J. (1998). "Atlas of micromorphology and mineralogist." Ottawa, ORSTOM.

Du, H., et al. (2016). "Assessment of wind and water erosion risk in the watershed of the Ningxia-Inner Mongolia Reach of the Yellow River, China." Ecological indicators **67**: 117-131.

El-Swaify, S. (1997). "Factors affecting soil erosion hazards and conservation needs for tropical steeplands." Soil technology **11**(1): 3-16.

Erkossa, T., et al. (2005). "Effect of different methods of land preparation on runoff, soil and nutrient losses from a Vertisol in the Ethiopian highlands." Soil Use and Management **21**(2): 253-259.

Eze, P. N., et al. (2016). "Tracing recent environmental changes and pedogenesis using geochemistry and micromorphology of alluvial soils, Sabie-Sand River Basin, South Africa." Geomorphology **268**: 312-321.

Fattet, M., et al. (2011). "Effects of vegetation type on soil resistance to erosion: Relationship between aggregate stability and shear strength." Catena **87**(1): 60-69.

FAO (country report), State of Biodiversity for food Agriculture in Angola, 2017. [retrieved in 29/05/2021]: http://www.fao.org/3/ca5272pt/ca5227pt.pdf

FAO,2014;DiariodaRepublica:[retrievedin20/04/2023]https://faolex.fao.org/docs/pdf/ang132051.pdf

FAO_Boosting_Africa_Soils.pdf (2006)

FAO, 2022: Retrieved in [https://farming.co.uk/news/world-soil-day-2022-fao-publishes-first-global-report-on-black-soils]

Fenta, A. A., et al. (2020). "Land susceptibility to water and wind erosion risks in the East Africa region." Science of the Total Environment **703**: 135016.

Figueiredo, A. E. S. (2016). "Dinâmica de nitrogênio em solos de florestas secundárias sob diferentes históricos de uso nos municípios de Santarém e Belterra, Amazônia Oriental."

Fonseca, A. F. d., et al. (2005). "Cation exchange capacity of an Oxisol amended with an effluent from domestic sewage treatment." Scientia Agricola **62**(6): 552-558.

Fritsch, E., et al. (2005). "Transformation of haematite and Al-poor goethite to Al-rich goethite and associated yellowing in a ferralitic clay soil profile of the middle Amazon basin (Manaus, Brazil)." European Journal of Soil Science **56**(5): 575-588.

Gupta, J. P., et al. (1981). "Soil erosion by wind from bare sandy plains in western Rajasthan, India." Journal of Arid Environments **4**(1): 15-20.

Gupta, P. and I. Rorison (1975). "Seasonal differences in the availability of nutrients down a podzolic profile." The Journal of Ecology: 521-534.

Guuroh, R. T., et al. (2018). "Drivers of forage provision and erosion control in West African savannas—A macroecological perspective." Agriculture, ecosystems & environment **251**: 257-267.

Hengl, T., et al. (2017). "Soil nutrient maps of Sub-Saharan Africa: assessment of soil nutrient content at 250 m spatial resolution using machine learning." Nutrient Cycling in Agroecosystems **109**(1): 77-102.

Higa, T. and J. F. Parr (1994). Beneficial and effective microorganisms for a sustainable agriculture and environment, International Nature Farming Research Center Atami.

Horvath, Z., et al. (2000). "Micromorphological and chemical complexities of a lateritic profile from basalt (Jos Plateau, Central Nigeria)." Chemical Geology **170**(1-4): 81-93.

Huang, J. and A. E. Hartemink (2020). "Soil and environmental issues in sandy soils." Earth-Science Reviews **208**: 103295.

Hurni, H., et al. (2010). "Land degradation and sustainable land management in the highlands of Ethiopia."

Jayne, T. S., et al. (2010). "Principal challenges confronting smallholder agriculture in sub-Saharan Africa." World development **38**(10): 1384-1398.

Jul-Larsen, E. and B. E. Bertelsen (2011). "Social security, poverty dynamics and economic growth in Angola's smallholder agriculture." CMI report.

Kaaya, G. P., et al. (1996). "Prospects for Biological Control of Livestock Ticks, Rhipicephalus appendiculatusandAmblyomma variegatum, Using the Entomogenous FungiBeauveria bassianaandMetarhizium Anisopliae." Journal of invertebrate pathology **67**(1): 15-20.

Khan, N., et al. (2013). "Method validation for simultaneous determination of chromium, molybdenum and selenium in infant formulas by ICP-OES and ICP-MS." Food chemistry **141**(4): 3566-3570.

Kihara, J., et al. (2020). "Micronutrient deficiencies in African soils and the human nutritional nexus: opportunities with staple crops." Environmental Geochemistry and Health **42**(9): 3015-3033.

Lal, R. (1995). "Erosion-crop productivity relationships for soils of Africa." Soil Science Society of America Journal **59**(3): 661-667.

Lal, R. and W. C. Moldenhauer (1987). "Effects of soil erosion on crop productivity." Critical Reviews in Plant Sciences **5**(4): 303-367.

Langdale, G., et al. (1991). "Cover crop effects on soil erosion by wind and water." Cover crops for clean water: 15-22.

Langston, G. and C. M. Neuman (2005). "An experimental study on the susceptibility of crusted surfaces to wind erosion: a comparison of the strength properties of biotic and salt crusts." Geomorphology **72**(1-4): 40-53.

Leinweber, P., et al. (1999). "Management effects on forms of phosphorus in soil and leaching losses." European Journal of Soil Science **50**(3): 413-424.

Lekasi, J., et al. (2001). "Managing manure to sustain smallholder livelihoods in the East African Highlands for high potential production systems of the Natural Resources Systems Programme Renewable Natural Resources Knowledge Strategy, Department for International Development." Managing manure to sustain smallholder livelihoods in the East African Highlands for high potential production systems of the Natural Resources Systems Programme Renewable Natural Resources Knowledge Strategy, Department for International Development.

Loomis, R. (1984). "Traditional agriculture in America." Annual Review of Ecology and Systematics **15**: 449-478.

Lowder, S. K., et al. (2016). "The number, size, and distribution of farms, smallholder farms, and family farms worldwide." World development **87**: 16-29.

Macphail, R. I., et al. (1990). "Soil micromorphological evidence of early agriculture in north-west Europe." World Archaeology **22**(1): 53-69.

Mafongoya, P. L., et al. (2006). "Managing soil fertility and nutrient cycles through fertilizer trees in southern Africa." Biological Approaches to Sustainable Soil Systems, Taylor & Francis: 273-289.

Masters, W. A., et al. (2013). "Urbanization and farm size in Asia and Africa: Implications for food security and agricultural research." Global Food Security **2**(3): 156-165.

Matson, P. A., et al. (1997). "Agricultural intensification and ecosystem properties." Science **277**(5325): 504-509.

Melese, A., et al. (2015). "Phosphorus status, inorganic phosphorus forms, and other physicochemical properties of acid soils of Farta district, northwestern highlands of Ethiopia." Applied and Environmental Soil Science **2015**.

Mendelsohn, J. M. (2019). Landscape changes in Angola. Biodiversity of Angola, Springer, Cham**:** 123-137.

Morris, M. L. (2007). Fertilizer use in African agriculture: Lessons learned and good practice guidelines, World Bank Publications.

Mujinya, B., et al. (2013). "Clay composition and properties in termite mounds of the Lubumbashi area, DR Congo." Geoderma **192**: 304-315.

Mwangi, W. M. (1996). "Low use of fertilizers and low productivity in sub-Saharan Africa." Nutrient Cycling in Agroecosystems **47**(2): 135-147.

Nagayets, O. (2005). "Small farms: current status and key trends." The future of small farms **355**: 26-29.

Nardoto, G. B., et al. (2008). "Understanding the influences of spatial patterns on N availability within the Brazilian Amazon forest." Ecosystems **11**(8): 1234-1246.

Ngetich, F. K., et al. (2012). The potential of organic and inorganic nutrient sources in sub-Saharan African crop farming systems.

Nunes, A. N., et al. (2011). "Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal." Applied Geography **31**(2): 687-699.

Olatunji, O., et al. (2007). "Influence of parent material and topography on some soil properties in southwestern Nigeria." Nigerian Journal of Soil and Environmental Research **7**: 1-6.

Oliveira, F. A. d., et al. (2001). "Disponibilidade de potássio e suas relações com cálcio e magnésio em soja cultivada em casa-de-vegetação." Scientia Agricola **58**(2): 329-335.

Oliveira, J. F., et al. (2013). "Soil discrimination using diffuse reflectance Vis–NIR spectroscopy in a local toposequence." Comptes Rendus Geoscience **345**(11-12): 446-453.

Ovadia, J. S. (2015). "State-led development in Angola and the challenge of agriculture and rural development." Portuguese Studies Review.

Pal, D., et al. (2003). "Use of hydraulic conductivity to evaluate the suitability of Vertisols for deep-rooted crops in semiarid parts of central India." Soil Use and Management **19**(3): 208-216.

Pansak, W., et al. (2008). "Changes in the relationship between soil erosion and N loss pathways after establishing soil conservation systems in uplands of Northeast Thailand." Agriculture, ecosystems & environment **128**(3): 167-176.

Pennock, D. (2019). "Soil erosion: The greatest challenge for sustainable soil management."

Pimentel, D. (2006). "Soil erosion: a food and environmental threat." Environment, development and sustainability **8**(1): 119-137.

Pimentel, D. and N. Kounang (1998). "Ecology of soil erosion in ecosystems." Ecosystems **1**(5): 416-426.

Ramaroson, V. H., et al. (2018). "Mineralogical analysis of ferralitic soils in Madagascar using NIR spectroscopy." Catena **168**: 102-109.

Rawlins, B., et al. (2012). "The advanced soil geochemical atlas of England and Wales."

Rware, H., et al. (2020). "Development and utilization of a decision support tool for the optimization of fertilizer application in smallholder farms in Uganda." African Journal of Food, Agriculture, Nutrition and Development **20**(4): 16178-16195.

Santos, L. d. S. (2018). "Otimização dos procedimentos de extração e desempenho analítico da espectrometria de emissão ótica com plasma acoplado indutivamente na análise de amostras de solos."

Scarciglia, F., et al. (2006). "Soil chronosequences on Quaternary marine terraces along the northwestern coast of Calabria (Southern Italy)." Quaternary International **156**: 133-155.

Schaefer, C., et al. (2002). "Pedogenesis on the uplands of the Diamantina Plateau, Minas Gerais, Brazil: a chemical and micropedological study." Geoderma **107**(3-4): 243-269.

Shahabinejad, N., et al. (2019). "The fractionation of soil aggregates associated with primary particles influencing wind erosion rates in arid to semiarid environments." Geoderma **356**: 113936.

Shakeri, S. and S. A. Abtahi (2018). "Potassium forms in calcareous soils as affected by clay minerals and soil development in Kohgiluyeh and Boyer-Ahmad Province, Southwest Iran." Journal of Arid Land **10**(2): 217-232.

Silver, W.L., Neff, J., McGroddy, M., Veldkamp, E., Keller, M. and Cosme, R., 2000. Effects of soil texture on belowground carbon and nutrient storage in a lowland Amazonian Forest ecosystem. *Ecosystems*, *3*, pp.193-209.

Simas, F. N., et al. (2005). "Chemistry, mineralogy and micropedology of highland soils on crystalline rocks of Serra da Mantiqueira, southeastern Brazil." Geoderma **125**(3-4): 187-201.

Sinare, H. and L. J. Gordon (2015). "Ecosystem services from woody vegetation on agricultural lands in Sudano-Sahelian West Africa." Agriculture, ecosystems & environment **200**: 186-199.

Sinha, A. and S. Biswas (2003). "Distribution of different forms of potassium in surface and subsurface horizons of some well established soils of west bengal under the order inceptisol." Journal of Interacademicia (India).

Sirjani, E., et al. (2019). "Portable wind tunnel experiments to study soil erosion by wind and its link to soil properties in the Fars province, Iran." Geoderma **333**: 69-80.

Smaling, E. (1993). An agro-ecological framework for integrated nutrient management, with special reference to Kenya, Wageningen University and Research.

Smith, D. B., et al. (2009). "Pilot studies for the North American Soil Geochemical Landscapes Project–Site selection, sampling protocols, analytical methods, and quality control protocols." Applied Geochemistry **24**(8): 1357-1368.

Smith, P., et al. (2016). "Global change pressures on soils from land use and management." Global change biology **22**(3): 1008-1028.

Solomon, D., et al. (2016). "Indigenous African soil enrichment as a climate-smart sustainable agriculture alternative." Frontiers in Ecology and the Environment **14**(2): 71-76.

Soropa, G., et al. (2019). "Nutrient status of sandy soils in smallholder areas of Zimbabwe and the need to develop site-specific fertiliser recommendations for sustainable crop intensification." South African journal of plant and soil **36**(2): 149-151.

Spiertz, J. (2009). "Nitrogen, sustainable agriculture and food security: a review." Sustainable agriculture: 635-651.

Sterk, G. (2003). "Causes, consequences and control of wind erosion in Sahelian Africa: a review." Land Degradation & Development **14**(1): 95-108.

Stoops, G. (1983). "Micromorphology of the oxic horizon." Soil micromorphology: soil genesis/edited by P. Bullock and CP Murphy.

Stoops, G. and V. Marcelino (2018). Lateritic and bauxitic materials. Interpretation of micromorphological features of soils and regoliths, Elsevier**:** 691-720.

Sun, W., et al. (2014). "Assessing the effects of land use and topography on soil erosion on the Loess Plateau in China." Catena **121**: 151-163.

Thanachit, S., et al. (2010). "Micromorphological characteristic of soils on the Nam Phong and Khon Buri catenae, northeast Thailand." Thai Journal of Agricultural Science **43**(2): 71-90.

Towett, E. K., et al. (2013). "Quantification of total element concentrations in soils using total X-ray fluorescence spectroscopy (TXRF)." Science of the Total Environment **463**: 374-388.

Towett, E. K., et al. (2015). "Total elemental composition of soils in Sub-Saharan Africa and relationship with soil forming factors." Geoderma Regional **5**: 157-168.

Toy, T. J., et al. (2002). Soil erosion: processes, prediction, measurement, and control, John Wiley & Sons.

Turmel, M.-S., et al. (2015). "Crop residue management and soil health: A systems analysis." Agricultural Systems **134**: 6-16.

Valério, N. and M. P. Fontoura (1994). "A evolução económica de Angola durante o segundo período colonial—uma tentativa de síntese." Análise Social: 1193-1208.

Vanlauwe, B., et al. (2001). "Combined application of organic matter and fertilizer." Sustaining soil fertility in West Africa **58**: 247-279.

Vendrame, P., et al. (2012). "The potential of NIR spectroscopy to predict soil texture and mineralogy in Cerrado Latosols." European Journal of Soil Science **63**(5): 743-753.

Vendrame, P. R. S., et al. (2007). "Availability of copper, iron, manganese and zinc in soils under pastures in the Brazilian Cerrado." Pesquisa Agropecuária Brasileira **42**(6): 859-864.

Vermeulen, S. J., et al. (2010). "Agriculture, food security and climate change: Outlook for knowledge, tools and action." CCAFS Report.

Vlek, P. L. (1990). "The role of fertilizers in sustaining agriculture in sub-Saharan Africa." Fertilizer research **26**(1): 327-339.

Vrieling, A., et al. (2014). "Towards large-scale monitoring of soil erosion in Africa: Accounting for the dynamics of rainfall erosivity." Global and Planetary Change **115**: 33-43.

Wilson, C., et al. (2002). "Soil management in pre-Hispanic raised field systems: Micromorphological evidence from Hacienda Zuleta, Ecuador." Geoarchaeology: An International Journal **17**(3): 261-283.

Wolfe, S. A. and W. G. Nickling (1993). "The protective role of sparse vegetation in wind erosion." Progress in physical geography **17**(1): 50-68.

Wolka, K., et al. (2018). "Effects of soil and water conservation techniques on crop yield, runoff and soil loss in Sub-Saharan Africa: A review." Agricultural water management **207**: 67-79.

Yanai, J., et al. (2014). "Evaluation of nitrogen status of agricultural soils in Java, Indonesia." Soil Science and Plant Nutrition **60**(2): 188-195.

Yu, Z., et al. (2001). "An evaluation of methods for the chemical decomposition of geological materials for trace element determination using ICP-MS." Geostandards Newsletter **25**(2-3): 199-217.

Zamani, S. and M. Mahmoodabadi (2013). "Effect of particle-size distribution on wind erosion rate and soil erodibility." Archives of Agronomy and Soil Science **59**(12): 1743-1753.

Zheng, F.-L. (2005). "Effects of accelerated soil erosion on soil nutrient loss after deforestation on the Loess Plateau." Pedosphere **15**(6): 707-715.

Zingore, S., et al. (2007). "Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe." Agriculture, ecosystems & environment **119**(1-2): 112-126.

Appendix 2

Appendix 2. 1: Survey of small farmers in Angola (Huambo)

Diagnosis of fertilization and land use.

Locality…

Gender…

Day/Month/Year

----/----/----/

1-How to you plough the soil?

Manual	
Tractor	
Animal	

2-How many hectares do you use for agriculture?

<1ha	
(2-5) ha	
>6ha	

3-Do you use fertilizer?

Yes	
Not	

4-What fertilizer do you use?

NPK	
NH_4	
Urea	
kitchen waste	

5-Organic fertilizer?

Pig	
Chicken	
Cow	
Goat	

6-Do you use herbicides and/or insecticides?

Yes	
Not	

7-How much fertilizer do you use?

<350kg/ha	
(350-500) kg/ha	
>500 kg/ha	

8-When do you apply the fertilizer?

Before planting	
after planting	

9-How often do you apply fertilizer?

0 days	
30day	
60 days	
every year	
every two years	
other	

10-What do you do with the grass after ploughing the land?

10.1-Burning

Yes	
Not	

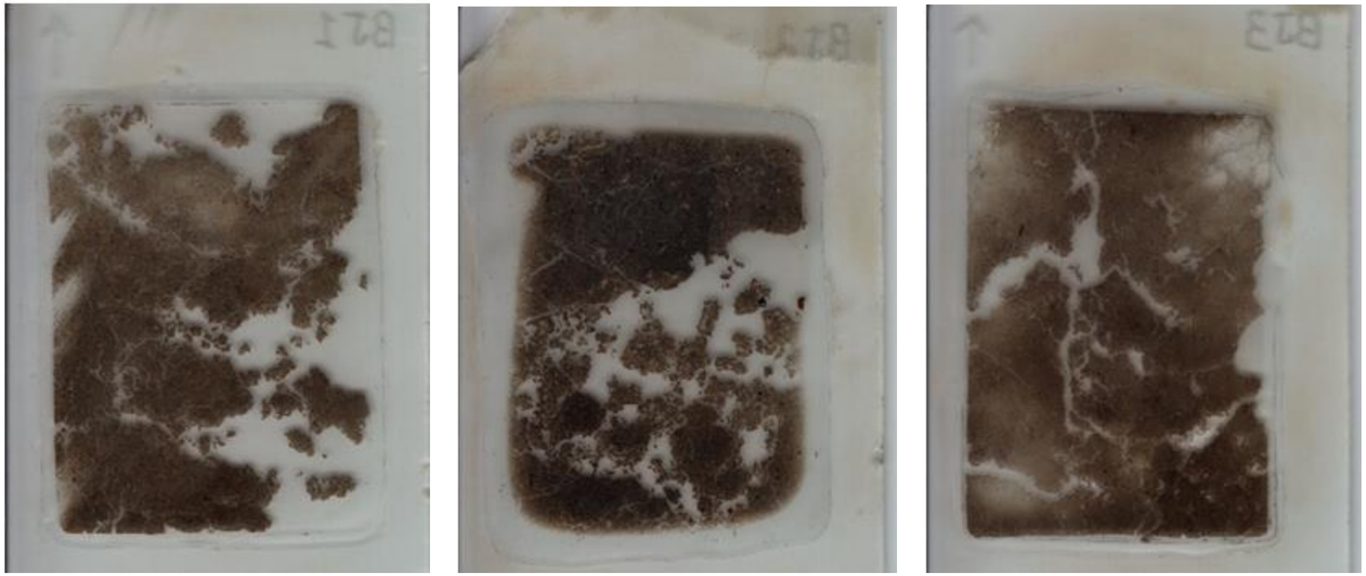
10.2-Cover the land.

Yes	
Not	

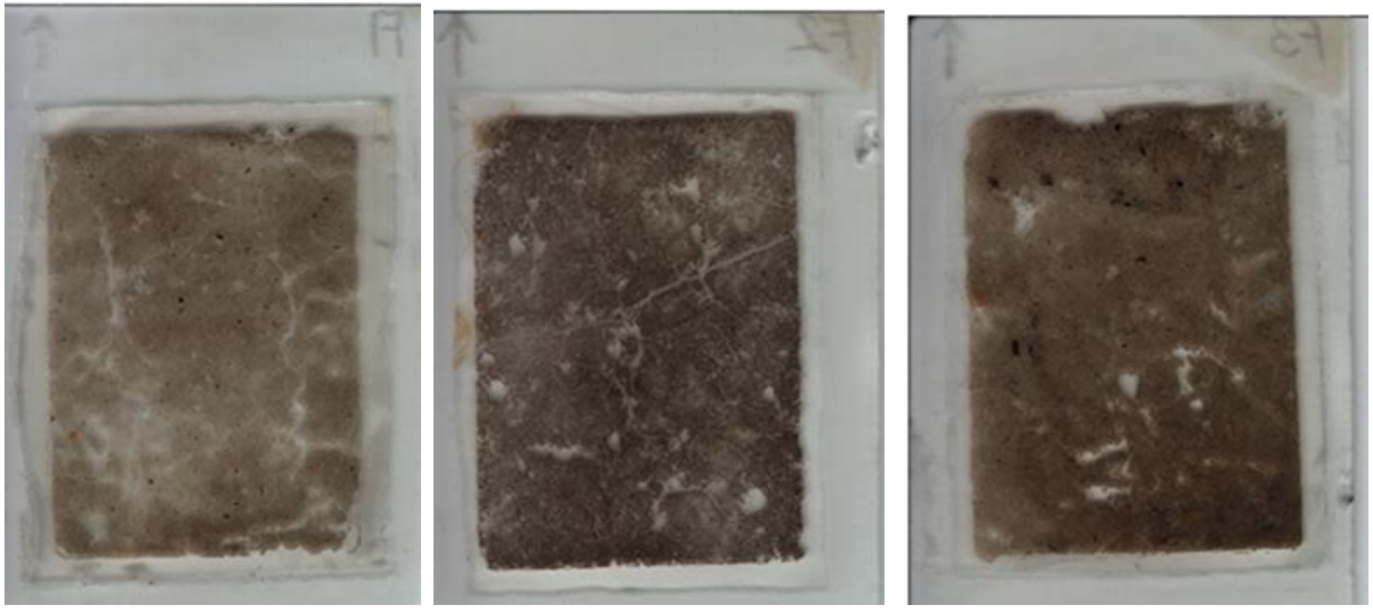
10.3-Do you think soil is good? (Quality of soil)

10.4-How is the best way to protect the soil?

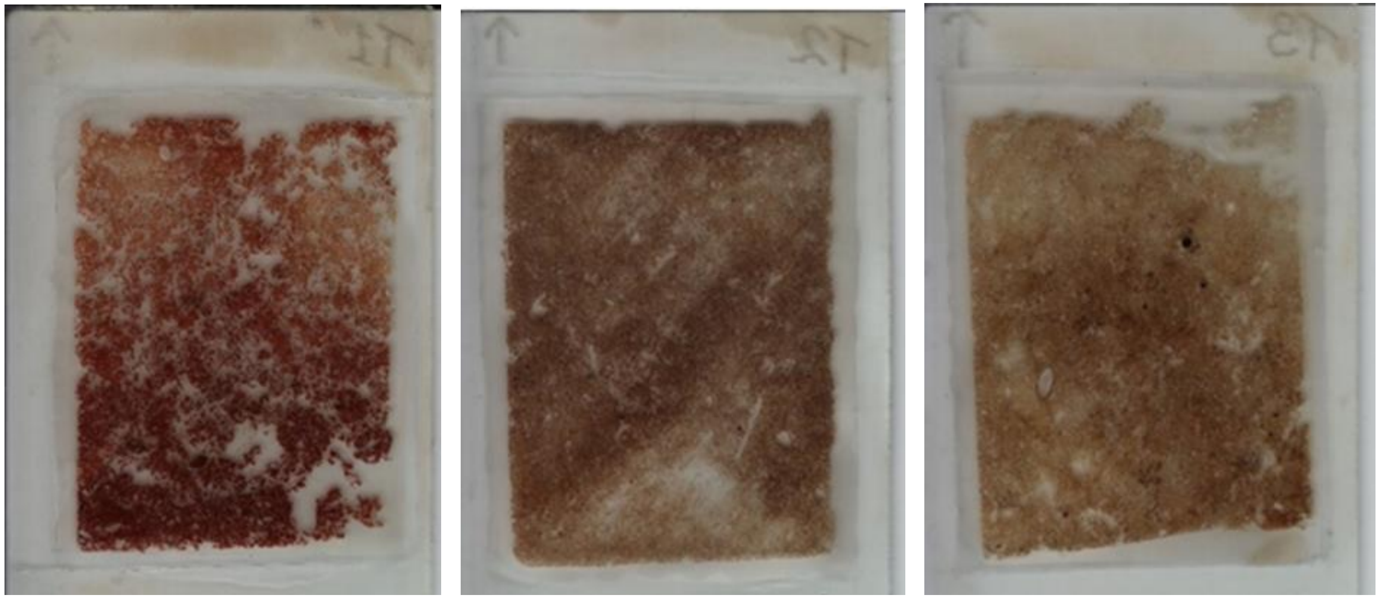
Appendix 4

Soil	Collection	Site	Slides
(?)	24/09/2019	Ramiro	 (a) (b) (c)
a) BJ1-Bom Jesus hill-slope profile 1; b) BJ2-Bom Jesus hill-slope profile 2; c) BJ3-Bom Jesus hill-slope profile 3			

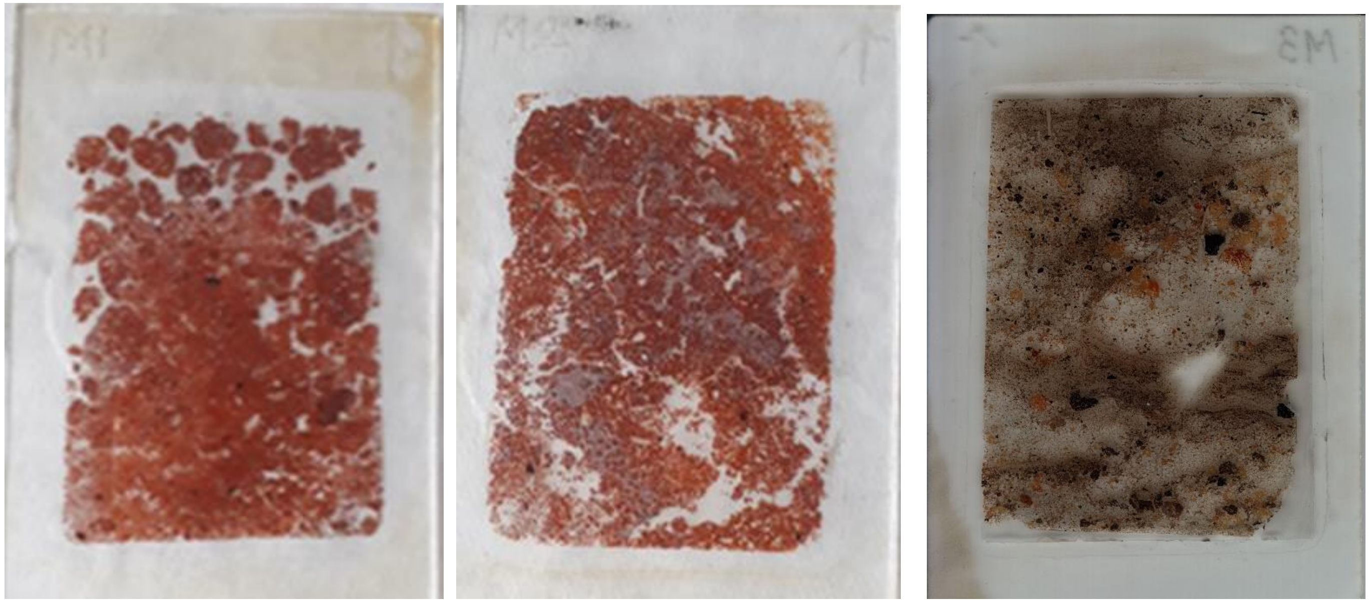
Appendix 4. 1: Slide scans for soil thin section-Bom Jesus

Soil	Collection	Site	Slides
(?)	22/09/2019	Funda	 (a) (b) (c)
a) F1-Funda hill-slope profile 1; b) F2-Funda hill-slope profile 2; c)F3-Funda hill-slope profile 3			

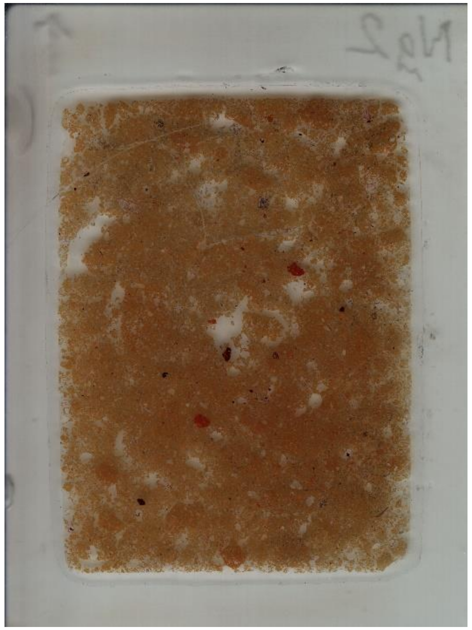
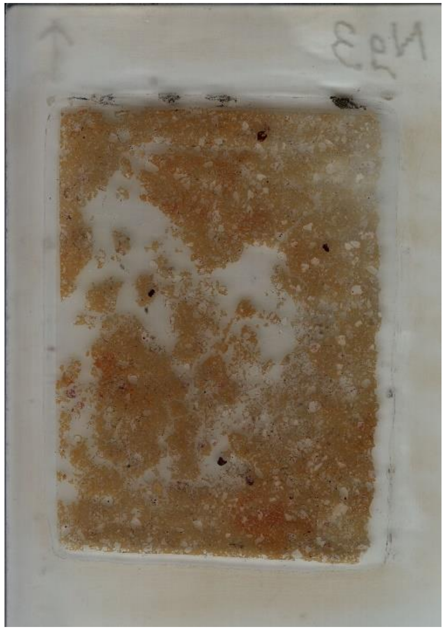
Appendix 4. 2: Slide scans for soil thin section- Funda

Soil	Collection	Site	Slides
(?)	24/09/2019	Talelo	 (a) (b) (c)
a)T1-Talelo hill-slope profile 1; b)T2-Talelo hill-slope profile 2; c)T3- Talelo hill-slope profile 3			

Appendix 4. 3: Slide scans for soil thin section - Talelo

Soil	Collection	Site	Slides
Ferralsosls	17/09/2018	Mungo	 (a) (b) (c)
a) M1-Mungo hill-slope profile 1; b) M2-Mungo hill-slope profile 2; c) M3- Mungo hill-slope profile 3			

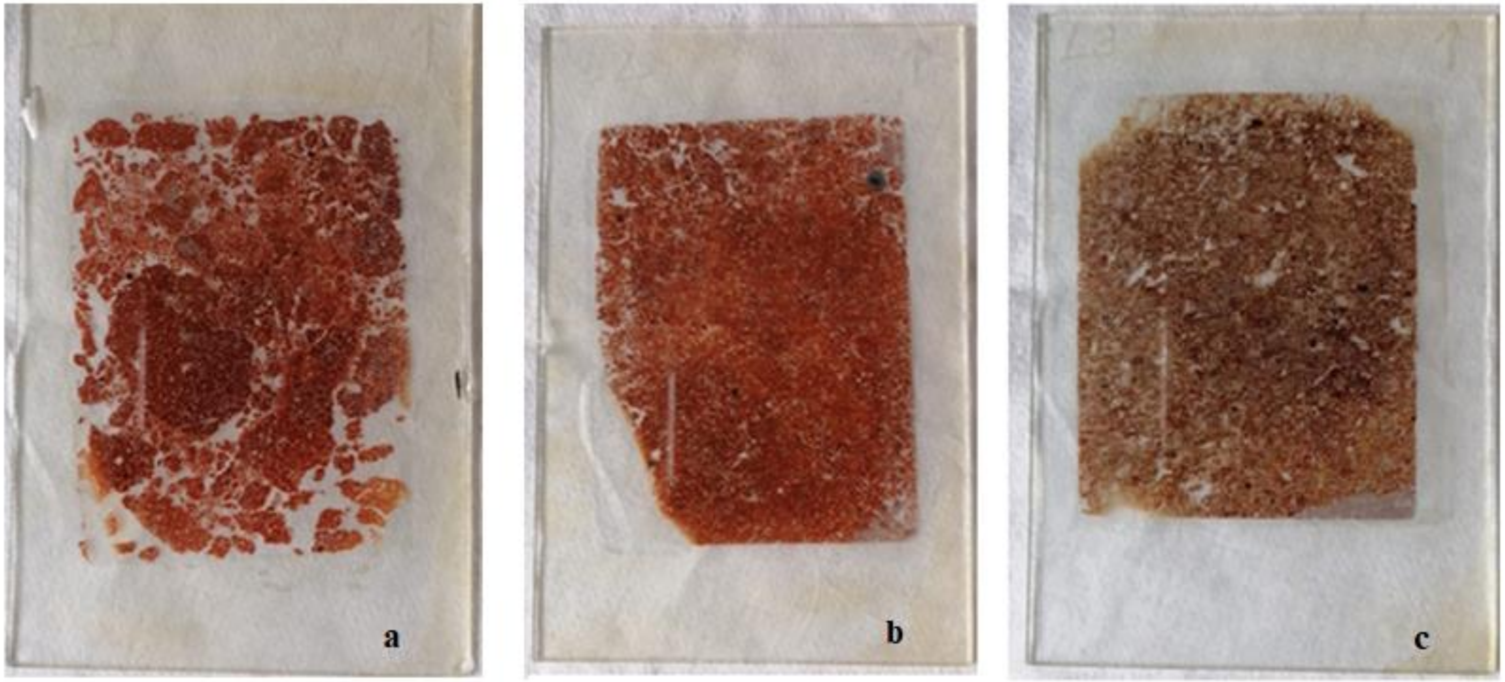
Appendix 4. 4: Slide scans for soil thin section - Mungo

Soil	Collection	Site	Slides
Ferralsosls	18/09/2018	Ngongo	 (a)  (b)  (c)
a)Ng1- Ngongoinga-hill-slope profile 1; b)Ng2-Ngongoinga- hill-slope profile 2; c)Ng3-Ngongoinga- hill-slope profile 3			

Appendix 4. 5: Slide scans for soil thin section - Ngongoinga

Soil	Collection	Site	Slides
Ferralsols	20/08/2018	Bailundo	 (a)  (b)  (c)
a) B1-Bailundo hill-slope profile 1; b)B2-Bailundo hill-slope profile 2; c)B3- Bailundo hill-slope profile 3			

Appendix 4. 6: Slide scans for soil thin section - Bailundo



a) L1-Lepi hill-slope-profile 1; b) L2-Lepi hill-slope- profile 2; c) L3-Lepi hill-slope-profile 3

Appendix 4. 7: Slide scans for soil thin sections:

clay				silt				sand			
		W	p			W	p			W	p
Bailundo	Lepi	2.255	**0.248**	Bailundo	Lepi	-4.001	**0.013**	Bailundo	Lepi	1.483	0.546
Bailundo	Mungo	3.660	**0.026**	Bailundo	Mungo	-6.246	**< .001**	Bailundo	Mungo	1.572	0.507
Lepi	Mungo	0.881	0.808	Lepi	Mungo	-0.721	0.867	Lepi	Mungo	-0.676	0.882

Appendix 4. 8: Comparisons soil fractions in Huambo province

clay				silt				sand			
		W	p			W	p			W	p
Bom Jesus	Funda	-5.842	< .001	Bom Jesus	Funda	2.071	0.586	Bom Jesus	Funda	7.248	< .001
Bom Jesus	Ramiro	-0.123	1.000	Bom Jesus	Ramiro	-0.123	1.000	Bom Jesus	Ramiro	0.123	1.000
Bom Jesus	ramiro	-7.001	< .001	Bom Jesus	ramiro	-7.083	< .001	Bom Jesus	ramiro	7.084	< .001
Bom Jesus	taleo	-6.645	< .001	Bom Jesus	taleo	-1.015	0.953	Bom Jesus	taleo	7.297	< .001
Funda	Ramiro	2.345	0.460	Funda	Ramiro	-1.493	0.829	Funda	Ramiro	-2.346	0.460
Funda	ramiro	-6.102	< .001	Funda	ramiro	-7.582	< .001	Funda	ramiro	6.916	< .001
Funda	taleo	-0.962	0.961	Funda	taleo	-1.907	0.661	Funda	taleo	3.024	0.204
Ramiro	ramiro	-2.213	0.520	Ramiro	ramiro	-2.212	0.521	Ramiro	ramiro	2.212	0.521
Ramiro	taleo	-2.341	0.462	Ramiro	taleo	-0.111	1.000	Ramiro	taleo	2.341	0.462
ramiro	taleo	5.843	< .001	ramiro	taleo	6.839	< .001	ramiro	taleo	-6.609	< .001

Appendix 4. 9: Comparisons soil fractions in Luanda province

Appendix 5

Huambo (Bailundo, Ngongoinga, Mungo and Lepi)

Appendix 5. 1: Chemical characteristics (macronutrients and micronutrients), pH, CEC and Base Sat-Bailundo

depth	N	Ca	K	Mg	P	S	Fe	Mn	Zn	Cu	Mo	Al	C	pH(H20)	pH(CaCl2)	CEC	Base Sat
cm	ppm															mmol.Kg	%
	Upper																
10	905.28	905.65	543.46	161.99	74.31	71.03	898.28	188.81	23.21	1.65	0.00	8030.81	14449.30	6.2	5.1	7.13	43.88
20	458.34	614.71	534.39	163.77	188.75	96.62	8881.5	142.51	11.55	4.85	0.00	20365.50	8247.47	6	4.9	4.43	45.88
30	311.37	388.04	402.6	83.16	37.67	23.19	945.2	98.04	2.39	0.00	0.00	7718.57	5527.04	6.1	5.1	-	-
40	167.16	354.6	315.44	93.17	52.58	8.05	715.7	39.96	0.1	0.00	0.00	8227.21	3737.92	5.9	5	-	-
50	77.39	399.25	362.72	139.09	4.38	6.46	1280.59	29.21	2.19	0.50	0.00	15872.14	2227.79	6	4.9	-	-
60	50.7	468.33	318.84	157.36	-2.55	6.69	731.22	10.03	0	5.78	0.00	7976.99	1697.40	6	5	-	-
	Middle																
10	1492.9	874.1	335.76	120.49	41.17	35.28	992.15	188.81	19.14	0.28	0.00	5169.75	24044.85	6.2	5.1	6.36	62.27
20	1045.77	948.58	220.11	114.76	15.15	32.56	788.7	205.11	14.98	0.68	0.00	4188.26	17193.63	6	4.9	5.56	71.23
30	717.65	1051.23	355.29	159.9	14.93	41.4	978.59	125.86	20.01	1.67	0.00	7669.39	13217.78	6.1	5.1	-	-
40	762.06	983.74	215.01	145.16	2.62	27.31	684.29	112.89	8.25	21.92	0.00	5949.55	16040.74	5.9	5	-	-
50	294.36	825.72	227.97	129.48	1.01	20.96	635.25	70.46	3.07	0.00	0.00	7085.72	8031.90	6	4.9	-	-
60	431.87	906.49	393.14	155.66	0.07	22.99	724.6	44.01	2.75	0.74	0.00	10224.23	10968.00	6	5	-	-
	Lower																
10	523.72	1214.98	755.98	204.51	165.47	75.87	2892.86	204.51	10.46	2.23	0.00	8042.42	9381.08	5.6	5	7.35	56.44
20	364.66	0	159.22	128.59	103.99	54.99	3210.86	128.59	9.11	4.24	0.00	6720.68	7856.99	5.5	4.9	7.07	54.74
30	69.29	543.85	104.27	82.2	72.49	35.43	3428.87	82.2	5.63	1.19	0.00	5791.43	3268.97	5.7	4.8	-	-
40	165.78	232.87	163.97	61.44	22.22	15.48	813.69	61.44	2.33	3.43	0.00	4353.58	4627.58	5.5	4.4	-	-
50	36.56	283.32	216.39	100.19	14.09	15.93	761.22	100.19	2.49	2.16	0.00	5080.74	1983.67	5.4	4.2	-	-
60	0	104.02	267.12	77.53	21.77	13.93	1301.68	77.53	1.73	0.35	0.00	6370.31	0.00	5	3.9	-	--

depth	N	Ca	K	Mg	P	S	Fe	Mn	Zn	Cu	Mo	Al	C	pH(H20)	pH(CaCl2)	CEC	Base Sat
cm	ppm															mmol.Kg	%
Upper																	
10	1435.09	516.98	341.84	90.82	154.99	85.71	11997.6	192.48	8.72	12.18	0.00	29410.52	49585.21	6.3	5.4	4.78	33.07
20	601.31	607.33	359.07	124.2	141.09	100.64	11096.48	180.71	7.72	4.21	0.00	23900.31	10649.37	6.4	5.1	7.07	32.1
30	190.84	0	168.87	76.55	0.83	4.59	544.41	53.7	2.88	4.48	0.00	8061.54	4505.37	6.1	5.2	-	-
40	136.29	535.44	296.52	99.43	111.4	74.6	18941.43	99.74	3.03	6.4	0.00	46872.77	3453.33	6.1	5.3	-	-
50	113.04	342.28	459.91	95.43	130.48	63.93	21519.53	81.91	3.87	9.25	0.00	51993.13	2935.12	6.1	5.5	--	-
Middle																	
10	493.41	672.96	839.18	412.7	32.63	40.86	839.18	145.31	7.97	6.92	0.00	16814.14	9668.20	5.6	4.8	5.86	18.03
20	310.38	262.34	909.4	236.16	30.07	37.83	909.4	139	4.90	0.74	0.00	17645.52	6050.92	5.5	4.7	5.25	23.85
30	2333.44	307.76	712.52	59.3	0.63	14.06	712.52	23.66	0.75	2.35	0.00	17656.12	4852.86	5.5	4.7	-	-
40	2437.27	256.28	407.18	57.53	-1.32	3.52	407.18	11.74	0.00	0.00	0.00	11227.51	3790.17	5.6	4.6	-	-
50	3451.25	25.49	645.79	-62.13	5.74	10.83	645.79	13.14	0.43	5.72	0.00	6690.70	2873.47	5.6	4.7	-	-
60	2364.11	172.18	585.59	108.93	-1.44	3.56	585.59	6.53	0.00	0.00	0.00	14174.56	2032.84	5.6	4.5	-	-
Lower																	
10	1016.45	9272.53	188.03	141.99	127.18	60.51	504.61	101.6	5.40	0.43	0.00	9272.53	23416.21	5	4.4	7.88	28.92
20	734.05	23679.08	288.31	96.7	145.4	82.16	4575.68	92.24	6.51	10.98	0.00	23679.08	14085.00	4.6	4.2	7.5	14.64
30	651.51	9381.29	592.8	145.46	12.43	31.34	1551.18	280.76	2.40	2.46	0.00	9381.29	11969.13	4.4	4.2	-	-
40	359.12	13584.81	292.48	146.73	1.08	23.06	2122.65	501.92	2.01	2.40	0.00	13584.81	7312.94	4.4	4	-	-
50	324.09	28404.09	151.14	68.83	-1.42	13.23	977.87	11.75	1.15	1.28	0.00	28404.09	6550.99	4.4	4.1	-	-
60	189.14	34758.43	412.48	96.18	130.44	74.71	5524.25	23.94	5.78	6.98	0.00	34758.43	5056.74	4.4	4.1	-	-

Appendix 5. 2: chemical characteristics (macronutrients and micronutrients), pH, CEC, and Base Sat- Ngongoinga

depth	N	Ca	K	Mg	P	S	Fe	Mn	Zn	Cu	Mo	Al	C	pH(H20)	pH(CaCl2)	CEC	Base Sat
cm	ppm															mmol.Kg	%
Upper profile																	
10	587.94	480.51	524.93	308.29	397.31	132.80	59274.32	407.65	28.60	28.72	0.10	0.00	15010.67	6.5	5.2	4.09	41.29
20	330.98	386.56	248.83	165.77	313.30	80.63	63540.85	337.29	12.20	21.85	-0.08	0.00	10257.92	6.3	5	3.95	39.29
30	147.17	468.64	256.29	193.46	318.16	58.71	69029.33	294.75	17.43	23.85	-0.23	0.00	6303.18	6.4	5.2	-	-
40	21.15	487.59	256.26	140.64	277.19	40.82	68465.16	249.11	12.83	22.33	-0.18	0.00	4076.52	6.5	5.5	-	-
50	99.91	313.39	124.82	102.21	234.21	24.93	67728.40	230.98	10.01	18.86	-0.23	0.00	3569.53	6.4	5.5	-	-
Middle profile																	
10	1424.93	1096.23	952.77	465.69	482.27	219.50	59298.90	343.81	34.37	32.73	-0.06	0.00	28050.21	5.9	5.1	9.57	41.47
20	559.14	653.41	678.99	319.88	324.71	100.98	58556.46	212.93	27.49	326.08	0.01	0.00	15927.61	5.7	4.8	9.36	23.09
30	308.94	490.14	480.68	231.19	279.78	67.96	57534.44	187.92	20.61	23.86	0.04	0.00	11787.09	5.6	4.8	-	-
40	224.42	413.81	428.01	243.61	275.68	52.30	61257.16	172.07	21.44	34.51	-0.03	0.00	8766.24	5.6	4.9	-	-
50	388.33	596.85	644.58	301.40	297.85	71.13	59293.58	198.03	29.13	29.77	0.01	0.00	10926.89	5.5	4.8	-	--
60	89.45	590.89	383.38	199.90	220.24	27.60	67464.47	321.48	17.93	26.77	-0.08	0.00	3038.30	5.7	5.4	-	-
Lower profile																	
10	265.19	155.16	1372.10	148.73	158.70	58.96	12701.49	138.08	11.27	9.51	-0.11	0.00	31574.99	6.3	6.2	8.9	10.14
20	1574.23	1499.86	475.10	451.18	374.08	167.82	18663.21	33.26	25.36	33.13	-0.07	0.00	45895.28	6.3	6.2	13.96	42.68
30	2564.00	827.51	923.60	299.96	266.39	113.39	15682.35	85.67	18.31	21.32	-0.09	0.00	74205.62	6.2	6.2	-	-
40	3316.37	3480.37	647.76	737.43	456.96	476.55	13301.86	34.18	30.48	31.14	0.00	0.00	149756.89	6.2	6.2	-	-
50	7842.48	5302.93	550.39	843.80	536.92	735.69	12287.10	22.78	24.05	27.40	-0.05	0.00	37495.15	6.2	6.2	-	-
60	1425.05	1657.80	745.13	631.06	377.00	217.42	14316.62	45.58	36.91	34.89	0.05	0.00	49585.21	6.2	6.2	-	-

Appendix 5. 3: chemical characteristics (macronutrients and micronutrients), pH, CEC, and Base Sat- Mungo

depth	N	Ca	K	Mg	P	S	Fe	Mn	Zn	Cu	Mo	Al	C	pH(H20)	pH(CaCl2)	CEC	Base Sat
cm	ppm															mmol.Kg	%
Upper																	
10	1327.45	305.12	0.50	46.65	1.30	11.03	478.37	2.75	0.17	0.52	0.15	10374.05	20590.14	6.6	4.8	2.95	18.56
20	713.16	1490.86	232.81	150.75	213.26	69.35	6641.08	224.63	14.66	7.10	0.09	7706.23	14501.03	6.4	4.7	5.97	73.18
30	236.72	1037.36	542.08	195.98	6.01	32.21	5836.59	201.55	5.98	7.40	0.15	7955.27	6102.19	6.3	4.6	-	-
Middle																	
10	538.95	831.00	524.06	158.56	13.88	43.49	876.65	162.42	4.87	3.77	0.08	8586.81	10962.55	6.4	4.9	5.23	23.51
20	280.69	766.39	446.71	173.33	0.53	27.83	2285.81	540.40	2.57	6.93	0.17	15209.56	8073.50	6.3	4.8	5.06	20.96
30	131.85	1311.85	438.28	241.82	0.77	37.32	1883.46	448.31	3.51	6.37	0.18	9546.45	4443.98	6	4.9	-	-
Lower																	
10	78.23	1821.91	499.39	216.83	270.19	82.71	5236.08	422.73	15.75	5.88	0.11	8248.07	4398.32	5.7	5.5	3.02	73.53
20	493.84	373.49	229.11	129.08	0.99	13.29	3297.93	230.83	1.08	1.28	0.19	14226.62	10271.22	5.7	5.1	7.77	27.94
30	241.51	383.40	561.70	217.73	248.90	60.56	50582.60	477.85	13.69	16.24	0.23	43108.25	4235.39	5.6	4.9	-	-

Appendix 5. 4: chemical characteristics (macronutrients and micronutrients), pH, CEC, and Base Sat- Lepi

depth	N	Ca	K	Mg	P	S	Fe	Mn	Zn	Cu	Mo	Al	C	pH(H20)	pH(CaCl2)	CEC	Base Sat
cm	ppm															mmol.Kg	%
Upper																	
10	16974.92	14417.27	10733.53	5525.09	827.22	268.39	33441.19	7000.74	8008.46	28.06	5494.85	91931.50	8361.64	6.3	6.5	4.07	60.71
20	12054.06	31920.50	11545.97	5798.99	1010.71	280.95	34273.59	7530.64	20889.43	27.58	5767.25	102160.46	7652.99	6.4	6.4	9.45	83.08
30	12003.37	33542.21	12409.45	6648.80	1741.19	283.06	35530.64	8093.82	24297.52	28.15	6612.41	110440.98	6788.38	6.2	6.3	-	-
40	11445.88	36044.79	10371.05	6048.51	1974.15	272.17	31769.33	6764.32	27133.70	25.62	6015.40	84732.90	5962.64	6.2	6.3	-	-
50	9886.31	22442.71	9857.67	6066.07	2132.28	272.96	32162.80	6429.47	16008.07	28.00	6032.87	80197.03	6657.58	6.2	6.3	-	-
60	11929.54	20810.04	11328.11	6421.18	2257.16	280.00	33361.52	7388.54	15017.43	26.73	6386.04	95055.46	7020.07	6.3	6.2	-	-
Middle																	
10	885.00	14417.27	10733.53	5525.09	827.22	268.39	38.64	11994.97	703.81	48743.76	9675.63	138670.04	13562.46	6.8	6.3	10.22	76.51
20	676.74	31920.50	11545.97	5798.99	1010.71	280.95	38.43	8482.04	758.78	41474.99	7945.23	87328.83	9891.86	6.6	6.3	10.09	84.14
30	568.69	33542.21	12409.45	6648.80	1741.19	283.06	35.71	6765.20	747.99	34716.62	6438.24	59901.30	7755.62	6.4	6.2	-	-
40	612.58	36044.79	10371.05	6048.51	1974.15	272.17	38.59	10209.68	851.81	46052.46	8957.81	110106.08	8195.40	6.4	6.2	-	-
50	611.53	22442.71	9857.67	6066.07	2132.28	272.96	37.95	10783.05	1361.47	47087.55	9587.34	120216.50	8403.76	6.3	6.3	-	-
60	541.80	20810.04	11328.11	6421.18	2257.16	280.00	38.90	11589.54	1518.64	48592.82	9814.87	130466.72	7272.96	6.2	6.3	-	-
70	495.40	10216.63	17411.89	9982.88	1002.59	697.53	37.58	11356.57	1662.50	47870.30	9928.24	124325.38	6010.31	6.2	6.3	-	-
Lower																	
10	973.13	7479.45	17417.75	8394.58	906.08	573.96	44103.99	11360.39	686.76	56.53	8348.63	121998.49	17558.9291	6.3	6.2	10.91	85.34
20	814.16	6891.47	15228.53	7746.25	957.36	488.38	40776.33	9932.51	686.62	37.99	7703.86	104834.66	11999.3044	6.3	6.2	-	-
30	763.56	6888.1	11499.06	6217.76	1221.86	445	32925.1	7500.04	767.45	37.09	6183.73	64795.08	11509.6785	6.3	6.2	-	-
40	715.95	9337.72	19913.53	9442.88	1697.39	475.17	47185.75	12988.21	3847.43	42.43	9391.2	153769.57	10950.4369	6.2	6.2	-	-
50	698.86	8927.69	18832.09	9496.01	1856.81	458.53	45822.31	12282.87	3745.25	40.6	9444.04	140981.69	10460.111	6.2	6.2	-	-
60	678.35	9345.12	19424.06	9876.84	2090.23	478.38	45365.65	12668.97	4739.6	41.18	9822.79	146433.61	10020.7791	6.1	6.2	-	-

Appendix 5. 5: Chemical characteristics (macronutrients and micronutrients), pH, CEC, and Base Sat- Bom Jesus

depth	N	Ca	K	Mg	P	S	Fe	Mn	Zn	Cu	Mo	Al	C	pH(H20)	pH(CaCl2)	CEC	Base Sat
cm	ppm															mmol.Kg	%
Upper																	
10	1777.25	30981.40	12902.40	8686.63	492.23	1171.85	37426.04	8415.34	708.29	43.66	8639.09	120185.13	24974.92	6.7	7	10.28	84.43
20	1008.62	32628.75	12748.92	8478.75	311.08	1240.31	36189.77	8315.24	998.93	43.32	8432.34	108860.91	15882.37	6.8	7	11.86	79.77
30	838.49	45908.70	12839.96	9408.80	683.14	1192.66	39571.93	8374.61	1105.29	46.98	9357.31	131652.82	16366.39	6.8	7	-	-
40	1376.93	35119.46	14930.54	8986.04	362.40	1263.29	38660.98	9738.16	918.42	44.15	8936.86	134293.55	19016.32	6.9	7		
50	400.55	152831.14	8697.92	26063.36	537.57	854.61	37801.82	5673.05	2337.00	30.82	25920.72	91482.90	56474.98	7.1	7.1		
60	203.83	224403.15	4066.83	0.00	760.12	580.00	17707.88	2652.51	2819.34	13.81	0.00	40306.86	101352.53	7.1	7.2		
Middle																	
10	889.87	117982.06	8537.70	7990.10	677.60	1027.65	30540.37	5568.55	2879.54	32.09	7946.37	81489.23	43492.89	6.9	7.1	13.21	87.89
20	551.55	98083.73	9128.16	7883.92	620.22	949.77	34316.32	5953.66	2191.45	36.64	7840.77	101149.12	15710.87	7	7.2	0	0
30	491.96	73469.92	10506.88	8742.04	659.26	1027.04	38698.06	6852.91	1673.33	39.14	8694.20	120911.73	15127.08	7	7.1		
40	546.69	46585.35	8186.90	7998.04	522.91	1010.31	35824.86	5339.74	1097.00	37.90	7954.27	87361.05	14559.85	7.1	7.2		
50	560.31	4.44	0.82	0.80	0.05	0.11	3.63	0.53	0.10	0.00	0.80	8.64	12193.85	7.2	7.2		
60	405.25	46534.35	9425.69	8331.87	575.89	1029.26	36720.11	6147.72	1138.79	39.50	8286.27	105633.91	12366.83	7.2	7.2		
70	379.44	105140.25	9375.82	8073.44	466.71	978.26	39682.44	6115.20	1927.81	34.13	8029.26	106865.35	14839.78	7.2	7.2		
80	415.76	52273.98	9976.30	8663.47	518.24	1063.85	38570.60	6506.85	1277.20	41.11	8616.06	108628.27	14145.19	7.2	7.2		
Lower																	
10	854.41	77639.73	9735.16	5630.87	264.38	1251.93	34412.89	6349.57	24364.49	47.4	5600.05	102479.32	16974.92	7	7.2	0	0
20	618.63	63333.08	9890.02	5681.34	307.6	1187.18	34555.45	6450.58	17458.31	50.18	5650.24	114534.61	12054.06	7.1	7.2	0	0
30	634.08	47266.45	9055.37	6185.89	461	1136.65	37723.09	5906.19	6910.28	46.67	6152.03	111141.91	12003.37	7	7.2		
40	459.76	112287.33	5457.51	3531.43	1366.03	1058.41	23588.89	3559.56	49254.77	35.77	3512.1	56781.27	11445.88	7	7.2		
50	390.6	105255.97	8482.88	4534.92	457.66	1267.38	29204.02	5532.79	49259.7	36.95	4510.1	86943.78	9886.31	7	7.2		
60	480.56	99439.47	7698.7	4312.49	480.15	1316.64	27808.62	5021.33	41434.76	37.99	4288.89	73203.71	11929.54	7	7.2		
70	431.26	89461.02	11090.83	4878.34	485.88	1374.93	30440.74	7233.78	32518.15	37.74	4851.64	102370	11844.85	7	7.2		
80	369.37	86555.27	10171.28	5011.72	456.97	1354.64	31975.7	6634.02	32364.56	40.46	4984.29	98057.65	11323.74	7	7.2		

Appendix 5. 6: Chemical characteristics (macronutrients and micronutrients), pH, CEC, and Base Sat- Funda

depth	N	Ca	K	Mg	P	S	Fe	Mn	Zn	Cu	Mo	Al	C	pH(H20)	pH(CaCl2)	CEC	Base Sat
cm	ppm															mmol.Kg	%
Lower																	
10	706.54	1971.97	18358.73	11181.7	123	222.96	54396.6	11974.13	209.66	45.98	11120.51	80846.48	8206.54747	7.6	6.7	12.43	87.13
20	528.96	1484.21	17155.64	12613.97	135.23	115.15	58971.37	11189.44	158.85	39.7	12544.93	83054.28	4490.4225	7.5	6.5	14.86	89.23
30	431.24	1207.47	17357.06	12283.52	159.02	104.43	58595.78	11320.8	134.5	39.96	12216.3	88955.7	3735.02594	7.2	6.4		
40	562.59	1246.34	16046.79	11559.63	163.24	99.22	54499.94	10466.21	129.59	36.57	11496.36	78006.07	4282.42036	7.1	6.4		
50	528.66	1531.5	19112.67	13063.49	179.01	125.95	60601.34	12465.87	147.33	41.62	12991.99	106278.09	3724.42333	6.9	6.3		
60	874.73	1918.81	20064.66	13161.95	146.57	206.38	64363.84	13086.79	209.48	44.14	13089.91	101571.36	7632.6722	6.7	6.3		
Middle																	
10	1018.99	4200.45	22581.43	13401.48	167.68	309.64	52190.25	14728.3	329.56	50.56	13328.14	72790.63	6618.50	6.6	6.6	16.84	87.54
20	1314.44	4210.96	23790.28	14283.84	181.35	276.84	58777.42	15516.75	309.91	54.84	14205.66	84007.97	9293.66	6.5	6.5	16.84	62
30	932.99	4117.65	23967.63	14967.28	198.11	267.13	63216.08	15632.43	352.61	57.24	14885.37	90245.33	7093.75	6.4	6.5		
40	810.49	3604.86	21683.62	14141.09	196.47	196.22	60512.95	14142.72	244.34	54.08	14063.7	89686.01	5847.28	6.5	6.5		
50	308.13	3832.22	14410.53	10476.07	186.03	193.25	81212.15	9398.99	195.47	58.25	10418.74	89514.31	4040.17	6.5	6.6		
60	212.14	4071.8	14481.78	10743.46	263.88	136.3	67278.09	9445.46	209.23	53.34	10684.66	82955.68	3072.90	6.5	6.5		
70	266.04	0	0	0	0	0	0	0	0	0	0	0	3535.78	6.5	6.5		
80	0	5367.68	13645.18	11491.15	278.46	104.05	62076.46	8899.81	213.39	64.58	11428.25	81494.63	0.00	6.5	6.5		
Lower																	
10	511.96	2411.77	6886.13	3149.16	279.76	206.01	19464.83	4491.35	151.79	12.38	3131.93	38352.92	9658.27196	6.6	6.5	8.86	90.97
20	450.81	2616.22	8886.29	4180.25	100.95	221.87	27090.26	5795.91	153.38	15.18	4157.37	55227.15	8521.2516	6.6	6.4	8.63	81.45
30	350.19	2180.19	8956.62	4416.29	145.35	190.45	30361.16	5841.78	125.8	20.29	4392.12	64528.1	5715.34133	6.6	6.5		
40	340.9	2335.7	9614.89	4856.19	1111.99	197.69	32800.09	6271.13	138.17	20.9	4829.62	69767.68	6519.49433	6.6	6.6		
50	136.83	2302.4	9854.47	5193.94	185.18	118.71	37213.89	6427.39	110.81	27.65	5165.51	80005.56	3355.60361	6.6	6.5		
60	84.51	2527.82	11114.5	6225.24	203.42	116.91	40991.5	7249.22	113.54	27.82	6191.17	86419.7	3235.43375	6.6	6.4		
70	146.45	2525.91	10260.12	5753.59	158.02	91.35	38279.56	6691.96	112.46	25.16	5722.1	80846.01	3620.42885	6.6	6.4		

Appendix 5. 7: Chemical characteristics (macronutrients and micronutrients), pH, CEC, and Base Sat- Talelo

depth	N	Ca	K	Mg	P	S	Fe	Mn	Zn	Cu	Mo	Al	C	pH(H20)	pH(CaCl2)	CEC	Base Sat
cm	ppm															mmol.Kg	%
Upper																	
10	92.91	181.83	1129.58	214.9	49.66	71.49	1970.16	736.75	12.37	7.65	213.72	8510.41	1607.10	8	5.9	3.23	50.53
20	41.29	41.55	810.38	158.44	137.35	52.57	1691.73	528.56	1.89	0.92	157.57	5575.95	1200.49	8	5.4	3.59	33.15
30	50.27	276.63	1149.84	264.75	127.22	59.87	2176.4	749.96	16.25	2.17	263.31	8355.62	950.09	7.9	5.9		
40	48.66	160.48	991.37	198.29	129.32	49.7	2195.35	646.6	13.03	24.31	197.21	7680.43	791.85	7.7	5.6		
50	13.45	85.94	1102.84	200.08	21.41	55.5	2257.63	719.31	191.08	2.67	198.98	9407.94	447.16	7.3	5.5		
60	38.79	0.00	995.17	186.89	37.52	40.90	2389.57	649.08	0.00	0.84	185.87	9294.58	696.47	7.4	5.5		
Middle																	
10	50.57	85.61	1040.74	160.33	42.32	84.4	1945.97	678.8	27.89	0.41	159.45	8556.37	1261.12	7.1	5.3	13.21	87.89
20	76.97	834.71	731.26	269.42	253.51	104.69	2209.14	476.95	16.67	11.08	267.95	7601.2	2049.69	7.1	5.1	3.48	53.99
30	0	712.3	889	276.98	119.61	91.17	2308.98	579.83	8.94	1.97	275.46	0.00	46.56	7	5.3	3.02	46.96
40	18.27	734.99	910.14	305.09	111.73	81.46	2539.11	593.62	13.29	31.11	303.42	10706.61	626.03	6.9	5.4		
50	24.68	0.00	976.55	169.63	22.77	68.27	2278.07	636.93	0	3.71	168.7	9963.59	518.93	6.7	5.4		
60	17.9	0.00	902.18	159.96	46.22	62.03	2213.53	588.43	74.02	3.37	159.08	8779.76	614.82	6.2	5.4		
70	15.83	135.6	635.84	119.84	33.64	34.42	1474.46	414.72	6.33	1.52	119.18	4661.16	419.06	6.2	5.3		
80	16.45	140.35	790.88	157.44	110.11	38.19	1905.56	515.83	10.66	5.18	156.58	7053.1	353.23	6.2	5.4		
90	0.00	59.59	567.8	94.72	55.49	25.23	1302.4	370.34	6.56	0.57	94.2	4514.77	0.00	6.2	5.4		
Lower																	
10	66.62	442.4	761.42	199.88	223.58	69.67	1622.85	496.62	43.69	6.38	198.79	4115.05	1439.70	6.5	5.2	4.48	46.46
20	60.46	209.93	556.35	160.73	188.65	58.42	1602.99	362.87	18.4	6.7	159.85	3742.23	1175.20	6.6	5.1	-1.67	243.38
30	58.24	137.59	1025.26	231.84	501.84	76.75	2416.32	668.71	20.22	6.81	230.57	8737.98	1164.16	6.3	5		
40	8	262.68	885.2	239.26	92.39	52.34	2390.7	577.36	24.37	2.04	237.95	7660.61	658.99	5.6	4.9		
50	32.32	205.06	1207.44	255.63	103.08	132.46	3523.63	787.53	19.03	4.98	254.23	10633.87	706.48	5.7	4.6		
60	33.01	154.11	1078.9	228.5	284.4	58.58	2793.54	703.69	27.02	7.14	227.25	8778.6	606.21	5.4	4.6		
70	34.63	8.22	1037.78	205.1	0	45	2622.38	676.87	2.75	1.07	203.97	9618.46	589.34	5.4	4.6		
80	45.34	143.05	1304.04	280.26	62.14	47.82	3143.16	850.53	15.45	5	278.73	12182.36	567.58	5.5	4.6		
90	35.58	81.72	832.12	184.23	61.07	35.9	2618.87	542.73	8.23	2.37	183.23	5563.56	745.80	5.6	4.7		
100	0	140.84	1930.46	424.26	86.41	52.52	4405.39	1259.1	18.71	1.61	421.94	0.00	0.00	5.4	4.6		

Appendix 5. 8: Chemical characteristics (macronutrients and micronutrients), pH, CEC, and Base Sat- *Ramiro*

Appendix 5. 9: post-hocs comparison sites (N)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 10: post-hocs comparisons-site (Ca)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 11: post-hocs comparisons-site (K)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 12: post-hocs comparisons (Mg)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 13: post-hocs comparisons-site (P)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 14: post-hocs comparisons-site (S)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 15: post-hocs comparisons-site (Fe)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 16: post-hocs comparison-site (Mn)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 17: post-hocs comparisons-site (Zn)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 18: post-hocs comparisons-site (Cu)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 19: post-hocs comparisons-site (Mo)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 20: post-hocs comparisons-site (AL)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 21: post-hocs comparisons-site (**pH(H_2O)**)

Comparison								
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

Note. Comparisons are based on estimated marginal means

Appendix 5. 22: post-hocs comparisons-site (pH(CaCl2))

Comparison								
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

Note. Comparisons are based on estimated marginal means

Nutrient versus profile

Appendix 5. 23: post-hocs comparison-profile (N)

Comparison								
profile		profile	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
1	-	2	1446.17	508	144	2.8478	0.014	0.015
	-	3	1440.57	510	144	2.8263	0.015	0.016
2	-	3	-5.60	478	144	-0.0117	1.000	1.000

Note. Comparisons are based on estimated marginal means

Appendix 5. 24: Post Hoc Comparisons – profile/**Ca**

Comparison								
profile		profile	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
1	-	2	3485	6931	144	0.5028	0.870	1.000
	-	3	673	6957	144	0.0967	0.995	1.000
2	-	3	-2812	6522	144	-0.4311	0.903	1.000

Note. Comparisons are based on estimated marginal means

Appendix 5. 25: Post Hoc Comparisons – profile**/K**

Comparison								
profile		profile	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
1	-	2	251	1393	144	0.180	0.982	1.000
	-	3	947	1398	144	0.677	0.777	1.000
2	-	3	696	1311	144	0.531	0.856	1.000

Note. Comparisons are based on estimated marginal means

Appendix 5. 26: Post Hoc Comparisons – profile/**Mg**

Comparison								
profile		profile	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
1	-	2	423	963	144	0.439	0.899	1.000
	-	3	1642	966	144	1.699	0.209	0.274
2	-	3	1219	906	144	1.346	0.372	0.542

Note. Comparisons are based on estimated marginal means

Appendix 5. 27: Post Hoc Comparisons – profile/**P**

Comparison								
profile		profile	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
1	-	2	47.3	112	144	0.423	0.906	1.000
	-	3	20.5	112	144	0.183	0.982	1.000
2	-	3	-26.7	105	144	-0.254	0.965	1.000

Note. Comparisons are based on estimated marginal means

Appendix 5. 28: Post Hoc Comparisons – profile/**S**

Comparison								
profile		profile	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
1	-	2	6.77	78.0	144	0.0867	0.996	1.000
	-	3	-86.52	78.3	144	-1.1048	0.513	0.813
2	-	3	-93.28	73.4	144	-1.2706	0.414	0.618

Note. Comparisons are based on estimated marginal means

Appendix 5. 29: Post Hoc Comparisons – profile/**Fe**

Comparison								
profile		**profile**	**Mean Difference**	**SE**	**df**	**t**	p_{tukey}	$p_{bonferroni}$
1	-	2	7153	4776	144	1.498	0.295	0.409
	-	3	9877	4794	144	2.060	0.102	0.123
2	-	3	2723	4494	144	0.606	0.817	1.000

Appendix 5. 30: Post Hoc Comparisons – profile/**Mn**

Comparison								
profile		**profile**	**Mean Difference**	**SE**	**df**	**t**	p_{tukey}	$p_{bonferroni}$
1	-	2	-110	945	144	-0.116	0.993	1.000
	-	3	653	948	144	0.689	0.771	1.000
2	-	3	763	889	144	0.858	0.668	1.000

Note. Comparisons are based on estimated marginal means

Appendix 5. 31: Post Hoc Comparisons – profile/**Mo**

Comparison								
profile		**profile**	**Mean Difference**	**SE**	**df**	**t**	p_{tukey}	$p_{bonferroni}$
1	-	2	133	987	144	0.135	0.990	1.000
	-	3	1670	991	144	1.685	0.214	0.282
2	-	3	1537	929	144	1.654	0.227	0.301

Note. Comparisons are based on estimated marginal means

Appendix 5. 32: Post Hoc Comparisons – profile/**Al**

Comparison								
profile		profile	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
1	-	2	5065.1	9647	144	0.52504	0.859	1.000
	-	3	5128.5	9683	144	0.52965	0.857	1.000
2	-	3	63.4	9078	144	0.00699	1.000	1.000

Note. Comparisons are based on estimated marginal means

Appendix 5. 33: Post Hoc Comparisons – profile/**pH(H_2O)**

Comparison								
profile		profile	Mean Difference	SE	df	t	p_{tukey}	$p_{bonferroni}$
1	-	2	0.327	0.132	144	2.47	0.039	0.044
	-	3	0.660	0.133	144	4.96	< .001	< .001
2	-	3	0.332	0.125	144	2.67	0.023	0.026

Note. Comparisons are based on estimated marginal means