Soil fertility constraints to small-scale agriculture in North-west Zambia

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DECLARATION

I, the undersigned, hereby declare that the work contained in this Masters thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

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ABSTRACT

The soils of north-west Zambia are largely unexplored and are regarded by local residents as problematic in providing sufficient nutrients for the staple crop of maize in the area. The area is semi-tropical, with an average rainfall of 1300mm annum^{-1} falling predominantly in the summer. The undulating landscape is dominated by *miombo* woodland interspersed with savanna grassland. Little work has been done on these soils and further information is required to understand their origin and their fertility status. The main objectives of this thesis were: 1) to classify and sample soils from a large number of small-scale agricultural lands, 2) to develop a better understanding of these soils chemical characteristics, 3) to determine the effect of vegetation clearance on soil fertility by sampling adjacent uncultivated land, and 4) to test locally derived rock dust as a soil ameliorant in pot trial.

Soils from 100 agricultural and adjacent bush/forest sites were classified and analysed to determine their fertility status. They were tentatively classified according to the WRB system and are dominated by Arenosols, Acrisols and Ferralsols with infrequent occurrences of Lixisols. Most of these soils have a sandy texture. The clay fraction comprises of gibbsite, kaolinite and hydroxyl-Al interlayered vermiculite (HIV), with a few soils also having some mica present. The soils are consistently acidic with 42% of soils sampled having a pH (KCl) <4.3. Furthermore, the subsoils proved to be equally if not more acidic than the topsoils. Low nutrient levels are invariably associated with the soil acidity, with 84% of soils having <15mg/kg P, 59% of soils <50 mg/kg K, 80% soils <300 mg/kg Ca, and 44% soils <80 mg/kg Mg.

Comparisons between cultivated and bushland soils showed no consistent changes to the soil acidity and fertility. This is contrary to research that was reviewed but is likely to have been affected by the spatial variability of these soils arising from the termite dominated landscape and the soils having been derived from different parent materials.

Amelioration of these soils is required in order to increase yields. It is thought that lime, used with an N, P, K, Zn and B fertilizer, will best remedy the deficiencies found in these soils. Using these nutrients could raise the yields of <1t.ha^{-1} to in excess of 5 t.ha^{-1}. Local soil ameliorants of crushed rock, ash, compost, green manure and termite mounds were also considered with pulverised granite being tested through factorial pot trials to determine its usefulness as a

source of K and alkalinity. It raised both soil pH and K levels but is of limited value as these rises were not significant enough to affect yield. It is recommended that future research should: 1) strategically sample across the district, classify soils and determine their fertility status; 2) compile a soil yield potential map and 3) undertake field trials to test the quantities and effectiveness of fertilizers alongside local soil ameliorants.

OPSOMMING

Die grootliks onverkende gronde van noord-wes Zambia word deur die plaaslike bewoners beskou as problematies vir die verskaffing van voldoende voedingstowwe vir die verbouing van mielies, die stapelvoedsel van die area. Die area is half-tropies, met ‘n gemiddelde reënval van 1300mm per jaar in ‘n jaarlikse reënseisoen. Die rollende landskap word gedomineer deur *miombo*-woude met savanna-grasvelde plek-plek tussenin. Min werk is reeds op hierdie gronde gedoen en verdere inligting word benodig om hul oorsprong en die vrugbaarheidstatus te verstaan. Die hoofdoelwitte van hierdie tesis was: 1) om gronde van ‘n groot aantal klein-skaalse landboulande te monster en te klassifiseer; 2) om ‘n beter begrip van die grondchemiese eienskappe te ontwikkel; 3) om die invloed van verwydering van vegetasie op vrugbaarheid te bepaal deur aangrensende, onbewerkte land te monster; en 4) om plaaslike rotsstof as ‘n grondverbeteringsmiddel in potproewe te toets.

Gronde van 100 landbou en aangrensende bos/woud areas is geklassifiseer en ontleed om hulle vrugbaarheidstatus te bepaal. Hulle is tentatief geklassifiseer volgens die WRB-sisteem en word gedomineer deur Arenosols, Acrisols en Ferrasols met ‘n seldsame voorkoms van Lixisols. Meeste van hierdie gronde het ‘n sanderige tekstuur. Die kleifraksie bestaan uit gibbsiet, kaoliniet en hidroksie-Al tussengelaagde vermikuliet (HIV). By sommige gronde is mika ook teenwoordig. Die gronde is altyd suur, Van die gronde wat ontleed is het 42% ‘n pH (KCl) < 4.3. Verder is bewys dat die ondergronde net so, indien nie suurder as die bogronde is nie Lae voedingstofvlakke word gereeld geassosieer met die grondsuurheid; 84% van die gronde het < 15mg/kg P, 59% < 50 mg/kg K, 80% < 300 mg/kg Ca en 44% < 80 mg/kg Mg.

Vergelykings tussen bewerkte en boslandgronde het geen konstante verandering in die grondsuurheid en grondvrugbaarheid getoon nie. Dit is in teenstelling met ander navorsingsresultate oor hierdie onderwerp, en is waarskynlik beinvloed deur die ruimtelike variansie van hierdie gronde wat afkomstig is vanaf die termiet gedomineerde landskap asook vanaf verskillende moedermateriale.

Verbering van hierdie gronde is nodig om opbrengste te verhoog. Daar word voorgestel dat kalk, saam met N-, P-, K-, Zn- en B-bemestingstowwe bebruik word om die tekorte wat in hierdie gronde gevind word, te verbeter. Die gebruik van hierdie voedingstowwe kan die opbrengs van < 1t.ha^{-1} tot meer as 5t.ha^{-1} verhoog. Plaaslike grond verbeteringsmiddels van

gebreekte rots, as, groenbemesting en termiethope is ook oorweeg. Fyn gemaalde graniet is getoets is met behulp van faktoriale potproewe, om die bruikbaarheid daarvan as ‘n bron van K en alkaliniteit te bepaal. Dit het beide die grond pH en K-vlakke verhoog, maar is van beperkende waarde om rede die verhoging nie betekenisvol genoeg was om die opbrengste te affekteer nie. Vir toekomstige navorsing word aanbeveel dat: 1) monsters strategies deur die distrik geneem word en dat hul klassifiseer en die vrugbaarheidstatus bepaal word; 2) stel ‘n grondopbrengs potensiaalkaart op; en 3) onderneem veldproewe en toets die hoeveelheid en effektiwiteit van bemestingstowwe teenoor plaaslike grond verbeteringsmiddels.

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INTRODUCTION

"For agriculture to have an appreciable effect on reducing poverty, the sector clearly must generate much greater gains in production and productivity to offset the growth in rural population" (Zulu, et al., 2000 p.31).

For the subsistence farmer in Mwinilunga district, NW Zambia, yields are consistently sub-optimal, with "food insecurity being prevalent…[and] households dependent on maize having shortages from December to March" (Kamwi et al., 2003 p.23). According to a government assessment conducted by Kamwi et al. (2003), the provision of health and education is "very poor" with only 23% of children completing primary school (Central Statistics Office and ORC, 2003). Unlike adjoining districts of northern Zambia, the area has no copper mines with poor access roads, no mains electricity, reliable water supply and only basic medical provisions. These issues are pertinent to the Millennium Development Goals (MDGs) (United Nations, 2000).

Soil is a valuable resource on which a nation's survival depends as its fertility or infertility affects agricultural productivity which, as Zulu et al. (2000) have stated, is crucial to production to feed the masses. The trend for maize production from small-scale farmers in Zambia shows a general decline of 2.2% annually (Zulu et al., 2000) and there are years when Zambia is a net importer of grain and the subsistence farmer is faced with extreme hunger (Gruhn et al., 2000). According to Gruhn et al. (2000) part of the explanation for this decline is the mismanagement of soil nutrients and their availability. Rainfall is seldom a limiting factor in the country, especially in the NW area which receives the highest rainfall.

By increasing soil productivity sustainably over time labour inputs could be reduced and maize production increased, reducing hunger and poverty. In order to address this successfully in the long term, an understanding of the soil fertility status is required (Kamprath, 2000), which must be done through a study of soil chemical and physical properties together with the identification and alleviation of other constraints, such as access to fertilizers, medical provisions and clean water, to sustainable agriculture (Sanchez et al., 2007).

The Mwinilunga soils were surveyed in 1982 by Ting-Tang et al. (1984) who undertook an exploratory soil survey building on earlier geological mapping undertaken during the 1950s and 1970s (Thieme and Johnson, 1974). The survey covered 3 districts in NW Zambia; however, the scope of the survey limited the scale of its application and thus a village level understanding of the key soil properties is required in order for yield potential to be understood and productivity to be raised. A pedological study at the village-level, sampling soils of farmers at different villages, combined with fertility analysis would meet these requirements.

From the soil descriptive work done by Ting-Tang et al. (1984) it appears that the soils are dominated by Arenosols derived from the Kalahari sands, with transitional soils (Ferralsols) and residual soils between the Kalahari sands also being common. In general the soils were considered to be of “low potential” with regard to agricultural productivity (Ting-Tang et al., 1984). Laboratory analysis by Ting-Tang et al. (1984) showed that the soils are acidic (pH in $CaCl_2 < 4.5$), have exchangeable Al (with acid saturation often >20%), low base status (<10% base saturation) and a predominantly kaolinitic clay fraction. Arenosols and Ferralsols in tropical areas are not necessarily of a low potential as fertilisers or other nutrient inputs can raise productivity (Bationo et al., 2006). The effectiveness of conventional fertilisers and their application to crops such as maize is well understood (Tisdale et al., 1994). Still, the effectiveness and requirements of non-conventional amelioration materials which are locally available such as crushed granite, manure, ash and compost are less well known. This thesis also seeks to explore the chemical composition and dissolution rate of such non-conventional ameliorants in order to assess their effectiveness in raising yield.

The objectives of this study were therefore:

1. to investigate the origin and formation of the soils in Mwinilunga district of north-west Zambia
2. to describe the soil types of the district and develop an understanding of their fertility status
3. to assess actual and potential yields of staple crops such as maize and cassava, and
4. to identify locally appropriate techniques for soil amelioration with a view to improving productivity.

Following a review of literature on tropical soil fertility in chapter 1, the first three objectives are addressed in chapter 2 while the fourth objective is focussed on in chapter 3 which reports an experimental study on the suitability of powdered rock as a soil ameliorant.

CHAPTER 1

Soil fertility constraints to agriculture in the tropics – a review

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1.1 Introduction

Research into agricultural productivity in the tropics has intensified over the past 40 years (Sarr, et al., 2005; Dierolf et al., 1997; Jha et al., 1996; Ritchey et al., 1982; Mokwunye and Melsted, 1973). As tropical regions experience land pressure from population growth, urbanisation and land clearance (Stocking, 2003) the need increases for appropriate local research (Palm et al., 2001). Many traditional practices have broken down and small-scale farmers in particular have removed large quantities of nutrients from their soils without much replenishment (Stocking, 2003; Sanchez, 2002). Appropriate management for meeting food demand is now a high research priority (Oenema et al., 2006). The objective of this chapter is to review recent research and how this has improved our knowledge of soil fertility in tropical regions.

1.2 Why acid soils exist in the tropics

"Acid soils are widespread in the humid and savannah regions of the world and predominant in the tropics" (Moniz et al., 1997 pvii). This section seeks to explain how such soils arise. Many parts of the tropics experience a high rainfall; this sees the onset of hydrolysis reactions which are progressively acidifying and long-term leaching of bases throughout the soil profile (Rowell, 1994). Parent material also plays a role in terms of buffering these reactions and if it is not basic, acidity is probable and its rate accelerated. Microbial respiration and the releasing of CO_2, which can transform to H_2CO_3 in water, can also acidify a system and Schroth et al. (2000) found that the common warm damp conditions of the tropics often promote this. Furthermore poor fertiliser choice and application can worsen the system, promoting acidification. A combination of some or all of the above leads to highly leached acidic soils with their associated Al toxicity as shown by Lilienfein et al. (2003) in Brazil. Al toxicity associated with acid soils in the tropics is much reported in literature, for example Brazil (Lilienfein et al., 2003), Kenya (Bationo et al., 1986), Tanzania (van Straaten, 2002), Zambia (Sakala, 1998) and South Africa (Farina et al., 2000).

It has also been reported in the tropics that some topsoils are more acidic than their subsoils (Horst, 2000). This is best explained by vegetation (be it ‘natural’ or agricultural) depleting the base rich soil by an acid secretion mechanism for cation uptake (Raven and Johnson, 2002) with the soil re-receiving only some of the bases in the form of organic matter. The continuation of this cycle coupled with leaching down the profile results in the CEC of the soil also being lowered, possibly to depletion, and concomitantly pH falls. This gives rise to a separate facet of acidity that is problematic in the tropics, namely subsoil acidity. Alva and Sumner (1990), Sumner (1993) and Garrido et al. (2003) all worked on the problem of subsoil acidity and highlighted the limitations of Al toxicity that this poses to crops and their roots. Sumner (1993) and Farina et al. (2000) among many others suggest various methods to counteract this, namely the application of gypsum or deeply incorporated agricultural lime.

1.3 Macronutrient availability

1.3.1 N

Nitrogen is frequently the nutrient element that limits yields in the tropics with a very high average annual depletion rate of 22 kg N per hectare of cultivated land over the last 30 years in sub-Saharan Africa (Sanchez, 2002) and, according to Shitumbanuma et al. (2007), it is the most limiting nutrient to crop production in most Zambian soils. In many tropical agroecosystems much of the N inputs are transformed to NO_3^- due to the heat and moisture and the majority is not taken up by plants but leached out of the system (Matson et al., 1999). Tropical regions with a dry season and a rainy season experience this in particular as the NO_3^- accumulates during the dry season but, if not utilised by plants, it is leached from surface soils. This then mobilizes a cation as the base cation supply is progressively depleted, and the leached cation will either be a proton or mobilized Al, both negative to plant growth. Managing N losses and its potential for further acidifying an acid system are pertinent to tropical agriculture (Shitumbanuma et al., 2007).

Stevenson (1982) proposed that in order to combat losses N transformation pathways need to be identified for the different tropical ecosystems in order to better understand N losses to a system. Using the approach of identifying loss pathways Vitousek and Matson (1988) have worked on reducing N losses in Hawaiian tropical forests and Solìs and Campo (2004) in the dryer areas of Mexico. Their work confirms long-standing knowledge on N loss pathways. More recently, Lemaire et al. (2007) have undertaken research to identify the most efficient and effective crops pertaining to per unit N uptake in order to better manage known loss pathways. They found that in the tropics C_3 pathway plants and dicotyledons had a higher N uptake per unit mass and therefore were more effective utilisers of soil N. They endeavoured to build on this platform and develop a model simulating N uptake of any given species in a given tropical environment, ultimately meaning completely effective management of N.

Until research such as that of Lemaire et al. (2007) reaches completion, insufficiency of N in tropical soils needs addressing in order to meet crop requirements; there are many options available, including making use of commercial fertilisers (Bornman et al., 1993; Eickhout et al., 2006). As a result of higher temperatures and rainfall, research in the Philippines by Sheehy et al., (2005) has shown that fertilisers must be applied in several split dressings to ensure sufficiency throughout growth, but this is often not cost effective and results in very high N losses. Recent research in Zimbabwe undertaken by Mbwera (2007) showed that application of DPRC-TSP-blended pellets added to cattle manure acted not only as source of N, but also provided some P and lowered the pH in the manures to a degree that nitrogen losses were reduced. Farmers could then apply the manures in the traditional way resulting in yield increases of up to 50%, largely attributable to elevated N and P levels.

Supplementary to conventional fertilisers, farmers can utilize many different N sources. One possibility is the non-symbiotic N-fixing bacterium *Azotobacter* (aerobic) or *Clostridium* (anaerobic) which is less common than the symbiotic *Rhizobium* bacteria. *Rhizobium* was and is traditionally used in crop rotation and mulching in much of the tropics (Troeh and Thompson, 2005). More recent research has capitalised on this symbiotic relationship working on inoculation methods of rhizobium. Sarr et al. (2005) undertook research with dissolved alginate beads containing *Rhizobia* and they found that this was the most effective method to improve crop growth when compared to manure or other sources of N. This improvement was explained by a more steady-state release of N, minimising losses and maximising uptake.

Manure has been used in farming for many generations and Seobi (2007) showed that its application to maize in South Africa over 3 years reduced N fertilizer requirements over that period. Hseu and Huang (2005) also indicate that sewage sludge can be of benefit to tropical agriculture. Loses through volatilization are high with high moisture regimes and temperatures.

It has been much debated as to whether the tradition of '*slash and burn'* is of more harm than good (Miller and Kauffman, 1998; Bauhus et al., 1993). Ellingson et al. (2000) undertook a study in Mexico over 2 years and showed that while the practice increased both N and pH, this was short-lived and in the long term the overall result was negative. This seems to reflect the general picture in the literature and thus is not viewed as an effective means of providing N in the long term.

Earthworms and their casts are also known to positively affect mineralization and thus the available pool of N in soils (Mariani et al., 2007). Where earthworms are not present in tropical soils, termites often exist and generally their functions have been shown to be similar to that of earthworms (Breuning-Madsen et al., 2007). This requires that there is N present for mineralization to occur and so should not be viewed as an N source.

1.3.2 P

In the tropics there are often low concentrations of available P and its poor solubility render it a nutrient that is often present but not available for plant use. George et al. (2006) and Vanlauwe and Giller (2006) explain that, contrary to N, the biological means to enhance its availability are limited. In tropical soils low P availability is exacerbated by *specific* sorption reactions, particularly with sesquioxides as they have an affinity for P, forming very stable complexes (McBride, 1994; McBride, 2000; Sharpley, 2000). Parfitt (1980) suggests that strongly leached tropical soils often have large amounts of variable charge arising from the amphoteric nature of the FeOH and/or AlOH groups which are likely to be dominant in a highly leached acidified system. At low pH ranges these surfaces hold a net positive charge and thus there is the potential for the sorption of anions, specifically P (Parfitt, 1980; Bloom, 2000). George et al. (2006) used sorption isotherms to show that leached, low pH, sesquioxide rich soils of the tropics experience high P sorption. In terms of managing these soils Cassia de Brito Galvao et al. (2007) explain that in order to increase P availability and to ensure its availability, soil pH needs to be raised to the point of zero charge (PZC).

To this end, research undertaken in Western Kenya on acid soils low in P shows that the application of traditional rock P applied with cattle manure treatments resulted in a continued and slow release of P. This was comparable to triple superphosphate as it was associated with a gradual raising of soil pH near to PZC (Thuita et al., 2007). Conversely Bationo et al. (1986) showed that in order to reach agronomic effectiveness, farmers must plan for rock P dissolution in the top 15cm over the soil of 3 years. The limitation of using rock P in many of the tropical areas, particularly to the more short-term smallholder farmers, is its low solubility.

In terms of other sources of P research work undertaken in Brazil by Fonseca et al. (2007) looked into the possibility of using reservoir sediments as a soil P ameliorant. However, they found that little P was available as it was complexed with the Fe and Al in the sediments. This concurs with Shitumbanuma et al. (2007) that sourcing P to ameliorate deficiencies is often challenging and thus working on increasing the availability of the P present is perhaps more appropriate. Ma et al. (2007) undertook research to investigate how the [CO_2] affects P availability in rice fields in China. It seems that under elevated [CO_2], soil P availability increased and thus they concluded that a means of managing limited P availability is to manage the [CO_2].

Kidd et al. (2007) investigated the bioavailability of P with the application of sewage sludge, conducting experiments in southern Spain over 10 years. They found that sewage sludge increased soil pH and Olsen-extractable P, but this was dominated by inorganic forms of P this is only useful when specific crops known to 'unlock' or make available inorganic P (such as legume crops or buckwheat) or if conditions are carefully considered such as when superphosphate, an inorganic P fertilizer, is applied.

Kwabiah et al. (2003 p.53) identified *Tithonia diversifolia* and *Croton megalocarpus* as "having the potential to release adequate P to replenish solution P for crop uptake" and Ndung'u et al. (2007) found the same in Western Kenya. The implication for tropical agriculture is that a viable and alternative source of P has been identified where other options are not plausible.

1.3.3 K

The bulk of soil K is unavailable in mineral form; however, some is fixed between adjacent tetrahedral layers of dioctahedral and trioctahedral micas, vermiculites and intergrade clay minerals (Sparks and Huang, 1985). K is often limited in tropical soils due to leaching in high rainfall areas and few sources of K, especially in sub-Saharan African (van Straaten, 2007). The burning of crop residues or bush clearing often releases K into the soil system, but this needs to be incorporated or it is easily lost from the soil system (Sanchez, 1976). Juo and Manu (1996) researched K losses in an agricultural system and found that where burning occurs K is often lost through plant uptake and soil loss through leaching, runoff and erosion.

Where soil K is limited it is useful and important to consider how best to apply and manage K and make K optimally available. To this end Le Roux and Sumner (1968) discuss the application of the quantity (Q)/intensity(I) (Q/I) concept with specific reference to soil K. In essence this concept explains that where there are low quantities of K present in a soil, if a plant shows a preference for K it can give rise to a higher potential buffer capacity (BC) by raising the I.

Unlike P there are no reported plants that significantly raise soil K levels. Traditionally potash is used to supply soils with the K required for a crop, and this is replenished each season with further applications (Dhanorkar et al., 1994). Manures and waste compost are often used to add K to soils, as Bhattacharyya et al. (2007) did on experimental rice-land plots in India. They compared the effectiveness of compost and manure as a source of K both with and without conventional K fertilizers. They found compost supplemented with low amounts of fertilizers were more efficient than K fertilizer alone. This is because it had a lower initial availability and then slowly became plant available. The residual K becomes more available due to the action of organic acids liberated during decomposition of organic matter (Dhanorkar et al., 1994).

1.3.4 Ca and Mg

In tropical agriculture the method of meeting crop demand of Ca and Mg is met via one of three pathways. Firstly through slash-and-burn (Zingore et al., 2007) supplemented with ad hoc addition(s) of ash and or manure or compost as farmers re-farm land with reduced fallow periods (Hőlscher et al., 1997). Secondly calcitic or dolomitic lime or gypsum is used in order to reach sufficiency or optimum levels for different crops (Bornman et al., 1993; Tri-state Fertilizer Recommendations, 1997) and thirdly, crop mulching. Juo and Manu (1996) found that mulching crop residue on a kaolinitic Alfisol in Nigeria kept Ca levels high and Mg levels double to that of no mulching but this requires sufficient crop rotation and fallow for effectiveness. As one or more of these practices is systematically followed, Ca and Mg requirements can be met.

1.3.5 S

“Widespread sulfur deficiencies and responses have been reported all over the tropics” (Sanchez, 1976, p.281). Such deficiencies have been recorded in both savannah soils and soils that have been recently cleared of virgin forests; in Sub-Saharan Africa S is limiting in

Alfisols and Oxisols with an annual rainfall >600mm (Acquaye and Kang, 1987). Additionally S deficiencies have been reported in Australia (ACIAR, 1998), Asia (Hitsuda, 2000) and Hawaii (Sanchez, 1976). In the past many fertilisers included the element in their composition (e.g. single superphosphate, ammonium sulfate or potassium sulfate) (Scherer, 2001) and it was generally considered that atmospheric S inputs were supplying adequate amounts of the element. However this viewpoint has changed with the report of S deficiencies.

Research into S deficiencies in both plants and soils has been more recent and in response to observations of the phenomenon (Seward, 2007; ACIAR, 1998). Solomon et al. (2001) undertook work in Ethiopia comparing the S distribution of soils that were under forestry with those of fertilised tea plantations of 25 years and those cultivated for 30 years. Losses were greatest under repeated cultivation. A loss of 41% S was recorded under tea plantation and 50% depletion under continuous cultivation, with losses being correlated to a decline in soil organic carbon. Therefore tropical soils likely to be S deficient have been identified as (i) those which experience annual burning, due to S being volatilised (Scherer, 2001), and/or (ii) Ultisols, Alfisols and Oxisols which all have a potential anion sorption capacity (Camberato and Pan, 2000).

Fertilization with S and meeting crop requirements is difficult due to the complicated dynamics of organic S compounds and the rate of mineralization for which there is little quantitative data. Zhao et al. (2007) report that fertilization and requirements of S are incomplete and require much more data of the dynamic processes to predict changes in S and organic S compounds. From the literature it seems that a basic rate of 10 to 40kg S $ha^{-1}annum^{-1}$ is thought to be sufficient to overcome S deficiencies in the tropics (Sanchez, 1976), but this needs updating and rigorous testing.

1.4 Micronutrient

Zn, B and Mo are the most commonly reported micronutrient deficiencies in the tropics (de Melo et al., 2007; Sanchez, 1976; Tisdale et al., 1994). The cause is a combination of parent material composition, hydrolysis, cropping history, effect of pH, organic matter content and redox potential (pe).

Manganese and Fe are frequently sufficient or even abundant in tropical soils (Silveira et al., 2006), but their solubility (along with Cu and Zn) is significantly affected by pH (Lindsay, 1979). Availability decreases with an increasing pH, particularly for Fe, with a thousandfold decrease in activity for every pH unit (Lindsay, 1979).

Bioavailability of Fe, Mn, Zn and Cu is affected by soil organic matter as well as the capacity of the soil to form both outer- and inner-sphere complexes, specifically with Cu and Zn (Stevenson, 1994) but also Mn (Mortvedt, 2000). Some of the complexes, specifically inner-sphere chelate complexes, are so stable that in tropical organic soils Cu deficiencies have been reported (Stevenson, 1994).

Redox reactions are especially significant with regard to microelement bioavailability. Soils that undergo water logging are more likely to have a higher pH (low pe) and more reduced ion species, and conversely soils that are freely draining are more likely to have a low pH (higher pe) and more oxidised species (James and Bartlett, 2000).

1.5 Infertility of acid soils in the tropics

Soil infertility arises if one or more of the following factors outlined below is playing a negative role in an acid soil environment;

a) Al toxicity
b) Ca or Mg deficiency
c) K deficiency
d) P deficiency
e) Zn, B or Mo deficiency
f) Mn toxicity

Aluminium toxicity, defined as a concentration of Al in the soil solution above 1ppm (Sanchez, 1976; Rowell, 1994), displays itself in *Zea mays* by the roots becoming thicker, stubby and showing some dead spots, resembling a 'club foot' (Horst et al., 1999). This then impedes the uptake and translocation of other plant nutrients, particularly Ca (Ryan et al., 1997) and in soils with a positive charge, P (Dobermann and Fairhurst, 2000). These symptoms are evident from the plant itself and can be confirmed by foliar analysis of plant Ca, P and K levels.

Poor growth and fertility in acid soils may also be attributed to Ca and Mg deficiencies which may occur independently from Al toxicity. An example of soils with such an Mg deficiency are the *Cerrado* soils of Brazil (Sanchez, 1997; Barringa et al., 2007) and Fox et al. (1991) describe examples of Ca deficient soils in Hawaii.

Manganese is very soluble at pH_{KCl} <5.5 (Stumm and Morgan, 1981) and if Mn is present in soil minerals, then at low pH values Mn toxicity is possible. Davis (1996) demonstrated that at low liming rates, insufficient to counter Mn toxicity, peanuts failed due to Mn toxicity and Ca deficiency. Similarly Hue et al. (2001) showed this in an Oxisol from Hawaii with soyabeans. Results from Hue et al. (2001) and Davis (1996) show a positive response to liming. Conversely Abruna et al. (1970) found yield responses did not necessarily correlate with liming as the Ultisol on which they worked saw [Mn] decrease such that Mn was deficient. Soil infertility is an area that is dynamic as there are many chemical interactions to consider. In order to raise soil fertility careful monitoring and thorough consideration of soil fertility and the parameters surrounding this is required.

1.6 Changing from shifting to continuous cultivation and its effects of soil acidity and fertility

Many tropical countries have witnessed rapidly increasing populations causing the agricultural trend to move towards continuous cultivation (Brady, 1996). Productivity of the traditional agricultural system relies on the short-term disruption of the ecosystem and involves clearing, burning, cultivating and allowing the land to return to its previous state (Palm et al., 1996). Crop:fallow ratios have either decreased or been obliterated (Hőlscher et al., 1997) resulting in increased pressure on soil structure and fertility. Much work has been undertaken comparing the effectiveness of slash-and-burn to that of continuous or even intensive production on soil structure and fertility (Hőlscher et al., 1997; Miller and Kauffman, 1998; Binam et al., 2004; Birang et al., 2003; Rumpel et al., 2006). Hőlscher et al. (1997) tested the benefits of the burning in slash-and-burn over time in the Eastern Amazon; they identified a 0.5 pH unit increase with [Al] being reduced to nearly nil and the CEC increasing by 5 cmol kg^{-1}. Exchangeable cations were shown to be dominated by Ca and some K. This data is comparable with that of Khanna et al. (1994), Rumpel et al. (2006) and Juo and Manu (1996) who worked throughout the tropics; all agreed that this is a short-lived benefit and that leaching and C loss soon follows (Rumpel et al., 2006) with a gradual decline in fertility status. The relatively efficient nutrient cycle of the forest system is disrupted and essentially destroyed with continuous cropping (Palm et al., 1996).

The following three points continuously recur in the literature:

1) The benefits of the ash in the traditional system are lost;
2) Compaction of the soil occurs with use of machinery (Fernandes, 2007; Hillel, 1980);
3) Disturbance of the soil results in organic matter losses. Rumpel et al. (2006) report 20-50% and increased soil crusting leading to soil erosion as explained by Morgan (1995).

1.7 Amelioration of soil acidity and infertility in the tropics

The rejuvenation of acidic soils involves acid/base reactions and aims at increasing the acid neutralising capacity (ANC) of a soil (Marschner and Noble, 2000). In both temperate and tropical environments this is achieved with the use of calcitic ($CaCO_3$) or dolomitic ($Mg{\cdot}CaCO_3$) lime (Troeh and Thompson, 2005). In subsistence agriculture wood ash, crushed rocks, compost, manure and green manure crops have been used as a source of alkalinity (Tittonell et al., 2005). Fundamental to the success of all rejuvenation possibilities is an understanding of lime requirement as well as how much of a particular substance is needed to raise a soil from sub-optimal to optimal pH (Bloom, 2000). Maize requires that pH (KCl) is >4.5 together with a maximum acid saturation of 15% of CEC (Bornman et al., 1993). A suitable source of alkalinity requires identification and this needs to be done alongside all the basic nutrient needs of a specific crop. Different liming materials and fertility rejuvenators will now be outlined and their potential usefulness in tropical agriculture considered.

1.7.1 Conventional fertilizers

Recent work undertaken by Sanchez et al. (2007) demonstrated that the use of conventional fertilizers on infertile soils effectively provides the nutrients that are essential in raising yields. Conventional N, P and K fertilizers and other inorganic fertilizers have proven benefits through widespread research in the tropics and elsewhere, for example Ghosh et al. (2006) in India and Kato et al. (1999) in the Amazon. The recent results given by Sanchez et al. (2007) show that acid, nutrient depleted soils with low yields of <1t.ha^{-1} can produce higher yields in excess of 5t.ha^{-1}. In Mwandama, Malawi, maize yields have been raised from 0.8 t.ha^{-1} to 6.5 t.ha^{-1} which is higher than previously reported for small-scale farmers farming manually. Sanchez et al. (2007) call this transformation the African green revolution and show that conventional fertilizers are highly effective. However, the purpose of this review is to focus on practices that make it possible to do without (or very little of) conventional fertilizers in regions where markets and infrastructure make access to such products impractical.

1.7.2 Lime and gypsum

The lime requirement of any soil can be calculated from the slope of a titration curve and its buffer capacity (quantity of alkali added to the soil that achieves a unit change in pH) is the reciprocal of the same slope (McBride, 1994). Lime requirement formulae vary from different organisations and institutions, but essentially they are all based on the principle of raising pH to the desired range in order to neutralise the active and exchangeable acidity. Quantities required can be accurately determined from a titration curve.

Soil acidity is seldom completely neutralised with the application of lime (Ritchey et al., 1999). In order to neutralise subsoil acidity lime must be incorporated into the subsoil. Sumner (1993) has shown the effectiveness of gypsum applied to the surface of soils in reaching the subsoils and providing Ca and can initiate the 'self liming' effect. Ritchey et al. (1999) also found that gypsum applied to the surface was superior to surface applied lime in terms of solubility with Farina et al. (2000) also showing this in South Africa.

1.7.3 Manure and compost

The addition of manure and compost to agricultural soils is an ancient agricultural practice (Palm et al., 2001). By adding organic matter to the soil the CEC is often raised and simultaneously the complexation of organic functional groups occurs lowering the active and exchangeable acidity. Bhattacharyya et al. (2007) demonstrated this by growing rice in India and undertaking soil analysis. They found that in addition to the organic complexation reactions there were added benefits of additional nutrients, in particular N and K. Singh et al. (2007) showed that N and P are the two nutrients for which manure and compost can most readily be used. The limitation to the use of manure and compost is its heterogeneity as Palm et al. (2001) explain. Furthermore the nutrient release characteristics are dependent on resource quality.

Many small-scale farmers in the tropics make use of compost and manure inputs (Sakala, 1998; Palm et al., 2001). Zingore et al. (2007) investigated manure application in comparison to dolomitic lime and N and P fertilizers on maize in Zimbabwe, finding that the combination of both manure and fertilizers resulted in greatest yields over time. They called for targeted application of mineral fertilizers alongside manure, and this is key in order to witness significant and consistent results from its use. To this end Palm et al. (2001) highlight the importance of SOM in agroecosystems and introduce an organic resource database to raise understanding of its use in tropical agriculture and thus increase one's ability to predict the function of organic inputs in tropical agroecosystems. Rowe et al. (2006) also investigated models for different application rates of manure given its heterogeneous composition.

1.7.4 Wood ash

"Wood ash is the ash from the combustion of the following: bark, wood, sawdust, leaves, woody debris, pulp, sludge from pulp and paper waste water treatment systems, and unbleached wood fibre" (Risse et al., 2002, p.2).

Wood ash contains oxides and hydroxides of Ca, Mg, K and, to a lesser extent, Na, making wood ash similar to burned or hydrated lime in its dissolution reactions. Loose wood ash has been shown by Saarsalmi et al. (2001) to give a highly alkaline solution (pH 11-13) when dissolved in water and "generally has a good acid-neutralizing capacity and ability to provide soil with base cations" (Saarsalmi et al., 2001, p.355/6). Decreased acidity and increased base saturation following the application of loose wood ash have been frequently reported (Eriksson, 1998; Kahl et al., 1996; Khanna et al., 1994). By comparison, agricultural lime contains only minimal amounts of other plant nutrients whereas a significant amount of P, Ca, Mg and K is added to the soil when wood ash is used as a liming material. Furthermore, trace elements are added, specifically Zn, B and Mo (Lickacz, 2002). The composition of ash is obviously completely dependent upon the vegetation source.

Lickacz (2002) undertook field trials in the South U.S. on *Zea mays,* finding a more rapid change in soil pH when wood ash is used as a liming material in comparison to limestone. The reason is twofold. Firstly, dissolution kinetics, which Risse and Harris (2006) show to be greater than limestone in all instances and secondly the particle size is consistently smaller or finer. Steenari et al., (1998) liken this accelerated dissolution to Ca speciation, suggesting that the granulation process transforms the Ca of the ash through the following steps: CaO (in burned lime) → $Ca(OH)_2$ (slaked like or portlandite; in wetted ash) →$CaCO_3$ (calcite; in carbonated ash) or limestone. Portlandite is considerably more soluble than calcite. Ohlsson (2000) also suggests that the swelling and hydration characteristics of ash, ash porosity, and the chemical inhibition of the dissolution process affect rate. The negative side to using ash as a neutraliser is that it usually requires double or more the quantity when compared to agricultural lime. On the other hand it is very finely divided and no pulverisation is required, with the process of pulverisation adding to the cost of agricultural lime.

The other reason ash is used in tropical agriculture is shown through the work of Risse and Harris (2006). They found an average of 2.6% K in the different ash samples they analysed, with a maximum of 13% K. Lickacz (2002) concluded that ash is both a viable and effective source and means of Ca and K in agriculture. This is especially true where small-scale farmers rely on fire wood to cook food and thus have a permanent supply of wood ash available.

1.7.5 Crushed rock, with specific reference to granite

Making use of crushed rock, specifically granite utilises the weathering of a primary mineral and its resultant products (Baeeal Silva et al., 2005). The general reaction following the addition of water via rain or irrigation to a mineral environment, gives the following reaction [1].

$$\underset{\substack{\text{feldspars}\\\text{micas}\\\text{chlorites}}}{\text{aluminosilicate}} + H_2CO_3 + H_2O \rightarrow HCO_3^- + H_4SiO_4 + [\text{cation}]_{aq} + [\text{aluminosilicate}] \qquad [1]$$

(Harley and Gilkes, 2000)

The aqueous cation that is released from mineral structure into soil solution has direct implications to nutrient supply and plant growth (Harley and Gilkes, 2000). Silicate weathering involves hydrolysis reactions with H_2O being both a reactant (as a source of H^+ ions) and also as a transporting agent.

Whether the pH increases or decreases is dependent on the reaction mechanism and the speciation reactions that occur following mineral dissolution. Many dissolution reactions consume H^+ ions [2], with the acidity being crucial for the reaction to proceed due to a proton source requirement (Drever, 1997).

$$\underset{\text{albite}}{2NaAlSi_3O_8} + 2H^+ + 9H_2O \longrightarrow \underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} + 4H_4SiO_4 + 2Na^+ \qquad [2]$$

Silicates dissolve fastest in very acid or alkaline solutions, thus having a potential for neutralising acidity and thus being considered as a liming material (McBride, 1994; Sparks, 1995; Sparks, 2000). Baeeal Silva et al. (2005) found the effectiveness of granite to be impractical on the soils they used in Australia and Harley and Gilkes (2000) found that it was seldom the best means to both neutralise acidity and act as a potential fertiliser.

There are many rocks that can be crushed and used in agriculture and Van Straaten (2002) outlines these. Van Straaten (2007) shows, with reference to rock phosphate, that the use of crushed rocks can greatly increase both yield quantity and quality. Where acidity and N are remedied though organic (manure or compost) or inorganic means, rock phosphate can be used to supply the P and the combination works well as an alternative to conventional fertilisers Van Straaten (2007). Bationo et al. (1986) and Thuita et al. (2007) found this to be true when growing maize in Western Kenya with Mbwera (2007) concurring in his findings from research in Zimbabwe.

1.7.6 Green manure crops

Several workers have demonstrated a rise in pH when plant residues are incorporated in the soil, for example Sakala (1998) in Zambia. Moyin-Jesu (2007) tested plant residues against conventional lime and fertilisers in Nigeria and found that the application of 6 t/ha of plant residue was superior to the recommended addition of conventional fertilisers. This could be described as chemically viable but practically questionable as applying 6 t/ha is an enormous task particularly where farming is manual.

The long-term effect of green manure cropping in the tropics has been well studied and soil fertility has consistently been shown to be improved only in the short-term (Hunter et al., 1997; Yan and Schubert, 2000; Peiter et al., 2001; Xu and Coventry, 2003). This is due to the quantities of nutrients added and the removal or harvesting of soil nutrients in crops following green manuring. Essentially a green manure crop can be used for either raising pH and/or adding specific nutrients, usually N or P (Kretzschmar et al., 1991; Xu and Coventry, 2003).

Soil pH is raised due to the ash alkalinity associated with plants (Marschner and Noble, 2000). Identifying the plant species that can most significantly contribute to alkalinity is therefore important for effectiveness and efficiency. Marschner and Noble (2000) incubated the leaf litter of 3 plant species (2 trees and sugar cane) at pH 3 and pH 4 (KCl) in order to identify the most effective neutralising plant. They found *Melia azedarach* (white cedar) had the highest ANC while Yan and Schubert (2000) found that both faba bean and wheat had were effective at providing alkalinity. Literature shows that the liming effect is short-lived and usually only effective for the season immediately following crop removal (Yan and Schubert, 2000; Xu and Coventry, 2003). Thus intercropping is often preferred over monocropping.

Tithonia diversifolia has long been recognized as an effective source of both N and P (Jama et al., 2000). Kwabiah et al. (2003) state that potentially it can release adequate P to replenish solution P for crop uptake, and can thus viably be considered for P fertilization. Similarly they identified *Croton megalocarpus* as a source of P when used as a green manure crop. Cong and Merckx (2005) under took trials in Vietnam using *Tithonia* as a source of P and their results correspond with both Kwabiah et al. (2003) in Nigeria and Jama et al. (2000) in India. Furthermore Ikerra et al. (2007) showed the effectiveness of *Tithonia* and *Sesbania* in Western Kenya and Uganda as an effective source of P and K.

In the tropics there are many plant and tree species known to fix N. For example Ramos et al. (2001) quantified biological N_2 fixation with leguminous green manures in the tropics using ^{15}N. They showed that crops were able to draw the greatest amount of N from sunhemp as a green manure. Patreze and Cordeiro (2004) investigated N-fixing in various tropical legume trees, finding that *Mimosa bimucronatra* was able to harness the most N with much root nodulation and with the lack of N in the soil being sufficiently corrected by biological N fixation. Galiana et al. (2002) experimented on sandy acid soils in Cote d'Ivoire with *Acacia mangium*, finding that its N-fixing potential was largely due to the existing gradient of fertility. This concurs with Jama et al.'s (2000) suggestion that green manures are merely the redistribution of nutrients as opposed to replenishment.

Mapfumo et al. (2005) undertook investigations in Zimbabwe estimating amounts of N fixed by naturally occurring legumes. They found that the naturally occurring legumes of *Crotalaria*, *Indigofera* and *Tephrosia* increased the total shoot biomass on nutrient-depleted soils by 3-17%. This contribution was significantly increased by up to 70% with the deliberate seeding of legume populations, showing that indigenous legume fallows hold much potential in the N-fixing ability.

Jama et al. (2000) question the effectiveness of green manures in the long-term holding the view that it is a temporary response to a nutrient deficiency and soil acidity problem. N-fixing legumes that exploit biological fixation of atmospheric N_2 are the exception and are effective with careful management and long crop rotations (Kretzschmar et al., 1991). Notwithstanding this, Jama et al. (2000) question the practicality of the quantities required for optimal plant nutrition.

1.8 *Zea mays*: Acid toxicity and acid tolerance

Toxic levels of Al inhibit root elongation as a consequence of root apex distribution, with root tips being the primary site of Al-induced injury (Vazquez et al., 1999). The exact mechanisms for Al-induced inhibition are not clearly established; however Gunse et al. (2000) suggest that it is toxic levels of Al in the apoplasm that is responsible for fast inhibition of root growth alongside Al crossing the plasma-membrane. This means that Al could inhibit cell division or severely affect other cell functions and thus cause early root defects (Vazquez et al., 1999). In order for a plant to survive it needs to adapt to elevated [Al] in the rhizosphere either by adapting to higher concentrations in cells, or developing a mechanism to stop Al crossing membranes (Sierra et al., 2006). Al-resistant plants exclude Al from the root apices by secreting organic acids (Jorge and Menossi, 2005). These then bind and form inner-sphere complexes with Al. The size of such complexes renders the ion too large for root uptake, thus protecting the plant from deleterious effects of Al (Jorge and Arruda, 1997). Much research has been done to understand this mechanism and develop cultivars which are no longer Al-sensitive but Al-resistant (Sierra et al., 2006; Jorge and Menossie, 2005; Poschenrieder et al., 2005; Gunse et al., 2000; Bennet et al., 2004).

In addition to Al toxicity in acid soils there is often limited availability of P. Thus both Al-tolerant and P-efficient cultivars have been developed for *Zee mays*. Sierra et al. (2006) undertook trials testing 2 such cultivars on an acidic Oxisol with pH4.5 and an Al saturation of 36% in the topsoil and >45% in the subsoil. They found that root tolerance increased yields by up to double, but they also concluded that assimilates and nutrient partitioning in the aboveground organs also play a major role in plant adaptation to Al.

Bennet et al. (2004) compared Al tolerance in commercially adapted cultivars of *Zee mays* alongside seed collected from traditional farmers in various areas of KwaZulu-Natal in South Africa. They found that the commercial maize cultivars all had lower levels of Al tolerance compared to those of the traditional farmers. This indicates that the selection of the Al-tolerant genes occurred in the traditional farmers' varieties as a response to environmental conditions. Traditional varieties were not homogeneous in their responses, but the fundamental issue was that their adaptation had resulted in greater Al-tolerance. This shows that it is possible to 'naturally select' those plants which have seemingly best adapted to acid conditions as an alternative to laboratory work on identifying organic acid excreting genes.

Al tolerant and low-P maize species can be used in conjunction with other soil rejuvenation practices in order to combat the problems associated with low fertility and acid soils.

1.9 The relationship between soil fertility and soil classification

Land capability is a system that was developed by the U. S. Department of Agriculture in the 1950s. It separates soils into classes of increasing land use limitations; classes vary from I – VII with I being a high potential soil (Sanchez, 1976). Criteria used in the original system related only to soil physical properties and not soil fertility. If land capability is to be utilized in the agricultural sector, soil fertility parameters alongside yield data need to be taken into account (Bouma, 2000). Increasingly this has been the case with the development of soil potential mapping (Van der Eyk et al., 1969; Fanning and Fanning, 1989; Dobermann and Oberthür, 1997; Habarurema and Steiner, 1997). Dobermann and Oberthür (1997) undertook mapping of soil fertility status in order to understand the inherent fertility potential for ricelands in the Philippines. A survey of this nature requires thorough soil and plant sampling and analyses with careful monitoring of yield. Soils can then be classified according to their yield potential and Dent and Young (1981) outline specific guidelines in order to maximise reliability and homogeneity of such a survey. Increased yield potential can be realised if the crop growth limitations are all eradicated.

Alternatively, exploiting local knowledge of soils has been attempted in Rwanda. Habarurema and Steiner (1997) used local farmers' knowledge of the land in terms of its yield potential and history. The criteria on which their soil suitability map was based were fertility (productivity), depth, structure and colour. They found linking local knowledge to scientific data problematic and failed to produce a soil potential map. Tittonell et al. (2005) undertook a similar procedure combining soil 'performance' in western Kenya which they gathered through interviews, and used this with soil analyses for essential nutrients. They then classified and mapped soils according to their yield potential.

The relationship between soil fertility and soil classification provides a bases for grouping soils with similar fertility limitations using quantitative limits. With such a system the profitability of fertilizer recommendations can be optimised and allows for a more informed choice for farm management. Combining the two disciplines allows for production potential to be understood better and for yields to be optimised in terms of Mitscherlich's growth law (Blackmer, 2000).

1.10 Conclusions

It is clear that acid soils are likely to exist in areas of the tropics where rainfall is high, even where the parent material is basic. The problem of acidity is often not confined to the topsoil and many areas experience subsoils acidity. This acidity can lead to Al toxicity and is harmful to the normal development of healthy plants.

The availability of macro and micronutrients to plants can be reduced as soils high in Al and Fe oxides can form specific complexes, particularly with P, S and B, and render these nutrients unavailable. N, P and K are often limiting in tropical agriculture and various amelioration methods were discussed, particularly as alternatives to conventional fertilizers. It has been reported that where acid soils exist they are potentially limiting to yield quantity and quality. The intensification of shifting cultivation gives rise to an overall decline in yield due to a loss of nutrient and organic rich topsoil and the continued harvesting of nutrients without replenishment. It is often necessary to raise the soil pH and to add macronutrients and sometimes micronutrients.

Soil replenishment is most effectively done through the use of conventional fertilizers; however, when these are not readily available, alternatives need to be considered. Various possibilities where considered and with the use of crushed rock and ash demonstrating effectives alongside manure/compost and organic waste.

Research priorities must seek to understand the nature of soils under study, comparing the difference between cultivated and un-cultivated land. This will show the effect clearing land has had on fertility and provide an improved understanding of the undisturbed soils. Once this is determined the most appropriate amelioration materials and quantities can be recommended and sourced in order to raise yields. Ultimately research of soil fertility in the tropics needs to aim to produce soil potential maps based on soil fertility status and soil types in order for potential to be better understood and achieved.

CHAPTER 2

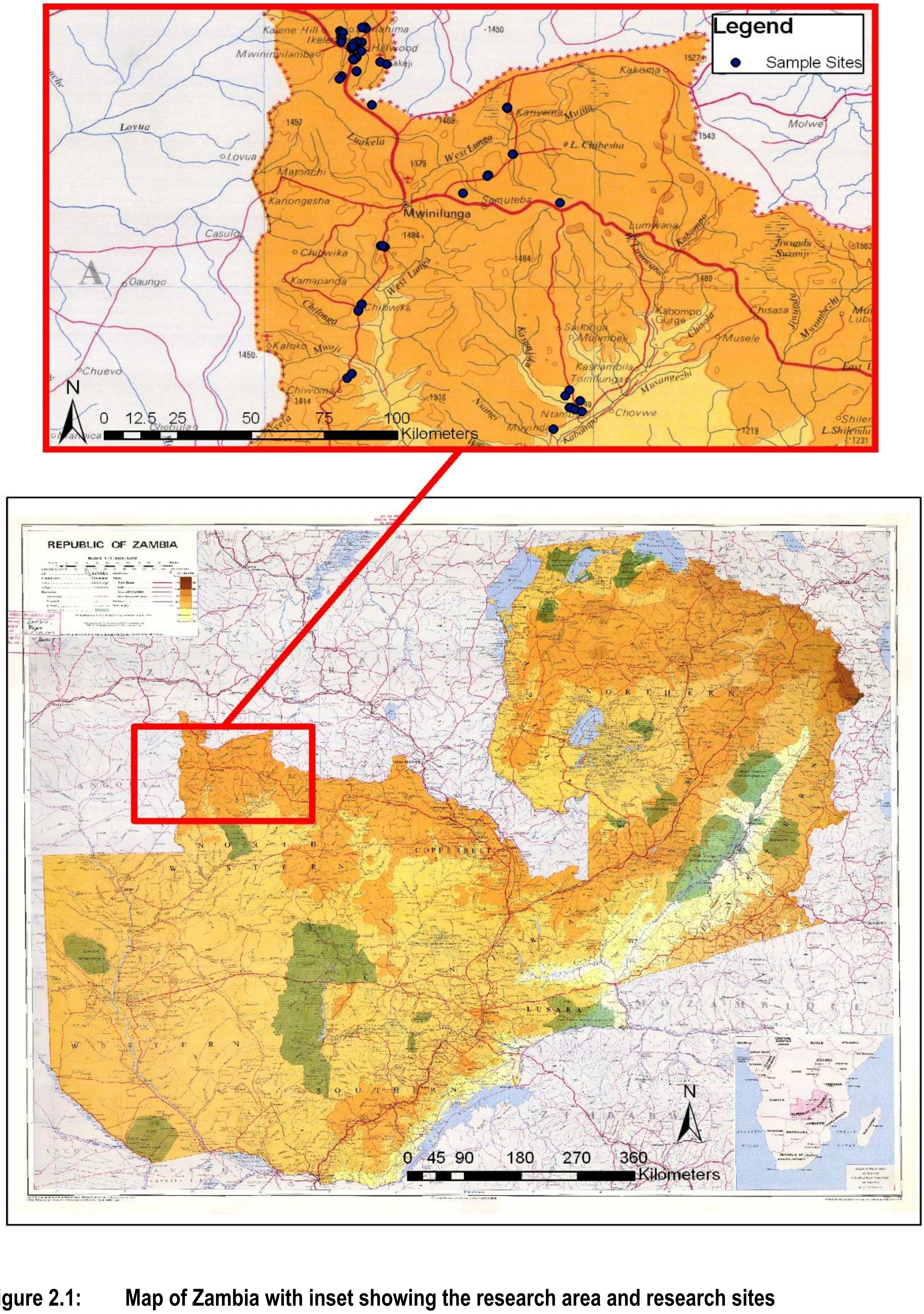
The soils of Mwinilunga district, north-west Zambia

2.1 Introduction to the research area

Zambia is a landlocked country in Sub-Saharan Africa situated largely on the central African plateau between 1000m and 1600m above sea level (Goma, 1994). It experiences a semi-tropical climate with a high unimodal rainfall, predominantly falling between November and March. The rainfall in Mwinilunga district averages 1300mm annum^{-1} (Makanda and Moono, 1999). High temperatures combine with peaks in precipitation to create suitable growing conditions. The highest temperatures occur just before the onset of the rains, with average summer highs of 32ºC and lows of 16ºC, and average minimum winter temperature of 5.5ºC for June and July . Frosts have been recorded but are rare and dependent on topography (Ting-Tang et al., 1984). The natural vegetation of NW Zambia on the undulating landscape is *miombo* or *mavunda* woodland and *dambo* grassland (Dalal-Clayton et al., 1985).

Zambia is composed of 9 provinces which are subdivided into 43 districts. The research area is the Mwinilunga district which is in the NW Province, shown in Figure 2.1. Here maize and cassava are the two cereals grown and consumed (Makandwa and Moono, 1999) with yields being consistently sub-optimal and food insecurity being problematic in this area (Sundewall and Sahlin-Andersson, 2006). Ting-Tang et al. (1984) call for a more comprehensive soil survey of the area north of Mwinilunga town where the yields are known to be poor and where soils are least studied.

Mwinilunga district is part of the ancient African surface, a plateau which, as a result of the 'warping' from the South and the Rift in the East has formed a 'depression' and is, in parts, deeply eroded from the changing drainage network of the area. This area is the headwaters of the Zambezi River and the Lunga River which is a tributary to the Zambezi River. Depressions in the plateau have been in-filled with aeolian deposits (Kalahari sands) and have subsequently been weathered and eroded (van Straaten, 2002).



Legend
Sample Sites
Kalene Hill
Lovua
Maronchi
Kanongesha
Mwinilunga
Casulo
Chibwika
Kamapanda
Chitonga
Kaloko
Chuevo
Chiwoma
Luakela
West Lunga
L. Chibesha
Samuteba
Lumwana
Kabompo
Jiwundu Swamp
Kabompo Gorge
Chisola
Musele
Chisasa
Chovwe
Kakoma
Molwe
N
0 12.5 25 50 75 100
Kilometers
REPUBLIC OF ZAMBIA
N
0 45 90 180 270 360
Kilometers

According to van Straaten (2002) the Precambrian geology of Zambia can be divided into several domains:

- The Paleoproterozoic (Eburnian) in the Bangweulu Block,
- The Mesoproterozoic (Kibaran) Irumide Belt,
- The Neoproterozoic Katanga Supergroup
- Phanerozoic rocks including the Karroo Supergroup, the Late Tertiary to Pleisocene Kalahari sands and recent sediments.

In the research area the geology can be dated to the Katanga, Karroo Supergroup and the Kalahari Group. The Katanga Supergroup is Neoproterozoic in age (c 950ma) and one finds the Upper and Lower Roan and West Lunga formations in this Supergroup in the Mwinilunga district (van Straaten, 2002). The Upper Roan formation found is the Luigishi formation which consists of psammitic biotite schist. The Lower Roan formation consists of pebbly feldspathic quartzite, argillite with interbedded quartzite and dolomite, argillaceous quartzite and feldspathic quartzite (Drysdall et al., 1972). The West Lunga formation is c800ma and consists of shales and tremolite-actinolite schist.

The Karoo Supergroup dates back to the Miocene. The formation that is found in Mwinilunga district is the Mabomba formation which consists of red and buff siltstone with basal conglomerate. This occupies a relatively small area in the south of the district (Appleton, 1984).

The Kalahari Group is fairly recent, Quaternary in age, and there are two formations in this group in the district; the Zambezi formation and the Barotse formation. The former dominantly comprises alluvium and unconsolidated quartz sand and basal gravel. The Barotse formation consists of quartz arenites, silicified carbonates, calcrete, porous white quartzite, chalcedony, chalcedonic breccia and pebbly arenite (Key, 2000a; Key, 2000b). The Barotse formation is found towards the very south of the district and was not sampled.

Ting-Tang et al. (1984) undertook an exploratory soil survey in the area using Landsat remote sensing data in conjunction with conventional methods of soil survey in order to classify soils of the district and understand agricultural potential in relation to crop suitability, according to the guidelines of Dent and Young (1981).

They classified soils on a general scale as:

Ferralsols –

- Xanthic Ferralsol – derived from Kalahari sand and Kundelungu shale, and also derived from basement complex consisting of gneiss and schist;
- Orthic Ferralsol – derived from Kalahari sand and Kundelungu meta-siltstone;
- Rhodic Ferralsol – derived from Kundulengu sandstone;
- Acric Ferralsol – derived from Kundulengu siltstone and shale.

Arenosols –

- Ferralic Luvic Arenosol - derived from Kalahari sand;
- Petroferric Ferralic Arenosol – derived from Kalahari sand.

The scope and scale of the survey by Ting-Tang et al. (1984) limited its application with few soils actually being sampled, particularly in the Ikelenge area where they did not sample or classify.

2.2 Materials and methods

One hundred subsistence farmers in Mwinilunga District who were willing to participate and whose farm fields were accessible were identified. Each farmer dug a soil pit (1.5X0.75X1.5m) in their field immediately following maize harvest (May and June 2006). Additionally a soil pit of the same dimensions was dug in adjacent natural vegetation. Slope angle and orientation and proximity to stream or river were recorded to better understand position in the landscape (Turner, 1991). In describing soil profiles horizons were first identified and their transitions recorded. Following this for each horizon, colour was noted in both the wet and dry state using the Munsell colour system (Munsell soil colour system, United States Department of Agriculture, 2000). Soil consistence was noted and texture was subjectively determined in the field from the feel of a wetted soil moulded between the fingers and thumb as described in Courtney and Trudgill (1984). Stone content was estimated, and described with the eye as described by Rowell (1994). The presence, size, quantity and depth of roots and pores was recorded as outlined in Turner (1991). The occurrence of mottles and their colour was recorded along with other features such as, cutans and/or concretions (Courtney and Trudgill, 1984). The colour, shape, height and proximity of termite mounds to the soil pit were noted.

Soils were initially classified according to the South African Taxonomic System (MacVicar and De Villiers, 1991), combining field observations of morphology with the analytical results.

These soils were then further classified according to the FAO-ISRIC-ISSS World Reference Base (WRB) for soils (2006). In each field and adjacent bush area a Jarret auger was used for subsoil sampling with three soil samples taken at random and mixed as described in Rowell (1994). A composite topsoil core sampler was also used with 7 small cores mixed to obtain a representative sample (Rowell, 1994). Soils were air-dried and passed through a 2mm sieve.

Soil pH was measured using distilled water and 1M KCl at a soil:solution ratio of 1:2.5 . If the pH was found to be less than pH_{KCl} 4.5, titratable acidity was measured using 0.01M NaOH and phenolphthalein (White, 1997). The filtered supernatant from a 1:5 soil:NH_4OAc extract was analysed by AAS for K, Na, Ca and Mg (White, 2006). Available P and K were determined using the Bray 2 method and spectrophotometry for P and AAS for K (Rowell, 1994). A 50g subsample of each 2mm sieved soil was milled and total values of C and N were determined by combustion using a EuroVector elemental analyser. All properties besides C and N were determined in duplicate on selected soils for an assessment of precision.

Trace elements (Cu, B, Mn, Zn) were determined using inductively coupled plasma-optical emission spectroscopy (ICP-OES) (Jobin-Yvon Emission, 1999). 5.0g of air-dried soil ($\leq$ 2 mm particle size) was used with 20 ml 0.1M HCl (at 20 $\pm$ 3°C). The analysis method is outlined in Appendix 1 based on the method of Jobin-Yvon Emission (1999).

Particle size analysis was done using the Davies (1984) method. The clay mineralogy was determined through XRD combining the methods of Theng et al. (1986) and Olson et al. (2000), details of which are outlined in Appendix 2. Samples were scanned from 3-40° 2θ. K-saturated slides were heated to 110°C overnight and 300°C for 5 hours (Olson et al., 2000) and following each heating they were analysed with an XRD instrument from 5-35 ° 2θ to identify the major clay peaks (Whitton and Churchman, 1987).

The method used for monitoring yield was determined based on local constraints regarding accessibility and one which had a high likelihood of success as the participating farmers are widely distributed in the district and maize harvest is governed by climate and so an exact date is impossible to pre-determine. Farmers were asked to measure a set area[1] in their maize field and collect the maize cobs from this set area. A 50kg sack was provided and it was requested that the harvested maize from the set area be de-cobbed and kept for weighing, which was undertaken by the author. The moisture content of the maize was not determined. Farmers

[1] A suggested size of 3m X 5m was given as a guideline.

were asked to give the crop, fertilizer and other amelioration history of the field under investigation, and this was undertaken through a brief interview using a translator from the local area. Place et al. (2007) outline methodologies that combine quantitative and qualitative research in soil and agricultural research in Kenya, finding that when conducted thoroughly the combination is valuable.

Additionally farmers were visited in mid-season and maize plants were examined for deficiency symptoms with these being recorded and photographed.

Sys et al. (1993) published soil yield potential of 45 main agricultural crops, including maize (*Zea mays*) using both soil fertility and climatic requirements. This literature has been used to award 'yield potential', giving soil groups a rating based on their potential.

2.3 Results and discussion

Fertility data pertaining to the bush-land and maize-land soils confirms that these soils are acidic with associated sub-optimal nutrient levels. Three broad groupings of soils have been identified based on parent material as outlined in Table 2.1.

Table 2.1: The three soil groups of Mwinilunga district based on parent material.

Soil Group	Parent material
Group 1	aeolian sands (Kalahari)
Group 2	weathered rock (shale, quartzite, granite)
Group 3	aeolian sand over weathered rock

Table 2.2 shows a summary of the analytical results for the three soil groups. The threshold values used for acidity are based on those quoted by Smalberger and du Toit (2001) with specific reference to maize. The macro and micronutrients values, also specifically for maize, are based on data provided by the Tri-state Fertilizer Recommendations (2005), Bornman et al. (1993) and Hazelton and Murphy (2007). The values used are indicators of optimal/suboptimal values so a value below the threshold implies deficiency.

Table 2.2: **Proportions (%) of the three soil groups of the district having values of key soil fertility parameters below the indicated threshold.**

	pH_{KCl} <4.3	[P] <15mg/kg	[Ca]<300mg/kg	[Mg]<80mg/kg	[K]<50mg/kg	*n*
Group 1	47	86	89	39	79	140
Group 2	43	87	69	49	45	55
Group 3	35	80	82	45	54	114

In each group a high proportion of soils are below the threshold fertility values. This indicates that there is a strong likelihood of soil fertility constraints on these soils. A selection from the full analytical and physical data (tabulated in Appendix 3 and 4 respectively) will now be presented graphically and discussed.

2.3.1 The effect of clearing and cultivating *miombo* savannah on soil chemistry

From Figure 2.2 the following general trends comparing maize-land and bush-land for selected chemical characteristics[2]: There is no convincing evidence that a change from bushland to maizeland has consistently altered the soil properties shown. Considering that this data has also not undergone any statistical analysis it is only possible to point out a few observations from the graphs. Firstly, the organic carbon (OC) content seems to be slightly higher in the bushland soils when compared to maizeland soils in the topsoils. This is expected as the uncultivated lands, especially woodlands drop leaves and add organic matter back into the soil. The lower values in the maizeland soils are likely to be caused by the clearing of land, which is removing the organic input, which is what Rumpel et al. (2006) reported on Amazon soils in Brazil. Secondly, more subsoils have a lower pH in bushland soils than in maizeland soils. The depletion of bases from the subsoils by deep rooting trees coupled with the breakdown of organic matter with increased leaching of bases in maizland soils seems to explain this and thus there seems to be lower Ca levels. On the whole, the pH is not much changed by the clearing of bushland. Thirdly, [B] has two clear clusters for both top and subsoils and this is regardless of maizeland or bushland. This highlighted an interesting pattern in the data and is discussed further in relation to the three soil groups in section 2.3.3 on page 30.

The spatial variability will also have had a marked effect on this data and thus limits its value. The landscape is a well covered with termite mounds across the three different soil groups and different parent materials. This will also have caused great variation and so future comparisons must consider spatial variability and address how this can be overcome.

[2] It should be noted that the dambo soils have been excluded from these graphs as their values where extremely high for OC and Ca due to the washing down of topsoil from higher slope positions and so it is misleading to the general trends. Further there was no suitable comparison to the cultivated land as the entire dambo was cultivated so the sample is from periphery land which is not a fence line comparison.

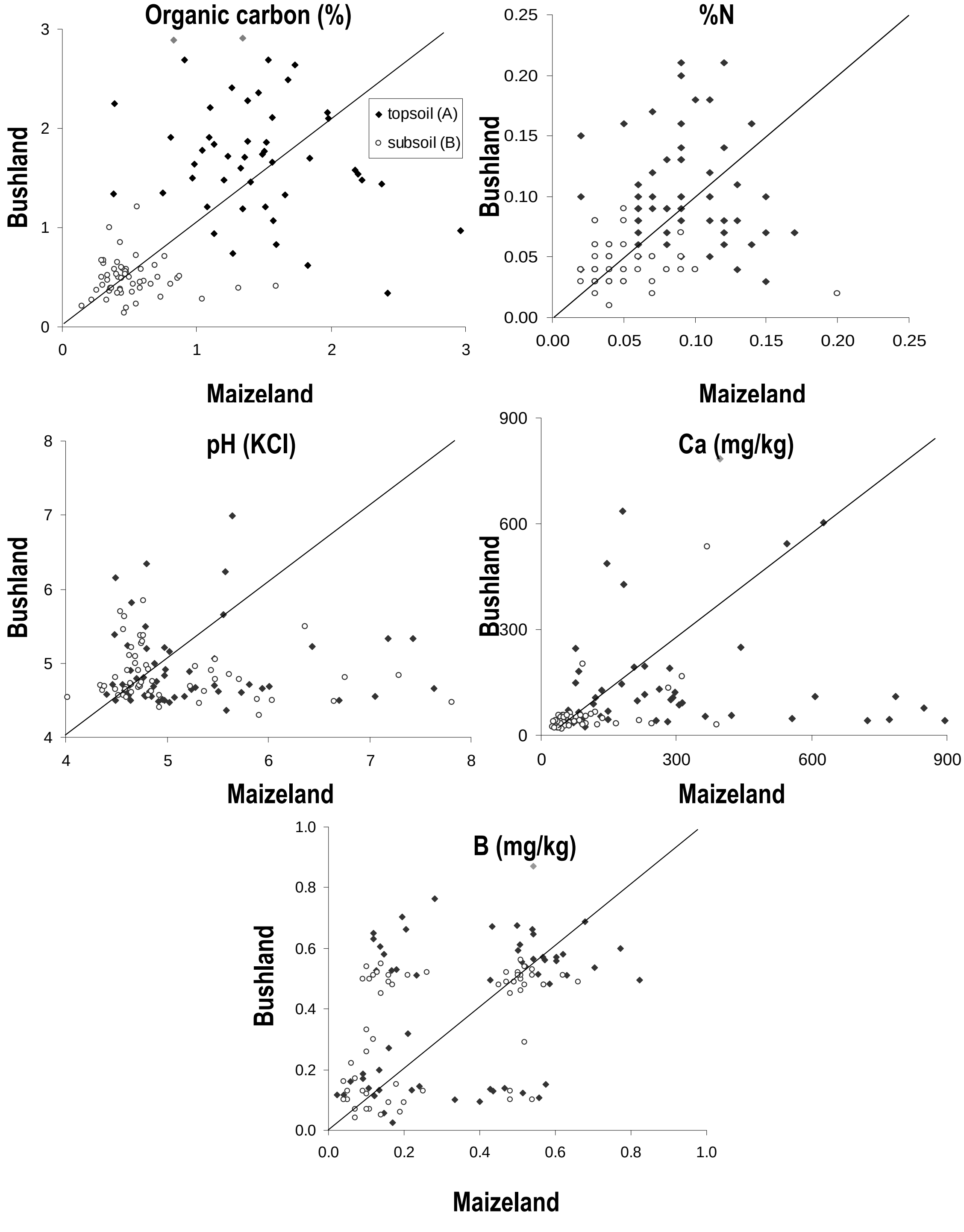


Figure 2.2: A comparison of maizeland and bushland soils with respect to selected chemical characteristics.

2.3.2 Soil acidity

The soils that were sampled have a consistently low pH, with 43% of all soils (both A and B horizons and bush and maizeland soils) having a pH (KCl) <4.30. The acid saturation % and its correlation to pH (KCl) is shown in Figure 2.3. Many of the soils fall below pH 4.5 where Al will be expected to be mobile, and thus acid saturation % values are high. Soils with a pH

(KCl) <4.3 have an average acid saturation of 48%. This concurs with the findings of Lilienfein et al. (2003) in Brazil, that in high rainfall areas, acid soils often acidify to levels which are potentially harmful to plants. Considering that Smalberger and du Toit (2001) suggest that maize prefers values <20% many of these soils are likely to be a harsh growing environment for maize if left unamended.

Figure 2.3 shows the pH and the acid saturation (%) for top and subsoils sampled in the district, indicating that generally subsoils have a lower pH and a higher acid saturation % when compared to topsoils. The median and average pH (KCl) values for all the topsoils sampled are 4.47 and 4.71, respectively, compared to 4.32 and 4.55 for the sub-soils. It is known that [Al] increases with a decreasing pH, and therefore its solubility is likely to be high in these soils, especially the subsoils. The correlation is weak (r^2 0.39 and 0.49), suggesting that pH is a poor indicator of Al toxicity.

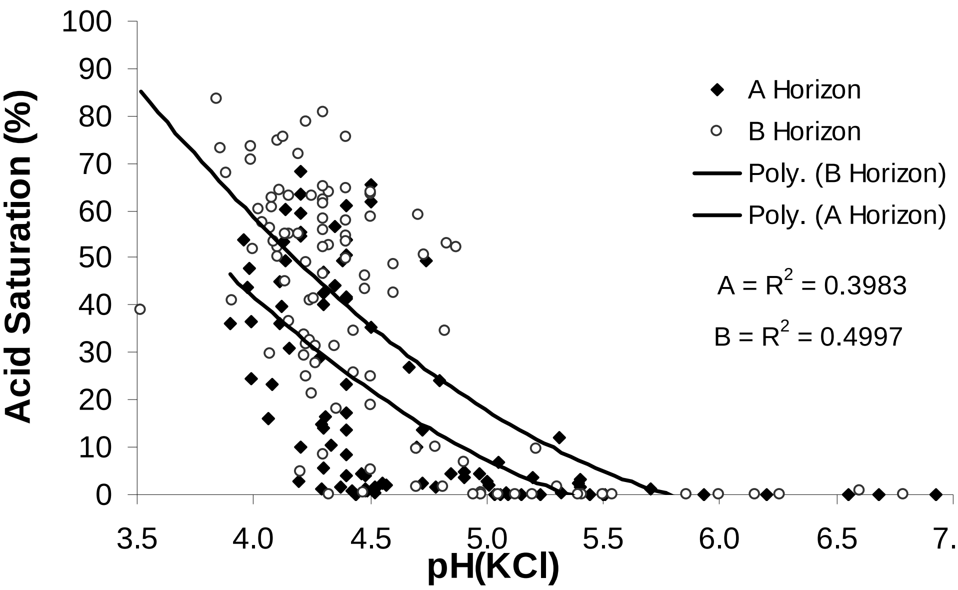


Figure 2.3: Correlation (2nd order polynomial) of pH(KCl) and acid saturation (%) of all maizeland and bushland soils in Mwinilunga district.

This is likely to have a negative effect on plant root systems according to data given by Van Raij and Quaggio (1997), and thus potentially limit plant growth. These soils have an average acid saturation of 20.17% (68% is highest value) for topsoils and 37% (83% is highest value) for subsoils, showing that the problems associated with subsoil acidity, discussed by Reeve and Sumner (1972) and Sumner (1994), are likely to active and limiting for maize in this area. Specific counteractive measures will be required in order to neutralise acidity and harness the limited basic cations and P that is present (Toma et al., 1999).

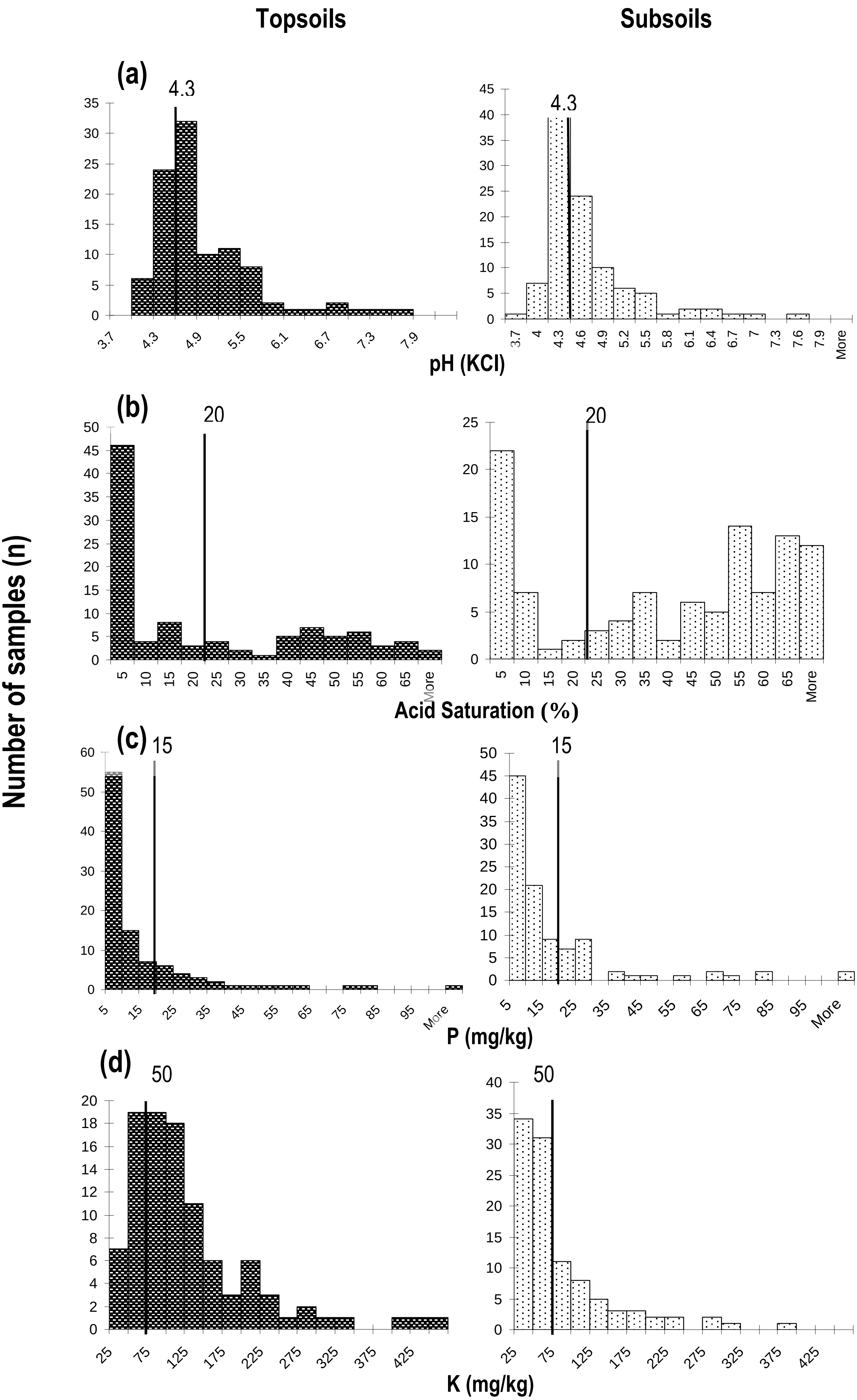
2.3.3 Fertility status of soils

The key fertility parameters are shown in Figure 2.4 for both the top and subsoils. The threshold values used are taken from the references given in section 2.3 and are all with specific reference to *Zea mays*, although not specifically applicable to the subsoil with regard to fertility, it is thought to be useful in terms of understanding the fertility status of the soils to include the threshold values for subsoils. pH and acidity have been discussed in section 2.3.2, and Figure 2.4(a) confirms that many of the top and subsoils' acidity is indeed likely to be limiting to plant growth. Figure 2.4(b) shows that acid saturation is more problematic in subsoils that topsoils, as pointed out earlier.

Plate 2.1(c) supports the data with the stunted root growth that is commonly encountered likely being from active acidity in topsoils. This is further supported by Plate 2.1(d) where acid loving wild ginger and bracken are flourishing. The value of ameliorating such soils is high, with Plate 2.1(e) showing the difference in maize that is grown with lime compared to without lime. The stark difference merely supports data that these soils are acidic and require neutralising to a more desirable pH.

In terms of fertility status, the majority of soils have sub-optimal levels of Ca, and this is greater in subsoils with 93% of subsoils and 66% of topsoils having suboptimal Ca. This is in line with the findings of Ritchey and Sousa (1997) who studied subsoil acidity and infertility in Oxisols in Brazil. With such poor levels of Ca, one would expect visible deficiencies of Ca, and this was observed in the young leaves, with these commonly being yellow and slow in opening. This was noted as being more common on soils in group 1 and group 3.

Figure 2.4(d) shows that K levels also tend towards sub-optimality, particularly in the subsoil. The K values are not as consistently low as Ca with 62% of subsoils being below the theoretical sufficiency and only 5% of topsoils. The reason for low levels in subsoils is suggested by Rowell (1994) to be that the exchange of K by H and then Al on exchange sites. The elevated K levels in topsoils are suggested to be from the addition of wood ash to topsoils. Wood ash is known to contain elevated levels of K and Ca (Risse and Harris, 2006) and thus elevate levels of K.



Topsoils
Subsoils
(a)
4.3
4.3
pH (KCl)
(b)
20
20
Acid Saturation (%)
(c)
15
15
P (mg/kg)
(d)
50
50
K (mg/kg)
Number of samples (n)

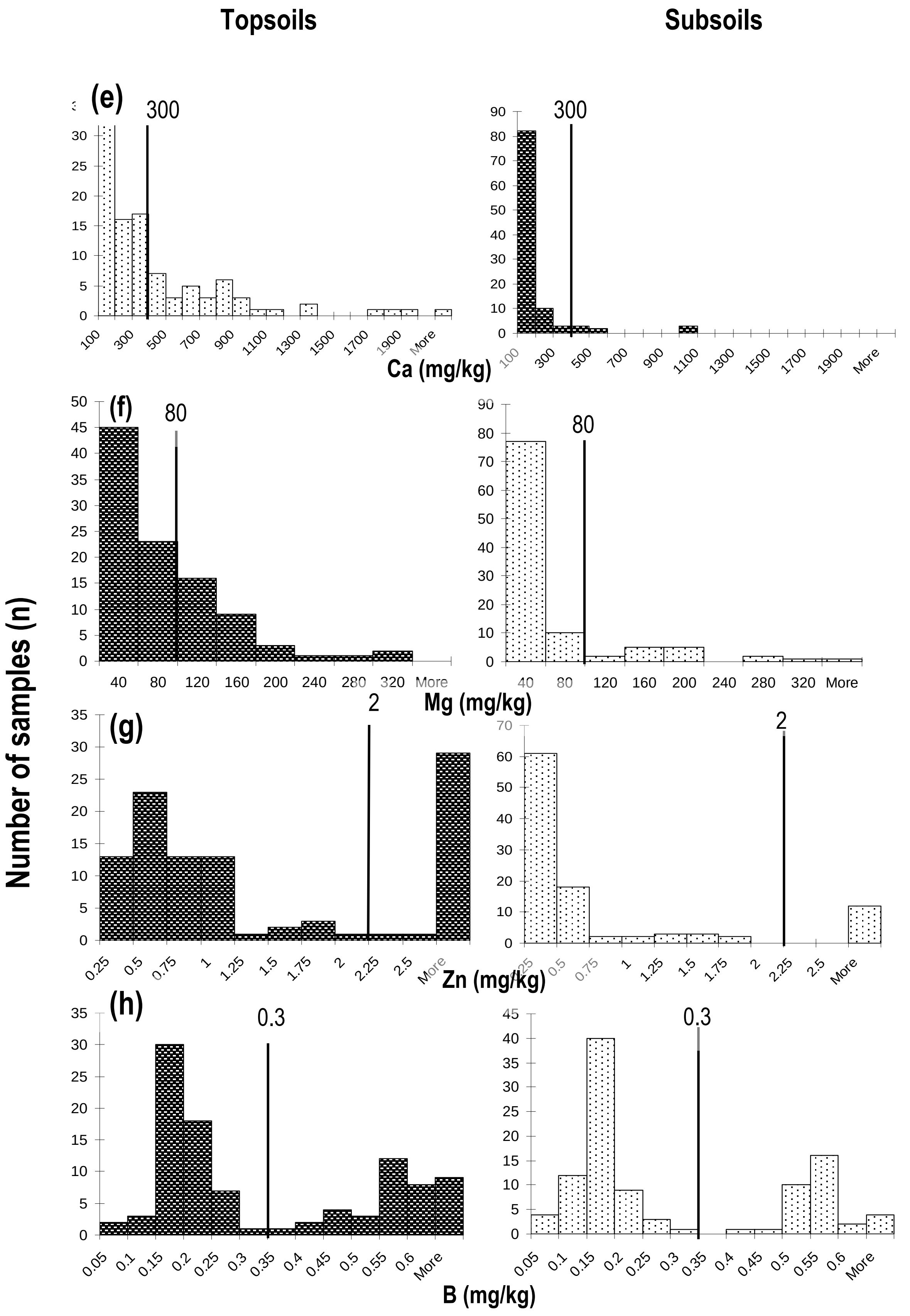


Figure 2.4: Histograms to show the nutrient status of the top and subsoils of Mwinilunga district. .The line and value indicate the divide between sub-optimal and optimal levels. For all, with the exception of acid saturation percentage, the area below the line is suboptimal. Threshold values are derived from Tri-state Fertilizer Recommendations (2005), Bornman et al. (1993) and Hazelton and Murphy (2007).

Most (78%) of the soils are Mg deficient, with subsoils again having lower levels compared to topsoils. Suboptimal Mg levels are generally associated with a low pH and the reason for this is thought to be as above for K. Additionally there is a limited source of Mg in the mineralogy of these soils and so mineral weathering will not be a likely source of Mg. Low concentrations of both Ca and Mg is likely to be a result of the soils being dominated by OM and 1:1 clays, known to retain Ca less tightly than 2:1 clay minerals. Kamprath (1984) found this to be true for highly weathered soils dominated by kaolinitic clays and Al/Fe oxides. The mineralogy of the soils is outlined in a later section, but it is suffice to say that these soils' CEC mostly arises from the organic matter content of topsoils and therefore Ca and Mg needs to be added to soils in order to elevate levels to sufficiency. Plate 2.1(a) supports the chemical data of deficiency with this being an example of a common observation in the field.

The soils are mostly very deficient in P with 81% of topsoils and 76% of subsoils having levels below sufficiency. The very low P values are associated with low pH values and thus much of the P is likely to be 'fixed' through bidentate and binuclear bonds with very slow, if any, desorption as Parfitt (1980) also found in sesquioxidic soils. Therefore it is not surprising that the occurrence of the purpling of leaves in maize plants (Plate 2.1(b)), which is a visible sign of P deficiency, was frequently observed in the field.

According to the literature the sufficiency/optimal quantity of zinc is between 1.5 mg/kg soil (Bornman et al., 1993) and 2 mg/kg soil (Tri-State Fertilizer Recommendations, 2005) using EDTA method. Figure 2.4(g) shows that many of the soils have suboptimal Zn levels. Tri-State Fertilizer Recommendations (2005) report that Zn deficiency is a common problem on sandy acid soils. Given that many of these soils are derived from Kalahari sands, and the source of trace elements is soil is from the parent material and not organic matter, Zn deficiency is to be expected due to low levels in the aeolian sand deposits. This poor micronutrient fertility of these soils is seen further in suboptimal B levels (<0.3mg/kg soil) in Figure 2.4 (h). The data gives a bimodal distribution. This was considered alongside soil parent material in the three soil groups using and this is shown with the frequency distribution in Figure 2.5. There is no clear geological trend except that where profiles are derived from local rock there seems to be a relatively high chance of B deficiency. Where Kalahari sands are the parent material the chances are about equal of finding deficiency as sufficiency.

Since the weathered rock (group 2) contains a variety of rocks no conclusions can be drawn other than further research needs to be undertaken investigating the link between trace element content to local geology and considering this alongside profile depth. The sampling method undertaken in this work is insufficient to look into this in more detail.

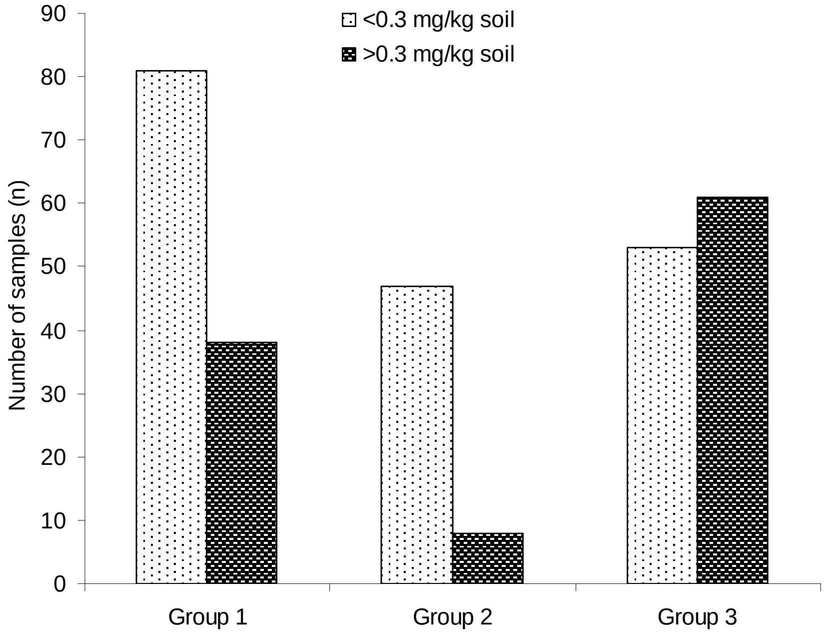


Figure 2.5: Frequency of soil samples in soil groups 1, 2 and 3 of Mwinilunga district that have suboptimal (<0.3 mg/kg soil) and optimal (>0.3 mg/kg soil) B levels.

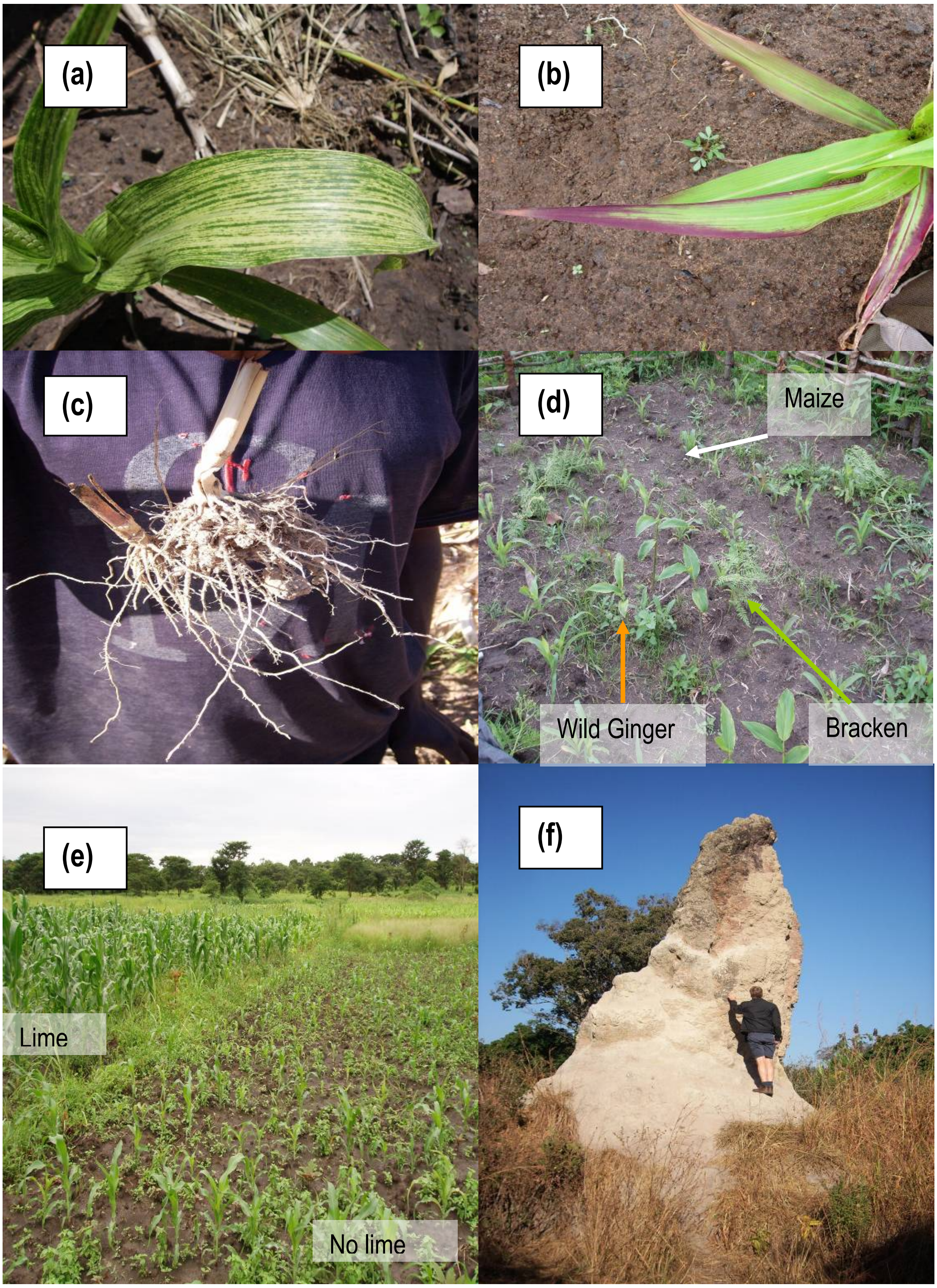


Plate 2.1: Photographs supporting the soil chemical data with visible signs of Mg deficiency (a) and P deficiency (b). The acid soil data is also confirmed visually with suspected Al toxicity (c) and acid loving plants of bracken and wild ginger out growing the maize (d). Lime used in a field adjacent to no lime shows the benefit of liming on these soils (e). An example of a termite mound typical of the area is shown in (f).

2.3.4 Fertility in relation to yield

The yield data that was collected from the field (appendix 3) was not significantly related to any of the soil chemical properties. Variation in yield is to be expected with the plethora of different weeding levels, seeds used, and different soil additions. This considered, the yields recorded are highly improbable as the average yield was 4.5 t. ha^{-1}. This is thought to be tenuous considering that plant densities were low, field observations showed visible signs of deficiencies and finally because subsistence farmers' yields without fertiliser additions are considered high at 2 tonnes ha^{-1} (Place et al., 2007; Ojeniyi and Adekayonde, 1999). Further, data is unreliable due to the different moisture contents of the maize that was harvested and weighed. Consequently none of the yield data is thought to be reliable and thus it is not used in this thesis.

The explanation for the unreliability of data is twofold and likely simultaneous; firstly, a misunderstanding through translator communication and secondly a common problem when working in the developing world context, of participants seeking to please the researcher (Tittonell et al., 2005; Sanchez, 1976) and therefore possibly putting more maize into their sack. Visual inspection of fields throughout the growing period indicated that many fields showed signs of deficiency, with some plants even failing to develop cobs. Common observations of maize upon harvest were as follows:

1) Stunted root growth of maize roots as is shown in Plate 2.1(c). This is from a field which has a subsoil pH (KCl) of 4.14 and an acid saturation of 54%. It failed to develop cobs.
2) Wilting of plants during heavy rains. According to Tisdale et al. (1994) this can be indicative of K deficiency.
3) Yellowing of entire maize plants. This is known to be N deficiency, and to be expected due to lack of N fertilisation. Sanchez et al. (2007) refer to N deficiency as being highly likely in most tropical soils.
4) Lack of weeding, leading to weeds sapping any available nutrients and resulting in poor maize growth, again a common complaint being lack of cob development.
5) Ash is frequently used, but neither evenly distributed nor thoroughly incorporated into the soil and thus its effectiveness is limited.

2.4 The soils of the district

This section draws together the field observations and the physical and chemical data from laboratory analysis which has already been discussed. The location of the different farmers' fields is shown in Figure 2.6 with each site marked with its site code and overlaying the geological map of the area.

Soils directly correlate to the geology and geomorphology of the area and as a result they can be grouped based on chemical and physical data and according to both their origin and landscape position. Given that the chemical data is not comprehensive enough for confirmed classification with the WRB system the following classifications given are all proposed classifications. It is proposed that the dominant soil groups found in this area are Arenosols, Acrisols, Ferralsols and Lixisols and this finding is in line with that of Ting-Tang et al. (1984). Using geology, geomorphology and soil morphology three main soil parent material groups have been identified;

Group 1. These have largely arisen from the Kalahari sands with underlying quartzite, siltstone and shale being very deep and having little influence on the overlying soils.

Group 2. These soils have developed from the quartzite, siltstone and shale.

Group 3. These soils more closely reflect the parent material underlying the Kalahari sand deposits.

The key properties of each group will now be outlined with examples of soil profiles.

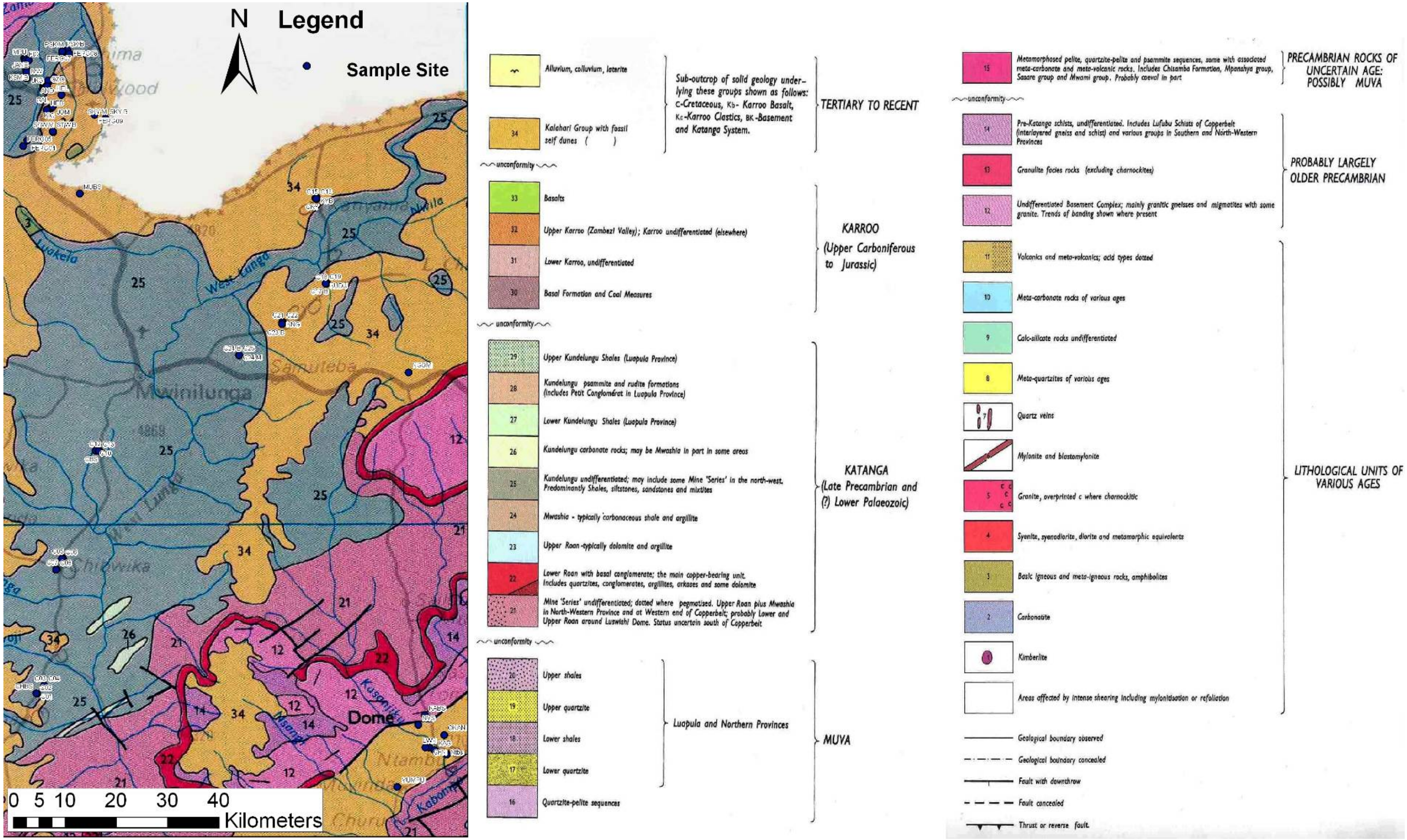


Figure 2.6: Map showing the sample sites of the farms in Mwinilunga District in relation to Geology with inset to show relation to geographical position in Africa and Zambia.

2.4.1 Group 1 – recent soils (Kalahari sands)

These soils are derived from the relatively recent Kalahari sand group. In this undulating landscape, they appear to mainly occupy mid- and foot-slope positions with the more organically enriched soils being in the valley bottom areas. These soils are provisionally classified as being Arenosols and Acrisols with a limited occurrence of Fluvisols.

The texture is sand to loamy sand with around 10% clay, and tending to be slightly luvic. The sand grains are dominantly fine and very fine but with some medium and coarse sized particles. Analysis showed that the sand fraction is only an average of 35% with a silt fraction of an average of 50% (see appendix 4). Ting-Tang et al. (1984) found that the very fine sand fell into the bracket of coarse silt, thus misleading the soil texture class. They explain that this is as a result of fining out of the Kalahari sands in a northerly direction, such that the smaller grained sands travel further, and thus this northern-most extremity has the finest sand. This also helps in understanding the soil texture as there is discrepancy over the size limits of sand and silt between the USDA system and the International Society of Soil Science (ISSS).
The USDA draws the line between sand and silt at 0.05mm whereas in the ISSS the boundary is 0.02mm (MacVicar and De Villiers, 1991). If the ISSS system is used then the Arenosols of Mwinilunga have 80% sand, and not 35% sand. However despite this, there is still a gap in understanding how coarse-grained sands can be found in close proximity (only 100km away in the Western Province) to fine-grained sands (Dalal-Clayton et al., 1985) but perhaps what is worth considering is the role of termites bio-turbating the soil and moving it over time.

According to Ting-Tang et al. (1984) sand grains are dominated by quartz, and Figure 2.7 shows quartz in both the top and subsoils, and have coatings of organic matter with this lessening down the profile. About 40% of both Acrisols and Arenosols were recorded as having bleached sand grains. This could be explained by the deposition of the Kalahari sand grains; considering their size, it is likely that they will have had low iron contents on deposition (Eswaran et al., 1996). Furthermore, chelation processes outlined by Ellis and Mellor (1995), are likely to be acting within the top 50cm of the profile and this will also have led to the bleached sand grains.

XRD analysis, shown in Figure 2.7 (a) and (b), reveals that the clay fraction is dominated by kaolinite and gibbsite with quartz and hydroxyl-Al interlayered vermiculite (HIV) also present.

This confirms that these sandy soils are deeply weathered, with the presence of gibbsite in particular indicating deep weathering having occurred.

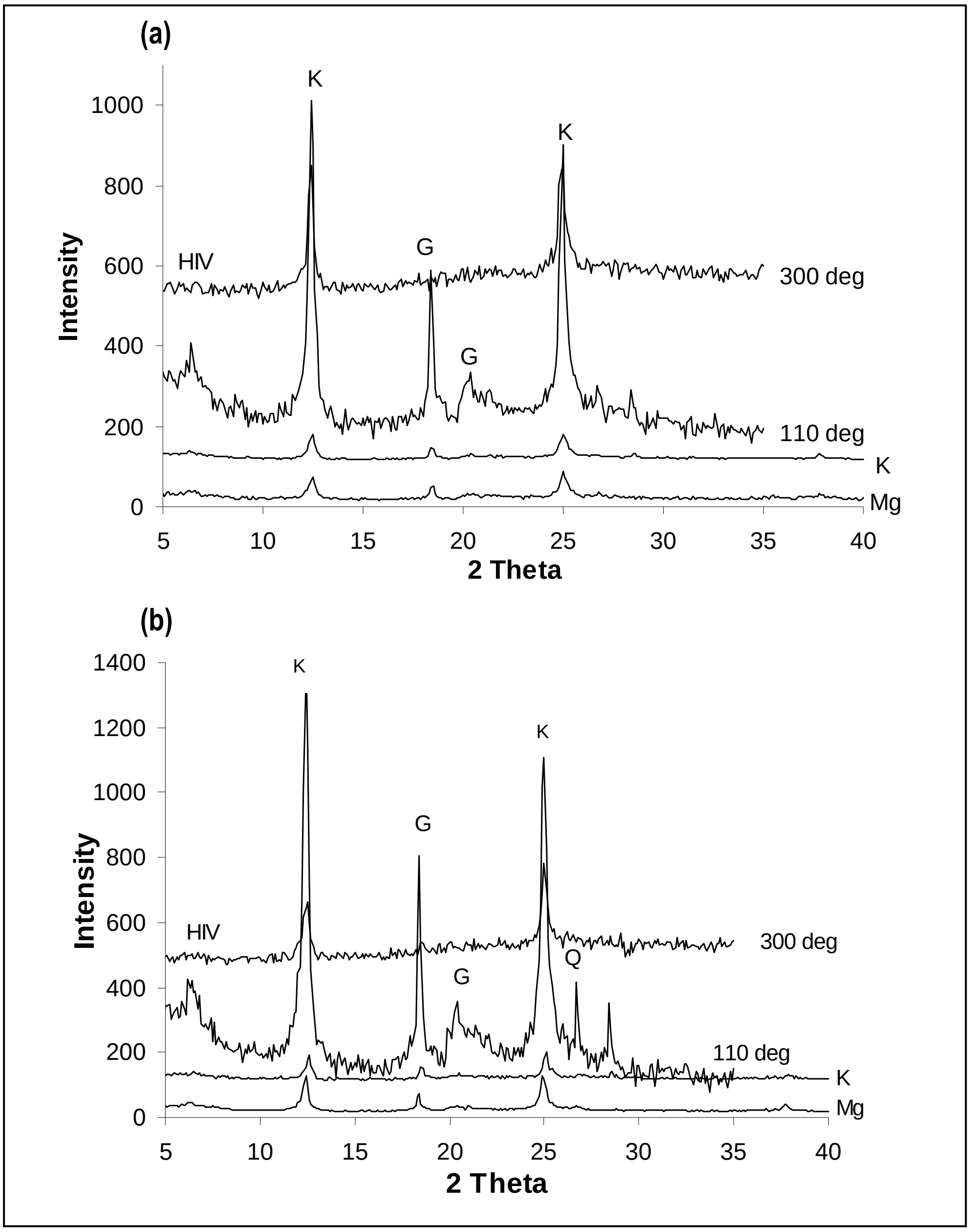


Figure 2.7: X-ray diffractograms of the clay fraction of the top (a) and subsoil (b) clay fractions of profile FISH (Albic Arenosol (Dystric)): K- and Mg-saturated air-dried specimens and K–saturated specimens heated to 110 and 300 ºC (K = kaolinite (7.2 and 3.5 Å) G = gibbsite (4.8 and 4.37Å), Q = quartz (3.34Å) and HIV = hydroxyl-Al interlayered vermiculite (14Å).

Sand particles have very little potential to develop a sizeable clay fraction and so these soils have a low CEC (average of 13 $mmol_c$/kg soil for the A horizon and 7 $mmol_c$/kg soil for the B_1 horizon) and are quite acid (average pH (KCl) of 4.4 in both A and B_1 horizons). They are not very fertile and their chemical properties are likely to be limiting to crop growth.

Soil formation has brought about a certain amount of reorganisation of the sands, sufficient to remove original stratifications and resulting in discernible horizons, but they are still structurally weak, with the exception of the Fluvisols the structure of which is moderate.

The consistence of these soils is loose in the dry state with a low bulk density arising from the influence of bioturbation, with the exception of the Fluvisols, as these do not favour termite activity. Using a model given by Saxton et al. (2006) and knowing the particle size distribution allows for the calculation of a bulk density of about 1.5 g.cm^{-3}. One would expect bulk density of sandy soils to be high with a clay soil being lower when using a model based on the pore size distribution. However the case in Mwinilunga is inverted due to the exceptionally high termite activity. Using a biological factor the bulk density would be about 1.1 g.cm^{-3}. These soils are mostly very porous with well developed micro-aggregation.

In some of the soils the development of an E horizon is evident, which, coupled with the low CEC and pH values would render such soils the least fertile in terms of cropping potential. Examples of the different soils found are shown in Figure 2.8, 2.9 and 2.10.

KIC MA & MB, Haplic Arenosol (Dystric) (South African classification – Tu 2120)

A

0-35cm	Dry; dark greyish brown 10YR 4/2; sand; weak; granular, fine and medium; friable; many fine and common medium roots; diffuse smooth transition.

B

35cm-65cm+	Dry; brown 10YR 5/3; loamy sand; weak; granular, fine and medium; friable; common medium roots, with roots stopping at 65cm; transition not reached.

Figure 2.8: Profile description and photo of a Haplic Arenosol (Dystric), Mwinilunga district.

JCH MA/MB – Albic Arenosol (Dystric) (South African classification - Vf 2120)

A	
0-20cm	Dry; brown 10YR 5/3; sand; weak; fine, single grain; loose; common fine and very few medium pores; gradual, smooth transition.
E	
20-30cm	Moist; light yellowish brown 10YR 5/3, sand; weak; fine, single grain; friable; common fine, med and coarse pores; gradual, smooth transition.
B	
30cm- 140cm+	Dry; light yellowish brown 10YR 6/4; sandy loam; weak-moderate; granular, fine and very fine; firm few medium and coarse pores; transition not reached.

Figure 2.9: Profile description and photo of an Albic Arenosol (Dystric), Mwinilunga district.

C07 MA & MB, Mollic Fluvisol Dystric (South African classification - Ik 2100)

A	
0-80cm	Dry; brown/dark brown 10YR 4/3; clay loam; moderate to strong, blocky, medium; hard; many fine, common medium and few coarse roots; 10cm overburden; diffuse, smooth transition.
B	
80-120cm+	Dry; yellowish brown 10YR 5/6; clay loam; moderate to strong, blocky, medium; hard; few roots; transition not reached.

Figure 2.10: Profile description and photo of a Mollic Fluvisol (Dystric), Mwinilunga district.

In the group 1 soils there is a visible accumulation of organic matter in the A horizon. Laboratory data confirm this, with an average of 1% carbon in Acrisols and Arenosols and 3.2% in Fluvisols.

In terms of soil features, termite mounds are common. They are light yellowish brown (10YR 6/4) and grayish brown (10YR 5/2) in the higher lying areas and black (10YR 2/1) in the bottomland (*dambo*) areas. The latter have significantly higher C (4.3%) and a CEC of 30 $mmol_c$/kg. Upland termite mounds often reach 4m in height (see plate 2.1(f)) with the bottomland termite mounds being much shorter, around 1m in height.

Mottles occur frequently and are in abundance in the subsurface horizons of the bottomland Arenosols. These are typically reddish yellow (10YR6/8) and yellowish red (5YR5/8) and increase in quantity and size down the profile. They are associated with the fluctuating water-table of the *dambo* areas which induces redox changes as suggested by Ting-Tang et al. (1984) and Dalal-Clayton et al. (1985) for Mwinilunga district and Ambrosi and Nahon (1986) in another tropical area.
In Mwinilunga district during the wet months of the rainy season, when *dambo* soils are mostly saturated, it was suggested by Ting-Tang et al. (1984) that the pH is elevated as a result of reducing conditions. This accords with basic principles as outlined by James and Bartlett (2000) and McBride (1994). Conversely with the drying-out of soils there is a fall in pH accompanying oxidation reactions. Consequently redoximorphic features are visible with red-yellow coloured mottles on ped faces and macro-pores. Buol et al. (1997) propose an explanation for such findings in general; suggesting that in the case of the entire horizon being saturated and reduced, the Fe is solubilized in a ferrous form. As the water-table recedes, the iron oxidises causing a diffusion gradient and resulting in ferrous iron from the ped interiors to oxidise on ped surfaces. Tonui et al. (2003) explain from their research in different tropical areas that this causes redox depletion of the ped interior, consisting mainly of quartz and kaolinite. This exhibits a white or grey colour and occurs from the de-ferruginization of the previously associated kaolinite and Fe oxyhydroxides as outlined by Buol et al. (1997). These offer an explanation for the colouring found in these soils and also for clay moving down the profile, since kaolinite aggregates free of Fe can be dispersed and the kaolinite will assume the potential to eluviate from the profile.

Group 1 soils have low cropping potential without chemical amendment. However the free draining quality and ideal climate make these high potential soils when suitably amended. According to tables by Sys et al. (1993), if farmed commercially with machinery and chemical amendment, they could reap at least 6 $t.ha^{-1}$ maize, however recent work undertaken by Sanchez et al. (2007) suggests that with chemical amendment and hybrid seeds these soils, if farmed manually, could also obtain 6 $t.ha^{-1}$.

2.4.2 Group 2

These soils have developed on psammitic biotite schist, shales, tremolite-actinolite schist and granite (Drysdall et al., 1972) and red and buff siltstone with basal conglomerate (Appleton, 1984) which has been exposed from stream incising. They are older than the two previous groups of soils and are tentatively classified as Lixisols and Nitisols. Texturally they have significantly higher clay contents (>20% and <45%) arising from the weathering of parent material, and an increase in clay content down the profile.

The primary mineral suite has contained a significant clay forming potential through hydrolytic weathering of shales and siltstone (Pedro, 1982). The pH of group 2 soils sampled on the shales was an average of about pH (KCl) 3.8. Both mica and kaolinite are found in the clay fraction (see Figure 2.11(a) and (b)).

Clay eluviation means that the B horizons have a well developed structure, with distinct peds and evidence of cutans (Figures 2.12 and 2.13). Generally the shape of peds is blocky (Figure 2.13), but the soils provisionally classified as Lixisols that have developed on shale have a moderate tendency to be prismatic in the B horizon.

The higher clay content of the Nitisols and some Lixisols results in their porosity being poor and these soils tend to be more compact. The bulk density is about 1.5 $g.cm^{-3}$. The bottomland soils which have high clay contents (~40% clay) but equally high carbon (2-3% OC) have a relatively lower bulk density of about 1.4 $g.cm^{-3}$.

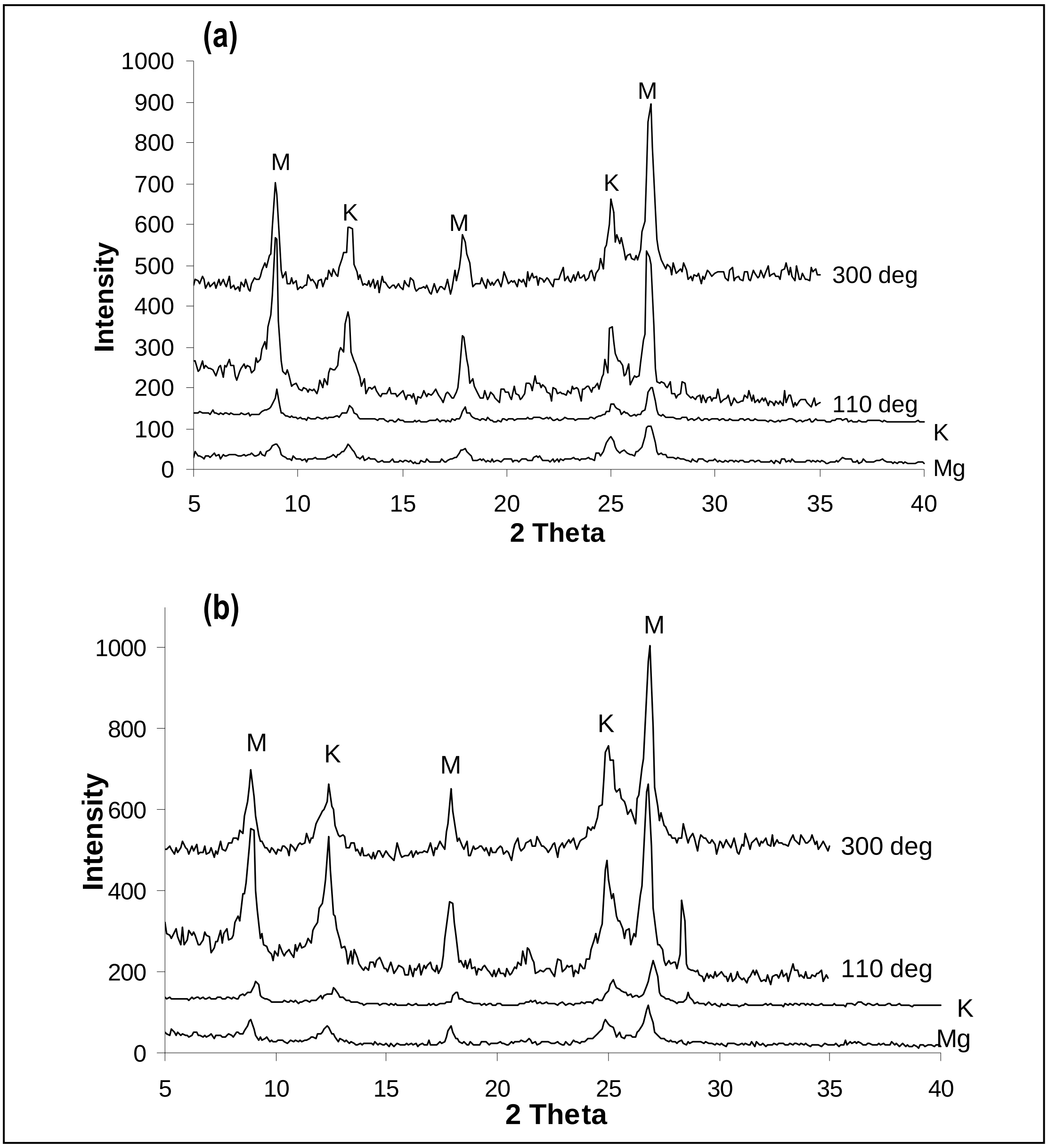


Figure 2.11: X-ray diffractograms of the clay fraction of the top (a) and subsoil (b) clay fractions of profile C09 (Haplic Lixisol (Rhodic)): K- and Mg-saturated air-dried specimens and K–saturated specimens heated to 110 and 300 ºC (K= kaolinite (7.2 and 3.5Å), M = mica (10 and 5Å).

The Lixisols that have a high silt content (~50%) and an average of ~20% clay have some pedoturbation to aid porosity and the bulk densities of these soils is about 1.4 $g.cm^{-3}$. The group 2 soils are less porous than those derived from Kalahari sands (group 1) and so more likely to be physically limiting to crop growth, but their consistence is not so hard that roots cannot penetrate and thus the higher clay content is more likely to be beneficial to the farmer as it has a higher CEC.

C07 BA & BB, Acric Nitisol (Eutric) (South African classification - Sd 1110)

Orthic A 0-30cm	Dry; light reddish brown 5YR 6/4; sandy clay loam; weak to moderate, blocky, fine; slightly hard; many fine, medium and coarse roots; gradual, smooth transition;
B_1 30-110cm+	Dry; red 2.5YR 4/6; clay loam; moderate, blocky, fine and medium; hard; few medium and coarse roots; transition not reached.

Figure 2.12: Profile description of Acric Nitisol (Eutric), Mwinilunga district.

C09 MA & MB, Haplic Lixisol Rhodic (South African Classification - Sw 2111)

A 0-25cm	Dry; light yellowish brown 10YR 6/4; sandy clay loam; weak to moderate, blocky, fine and medium; soft; common medium and fine roots, no coarse roots; gradual, smooth transition;
B 25-160cm	Dry; yellow 10YR 7/6; clay loam; moderate, blocky, medium; slightly hard; few medium, few fine and no coarse roots; quartz stoneline at 50cm; gradual, smooth transition;
C 160-175cm+	Slightly moist; shale; signs of wetness present.

Figure 2.13: Profile description of Haplic Lixisol (Rhodic), Mwinilunga district.

The colours of these soils vary depending on slope position. The soils developed on shales tend to be yellow-red with the red hues and purple colours being in the shale itself (A horizon = light yellowish brown 10YR 6/4, B horizon = yellow 10YR 7/6). Soils developed on the red siltstones are a red colour (A horizon = light reddish brown 5YR 6/4, B horizon = red 2.5YR

4/6). Lower slope positions of the soils from red siltstones have a much darker topsoil due to the accumulation of organic matter (A horizon = brown/dark brown 10YR 4/3, B horizon = yellowish brown 10YR 5/6).
Colours are fairly uniform, with mottling being unusual in these soils but with some cutan coatings on peds in the higher clay content soils and some slickensides recorded in a small number of the bottomland soils.

In terms of fertility these soils have the highest CEC values and more than 50% of these soils have sufficient K and Mg with Ca being the most limiting basic cation as only 31% of soils have sufficient levels. About 23% of soils have sufficient P levels and thus P is likely to be limiting but this is across all soils and probably related to composition of the parent material. The higher K values are possibly explained by the presence of mica. In terms of fertility, group 2 soils have the highest proportion of soils being marked as sufficient in macronutrients. Aeration of the more dense soils would be required, but they are likely to give the highest yields when acidity and low Ca are ameliorated.

2.4.3 Group 3

Where the Kalahari sands have been largely removed or have not been deposited to a large extent, soils have developed reflecting both the sands and the different underlying parent materials (granite, arkosic quartzites with basal quartz-pebble conglomerate and/or Kundulungu siltstone). The types of soils that occur on this parent material group are provisionally classified as being dominated by Ferralsols with some Acrisols.

The texture of group 3 is reflected by the strong admixture of Kalahari sand, particularly in the upper part of the profile giving a significant textural gradient – sandy loam topsoils that change clearly to a sandy clay loam in the subsoil. The sand grade is dominantly fine (average of 55% fine and very fine sand) with some medium sand (an average of 8.8%) and only 1% coarse sand. The clay content is relatively low (~15%), but fractionally higher than that of the Kalahari sands as the parent material has a low clay-forming potential.
The parent material combined with the intense weathering, results in kaolinite being the dominant clay mineral in both the top and subsoils (Figure 2.14). According to Ting-Tang et al. (1984), other than the low-activity kaolinite, amorphous sesquioxides of Al and Fe are found in abundance.

There is little development of structure in these soils but they are more structured than the Arenosols and Acrisols derived solely from the Kalahari sands. The subsoils show a greater degree of pedogenesis, but are not developed enough to be classified as structured. They lack well-formed peds in the moist state and tend to be dominated by porous micro-aggregates. Consequently these soils are highly porous with very low bulk density (about 1.2 g.cm^{-3}).

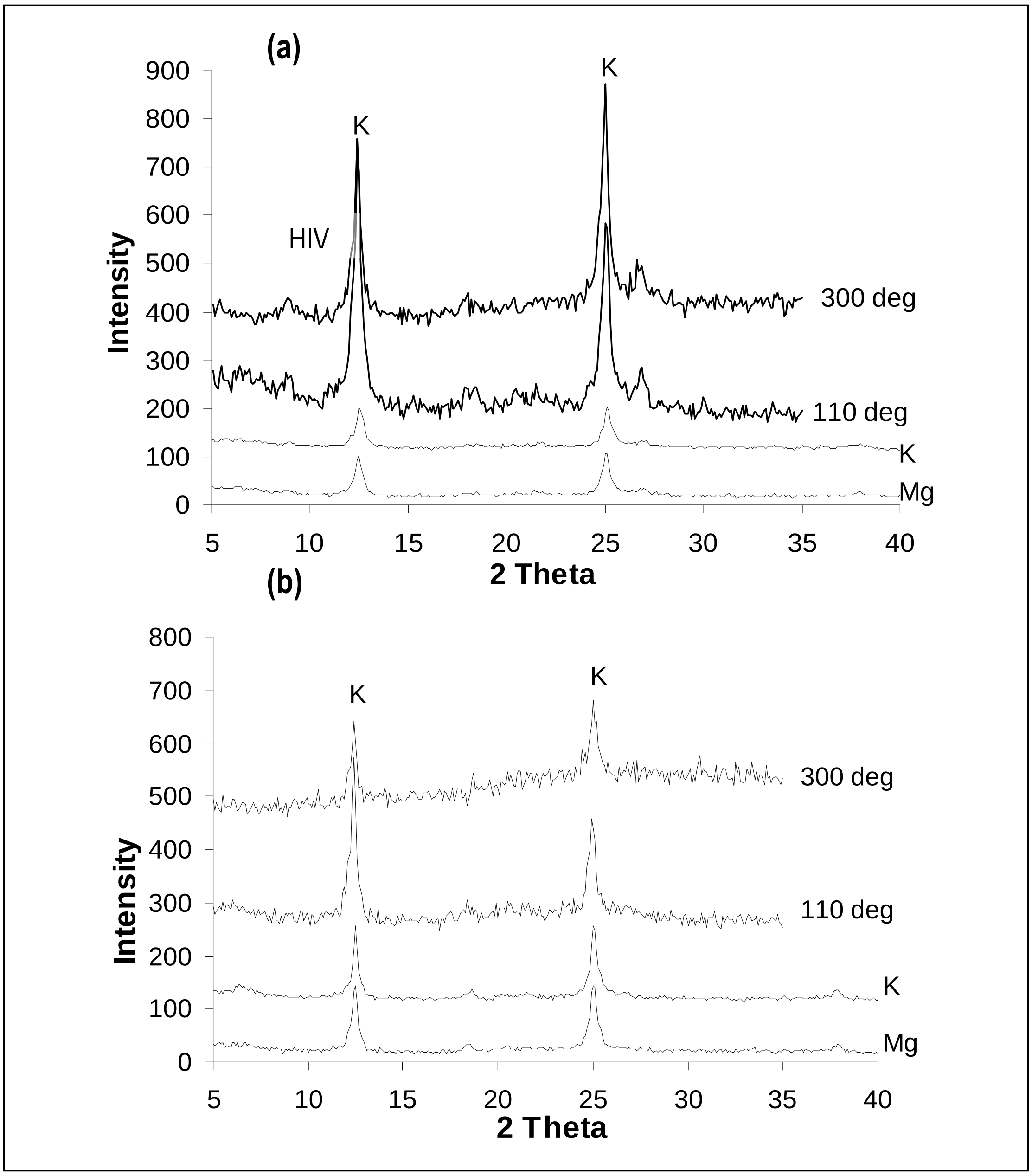


Figure 2.14: X-ray diffractograms of the clay fraction of the top (a) and subsoil (b) clay fractions of profile KSM (Haplic Ferralsol (Dystric)): K- and Mg-saturated air-dried specimens and K–saturated specimens heated to 110 and 300 ºC (K= kaolinite, 7.2 and 3.5Å, HIV = hydroxyl-Al interlayered vermiculite (14Å).

Weathering has occurred under well-drained, oxidising conditions and in the red-coloured soils, the iron present has coated sand particles. These soils are mostly uniform in colour with changes down the profile being gradual and transitions between horizons being gradual to diffuse. Soil colours reflect topographic position, with soils of a red hue being in higher slope positions and becoming more yellow and less red the lower the slope.

Where an albic horizon has developed (see Figure 2.16) conditions have been sufficient for the removal of Fe and organic coatings; this is understandable as these soils have an average of 1.3% C and are acidic (pH_{KCl} 4.4) and likely to hold a zero or positive charge within 100cm of the soil surface (see pH_{H2O} and pH_{KCl} values in Appendix 3 with this frequently being <1).

Evidence for deep lateritization in the majority of these soils was recorded, and Ting-Tang et al. (1984) also reported that some of the soils have underlying laterite (plinthite) or saprolite (Figure 2.15 shows such a profile). The occurrence of plinthite that does not harden upon exposure is not uncommon, especially in bottomland soils. According to the WRB (2006) definition, plinthite must harden upon exposure and thus there are proposed Ferralsols and Acrisols in this area that do not qualify as plinthic but the pedogenic processes associated with plinthite may well be occurring.

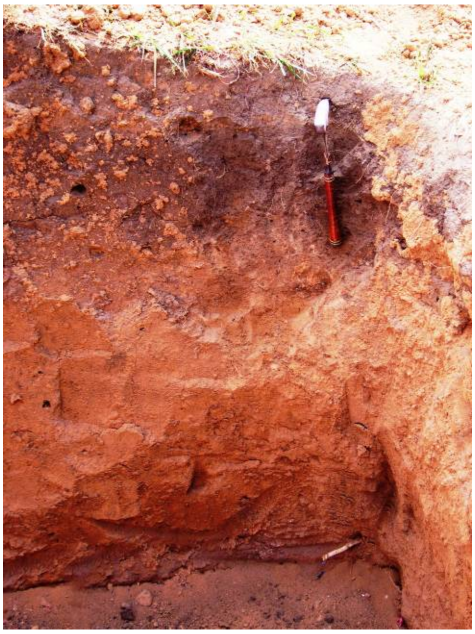
In some of the mid- and lower-slope areas evidence for podzolisation was noted. Bleached sand grains are encountered, especially in Acrisols, and podzols were found within the Mwinilunga district, but not in any of the soils studied. Not all soils have developed an E horizon, and few have developed a spodic horizon, but processes associated with podzolisation may explain the removal of the Fe and organic matter from the bleached sands.

FIX MA & MB, Haplic (Plinthic) Ferralsol (Dystric) (South African classification - Av 1200)

A 0-25cm	Dry; light yellowish brown 10YR 6/4; loamy sand; weak, blocky, fine; soft; many fine and medium roots, common coarse roots; diffuse, smooth transition.
B 25-120cm	Dry; reddish yellow 5YR 7/6; sandy clay loam; weak-apedal; blocky, fine; slightly hard; few fine, medium and coarse roots; gradual, smooth transition.
B 120-150cm+	Slightly moist; Yellowish red 7.5YR 6/8; sandy clay loam; moderate, blocky, coarse; very few medium roots; deep red and black concretions (some magnetic) increasing with depth; transition not reached.

Figure 2.15: Profile description and photo of a Haplic (Plinthic) Ferralsol (Dystric), Mwinilunga district.

LIC BA & BB, Posic Ferralsol (Dystric) (South African classification - Ct 2100)



A 0-35cm	Dry; dark grey 10YR 4/1; sand; moderate; blocky; friable; many fine and medium, few coarse roots; abrupt smooth transition.
E 35-50cm	Dry; grayish brown 10YR 5/2; loamy sand; weak; granular, fine; friable; few roots; gradual smooth transition.
B 50-140cm+	Dry; yellow 10YR 7/8; sandy loam; weak – moderate; blocky, fine; friable; very few roots; transition not reached.

Figure 2.16: Profile description and photo of a Posic Ferralsol (Dystric), Mwinilunga district.

Termites and their associated mounds occur in the Ferralsols, with the red termite mound colour being described as brown (7.5YR 5/4). These red hued termite mounds occur less frequently than the yellow coloured mounds (they are light yellowish brown (10YR 6/4) and grayish brown (10YR 5/2)), and are less frequent than in the Arenosols. There appears to be a correlation between colour and quantity of termite mounds, with fewer termite mounds in the redder soils, perhaps connected to the greater cementing effect of the Fe involved in the soil profiles, although termite mounds exceeding a height of 3m are common. From the soils and occurrence of termite mounds in Mwinilunga district, the suggestion of Fanning and Fanning (1989) that pedoturbation provides a more oxidative environment though increased aeration is not directly applicable to these soils. If there are fewer termite mounds and therefore less termite activity in the reddish hued, oxidised, Ferralsols, then there should be more termite mounds. However, Watts (1980) explains that these soils are limiting for termites because there is low subsoil water availability and thus there are fewer mounds. This is in line with the topographic position of the red soils, as water is likely to be deeper and less accessible.

Faunal activity is significant in improving microstructure and in maintaining a low bulk density and a high porosity in these soils. Despite there being fewer termite mounds in the red coloured soils, their presence is sufficient for their bio-turbation to affect soil structure. Horizon boundaries are less clear and the horizon material is quite homogenous. This was also found by Bateman et al. (2003) when looking at pedoturbation in sandy upland soils in Lee County, Texas, USA. It is thought that a combination of the oxidative environment and the pedoturbation accounts for the well mixed profile

In terms of fertility and nutrient availability, group 3 soils can also be considered acidic (average pH_{KCl} 4.2) with a low base status, Acric Ferralsols have the lowest CEC (<24 $cmol_c kg^{-1}$ clay) with Haplic Ferralsols consistently having a low P availability, averaging about 1 mg/kg. They are well aerated soils and so physically conditions are conducive to deep rooting. The nutrient levels are on average higher than the Kalahari sands (see Table 2.1) with K and Mg being significantly less limiting but with Ca being much more limiting than in soils developed on Kalahari sands. This is due to a higher OC on average and resultantly a higher CEC. These soils have a higher cropping potential than the Kalahari sands.

2.5 Amelioration of acid soils in the district – data for local soil ameliorants

The fertility data presented in this chapter show that these soils tend to be sub-optimal with respect to both macro and micronutrients. To this end it is recommended that on any given soil in the district, the farmer should seek to raise the nutrient levels to sufficiency. Various options are available and ideally commercial fertilisers will meet this need as has been shown widely (e.g. work in the Millennium villages done by Sanchez et al., 2007). Many farmers complain of the cost and availability, but Sanchez et al. (2007) show that with careful management and involvement from all stakeholders this can be overcome and should not be accepted as a reason for poor yields. In the interim before fertilizers become available Bhattacharyya et al. (2007) have recommended that making use of local materials should be considered. In the Mwinilunga district the most obvious possibilities are termite mounds, compost/manure, ash, crushed rock and green manure crops.

Termite mounds are used in eastern Zambia as a source of alkalinity (van Straaten, 2002). Several samples were taken from some of the many termite mounds in the research area. The outer samples was taken from the mound surface and the inner sample 50cm inside the termite mound. The results are summarised in Table 2.3.

Table 2.3: Outline of the chemical characteristics of termite mounds sampled according to colour in Mwinilunga district.

Mound colour	Sample position	pH (KCl)	Total C (%)	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)
Red	Exterior	4.96	0.72	9	206	237	104
	Interior	4.64	0.81	3	25	150	82
Yellow	Exterior	3.99	0.61	3	147	147	69
	Interior	3.88	0.76	5	55	177	86
Black	Exterior	4.75	4.30	9	273	222	87
White	Exterior	4.20	0.52	15	184	694	95
	Interior	4.02	0.89	7	90	299	89

The termite mounds with the highest pH values and consistently the highest cation values were the exterior of the red termite mounds. These are found on the more oxidised group 3 soils. They may be beneficial to add to soils in terms of adding CEC and some nutrients, but they cannot be viewed as a suitable source of nutrients and alkalinity. A physical benefit from a higher clay content might possibly justify their use as a soil ameliorant.

Miombo ash was sampled, acid digested, and analysed for basic cations. Ash is widely available as traditionally all cooking is performed over a fire from miombo wood. The ash has a high pH (11.6) but a low CCE value of 10.3. This CCE value means that quantities required are likely to be high and impractical. The ash could prove to be a useful source of K, Ca and Mg for these soils with contents of 4.2, 0.7 and 0.1% respectively. The application of ash needs to be systematic and it needs to be thoroughly mixed into the soil in order to maximise its effectiveness throughout the profile and to neutralise acidity in the rhizosphere. Further research identifying suitable quantities for the different soil groups and its effectiveness in terms of solubility is required.

Manure and compost are available from local chickens and pigs, but there are few animals and so the quantity is very limited. Therefore it is not considered viable for use.

Harley and Gilkes (2000) encourage the use of crushed rocks such as dolomites in agriculture. They also consider the use of granite, but suggest that due to its composition its usefulness as a source of alkalinity is unlikely. This prospect is considered in more detail in Chapter 3.

CHAPTER 3

Powdered granite effects on acid soil and soil plant interaction involving base cations

3.1 Introduction and hypothesis

Soil fertility constraints in NW Zambia are known to limit crop growth and food production and are exacerbated due to the poor supply of conventional fertilisers in the area (Kamwi et al., 2003). The motivation of this chapter is to investigate the possibility of harnessing locally available rock as a means of ameliorating soil acidity and providing K for maize plants.

One of the locally available rocks is granite, it is K-feldspar leucogranite, which is locally foliated and with fine-grained biotite-xenoliths. Biotite and feldspar, both common constituents of granite, are known to dissolve in acidic solutions (pH 2-3) at a rate per unit surface area of K $\approx 10^{-11}$moles/m^2/sec (McBride, 1994 p.226), this rate will differ at higher pH values but perhaps dissolution will release sufficient K and alkalinity for partial relief of the low pH and K values. Field trials undertaken by Baeel Silva et al. (2005) to determine the neutralising effectiveness on acidic nutrient depleted soils in Australia showed that there was insufficient K and alkalinity for granite to be seriously considered as an ameliorant. Harley and Gilkes (2000) generally concur with this statement, but encourage further mineral-specific research.

Soil analyses of the area surrounding the granite shows the soils to be acidic of which 42% have a pH<4.3(KCl) and with 62% of subsoils containing <50mg/kg soil K. It is known that granite is unlikely to contain sufficient K and alkalinity; however, given the limited fertilizer availability and affordability granite was considered to be potentially chemically plausible due to the special circumstances of very acid soils coupled with limited availability of regular fertilizers.

Parameters that need to be determined are the neutralising capacity of the granite and whether this is sufficient to ameliorate acidity at realistic rates of application. Additionally the potential of the granite as a source of K to maize plants needs to be explored. Pot trials are considered valuable for determining such factors (Rayner, 1969) and thus will be used as a tool in this investigation.

Hypothesis:

Pulverised granite is a viable and suitable substitute (i) for K fertilizer and (ii) for lime in neutralising soil acidity harnessing the K and alkalinity from the following reaction:

$2KAlSi_3O_8 + 9H_2O + 2H^+ \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4H_4SiO_4$

3.2 Methods and Materials

3.2.1 Soil collection and preparation

An acidic, loamy clay topsoil (pH_{KCl} 3.56) from the Welgevallen experimental farm, Stellenbosch was collected, air dried and passed through a 5mm sieve. The soil was pre-treated with a basal dressing of 3g/kg N (NH_4NO_3), 0.6g/kg P ($(NH_4)_2HPO_4$) and 200mg/kg Mg ($MgCl_2$) to cover crop requirements. It was thoroughly mixed into the soil using a cement mixer.

3.2.2 Crushed granite and experiment outline

Granite (pH_{KCl} 11.21) was collected from NW Zambia near Kalene hospital (24º11'10'' and 11º07'00'') on the granite outcrop at a hydro electric power plant construction site. Granite was collected as partially pulverised from a rock crusher, this was then sieved to <500µm. A factoral experiment was conducted to compare granite as a source of K and as an acid neutraliser with K (1g/kg KCl) and/or lime (3g/kg $CaCO_3$) similar to that of Carter and Singh (2004). The experiment consisted of a 4x2x2 factoral design, with three replications. Each of the treatments consisted of four different granite levels (G0 = 0g, G1 = 7.5g, G2 = 15g and G4 = 30g per kg soil). These values were based upon the neutralising reactions of different quantities of granite added to 20g of soil in a 50ml 1M KCl solution and observed over 12, 24, 48, 72, 96, 120 and 240 hours.

The granite was mixed with the soil in a plastic bag for 5 minutes and then placed into a pot, sealed at the bottom. Pots were watered to field capacity (FC) before planting. Six maize seeds were sown in pots containing 1kg of soil and were thinned to four plants after they reached a height of 15cm. The plants were irrigated with tap water to FC level on a daily basis to ensure that water was not a limiting factor. Deficiencies were noted throughout the growing of plants. Maize plants were harvested at 5 weeks and their wet and oven-dried masses recorded. Soil samples were taken by extracting four core samples per pot. These were air-dried, passed through a 2mm sieve and analysed. The maize roots were separated and examined qualitatively for differences in relation to treatment.

3.2.3 Analytical

The dry plant samples were milled, ashed and dissolved in a 1:1 dilution of HCl, according to Ryan et al. (1981). This ashed material was then analysed for P, K, Ca and Na using AAS. Soil pH was measured using distilled water and 1M KCl (1:2.5 soil:solution). If the pH was found to be less than pH_{KCl} 4.5, titratable acidity was measured using 0.01M NaOH and phenolphthalein (White, 1997). The supernatant from a 1:5 soil:NH_4OAc filtrate was analysed by AAS for K, Na, Ca and Mg. Available P was determined using the Bray 2 method (Rowell, 1994). The data was analysed statistically for significance of relationships and to test the hypothesis using analysis of variance (ANOVA) in Statistica (Statsoft Inc., 2008) .

3.3 Results and discussion

The raw data (appendix 6), when tested with ANOVA (appendix 7) showed the interactions between different variables and compared granite to lime. Figure 3.1 (a) shows the change in pH at the different granite levels, G0-G4. G4 raised soil pH to 3.9 from 3.7, but the lime treatment of only 3g/kg raised the pH to 5.34 (see Table 3.1). Granite treatment G4 does alter pH. Considering it is ten times the lime quantity however, and raised pH only slightly, granite is effectively useless in the short term. This was confirmed through ANOVA with granite not having a significant effect when compared to lime. Root inspection also showed that on lime treated soils there were many more fine roots and it was noted that the roots on soils without lime and with no granite (G=0) the roots were only in the top 5cm of the pot. Combinations of these two observations strongly indicate a likely Al toxicity. There were no improvements at the high levels of granite.

On average, the addition of granite raised the soil K levels from 54mg/kg (G0) to 74mg/kg (G4), see Table 3.2 and Figure 3.1 (b1). Where KCl (1g/kg) was added, the soil K levels were raised to an average of 471mg/kg soil. ANOVA showed that the addition of KCl and lime significantly increased yield, however the addition of granite in the absence of lime or KCl was not significant in relation to yield.

Table 3.1: Yield, pH, acidity and macronutrient data for the different K and Lime treatments, with all values averaged over the different granite treatments. K1 indicates use of KCl fertiliser and L1 indicates use of lime. The results are for the average values of all three different levels of granite (G0-4).

				Soil NH_4OAc extractable cations (mg/kg)				Plant nutrient data (%)			
	pH (KCl)	Titratable acidity (mmol/kg)	Yield (g)	Ca	Mg	Na	K	Ca	Mg	Na	K
K1L1	5.34	0	3.19	1252	270	405	401	0.44	0.29	0.15	5.57
K0L1	5.28	0	2.97	1136	266	429	54	0.51	0.74	0.14	2.02
K1L0	3.74	9.35	2.35	397	286	419	471	0.18	0.34	0.09	5.87
K0L0	3.81	7.22	1.53	472	265	419	74	0.23	0.64	0.12	1.9

Table 3.2: pH, acidity and K values for granite treatments G0, G1, G2 and G4 in the absence of lime (L0) and KCl (K0). Values are an average of the three replications.

Treatment	pH	acidity (mmol/kg)	Soil K(mg/kg)
K0L0G0	3.74	7.19	53.67
K0L0G1	3.77	7.33	54.33
K0L0G2	3.86	7.06	59.33
K0L0G4	3.86	7.30	74

Soil Ca was slightly elevated from the addition of granite at the highest addition, G4 (see Figure 3.1(c1)) however, considering the quantity of granite that was added the difference is not significant enough to be worthwhile. This is confirmed with no significant change in the plant Ca levels as Figure 3.1(c2) shows.

Mg levels are consistently lower in K treated soils in the presence or absence of lime across all granite treatments. Figure 3.2(d) shows that this is greater in the absence of lime. This antagonistic interaction has previously been observed and reported (Huang et al., 1990; Grunes et al., 1992; Ohno and Grunes, 1985). Highly hydrated Mg is bound weakly in cell walls and, according to Wilkinson and Grunes (2000), possibly at the binding sites on the plasma membrane. Other cations (in this case K in particular) compete quite effectively with Mg and strongly depress its uptake. Furthermore “competition from K generally has a greater effect on Mg translocation to the shoot than on the Mg adsorption by the root” (Wilkinson and Grunes, 2000 p.D99). Thus, when K is added it ‘out-competes’ Mg and additionally has a negative effect on Mg translocation causing the levels to decrease in the plant matter. This seems to be further increased with the addition of lime.

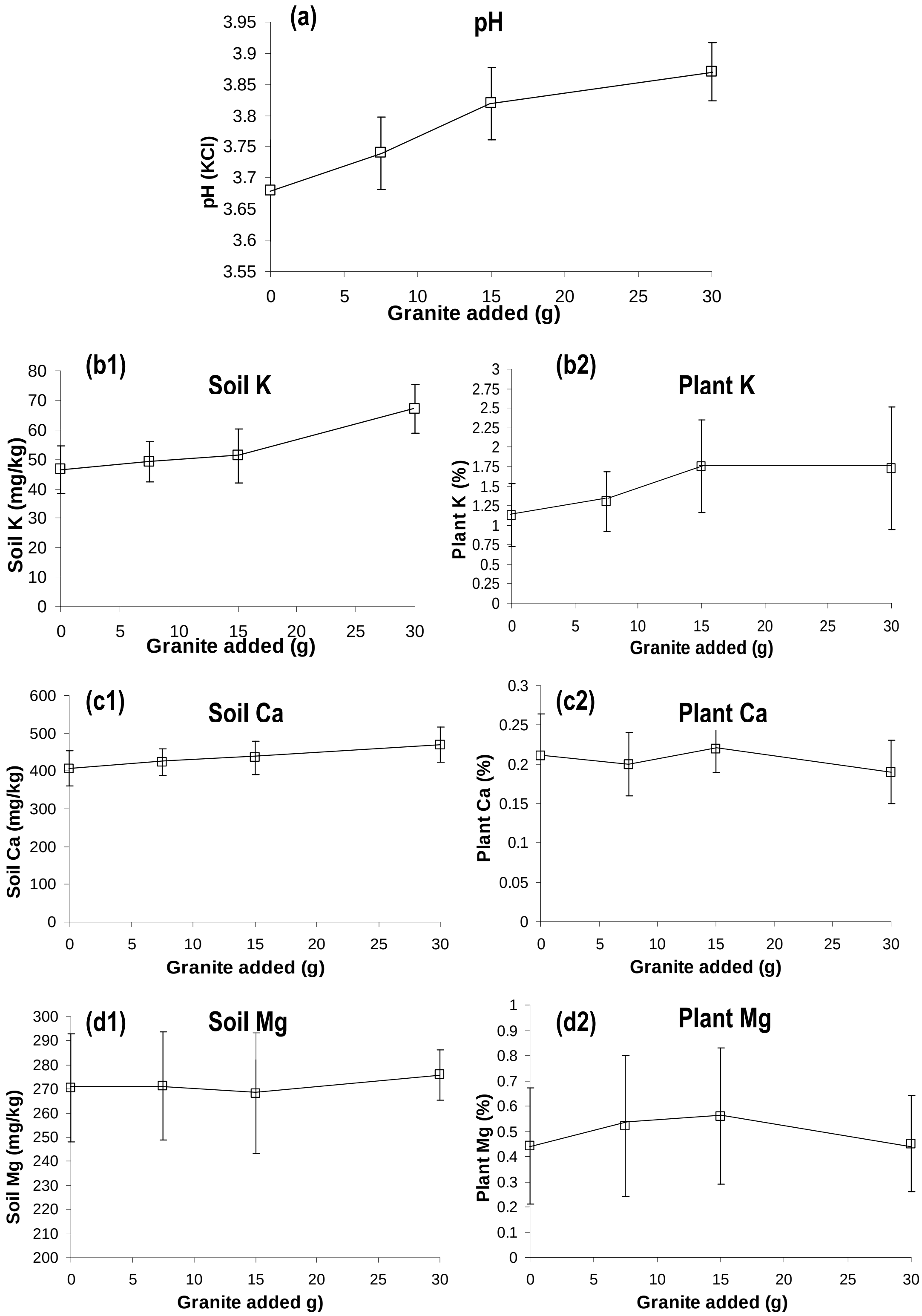


Figure 3.1: The effect of granite addition on soil pH (a), and both soil and plant macronutrients (b, c and d 1 and 2), bars denote standard deviation from mean.

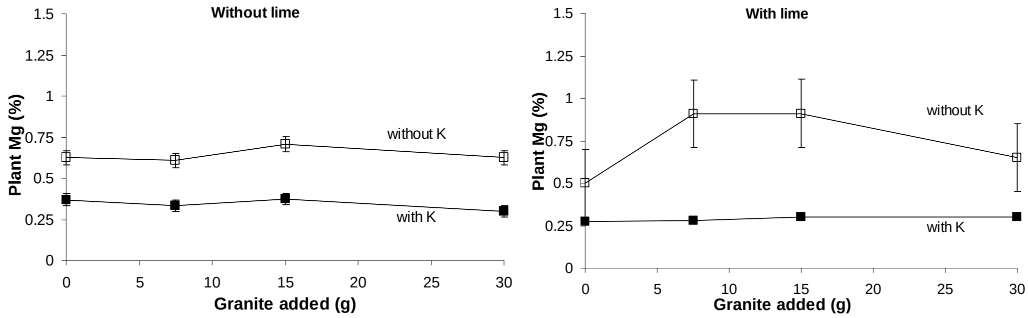


Figure 3.2: The effect of soil granite additions on plant Mg(%) both with and without KCl fertiliser and with and without lime, bars denote standard deviation.

Another relationship that is strongly supported with the data is that of the acidifying affect in the rhizosphere with the addition of KCl. Figure 3.3 indicates that the addition of K acidifies the soil by ~2mmol/kg and this is also shown in the data in Table 3.1. Concomitantly, the sum of exchangeable bases in the plant material goes up by a similar amount (~2.7 $mmol_c$/kg). The uptake of cations by plant roots is a fundamental mechanism which is shown clearly in the data. The explanation for this is the processes of passive diffusion or active transport. Crudely, ions move from a high concentration or potential (Ψ) in soil solution phase to a low potential (Ψ) in plant root cells. The concentration of ions in the so-called apparent free space in the root cell is normally less than the bulk solution, thus a concentration gradient exists for the movement to occur (Raven and Johnson, 2002). Additionally, interior surfaces of cells in the cortex are negatively charged and thus attract cations (Tisdale, et al., 1994). In order to maintain electrical neutrality protons are released across the membrane, raising the concentration of protons on the outer membrane side (decreasing pH). As membranes are impermeable to protons, the continuation of this creates a concentration gradient through which basic cations are taken up (Raven and Johnson, 2002). It is apparent then that this active process results in a net acidifying effect in the rhizosphere and could affect soil pH.

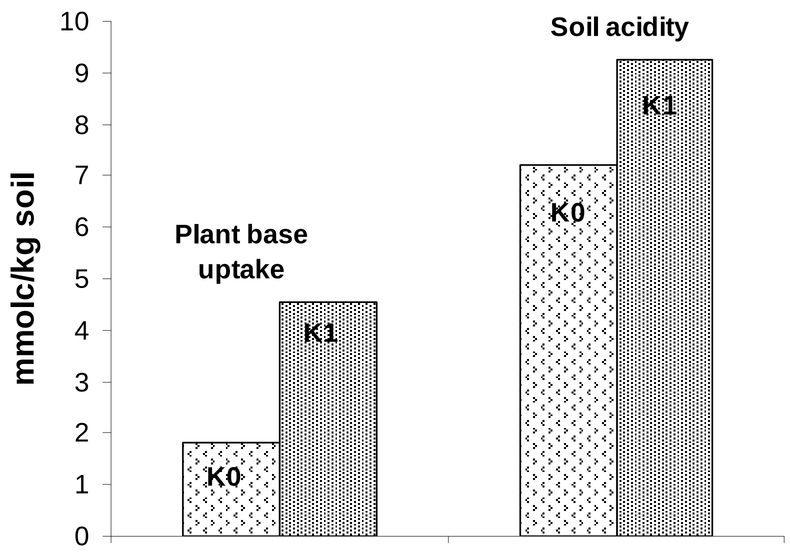


Figure 3.3: The effect of the addition of KCl (K1) and no KCl (K0) on plant base uptake and soil acidity.

3.4 Conclusions

The viability of using crushed granite as an acid ameliorant and K fertiliser was shown to be limited in effectiveness and likely to be impractical as the quantities of granite required are large. Granite made no significant impact in raising soil pH but did raise K levels from ~50mg/kg to ~70mg/kg soil. However, the quantity required to reach this level was high (G4) with the effect not being significant when compared to the addition of KCl. This quantity is thirty times that of the KCl addition producing nowhere near the same effect and as such is nominal as a K fertilizer.

The antagonistic interaction of K and Mg was observed with a decrease in the Mg levels in the plant matter with the addition of KCl to the soil. The addition of K as KCl clearly showed the acidification of the soil with an increase in titratable acidity equal to the increase in base uptake in the plant matter. The application of lime across G0-G4 resulted in the plant Ca and K undergoing an antagonistic relationship.

As a recommendation it is suggested that conventional fertilizers and lime are used and where not possible, more appropriate and effective means of soil acidity amelioration and nutrient fertilisation be explored and tested, such as ash, manure and local dolomite.

CHAPTER 4

General discussion and conclusions

Following a review of the literature it was apparent that there is little known of the soils of Mwinilunga district in terms of their fertility status, classification and yield potential. Ting-Tang et al. (1984) indicated that in particular the area north of Mwinilunga was lacking in fertility data and information and/or profile descriptions. Coupled with poor information on these soils, farmers were complaining of poor yields and the associated poverty (Makanda and Moono, 1999).

Bationo et al. (2006) recognise and have highlighted the usefulness of fertilizers in sub-Saharan Africa through many different field trials in different climatic areas. Palm et al. (2001) explain that availability and accessibility of fertilizers in remote areas of Africa can be limiting despite the wealth of knowledge of their effectiveness. Where fertilizers are available, Gruhn et al. (2000) show that mismanagement can exacerbate fertility constraints as opposed to increasing yields and their use needs to be appropriate for the soils being ameliorated. This in turn may place further financial strain on rural communities, and warrants further investigation.

From the literature it became clear that the objectives of this thesis should be to investigate the origin and formation of the soils in Mwinilunga district of north-west Zambia, describing the soil types of the district in order to develop an understanding of their fertility status. This was to be done alongside determining the actual yields in order for suggestions of amelioration to be appropriate and to set targets that are high yet realistic and achievable within the constraints.

Soils were sampled with profile descriptions done for both the maizeland and bushland of 100 subsistence farmers. These soils are derived from Kalahari sands or quarzitic-schist with some siltstones and shales. The high rainfall of the area and the parent material has led to the formation of acidic low fertility soils. Many soils have sub-optimal levels of P, K, Ca, Mg, Zn and B. This is across both the bushland and maizeland samples so there seems to be no clear impact, in terms of soil fertility, of the conversion of forested land to agricultural land. This finding is contrary to research in Brazil by Hőlscher et al. (1997) and Miller and Kauffman

(1998) and in Africa by Palm et al. (1996). Bushland soils confirmed that the problem of acidity is a natural one, that it extends to the subsoil and that agriculture has not yet exacerbated this problem.

Yields are reported by residents as often being insufficient to feed families, a problem that is frequently encountered across sub-Saharan Africa (Sanchez et al., 2007). However the yield data recorded was not reliable so could not be used in the thesis. It is therefore suggested that monitoring that is reliable and has worked at the village level, such as used by Sanchez et al. (2007) in Malawi, Kenya, Tanzania and Uganda, is used in future work in order for actual yields to be known and related to fertility constraints.

Despite the poor yield data, from soil descriptions and analytical data, it is apparent that these soils are acidic, leached, base-depleted soils. Regardless of excellent growing conditions, soils fertility is a major constraint to yield and so on a practical level the farmer is not entirely able to subsist. Topsoil acidity and infertility requires amelioration, however, data show that the problem extends to the subsoil. Therefore merely reducing topsoil acidity and infertility will likely be only a temporary fertility solution. Rather the fertility needs to be raised down the profile, especially considering the high rainfall and sandy soils and consequently, the high leaching. As a result of this it seems that the approach of Palm et al. (2001) and Bhattacharyya et al. (2007), of solely using organic additions will not suffice. It is considered that the use of commercial fertilizers and lime will have the most dramatic effect on yield.

Fertiliser's that the fertiliser industry in Zambia currently produces contain N, P and K as standard components with both B and Zn also included. These trace elements are commonly deficient across the country and so making use of these products that are already available and tailored to the nutrient deficiencies is recommended. This should happen in conjunction with exploring and testing the dolomite that is shown on the geological map of the area, north of Kalene, as a source of alkalinity, Ca and Mg.

Given the increasing drive in subsistence agriculture research to make use of locally available products, ash, compost/manure and termite mounds have also been considered with crushed granite being tested in this study as sources of alkalinity and plant nutrients.
Crushed granite from Kalene was tested as a source of alkalinity and K through pot trials. This did not prove viable as it contains insufficient alkalinity and K to make a real impact on yield.

The initial data from the analysis of miombo ash is thought to be worth considering for pot trials and possible field trials due to its K content and a CCE of 10. This will not have as dramatic an effect as calcitic or dolomitic lime but does have the benefit of being readily available and containing some K.

A further element of sustainable agriculture, permaculture, could also be beneficial in this area. Permaculture is an holistic approach at working within parameters, which in Mwililunga is the acidic soils, the high rainfall and the poor access and availability of fertilisers. Employing permaculture would require a thorough understanding of culture as well as agriculture, as it is a way of life and not just an agricultural system. It is thought that the millennium development villages of Sanchez et al. (2007) would be a more appropriate and effective means of increasing productivity and the knock-on effects of better nourished people.

Acid tolerant crop maize varieties would prove valuable in this area in order to reduce the amount of lime required and increase the availability of P to plants, which is very useful considering the low P values that were recorded. Varieties that have been developed by Sierra et al. (2006) could be useful although it may be worthwhile developing cultivars that are Al resistant in the area considering the findings of Bennet et al. (2004) in South Africa.

Different crops are also an option for farmers in the area, perhaps French bean or millet as they have been shown by Pal (1998) to be more acid-tolerant than maize, and these also are of greater nutritional value.

Weed control was not monitored in different fields and will have affected the yield. Weeding is essential in order to maximise the nutrients to the crop and thus is important for future consideration.

In summary then, this thesis has increased the knowledge and understanding of the soils of this area and to date has already been used to draw attention to donors in considering using fertilisers in a manner similar to that of Sanchez et al. (2007). Further work needs to be done more systematically in order for a soil potential map to be compiled. This would require thorough sampling and analysis.

Field trials are also required in order to know what the maximum yields obtainable are. To date it was thought that up to 2 $t.ha^{-1}$ was the realistic high (Place et al., 2007), but the work of Sanchez et al. (2007) shows that this is not accurate. In Malawi yields of 6 $t.ha^{-1}$of maize have been achieved on fields that were manually planted and maintained. This was done with the use of hybrid seeds and commercial inorganic fertilisers, with demonstrations on correct application and management practices. The only commercial farmer in the research area, Mr. Peter Fisher added N, P, K, Zn and B fertilizer, with 6 top dressings of N in the season during which field work for this study was conducted. He achieved a maize yield of 11 $t.ha^{-1}$ on average. This was done with high plant densities and with mechanical equipment. Nonetheless it shows that the yields that are currently achieved are extremely poor considering the potential and so further work should be undertaken in order to better understand the optimum way to farm the soils of the area. If high inputs are attainable and profitable then the real constraint is one of having the financial means to initiate the process, rather than acid soil infertility.

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APPENDICES

Appendix 1: Method for trace element analysis

The method is used for the determination of minor / trace elements (Cu, Mn, Zn) using inductively coupled plasma-optical emission spectroscopy (ICP-OES) (Jobin-Yvon Emission, 1999). Weigh 5.0g of air-dried soil ($\leq$ 2 mm particle size) into an extraction bottle. Add 20 ml 0.1M hydrochloric acid (at 20 $\pm$ 3°C) to the extraction bottle, using a dispenser, and shake horizontally on a reciprocal shaker (set at dial setting 70) for 15 minutes ($\pm$ 1 minute). Filter, immediately, through a filter paper into a suitable container. Submit the solutions for measurement using ICP-OES. Calculate the concentration of the analytes using the following formula.

$$\text{Acid-extractable metals} = \frac{\text{ICP reading (mg/l)} * 20}{m} \text{ mg/kg}$$

Where m = mass of the sample.

Appendix 2: X-ray diffraction (XRD) method

The clay mineralogy was determined through XRD. The soils were prepared in the following way which combines the method used by Theng et al. (1986) and Olson et al. (2000); 100g of air-dried <2mm sample was placed in a 250ml plastic bottle; distilled water was added to form a liquid slurry. The clay was dispersed by raising the pH to approximately pH10 with $NaCO_3$ and shaken for 3-4hours on a reciprocal shaker. Following shaking, the slurry was transferred to a large 5L plastic jar and filled to the top with distilled water. The suspension containing the clay fraction was siphoned at a depth of 18cm after an 18 hour settling period according to table given in Whitton and Churchman (1987). The clay suspension was then flocculated. This was done by lowering the pH to between pH7 and pH5 by adding 1M HCL (5-10mL). Less than 30g of $MgCl_2$ was added to samples for which a pH correction was not sufficient to flocculate the samples (this was done as necessary, 1 spoon at a time and then stirred). The flocculated, concentrated clay suspension was then split into two fractions, one of which was be made with a 0.5M $MgCl_2$ solution and the other with a 1M KCl solution to promote Mg- and K- saturation respectively on the exchange sites (Chruchman, 2000). The K- and Mg- clay slurries were shaken by hand, and then centrifuged at 5000rpm for 5 minutes to dewater the sample. The samples were then washed again with 0.5M $MgCl_2$ and KCl solutions, concentrated by centrifugation, and then they were washed 3 times with the relevant solution (similar to that of Olson et al., 2000; Whitton and Churchman, 1987).

Excess salts were then removed. This was done by washing and centrifugation with a 1:1 methanol-water solution, allowing the clay to maintain its flocculated state as the ionic strength decreased. Samples were washed twice in 1:1 methanol:water and tested to check if free of chlorides with $AgNO_3$. If the supernatant was not clear the clay was washed with pure methanol twice and re-tested. Samples which were still showing as containing chlorides were then washed until they showed clear with acetone.

The sample was smeared onto a clean, dry glass slide with a spatula. Once they were air dried they were measured using an XRD machine from 3-40° 2θ. K- saturated slides were heated to 110°C overnight and 300°C for 5 hours (Olson et al., 2000) and following each heating they were analysed with an XRD machine 5-35 ° 2θ to identify the major clay peaks (Whitton and Churchman, 1987). The Brag equation ($n\lambda = 2d \sin\theta$) was then used and as θ and λ are known *d*, that is the interlayer spacing, can be calculated and clay minerals identified (Olson, et al., 2000).

Appendix 3: Analytical data for soils. BA = bushland topsoil sample, BB = bushland subsoil sample, MA = maizeland topsoil sample, MB = maizeland subsoils sample. C1 = group 1 soils, C2 = group 2 soils, C3 = group 3 soils.

			Bray		NH_4OAc				KCl extract.						EDTA			Hot H_2O		
Sample name	pH KCl	pH H_2O	P	K	Ca	Na	Mg	K	Acidity	Σbases	ECEC	Acid Sat	Total C	N	Mn	Cu	Zn	B	Yield	Soil Group
			mg/kg						mmol$_c$/kg			%			mg/kg				t/ha	
AXS BA	4.12	5.00	3	39	39	14	51	41	8.9	6.3	15.2	58	1.3	0.05	1.2	0.4	0.2	0.2		1
AXS BB	4.07	4.80	11	14	40	11	80	40	12.5	7.4	19.9	63	0.5	0.03	0.6	0.1	0.1	0.3		1
AXS MA	4.14	5.10	0	54	83	20	63	55	9.8	10.0	19.7	49	1.4	0.06	0.8	0.3	0.2	0.1	5.3	1
AXS MB	4.10	4.50	25	18	40	10	67	23	18.6	6.3	25.0	75	0.4	0.03	0.2	0.2	0.8	0.2	5.3	1
BAM BA	4.00	4.20	0	101	66	28	79	103	10.7	11.7	22.4	48	1.9	0.09	3.1	0.5	6.5	0.1		1
BAM BB	4.18	4.70	66	22	41	10	88	26	2.7	7.4	10.1	27	0.5	0.08	0.2	0.2	2.4	0.1		1
BAM MA	4.29	5.30	2	181	1232	121	74	142	1.0	78.5	79.5	1	1.8	0.09	19.4	0.2	14.2	0.4	5.3	1
BAM MB	6.79	6.90	7	158	88	18	79	188	0.0	14.1	14.1	0	0.5	0.02	0.4	0.1	0.2	0.2	5.3	1
C 05 BA	5.16	6.00	6	174	545	162	69	182	0.0	48.4	48.4	0	3.2	0.21	78.4	2.0	1.8	0.1		1
C 05 BB	4.35	5.30	13	38	30	20	78	42	4.4	7.6	12.0	37	0.3	0.04	6.5	1.2	0.3	0.1		1
C 05 MA	7.56	7.70	4	409	2212	230	106	381	0.0	144.1	144.1	0	2.2	0.15	29.3	0.1	0.6	0.3	3.4	1
C 05 MB	5.54	6.10	130	271	284	155	107	305	0.0	39.6	39.6	0	0.4	0.09	35.8	1.6	1.1	0.1	3.4	1
C 07 MA	4.48	5.60	2	96	1288	286	86	107	0.9	94.7	95.6	1	3.2	0.15	21.2	1.4	0.7	0.2	2.0	1
C 07 MB	4.94	5.90	4	42	969	242	101	55	0.0	74.4	74.4	0	1.0	0.07	6.4	2.1	0.4	0.1	2.0	1
C 15 MA	4.29	5.60	2	63	148	26	80	60	2.6	14.6	17.1	15	1.0	0.06	1.1	0.5	2.2	0.0	4.2	1
C 15 MB	4.24	5.10	17	36	53	11	90	33	5.8	8.4	14.2	41	0.4	0.03	0.2	0.4	12.8	0.0	4.2	1
C 20 BA	4.00	5.10	22	51	126	58	88	53	6.2	16.3	22.5	27	1.7	0.09	14.1	0.8	0.6	0.2		1
C 20 BB	4.19	5.00	7	11	42	11	81	11	9.0	6.8	15.8	57	0.4	0.03	0.5	0.4	0.2	0.1		1
C 20 MA	4.35	4.80	9	27	213	29	77	25	13.4	17.0	30.4	44	1.4	0.06	2.5	0.6	0.3	0.2	3.0	1
C 20 MB	3.52	4.70	4	45	50	18	59	43	4.9	7.6	12.5	39	2.0	0.09	1.0	0.9	0.6	0.2	3.0	1
C 22 BA	4.16	5.00	12	17	39	9	71	15	8.2	6.2	14.5	57	0.3	0.03	0.3	0.5	0.2	0.3		1
C 22 BB	4.13	4.60	3	12	67	10	75	12	14.8	7.8	22.6	66	0.4	0.03	0.3	0.4	0.5	0.2		1
C 22 MA	3.99	5.50	36	28	61	16	61	25	2.5	7.7	10.1	24	1.1	0.06	1.6	0.6	0.6	0.1	4.0	1
C 22 MB	4.15	4.70	3	15	45	10	58	17	10.2	6.0	16.2	63	0.4	0.03	0.5	0.5	4.0	0.2	4.0	1
CHIEF BA	4.05	4.60	3	43	43	17	73	44	11.5	7.9	19.4	59	1.5	0.08	2.1	0.6	0.4	0.1		1
CHIEF BB	4.19	4.60	31	15	36	9	79	25	8.0	6.6	14.6	55	0.3	0.04	0.3	0.2	0.1	0.1		1
CHIEF MA	4.48	5.50	6	80	297	45	79	75	1.0	24.0	24.9	4	0.9	0.02	4.1	0.4	4.4	0.2	0.2	1
CHIEF MB	4.08	4.70	22	30	44	11	75	30	11.0	7.1	18.2	61	0.4	0.03	0.6	0.2	2.6	0.1	0.2	1
ELK BA	4.04	4.59	3	43	47	16	81	84	13.6	9.4	23.0	59	1.6	0.07	1.0	0.4	2.2	0.1		1

			Bray		NH_4OAc				KCl extract.						EDTA			Hot H_2O		
Sample name	pH KCl	pH H_2O	P	K	Ca	Na	Mg	K	Acidity	Σbases	ECEC	Acid Sat	Total C	N	Mn	Cu	Zn	B	Yield	Soil Group
			mg/kg						mmol$_c$/kg			%			mg/kg				t/ha	
ELK BB	4.12	5.00	4	21	37	9	84	24	14.0	6.9	20.9	67	0.4	0.03	0.2	0.2	0.1	0.3		1
ELK MA	4.15	5.13	2	97	147	27	69	93	6.7	15.0	21.7	31	1.3	0.07	1.4	1.0	2.9	0.1	6.0	1
ELK MB	4.04	4.66	18	39	58	14	85	35	11.6	8.7	20.3	57	0.4	0.02	0.5	0.3	6.0	0.1	6.0	1
FAT BA	4.05	4.60	59	99	97	23	71	96	6.9	12.3	19.1	36	1.7	0.09	2.4	0.4	0.5	0.5		1
FAT BB	4.04	4.80	9	38	57	9	84	36	15.4	8.2	23.6	65	0.7	0.04	1.4	0.1	0.1	0.5		1
FAT MA	6.68	7.30	28	315	848	91	87	332	0.0	62.3	62.3	0	1.1	0.06	9.8	0.5	4.5	0.6	3.3	1
FAT MB	4.24	5.30	2	85	246	40	82	103	10.6	21.9	32.4	33	0.6	0.05	1.2	0.2	1.0	0.5	3.3	1
FISH BA	4.00	4.80	67	80	72	24	101	103	12.1	12.6	24.7	49	2.2	0.11	2.6	0.8	0.5	0.6		1
FISH BB	4.11	4.90	1	14	50	9	91	21	10.6	7.8	18.3	58	0.5	0.04	0.4	0.4	0.2	0.5		1
FISH MA	3.96	3.80	10	44	73	17	90	56	12.1	10.4	22.5	54	1.5	0.09	4.5	0.4	11.9	0.6	11.8	1
FISH MB	4.14	4.90	2	15	51	8	89	18	6.2	7.6	13.7	45	0.5	0.04	0.3	0.3	1.5	0.5	11.8	1
GUI BA	3.97	4.40	5	48	57	17	77	52	11.2	8.9	20.1	56	1.0	0.06	1.4	0.4	0.4	0.5		1
GUI BB	4.04	4.60	9	18	40	5	88	18	12.7	6.7	19.4	66	0.4	0.04	0.4	0.2	0.1	0.5		1
GUI MA	6.55	7.20	22	227	1060	137	81	234	0.0	74.0	74.0	0	2.0	0.11	20.9	0.4	2.8	0.7	2.7	1
GUI MB	4.25	5.30	78	199	100	39	115	245	5.3	19.5	24.8	21	0.5	0.04	0.8	0.1	0.2	0.6	2.7	1
HEB BA	4.06	4.89	4	50	90	21	75	51	10.3	10.8	21.1	49	1.5	0.08	3.0	0.6	0.5	0.6		1
HEB BB	4.20	4.87	11	18	49	5	87	16	9.9	7.1	17.0	58	0.6	0.05	0.1	0.4	0.1	0.5		1
HEB MA	3.99	4.58	1	140	183	44	85	161	11.8	20.6	32.4	37	1.5	0.09	5.1	0.7	0.5	0.6	4.0	1
HEB MB	4.27	4.95	20	168	87	17	87	188	5.4	14.3	19.8	28	0.6	0.04	0.6	0.3	0.2	0.6	4.0	1
JANE BA	4.83	4.77	3	220	348	92	90	237	5.4	35.1	40.4	13	4.0	0.20	99.7	0.7	3.5	0.7		1
JANE BB	4.99	5.45	24	60	54	16	99	82	0.7	10.4	11.1	6	0.6	0.03	29.4	0.3	0.2	0.5		1
JANE MA	5.01	5.76	1	185	364	72	78	185	0.6	32.3	33.0	2	1.4	0.08	32.6	0.6	20.6	0.5	4.0	1
JANE MB	4.43	5.36	40	74	74	24	90	87	6.2	11.9	18.1	34	2.5	0.26	6.2	0.4	4.4	0.5	4.0	1
JCH BA	4.74	4.77	4	45	54	21	80	50	13.1	9.2	22.3	59	1.5	0.10	0.9	0.4	0.5	0.5		1
JCH BB	4.06	4.89	1	21	29	6	75	23	13.8	5.9	19.7	70	0.4	0.04	0.0	0.3	0.2	0.5		1
JCH MA	6.20	6.86	3	153	725	83	77	163	0.0	50.6	50.6	0	1.1	0.06	12.5	0.5	1.7	0.6	4.7	1
JCH MB	4.73	4.96	61	80	93	21	84	90	12.7	12.4	25.1	51	0.6	0.03	1.3	0.2	2.6	0.5	4.7	1
JOM BA	4.22	4.99	13	49	37	15	74	50	1.7	7.6	9.3	18	1.9	0.09	1.6	0.5	0.5	0.5		1

			Bray		NH_4OAc				KCl extract.						EDTA			Hot H_2O		
Sample name	**pH KCl**	**pH H_2O**	**P**	**K**	**Ca**	**Na**	**Mg**	**K**	**Acidity**	**Σbases**	**ECEC**	**Acid Sat**	**Total C**	**N**	**Mn**	**Cu**	**Zn**	**B**	**Yield**	**Soil Group**
			mg/kg						mmol$_c$/kg				%		mg/kg				t/ha	
JOM BB	4.23	4.89	2	51	50	13	82	54	1.4	8.5	9.9	14	0.6	0.03	5.4	0.4	0.3	0.5		1
JOM MA	4.30	4.98	15	70	78	18	74	75	0.6	10.6	11.2	6	1.0	0.08	0.8	0.4	0.4	0.5	3.3	1
JOM MB	4.30	4.75	2	21	36	6	77	19	0.6	6.1	6.7	8	0.3	0.04	0.0	0.2	0.2	0.5	3.3	1
KIC BA	4.05	5.00	8	73	42	19	93	71	1.8	9.6	11.4	16	2.1	0.10	0.7	0.5	0.5	0.5	7.0	1
KIC BB	4.24	4.80	2	12	31	6	93	12	1.8	6.4	8.2	21	0.5	0.05	0.0	0.2	0.1	0.5		1
KIC MA	4.20	4.60	27	72	91	4	89	80	1.2	10.8	12.0	10	1.7	0.09	2.1	0.5	5.2	0.5	4.7	1
KIC MB	4.27	4.80	1	13	36	7	87	14	3.0	6.5	9.4	31	0.6	0.10	0.0	0.1	0.2	0.5	4.7	1
MCH BA	4.14	4.40	2	35	36	14	63	38	18.6	6.7	25.3	74	2.3	0.10	2.8	0.4	0.3	0.5		1
MCH BB	4.46	5.20	7	17	33	6	82	18	3.4	6.2	9.6	36	0.3	0.03	0.0	0.1	0.2	0.5		1
MCH MA	4.72	4.50	2	66	76	29	54	77	1.7	10.5	12.2	14	1.7	0.08	4.2	0.4	0.5	0.5	4.0	1
MCH MB	3.99	4.80	8	18	28	5	68	21	12.9	5.3	18.2	71	0.5	0.04	0.3	0.1	0.8	0.5	4.0	1
OZO BA	4.12	4.96	2	60	52	22	57	72	15.8	8.7	24.6	64	2.3	0.09	3.7	0.6	5.7	0.6		1
OZO BB	3.90	4.23	7	15	38	7	82	21	14.2	6.5	20.8	69	0.5	0.03	0.3	0.1	0.1	0.5		1
OZO MA	4.40	5.26	2	64	231	37	86	72	3.2	20.1	23.3	14	1.3	0.07	3.2	0.5	1.3	0.5	2.3	1
OZO MB	4.32	5.09	22	20	57	12	88	25	9.3	8.3	17.6	53	0.8	0.05	1.2	0.2	0.3	0.5	2.3	1
PSK BA	4.05	4.85	2	83	91	37	95	96	17.1	14.2	31.3	55	2.4	0.13	3.2	0.3	0.3	0.6		1
PSK BB	4.07	4.87	12	19	34	9	76	25	22.1	6.4	28.5	78	0.7	0.05	0.6	0.2	0.1	0.5		1
PSK MA	4.14	4.66	1	75	99	21	76	93	18.9	12.4	31.2	60	1.6	0.08	1.7	0.3	0.2	0.5	5.7	1
PSK MB	4.13	4.55	15	17	40	9	96	24	23.3	7.5	30.8	76	0.7	0.05	0.4	0.2	0.1	0.5	5.7	1
SAL BA	4.16	4.50	3	63	52	21	82	75	15.2	9.8	25.0	61	1.7	0.08	1.8	0.4	7.3	0.7		1
SAL BB	3.97	4.84	8	15	29	8	96	19	11.9	6.7	18.6	64	0.5	0.05	0.1	0.2	3.8	0.5		1
SAL MA	4.13	4.76	1	44	62	21	85	52	11.3	9.9	21.2	53	1.1	0.06	1.5	0.6	1.6	0.6	5.7	1
SAL MB	4.11	4.75	9	17	31	7	85	20	11.4	6.3	17.8	64	0.5	0.05	0.2	0.2	0.2	0.5	5.7	1
SKY BA	4.31	5.40	2	28	34	13	101	29	9.8	7.9	17.8	55	1.1	0.05	0.9	0.4	0.4	0.5		1
SKY BB	3.96	4.90	4	12	23	5	80	11	7.3	5.3	12.6	58	0.5	0.04	1.4	0.3	0.8	0.3		1
SKY MA	4.44	4.70	1	114	118	33	104	131	0.0	16.5	16.5	0	1.7	0.08	18.1	0.5	0.4	0.5	2.7	1
SKY MB	4.14	4.70	20	16	26	7	98	12	7.8	6.4	14.3	55	0.4	0.05	0.1	0.2	2.6	0.5	2.7	1
SSK BA	4.29	5.07	2	53	44	17	94	58	12.2	9.1	21.4	57	2.6	0.10	1.3	0.2	0.4	0.7		1

			Bray		NH_4OAc				KCl extract.						EDTA			Hot H_2O		
Sample name	**pH KCl**	**pH H_2O**	**P**	**K**	**Ca**	**Na**	**Mg**	**K**	**Acidity**	**Σbases**	**ECEC**	**Acid Sat**	**Total C**	**N**	**Mn**	**Cu**	**Zn**	**B**	**Yield**	**Soil Group**
			mg/kg						mmol$_c$/kg			%			mg/kg				t/ha	
SSK BB	4.87	5.18	13	28	22	6	57	26	0.1	4.7	4.8	2	0.6	0.04	0.1	0.2	5.7	0.5		1
STW MA	3.97	4.31	20	88	90	24	86	93	9.7	12.6	22.3	44	1.7	0.06	1.9	0.4	1.2	0.5	6.3	1
STW MB	3.91	4.24	2	191	37	7	71	19	4.2	6.0	10.1	41	0.4	0.05	0.0	0.1	2.9	0.5	6.3	1
TIS MA	5.03	5.55	1	137	340	55	76	150	0.0	28.7	28.7	0	1.3	0.07	5.5	0.6	2.4	0.5	3.0	1
TIS MB	4.23	5.30	16	67	71	12	100	80	10.4	10.9	21.3	49	0.3	0.03	0.3	0.1	0.2	0.5	3.0	1
TRH BA	4.39	5.20	13	170	247	62	82	195	4.9	26.0	30.9	16	2.5	0.13	13.3	0.4	3.6	0.6		1
TRH BB	4.14	4.90	2	24	38	9	90	28	12.5	7.2	19.7	63	0.4	0.03	0.5	0.4	0.2	0.5		1
TRH MA	4.40	5.30	12	117	206	35	87	141	4.3	20.7	25.0	17	1.1	0.05	2.3	0.4	0.9	0.6	6.7	1
TRH MB	4.08	4.87	4	32	36	9	90	38	12.4	7.4	19.8	62	0.3	0.03	0.6	0.1	0.2	0.5	6.7	1
TYN BA	4.19	5.10	53	72	42	17	88	77	0.2	9.3	9.5	2	1.4	0.04	1.1	0.4	3.1	0.6		1
TYN BB	4.31	4.96	2	19	28	5	93	17	1.8	6.4	8.2	22	0.4	0.02	0.0	0.1	0.2	0.5		1
TYN MA	5.32	5.75	32	127	267	60	106	135	0.1	26.4	26.5	0	1.3	0.06	6.3	0.4	5.3	0.7	6.0	1
TYN MB	4.32	4.93	2	24	45	13	85	28	0.0	7.8	7.8	0	0.3	0.04	0.1	0.2	0.4	0.5	6.0	1
VIX BA	4.25	5.04	14	75	115	27	97	78	0.2	24.1	24.3	1	2.4	0.12	3.2	0.5	2.4	0.6		1
VIX BB	4.41	5.37	2	33	57	9	98	37	0.7	15.3	16.0	5	0.7	0.08	0.8	0.3	0.3	0.5		1
CKY MA	4.30	4.90	17	43	55	16	78	56	6.0	8.9	14.9	40	1.0	0.06	14.7	0.4	0.3	0.2	3.6	1
CKY MB	4.50	4.80	0	28	27	7	79	76	1.7	7.3	9.0	19	0.3	0.07	7.4	0.3	0.1	0.1	3.6	1
FERG 01A	4.20	5.20	7	45	61	24	101	58	13.5	10.9	24.4	55	1.5	0.04	1.7	0.4	2.8	0.2	4.3	1
FERG 01B	4.30	4.90	12	28	18	4	10	54	12.8	3.1	15.9	81	0.5	0.04	0.3	0.1	0.1	0.1	4.3	1
FERG 01 GA	4.20	5.20	4	23	41	8	80	63	13.5	7.8	21.3	63	2.0	0.05	1.7	0.4	2.8	0.2	4.0	1
FERG 02 A	4.40	5.40	4	49	78	25	82	86	8.4	11.8	20.2	42	1.3	0.09	2.0	0.4	0.9	0.2	6.9	1
FERG 02 B	4.30	5.00	8	19	33	7	87	58	13.8	7.5	21.3	65	0.5	0.03	0.3	0.1	0.1	0.1	6.9	1
FERG 02 GA	4.40	5.40	6	51	83	24	84	87	8.4	12.0	20.4	41	1.3	0.19	2.0	0.4	0.9	0.2	4.9	1
FERG 02 GB	4.30	5.00	11	29	39	10	85	72	13.8	8.3	22.1	62	0.5	0.07	0.3	0.1	0.1	0.1	4.9	1
FERG 03 A	4.20	5.00	11	32	58	11	9	55	12.2	5.6	17.9	68	1.3	0.08	1.7	0.4	0.2	0.1	2.8	1
FERG 03 B	4.30	5.10	3	21	26	6	85	52	10.9	6.8	17.8	61	0.4	0.03	0.4	0.2	0.2	0.2	2.8	1
FERG 04 A	4.20	5.10	7	63	28	7	91	63	11.0	7.5	18.5	59	1.3	0.04	0.7	0.2	0.3	0.1	2.7	1
FERG 04 B	4.40	4.80	3	20	26	6	91	50	8.4	7.1	15.5	54	0.8	0.03	2.9	0.5	0.4	0.1	2.7	1
FERG 05 A	4.40	5.20	26	22	43	9	76	120	10.8	9.3	20.1	54	1.2	0.02	0.7	0.2	0.3	0.1	5.0	1

Sample name	pH KCl	pH H_2O	Bray P	Bray K	NH_4OAc Ca	NH_4OAc Na	NH_4OAc Mg	NH_4OAc K	KCl extract. Acidity	Σbases	ECEC	Acid Sat	Total C	N	EDTA Mn	EDTA Cu	EDTA Zn	Hot H_2O B	Yield	Soil Group
			mg/kg						mmol$_c$/kg			%			mg/kg				t/ha	
FERG 05 B	4.50	5.30	7	20	22	6	74	50	10.6	6.1	16.7	64	0.8	0.04	0.2	0.3	0.2	0.1	5.0	1
FERG 05 GA	4.40	5.20	60	32	58	9	95	61	10.8	9.4	20.2	54	1.2	0.07	0.7	0.2	0.3	0.1	3.8	1
FERG 05 GB	4.50	5.30	6	27	31	6	99	46	10.6	7.5	18.2	59	1.2	0.10	0.2	0.3	0.2	0.1	3.8	1
FERG 06 A	4.50	5.10	7	18	19	5	90	23	9.4	5.9	15.3	62	0.3	0.03	0.4	0.2	0.1	0.1	4.7	1
FERG 06 B	4.40	5.20	4	14	31	6	71	54	12.0	6.5	18.5	65	1.0	0.09	0.6	0.3	0.2	0.1	4.7	1
FERG 07 A	4.20	5.10	8	38	42	8	88	64	10.0	8.2	18.2	55	1.8	0.08	0.8	0.4	0.3	0.1	6.0	1
FERG 07 B	4.60	5.20	5	10	30	7	84	113	6.3	8.5	14.9	43	0.3	0.04	0.3	0.1	0.1	0.1	6.0	1
FERG 07 B2	4.60	5.20	3	41	26	6	86	48	6.3	6.7	13.1	48	0.2	0.02	0.3	0.1	0.1	0.1	6.0	1
FERG 08 A	4.30	5.00	6	32	88	26	107	63	11.3	12.8	24.2	47	1.7	0.05	2.4	0.4	0.2	0.1	4.0	1
FERG 08 B	4.30	5.10	4	19	28	10	109	45	11.4	8.1	19.5	58	0.3	0.02	0.2	0.2	0.1	0.1	4.0	1
FERG09MA	4.50	5.30	0	20	32	8	11	286	12.5	10.1	22.6	55	1.1	0.10	3.5	0.4	0.3	0.1	2.7	1
FERG09 CA	4.50	5.30	0	25	33	10	93	53	12.5	7.9	20.4	61	1.3	0.04	3.5	0.4	0.3	0.1		1
FERG09MB	4.50	5.30	1	9	24	5	86	47	11.6	6.5	18.1	64	0.8	0.02	0.6	0.2	0.2	0.1	2.7	1
FERG 09CB	4.50	5.31	2	22	18	5	80	26	11.6	5.4	17.0	68	0.9	0.06	0.6	0.2	0.2	0.1		1
KABS MA	5.20	5.70	3	109	172	80	82	118	0.8	21.8	22.6	4	0.7	0.05	19.8	0.3	0.2	0.1	8.5	1
KABS MB	4.30	5.40	0	84	56	67	12	126	15.3	12.2	27.4	56	0.4	0.02	8.9	0.1	0.1	0.2	8.5	1
KCON A	4.40	5.10	19	30	25	8	83	52	7.2	6.9	14.1	51	0.8	0.06	5.2	0.3	0.2	0.1		1
KCON B	4.60	5.20	4	20	21	4	10	55	7.8	3.2	11.0	71	0.3	0.03	1.6	0.1	0.0	0.1		1
KHS GA	5.40	6.20	4	172	389	53	105	219	0.6	34.0	34.6	2	1.0	0.06	3.8	1.0	2.5	0.2	7.7	1
KHS GB	6.60	7.30	1	203	458	68	94	108	0.3	35.3	35.6	1	0.6	0.04	1.9	0.9	1.7	0.4	7.7	1
KNG MA	5.00	6.00	3	53	759	51	83	99	1.4	48.4	49.8	3	3.2	0.14	15.5	0.9	0.4	0.2	6.5	1
KNG MB	4.30	4.90	60	9	42	5	73	106	14.1	8.4	22.5	63	0.6	0.02	9.1	1.1	0.1	0.1	6.5	1
MMB MA	4.90	5.50	12	42	531	67	106	48	2.0	37.9	39.9	5	2.7	0.12	7.3	0.2	1.0	0.2	0.0	1
MMB MB	4.40	4.70	0	8	24	13	97	40	22.8	7.5	30.3	75	0.7	0.04	0.3	0.3	0.1	0.1	0.0	1
MUBS MA	4.40	4.70	2	34	16	6	63	38	7.9	5.0	12.9	61	0.6	0.05	0.6	0.4	0.1	0.1	1.2	1
MUBS MB	4.40	4.80	1	35	23	5	105	30	9.4	6.9	16.4	58	0.3	0.02	0.6	0.2	0.1	0.1	1.2	1
NDS A	5.05	5.89	101	71	413	80	63	83	2.4	32.2	34.6	7	1.4	0.06	35.6	0.4	0.7	0.1	6.5	1
NDS B	4.83	5.35	13	21	26	10	90	51	8.3	7.3	15.6	53	0.2	0.01	4.9	0.4	0.1	0.1	6.5	1
NGOM MA	4.40	4.80	1	24	124	23	89	58	4.1	13.5	17.5	23	1.0	0.04	3.8	0.4	0.5	0.1	5.0	1
NGOM MB	4.70	5.00	5	17	16	5	72	22	0.1	4.9	4.9	2	0.4	0.02	0.2	0.2	0.1	0.1	5.0	1
NTBS GA	4.50	5.20	41	34	61	29	85	43	5.6	10.2	15.8	35	0.3	0.02	9.1	0.5	0.1	0.1	3.5	1
NTBS GB	4.30	5.20	5	8	28	9	91	20	11.5	6.6	18.1	63	0.1	0.05	1.8	0.3	0.1	0.1	3.5	1

Sample name	pH KCl	pH H_2O	Bray P	Bray K	NH_4OAc Ca	NH_4OAc Na	NH_4OAc Mg	NH_4OAc K	KCl extract. Acidity	Σbases	ECEC	Acid Sat	Total C	N	EDTA Mn	EDTA Cu	EDTA Zn	Hot H_2O B	Yield	Soil Group
			mg/kg						mmol$_c$/kg			%			mg/kg				t/ha	
NTBS MA	4.40	5.10	3	20	29	6	84	57	7.2	7.1	14.3	51	0.5	0.03	6.5	0.4	0.2	0.1	2.0	1
NTBS MB	4.40	4.90	5	32	27	8	99	58	9.0	7.8	16.8	53	0.2	0.05	1.7	0.3	0.1	0.1	2.0	1
OKAN MA	4.52	5.20	6	57	782	111	12	85	0.6	51.0	51.7	1	1.7	0.07	38.6	1.0	0.5	0.2	4.8	1
OKAN MB	5.05	5.80	5	27	101	26	94	58	0.0	12.7	12.7	0	0.2	0.01	2.5	0.4	0.1	1.0	4.8	1
AND MA	4.33	5.37	10	199	280	59	73	201	3.2	27.3	30.5	10	1.7	0.09	3.9	0.4	3.0	0.1	3.7	3
AND MB	4.07	4.85	13	59	74	15	69	57	12.2	9.4	21.6	56	0.4	0.04	0.9	0.3	0.3	0.1	3.7	3
C 02 MA	5.08	5.90	15	258	626	115	63	219	0.2	49.2	49.4	0	1.3	0.11	45.1	1.2	0.8	0.2	4.6	3
C 02 MB	4.98	6.00	13	118	369	160	81	131	0.1	38.7	38.8	0	0.3	0.03	8.0	1.2	0.3	0.1	4.6	3
C 06 MA	5.09	5.90	2	83	287	113	84	75	0.0	29.4	29.4	0	0.8	0.09	20.9	1.5	0.8	0.1	6.6	3
C 06 MB	5.41	6.00	3	25	167	194	86	30	0.0	29.0	29.0	0	0.3	0.03	6.0	0.8	0.2	0.2	6.6	3
C 14 BA	4.13	5.20	70	32	132	21	82	33	7.0	12.8	19.8	36	0.7	0.05	3.6	0.8	8.4	0.1		3
C 14 BB	4.20	5.00	14	11	55	10	76	14	10.3	7.3	17.6	59	0.5	0.03	0.3	0.4	0.9	0.1		3
C 14 MA	5.23	6.20	0	94	398	42	74	92	0.0	29.0	29.0	0	0.8	0.05	3.8	0.5	8.4	0.1	7.2	3
C 14 MB	4.22	5.50	78	65	138	25	91	67	6.1	14.6	20.7	29	0.6	0.05	0.7	0.5	7.7	0.1	7.2	3
C 16 MA	4.49	5.80	2	120	208	44	63	113	0.1	19.6	19.8	1	1.1	0.07	5.5	0.8	10.8	0.6	2.9	3
C 16 MB	4.22	4.80	24	64	66	13	86	49	4.8	9.4	14.2	34	0.6	0.03	0.6	0.5	1.1	0.2	2.9	3
C 21 MA	4.46	5.50	13	51	229	5	55	63	0.7	15.8	16.5	4	2.0	0.10	1.5	0.5	0.6	0.1	4.3	3
C 21 MB	4.15	4.90	3	19	51	14	69	51	9.8	8.0	17.8	55	0.4	0.03	0.1	0.4	0.1	0.1	4.3	3
C 24 BA	4.10	5.80	2	78	784	118	59	167	6.4	55.9	62.3	10	2.9	0.16	28.5	0.9	13.5	0.2		3
C 24 BB	4.17	5.10	70	26	46	13	70	26	15.7	7.1	22.8	69	1.2	0.09	5.5	1.2	0.3	0.1		3
C 24 MA	4.52	5.70	2	80	423	2	56	68	0.1	25.5	25.6	0	3.0	0.14	14.8	0.8	0.8	0.2	2.3	3
C 24 MB	4.10	4.90	5	37	76	23	68	36	10.4	9.6	20.0	52	1.3	0.08	4.1	1.0	5.3	0.2	2.3	3
C 25 MA	4.12	5.10	18	74	116	41	64	72	9.2	13.8	23.0	40	2.2	0.12	9.6	1.2	0.4	0.1	2.6	3
C 25 MB	4.23	4.80	126	22	52	19	73	22	2.6	7.9	10.6	25	0.7	0.04	5.2	0.9	3.2	0.1	2.6	3
CSA BA	4.42	5.20	3	99	194	45	52	91	3.5	18.0	21.5	16	1.8	0.10	6.1	0.5	13.7	0.2		3
CSA BB	4.40	5.20	34	61	63	17	62	52	3.4	8.5	12.0	29	0.7	0.05	1.5	0.3	0.3	0.1		3
CSA MA	5.93	5.70	5	117	608	79	58	104	0.0	42.1	42.1	0	1.0	0.06	8.1	0.4	4.2	0.2	3.7	3
CSA MB	4.15	4.60	9	84	63	16	84	86	6.0	10.3	16.3	37	0.5	0.03	0.8	0.2	0.1	0.2	3.7	3
ESI BA	4.19	5.32	72	81	110	35	74	130	6.0	14.9	20.9	29	1.7	0.08	3.9	0.5	1.0	0.1		3

Sample name	pH KCl	pH H_2O	Bray P	K	NH_4OAc Ca	Na	Mg	K	KCl extract. Acidity	Σbases	ECEC	Acid Sat	Total C	N	EDTA Mn	Cu	Zn	Hot H_2O B	Yield	Soil Group
			mg/kg						mmol$_c$/kg			%			mg/kg				t/ha	
ESI BB	4.25	4.99	5	20	41	10	70	20	8.0	6.4	14.4	55	0.4	0.04	0.1	0.2	0.1	0.1		3
ESI MA	6.93	8.43	5	755	1874	256	89	685	0.0	136.4	136.4	0	2.1	0.09	21.0	0.1	8.8	0.4	9.0	3
ESI MB	5.86	6.98	2	278	100	200	90	325	0.0	33.9	33.9	0	0.5	0.02	0.3	0.1	0.3	0.3	9.0	3
FAN BA	4.20	5.10	2	152	249	55	80	150	0.6	24.3	25.0	3	2.2	0.11	10.0	0.7	3.6	0.8		3
FAN BB	4.06	5.20	3	41	59	11	89	51	10.2	9.0	19.3	53	0.5	0.04	0.2	0.3	0.3	0.5		3
FAN MA	4.11	5.00	14	40	132	19	69	43	9.9	12.2	22.1	45	1.2	0.06	1.5	0.3	0.5	0.1	8.0	3
FAN MB	4.02	4.70	13	29	58	11	77	20	11.8	7.7	19.5	60	0.4	0.03	0.6	0.1	0.2	0.1	8.0	3
FISH 02 BA	4.01	5.00	12	70	196	51	87	78	8.2	19.8	28.0	29	3.4	0.18	19.2	0.5	1.3	0.6		3
FISH 02 BB	4.21	5.10	0	12	45	5	77	13	6.0	6.4	12.4	49	0.4	0.03	0.4	0.2	1.4	0.5		3
FISH 02 MA	3.98	4.90	10	33	84	20	94	69	10.6	11.6	22.3	48	1.4	0.07	1.9	0.3	0.4	0.5	15.4	3
FISH 02 MB	4.25	5.20	2	10	51	4	89	14	12.2	7.1	19.2	63	0.4	0.04	0.2	0.2	0.2	0.5	15.4	3
FIX BA	4.06	5.20	2	138	70	25	88	158	11.0	13.5	24.5	45	2.7	0.13	36.7	0.7	1.2	0.5		3
FIX BB	4.59	5.70	10	62	47	10	92	71	1.4	9.0	10.4	14	0.4	0.04	11.1	0.2	0.2	0.5		3
FIX MA	4.52	5.50	16	220	307	101	85	232	0.6	33.4	33.9	2	2.2	0.12	29.4	0.6	11.1	0.6	3.3	3
FIX MB	4.26	4.90	31	79	67	14	79	91	7.2	10.3	17.5	41	0.6	0.04	13.6	0.3	0.6	0.5	3.3	3
HEL BA	4.71	4.47	1	100	122	36	84	101	0.7	15.4	16.0	4	2.7	0.15	4.8	0.5	1.3	0.7		3
HEL BB	5.13	5.08	10	18	38	5	89	21	0.0	6.7	6.7	0	0.4	0.03	0.1	0.2	0.8	0.5		3
HEL MA	5.31	5.78	0	108	256	42	86	116	3.2	23.0	26.2	12	1.5	0.08	2.9	0.6	2.8	0.5	2.7	3
HEL MB	4.87	4.29	20	57	52	10	79	65	9.3	8.5	17.8	52	0.3	0.03	0.1	0.1	0.1	0.4	2.7	3
IBS BA	4.72	5.00	0	57	109	35	93	64	1.9	14.0	15.9	12	1.8	0.08	7.1	0.7	0.7	0.5		3
IBS BB	4.71	4.70	9	16	35	7	88	29	2.6	6.9	9.5	27	0.6	0.04	0.3	0.3	0.1	0.5		3
IBS MA	4.74	4.90	0	64	94	15	82	73	11.0	11.3	22.4	49	0.4	0.02	0.7	0.3	0.9	0.5	6.3	3
IBS MB	4.78	5.00	8	79	42	8	93	97	1.0	9.2	10.3	10	0.3	0.03	0.1	0.1	3.4	0.5	6.3	3
IVW BA	5.32	5.60	1	191	488	107	70	204	0.0	41.6	41.6	0	3.1	0.17	64.7	0.5	1.1	0.7		3
IVW BB	5.20	5.10	11	36	58	15	78	33	0.3	8.4	8.7	4	0.6	0.04	41.6	0.3	1.0	0.5		3
IVW MA	4.97	5.20	2	191	121	56	97	192	0.9	19.8	20.8	5	2.1	0.12	75.9	0.7	4.7	0.6	2.0	3
IVW MB	5.21	5.10	6	27	38	8	82	35	0.8	7.0	7.8	10	0.4	0.03	34.4	0.2	1.7	0.5	2.0	3
JEC BA	4.84	5.01	9	77	76	32	67	81	0.6	11.4	12.0	5	1.9	0.09	4.0	0.7	0.9	0.6		3

			Bray		NH$_4$OAc				KCl extract.							EDTA			Hot H$_2$O		
Sample name	**pH KCl**	**pH H$_2$O**	**P**	**K**	**Ca**	**Na**	**Mg**	**K**	**Acidity**	**Σbases**	**ECEC**	**Acid Sat**	**Total C**	**N**	**Mn**	**Cu**	**Zn**	**B**	**Yield**	**Soil Group**
			mg/kg						mmol$_c$/kg			%			mg/kg				t/ha	
JEC BB	4.87	4.93	13	25	34	8	90	20	1.1	6.7	7.9	14	0.5	0.04	0.5	0.3	0.2	0.5		3
JEC MA	4.67	5.60	24	113	312	66	76	124	10.1	27.6	37.7	27	1.5	0.09	3.0	0.6	2.9	0.6	6.3	3
JEC MB	4.32	5.50	1	109	44	11	88	113	17.4	9.8	27.3	64	0.4	0.06	0.7	0.4	0.2	0.5	6.3	3
JKG BA	4.89	5.17	14	167	180	64	67	173	1.6	21.7	23.3	7	1.5	0.09	6.4	0.5	6.0	0.6		3
JKG BB	4.76	4.87	2	44	35	12	74	48	2.7	7.2	9.9	27	0.4	0.03	0.3	0.1	0.3	0.5		3
JKG MA	7.14	7.68	75	394	1774	127	71	365	0.0	111.7	111.7	0	1.6	0.09	26.3	0.2	11.2	0.7	4.7	3
JKG MB	7.31	8.19	52	359	951	148	84	362	0.5	72.8	73.3	1	0.7	0.04	8.6	0.4	1.3	0.7	4.7	3
KSM BA	5.66	5.90	9	131	427	80	69	143	0.0	34.7	34.7	0	0.2	0.06	12.2	0.4	16.5	0.5		3
KSM BB	5.35	5.60	1	102	41	12	95	108	0.0	9.9	9.9	2	1.5	0.13	5.2	0.1	6.3	0.5	4.7	3
KSM MA	4.78	6.70	54	191	772	69	71	192	1.0	52.4	53.3	0	0.3	0.09	19.5	0.3	11.4	0.5	4.7	3
KSM MB	6.15	6.20	1	123	124	58	98	132	0.0	18.7	18.7	66	1.2	0.09	3.2	0.5	0.5	0.5		3
LIC BA	4.21	5.10	10	43	42	21	48	46	13.7	7.1	20.8	68	0.7	0.08	1.8	0.5	0.2	0.9		3
LIC BB	4.12	4.90	7	27	26	6	44	27	9.2	4.4	13.6	36	1.3	0.12	1.4	0.3	0.2	0.5	2.7	3
LIC MA	4.11	5.20	23	89	293	67	90	122	15.3	27.2	42.5	53	0.4	0.04	4.6	0.6	0.5	0.6	2.7	3
LIC MB	4.09	4.60	2	24	33	9	63	23	6.6	5.7	12.3	11	3.5	0.14	0.6	0.3	0.1	0.6		3
MPU BA	4.57	5.00	3	96	108	38	78	104	1.7	14.6	16.3	52	0.6	0.04	36.1	0.7	0.5	0.6		3
MPU BB	4.28	5.20	13	26	33	8	71	27	6.5	6.1	12.6	2	2.4	0.13	11.0	0.4	0.3	0.6	2.7	3
MPU MA	4.37	5.10	1	160	896	126	89	172	1.1	63.5	64.7	0	4.0	0.20	51.8	0.4	5.8	0.8	2.7	3
MPU MB	6.26	6.60	66	53	63	20	92	64	0.0	10.4	10.4	58	1.2	0.07	35.3	0.4	0.3	0.5		3
PEF BA	4.00	4.80	57	30	41	13	89	39	11.0	7.9	18.9	55	0.4	0.02	0.6	0.4	0.2	0.5		3
PEF BB	4.19	4.90	5	12	29	8	76	18	7.3	5.8	13.1	49	0.4	0.02	0.0	0.2	0.1	0.5	4.0	3
PEF MA	4.38	4.70	1	26	60	20	95	36	9.4	9.6	19.1	72	0.4	0.04	2.9	0.4	7.5	0.5	4.0	3
PEF MB	4.19	4.60	12	258	48	9	80	59	20.6	8.1	28.7	10	1.6	0.07	0.5	0.3	0.2	0.5		3
SIP BA	4.70	5.31	2	126	149	62	92	142	2.2	20.3	22.5	13	0.5	0.04	31.9	0.6	1.3	0.7		3
SIP BB	4.47	5.90	13	124	38	15	104	147	1.7	11.4	13.1	3	1.2	0.06	23.3	0.3	2.1	0.5	2.7	3
SIP MA	4.19	7.05	2	252	523	116	89	270	1.3	46.6	47.8	0	0.6	0.05	122.6	0.8	4.9	0.9	2.7	3
SIP MB	6.00	5.96	23	206	95	54	93	220	0.0	19.0	19.0	57	2.5	0.14	26.3	0.4	0.3	0.6	2.7	3
SSK MA	4.35	4.88	1	48	80	17	92	57	14.2	10.9	25.1	79	0.4	0.03	2.3	0.3	0.6	0.6	2.7	3

			Bray		NH$_4$OAc				KCl extract.							EDTA			Hot H$_2$O		
Sample name	**pH KCl**	**pH H$_2$O**	**P**	**K**	**Ca**	**Na**	**Mg**	**K**	**Acidity**	**Σbases**	**ECEC**	**Acid Sat**	**Total C**	**N**	**Mn**	**Cu**	**Zn**	**B**	**Yield**	**Soil Group**
			mg/kg						mmol$_c$/kg			%			mg/kg				t/ha	
SSK MB	4.23	4.66	19	19	38	8	81	19	24.0	6.5	30.5	61	1.8	0.08	0.1	0.1	0.1	0.5		3
STW BA	4.18	4.69	7	41	43	19	72	43	12.7	8.0	20.7	61	0.4	0.05	2.2	0.4	4.8	0.6		3
STW BB	3.99	4.92	0	18	28	6	69	16	8.4	5.3	13.7	41	1.2	0.07	0.0	0.1	3.1	0.5		3
TIS BA	4.11	5.18	15	56	108	25	71	62	8.4	12.2	20.6	63	0.3	0.03	1.4	0.4	2.6	0.6		3
TIS BB	4.14	5.07	0	32	41	8	93	39	12.9	7.7	20.6	16	2.2	0.08	0.3	0.2	3.1	0.5	4.3	3
VIX MA	4.31	4.90	0	89	74	30	101	97	2.6	13.1	15.7	1	0.5	0.02	3.7	0.4	0.3	0.5	4.3	3
VIX MB	4.47	5.11	1	27	45	6	76	34	0.1	14.1	14.2	8	2.2	0.09	0.4	0.3	0.2	0.5	3.2	3
CBS GA	4.40	5.20	2	97	146	31	102	137	1.6	17.9	19.5	5	0.2	0.17	66.9	0.9	0.4	0.3	3.2	3
CBS GB	4.50	5.10	14	27	103	19	97	35	0.6	11.8	12.5	4	1.0	0.04	49.1	0.7	0.2	0.2	4.0	3
CFN MA	4.40	5.10	19	21	99	25	96	99	0.6	13.7	14.3	5	0.4	0.06	0.2	0.0	0.1	0.1	4.0	3
CFN MB	4.20	4.60	3	37	27	6	91	46	0.4	7.0	7.3	3	0.6	0.05	0.8	0.4	0.1	0.1	7.3	3
CHBS GA	5.40	5.60	2	38	194	34	77	47	0.6	17.1	17.7	5	1.0	0.08	10.8	0.2	0.2	0.1	7.3	3
CHBS GB	5.50	5.60	32	34	38	9	104	44	0.4	8.3	8.7	4	0.8	0.10	3.8	0.3	0.2	0.1	7.8	3
KABS GA	4.90	6.00	3	124	255	111	110	167	1.2	31.0	32.2	7	0.3	0.04	15.1	0.5	0.3	0.1	7.8	3
KABS GB	4.90	5.80	9	167	187	199	84	238	2.6	35.7	38.3	3	0.8	0.02	7.0	0.3	0.1	0.1	8.0	3
KAS MA	5.39	5.70	3	133	243	59	81	255	0.7	27.1	27.8	3	0.7	0.10	5.1	0.6	8.3	0.2	7.5	3
KAS MA	4.72	5.20	4	140	293	56	87	166	0.7	27.3	28.0	44	0.2	0.02	5.1	0.6	8.3	0.2	8.0	3
KAS MB	4.48	5.38	10	78	40	13	88	186	9.0	11.7	20.7	46	0.2	0.05	4.5	0.2	0.3	0.1	7.5	3
KAS MB	4.48	5.40	9	23	38	11	73	177	9.0	10.5	19.5	10	2.7	0.14	4.5	0.2	0.3	0.1	1.2	3
KUDU MA	4.70	5.60	3	66	574	134	93	84	5.2	46.0	51.2	2	0.6	0.03	28.6	0.8	0.8	0.2	1.2	3
KUDU MB	5.30	5.60	15	27	480	98	88	54	0.6	37.4	38.0	42	0.9	0.10	12.1	0.5	0.2	0.1	0.6	3
KYB MA	4.30	5.00	2	65	59	10	98	60	7.1	9.6	16.7	25	0.5	0.03	1.0	0.6	0.3	0.1	0.6	3
KYB MB	4.50	4.90	25	18	37	18	84	84	3.0	9.2	12.2	24	0.9	0.02	0.2	0.1	0.1	0.1	3.6	3
LWN GA	4.80	5.40	6	95	141	85	10	137	5.8	18.0	23.8	10	0.5	0.09	8.6	0.8	0.2	0.1	3.6	3
LWN GB	4.70	5.40	0	94	194	175	102	200	3.6	33.8	37.4	4	2.7	0.17	15.4	0.8	0.1	0.1	5.3	3
MABS MA	4.85	5.60	4	213	675	117	95	235	2.5	53.7	56.1	59	0.4	0.03	56.9	0.2	1.7	0.4	5.3	3
MABS MB	4.71	5.50	3	129	93	76	103	195	29.3	20.4	49.7	1	0.8	0.10	14.5	0.8	0.2	0.1	7.0	3
MUMPU MA	5.70	6.00	4	89	322	50	74	95	0.3	25.9	26.2	50	0.1	0.03	4.2	0.7	0.4	0.1	7.0	3
MUMPU MB	4.40	4.90	8	33	32	11	91	43	7.4	7.5	15.0	59	0.9	0.06	0.4	0.4	0.1	0.1		3
NTBS CA	4.20	5.10	4	47	37	24	11	73	8.8	6.2	15.0	59	0.2	0.06	5.8	0.7	0.3	0.1		3

			Bray		NH_4OAc				KCl extract.						EDTA			Hot H_2O		
Sample name	**pH KCl**	**pH H_2O**	**P**	**K**	**Ca**	**Na**	**Mg**	**K**	**Acidity**	**Σbases**	**ECEC**	**Acid Sat**	**Total C**	**N**	**Mn**	**Cu**	**Zn**	**B**	**Yield**	**Soil Group**
			mg/kg						$mmol_c/kg$			%			mg/kg				t/ha	
NTBS CB	4.40	5.10	6	9	22	7	79	39	8.9	6.1	15.0	2	0.6	0.04	0.6	0.3	0.1	0.1	5.6	3
NTD GA	4.86	5.30	1	66	182	48	90	164	0.4	21.3	21.6	2	0.3	0.03	2.1	0.2	0.1	0.1	5.6	3
NTD GB	4.81	5.50	4	114	39	27	80	216	0.2	13.2	13.4	0	0.6	0.05	1.1	0.2	0.1	0.1		3
C 01 BA	5.00	5.80	1	35	209	40	59	36	0.0	17.2	17.2	9	0.1	0.04	20.4	0.5	0.6	0.1		2
C 01 BB	4.34	5.40	41	21	55	19	81	23	0.8	8.4	9.2	14	0.8	0.09	6.5	0.6	0.2	0.1	4.1	2
C 01 MA	4.30	5.30	5	85	181	301	76	92	6.5	39.8	46.3	30	0.2	0.07	23.2	1.2	0.2	0.4	4.1	2
C 01 MB	4.07	5.40	1	29	92	653	72	33	26.8	63.0	89.8	0	1.4	0.10	7.2	0.6	0.4	0.1		2
C 03 BA	5.84	6.70	2	291	635	145	86	310	0.0	55.5	55.5	8	0.2	0.05	46.2	0.9	5.4	0.1		2
C 03 BB	4.95	6.00	12	60	202	128	78	48	2.1	25.3	27.4	0	1.1	0.09	14.7	0.6	0.2	0.1	3.0	2
C 03 MA	5.06	5.90	3	109	546	114	79	110	0.0	43.0	43.0	0	0.2	0.02	35.0	0.8	0.4	0.1	3.0	2
C 03 MB	5.12	6.40	5	68	389	133	69	72	0.0	35.3	35.3	0	2.9	0.18	18.4	0.8	0.2	0.0		2
C 04 BA	5.74	6.60	3	169	603	170	94	174	0.0	52.8	52.8	20	0.6	0.06	79.8	0.6	1.5	0.3		2
C 04 BB	4.55	5.70	23	114	535	119	88	122	11.2	43.6	54.8	0	2.1	0.12	32.4	1.9	0.8	0.1	5.0	2
C 04 MA	5.15	5.90	47	193	835	177	77	204	0.0	65.0	65.0	0	0.3	0.04	59.5	0.9	1.4	0.2	5.0	2
C 04 MB	4.98	5.70	24	132	312	137	98	149	0.0	35.1	35.1	0	3.0	0.21	31.5	1.1	0.2	0.1		2
C 06 BA	6.49	6.90	1	41	1152	253	74	288	0.0	89.3	89.3	46	0.5	0.06	127.1	1.9	62.9	0.7		2
C 06 BB	4.28	5.50	2	137	166	113	90	151	21.5	25.5	47.1	14	1.5	0.10	19	1.7	1.1	0.2		2
C 07 BA	4.31	5.40	2	62	339	73	87	65	4.7	28.5	33.2	75	1.0	0.07	26.6	3.0	0.3	0.1		2
C 07 BB	4.00	5.00	4	44	134	21	101	49	42.0	14.1	56.1	1	3.2	0.14	16.4	2.6	0.5	0.1	3.2	2
C 08 MA	4.42	5.50	3	79	1649	48	70	101	0.6	92.1	92.7	0	0.9	0.08	8.3	1.3	0.6	0.2	3.2	2
C 08 MB	5.39	6.20	3	56	921	315	65	64	0.0	76.7	76.7	56	1.9	0.14	6.3	1.5	0.3	0.1		2
C 09 BA	3.87	4.70	1	118	102	75	67	123	21.9	17.4	39.3	83	0.4	0.06	75.1	1.8	1.0	0.1		2
C 09 BB	3.80	4.80	5	46	34	28	107	50	47.4	10.0	57.3	23	1.3	0.11	4.4	0.8	0.3	0.1	0.5	2
C 09 MA	4.08	5.20	2	88	261	101	94	92	8.5	27.9	36.4	83	0.3	0.03	58.0	1.4	0.7	0.1	0.5	2
C 09 MB	3.84	4.80	3	53	40	33	67	54	45.2	9.0	54.2	16	1.6	0.11	7.2	0.8	0.4	0.1	2.0	2
C 10 MA	4.06	5.20	1	92	286	97	67	92	5.4	27.6	33.0	74	0.3	0.04	64.8	1.8	0.8	0.2	2.0	2
C 10 MB	3.99	4.90	6	55	49	46	83	63	32.1	11.5	43.6	9	1.4	0.07	24.3	0.8	0.2	0.1		2

Sample name	pH KCl	pH H_2O	Bray P	K	NH4OAc Ca	Na	Mg	K	KCl extract. Acidity	Σbases	ECEC	Acid Sat	Total C	N	EDTA Mn	Cu	Zn	Hot H_2O B	Yield	Soil Group
			mg/kg						mmol$_c$/kg			%			mg/kg				t/ha	
C 11 BA	4.33	5.60	2	142	77	106	83	174	2.0	20.8	22.8	70	0.3	0.02	40.4	0.7	0.7	0.1		2
C 11 BB	4.40	5.60	4	132	27	105	64	144	37.9	16.6	54.5	1	1.2	0.08	11.6	0.3	0.3	0.1	6.1	2
C 11 MA	4.48	5.60	2	120	134	139	41	118	0.3	23.1	23.4	32	0.4	0.05	37.4	0.6	0.8	0.1	6.1	2
C 11 MB	4.23	5.30	5	133	36	111	86	136	8.5	18.3	26.8	0	2.4	0.15	7.0	0.4	0.3	0.0	6.5	2
C 12 MA	5.44	6.10	3	116	999	157	95	110	0.0	70.0	70.0	73	0.8	0.07	51.8	0.4	0.9	0.2	6.5	2
C 12 MB	3.86	5.00	9	43	121	55	73	42	40.6	14.9	55.5	34	2.4	0.16	19.2	1.5	0.3	0.1		2
C 13 BA	3.98	5.00	3	217	195	146	74	226	16.0	30.9	46.9	73	0.5	0.04	94.7	2.1	0.9	0.1		2
C 13 BB	4.01	5.10	6	147	53	45	81	157	37.2	13.9	51.1	36	1.3	0.11	6.0	1.2	0.4	0.0	0.7	2
C 13 MA	3.90	5.10	3	126	179	90	66	124	12.6	22.5	35.2	68	0.5	0.07	30.9	1.3	0.5	0.1	0.7	2
C 13 MB	3.88	4.90	4	113	41	36	106	121	26.8	12.7	39.5	19	2.1	0.12	5.4	0.8	0.2	0.0		2
C 17 BA	4.21	5.20	5	139	190	108	91	142	6.2	26.1	32.3	47	0.7	0.05	34.3	2.0	9.1	0.0		2
C 17 BB	4.31	5.30	0	86	58	28	85	86	10.0	11.1	21.1	2	3.0	0.17	27.4	1.2	7.8	0.3	2.4	2
C 17 MA	4.57	5.50	3	60	558	120	63	58	0.8	42.1	42.9	31	0.5	0.05	57.0	1.3	0.6	0.0	2.4	2
C 17 MB	4.35	5.50	3	19	89	51	76	20	5.7	12.5	18.2	0	1.8	0.11	23.4	1.1	0.1	0.1	2.9	2
C 18 MA	5.51	6.30	6	277	786	138	67	266	0.0	60.5	60.5	18	0.7	0.05	25.9	0.9	9.2	0.4	2.9	2
C 18 MB	4.36	5.30	3	34	218	58	82	33	4.5	20.2	24.7	0	2.0	0.13	23.9	0.9	0.3	0.2	3.4	2
C 19 MA	4.97	5.80	31	83	443	143	65	76	0.2	38.9	39.0	26	0.9	0.06	29.0	1.8	1.9	0.3	3.4	2
C 19 MB	4.43	5.30	6	28	111	42	69	25	4.4	12.7	17.1	33	1.6	0.10	35.5	1.6	1.4	0.1		2
C 23 BA	4.08	5.20	2	44	146	63	67	41	8.3	16.5	24.8	68	0.6	0.05	28.0	1.8	3.1	0.2		2
C 23 BB	4.19	5.20	4	11	44	13	71	14	14.4	6.7	21.1	29	1.5	0.09	6.8	1.2	0.6	0.2	3.6	2
C 23 MA	4.28	5.20	15	61	149	39	92	110	7.1	17.5	24.6	55	1.6	0.10	11.4	1.4	0.3	0.4	3.6	2
C 23 MB	4.19	4.80	2	14	55	24	72	15	10.1	8.3	18.3	0	1.6	0.06	10.7	1.2	0.2	0.1		2
JON BA	4.27	5.09	73	394	1005	147	89	387	0.0	76.3	76.3	1	1.6	0.06	16.1	0.3	7.6	0.8		2
JON BA	4.66	5.08	8	120	86	42	93	140	0.1	15.4	15.5	24	0.5	0.01	0.0	0.0	0.0	0.6		2
JON BB	4.79	4.38	1	12	25	6	85	16	1.8	5.8	7.6	35	0.5	0.03	0.0	0.2	0.2	0.5	7.0	2
JON MB	4.82	5.86	1	39	51	16	87	42	4.6	8.7	13.4	0	1.8	0.08	9.6	0.2	0.1	0.5	6.7	2
CVAG MA	5.50	6.40	80	203	746	179	114	237	0.1	63.2	63.4	9	0.3	0.02	35.5	0.9	0.8	0.2	6.7	2
CVAG MB	5.20	6.10	39	38	25	8	90	45	0.7	7.0	7.7	2	1.9	0.09	24.1	1.3	0.2	0.1	6.3	2

Sample name	pH KCl	pH H_2O	Bray P	Bray K	NH_4OAc Ca	NH_4OAc Na	NH_4OAc Mg	NH_4OAc K	KCl extract. Acidity	Σbases	ECEC	Acid Sat	Total C	N	EDTA Mn	EDTA Cu	EDTA Zn	Hot H_2O B	Yield	Soil Group
			mg/kg						mmol$_c$/kg			%			mg/kg				t/ha	
WIBS MA	4.55	5.50	3	92	209	180	96	139	0.8	33.1	33.9	52	0.4	0.02	24.0	1.1	0.4	0.2	6.3	2
WIBS MB 1	4.00	5.00	2	30	56	196	86	40	25.6	23.9	49.5	50	0.2	0.03	5.5	0.7	0.2	0.1	6.3	2
WIBS MB 2	4.10	5.00	10	26	41	241	14	67	24.8	24.5	49.3	58	1.3	0.05	9.0	0.5	0.2	0.1		2

Appendix 4: Particle size analysis for 25 samples from Mwinilunga district. Lab number identifies the sample with column headings indicating the mass of different particle size fractions with the texture class given in the final column.

Lab.	"si+cl"		---clay--		---vfs---		---fs---		----ms----		----cos----		---vcos--		---Prelim. analysis(kg/100kg)----							Sum			(kg/100kg)						Soil texture
Number	bk	b+s	bk	b+s	bk	b+s	bk	b+s	bk	b+s	bk	b+s	bk	b+s	clay	silt	vfs.	fine s.	med	cos.	vcos	fract.	clay	silt	tot s	vfs	fs	ms	cos	vcos	class
CO7 MB	47.7	48.4	46.5	47.1	55.4	56.4	57.8	61.9	59.8	60.4	49.0	49.2	47.4	47.5	48.0	22.0	4.9	20.4	2.9	0.7	0.4	99.3	48.0	22.0	29.3	4.9	20.4	2.9	0.7	0.4	**CLAY**
CO5 MA	49.9	50.7	48.5	48.7	55.4	57.2	52.9	54.2	57.5	58.4	49.6	50.0	47.5	47.9	14.0	57.0	9.0	6.6	4.1	2.0	1.6	94.2	14.0	57.0	23.2	9.0	6.6	4.1	2.0	1.6	**SILT LOAM**
CO5 MB	52.1	52.7	50.4	50.7	55.8	56.7	57.5	60.5	51.6	54.4	45.2	45.5	49.0	49.3	26.0	31.0	4.2	15.1	14.0	1.6	1.6	93.4	26.0	31.0	36.4	4.2	15.1	14.0	1.6	1.6	**LOAM**
CO9 BA	50.6	51.4	46.6	46.8	53.9	54.7	57.5	59.0	53.4	54.3	47.6	48.0	47.4	47.6	20.0	58.0	3.6	7.2	4.7	1.8	1.4	96.9	20.0	58.0	18.8	3.6	7.2	4.7	1.8	1.4	**SILT LOAM**
CO9BB	47.4	48.2	48.1	48.3	50.6	51.8	56.6	57.4	54.7	54.8	48.4	48.7	49.0	49.5	23.0	55.0	6.1	4.0	0.6	1.8	2.3	92.8	23.0	55.0	14.8	6.1	4.0	0.6	1.8	2.3	**SILT LOAM**
C15 MA	49.6	49.7	49.1	49.2	53.7	55.6	59.1	65.0	50.9	57.9	48.3	50.0	52.0	52.3	6.0	7.0	9.6	29.7	34.9	8.1	1.6	96.9	6.0	7.0	83.9	9.6	29.7	34.9	8.1	1.6	**LOAMY SAND**
C15 MB	48.2	48.4	51.8	51.9	53.5	55.8	53.3	59.3	52.4	57.6	49.2	50.9	47.4	47.5	4.0	11.0	11.2	30.0	26.2	8.2	0.5	91.1	4.0	11.0	76.1	11.2	30.0	26.2	8.2	0.5	**LOAMY SAND**
C17 MA	47.7	48.3	49.9	50.4	50.3	51.9	58.0	63.0	53.4	54.6	48.8	49.0	48.3	48.4	49.0	9.0	7.9	25.0	5.9	0.9	0.6	98.3	49.0	9.0	40.3	7.9	25.0	5.9	0.9	0.6	**CLAY**
C17 MB	49.0	49.6	49.9	50.2	50.2	51.5	57.9	60.5	58.4	60.1	48.2	48.4	51.5	52.6	28.0	30.0	6.3	12.8	8.7	0.6	5.4	91.8	28.0	30.0	33.8	6.3	12.8	8.7	0.6	5.4	**CLAY LOAM**
FISH BB	47.6	47.9	46.4	46.5	53.2	55.4	52.2	53.2	49.9	59.8	47.9	49.0	47.3	47.4	14.0	13.0	11.1	5.2	49.7	5.6	0.4	98.8	14.0	13.0	71.9	11.1	5.2	49.7	5.6	0.4	**SANDY LOAM**
FIX MA	49.2	49.9	48.2	48.5	50.2	55.0	51.2	52.9	57.2	57.5	49.5	49.6	47.2	47.5	22.0	41.0	24.0	8.3	1.7	0.4	1.8	99.2	22.0	41.0	36.2	24.0	8.3	1.7	0.4	1.8	**LOAM**
FIX MB	51.4	52.1	50.8	50.9	50.2	54.4	54.3	55.4	51.3	51.6	45.1	45.2	48.7	49.0	11.0	50.0	20.9	5.6	1.5	0.7	1.3	91.0	11.0	50.0	30.0	20.9	5.6	1.5	0.7	1.3	**LOAM / SILT LOAM**
CO2 MA	49.9	50.6	46.4	46.6	50.6	53.9	54.9	56.7	51.6	53.4	47.5	47.6	47.3	47.4	19.0	42.0	16.9	8.7	8.8	0.7	0.2	96.1	19.0	42.0	35.2	16.9	8.7	8.8	0.7	0.2	**LOAM**
CO2 mB	46.7	47.4	47.8	48.1	48.4	50.6	54.2	56.6	52.9	54.7	48.2	48.4	48.9	49.0	25.0	40.0	11.0	12.1	9.0	0.7	0.5	98.3	25.0	40.0	33.3	11.0	12.1	9.0	0.7	0.5	**LOAM**
CO4 BA	48.8	49.6	48.7	49.1	48.8	52.0	58.3	59.1	50.1	50.9	48.3	48.3	51.9	51.9	27.0	47.0	16.4	3.8	4.1	0.5	0.2	98.8	27.0	47.0	24.8	16.4	3.8	4.1	0.5	0.2	**LOAM**
CO4 BB	47.4	48.2	51.5	51.8	49.6	53.5	52.8	53.3	52.8	53.1	49.2	49.2	47.3	47.4	31.0	44.0	19.6	2.3	1.4	0.2	0.3	98.7	31.0	44.0	23.7	19.6	2.3	1.4	0.2	0.3	**CLAY LOAM**
C07 MA	46.9	47.8	49.4	49.9	49.0	50.3	57.5	58.0	52.5	53.0	48.6	48.8	48.3	48.3	44.0	41.0	6.3	2.6	2.2	1.2	0.4	97.8	44.0	41.0	12.8	6.3	2.6	2.2	1.2	0.4	**SILTY CLAY**
IBS MA	47.0	47.6	46.2	46.4	51.6	53.2	46.8	52.2	48.9	49.9	46.5	47.9	47.0	47.3	14.0	34.0	7.6	26.7	5.0	7.2	1.6	96.1	14.0	34.0	48.1	7.6	26.7	5.0	7.2	1.6	**LOAM**
IBS MB	48.9	49.2	47.9	48.2	48.6	50.2	46.3	51.2	52.2	57.2	47.8	49.5	46.9	47.2	23.0	8.0	8.0	24.9	24.9	8.4	1.5	98.5	23.0	8.0	67.6	8.0	24.9	24.9	8.4	1.5	**SANDY CLAY LOAM**
ESI MA	51.1	51.5	50.0	50.3	47.7	50.2	49.9	54.2	46.6	51.3	44.3	45.1	48.7	48.7	31.0	5.0	12.6	21.6	23.3	3.8	0.2	97.3	31.0	5.0	61.3	12.6	21.6	23.3	3.8	0.2	**SANDY CLAY LOAM**
IBS MA	49.6	49.9	46.1	46.4	48.1	50.6	49.4	54.9	47.5	51.6	46.8	47.5	47.3	47.3	24.0	10.0	12.2	27.8	20.9	3.5	0.1	98.5	24.0	10.0	64.5	12.2	27.8	20.9	3.5	0.1	**SANDY CLAY LOAM**
IBS MB	46.4	46.7	47.5	47.8	46.7	48.4	47.6	54.2	48.5	52.9	47.6	48.2	48.8	48.9	20.0	7.0	8.4	32.9	21.9	3.1	0.2	93.4	20.0	7.0	66.4	8.4	32.9	21.9	3.1	0.2	**SANDY CLAY LOAM**
SAL MB	48.4	48.8	48.4	48.7	46.4	48.8	52.3	58.3	46.8	50.1	47.6	48.3	51.8	51.9	28.0	9.0	11.7	30.1	16.6	3.2	0.2	98.7	28.0	9.0	61.7	11.7	30.1	16.6	3.2	0.2	**SANDY CLAY LOAM**
FISH MA	47.2	47.4	51.3	51.5	47.2	49.6	46.0	52.8	47.8	52.8	48.8	49.2	47.3	47.3	16.0	7.0	11.9	34.1	25.0	2.0	0.1	95.9	16.0	7.0	73.0	11.9	34.1	25.0	2.0	0.1	**SANDY LOAM**
FISH MB	46.5	46.9	49.2	49.4	46.8	49.0	52.0	57.5	47.6	52.5	47.8	48.6	48.2	48.3	21.0	9.0	11.0	27.4	24.5	3.7	0.2	96.7	21.0	9.0	66.7	11.0	27.4	24.5	3.7	0.2	**SANDY CLAY LOAM**
FISH BA	48.4	48.7	49.4	49.6	46.8	48.9	46.8	52.6	46.5	51.5	45.8	46.8	51.3	51.4	17.0	9.0	10.4	29.0	25.2	4.9	0.3	95.8	17.0	9.0	69.8	10.4	29.0	25.2	4.9	0.3	**SANDY LOAM**

Appendix 5: Soil profile descriptions. Each profile has a code to identify its field location followed by BA/BB for bushland soils or MA/MB for maizeland soils.

AND BA & BB, Posic Ferralsol (Dystric)(Cv 1200)

A
0-50cm — Dry; dark yellowish brown 10YR 4/4; loamy sand; weak, tending towards moderate, blocky; soft; many fine, medium and coarse roots; diffuse, smooth transition;

B
50cm+ — Slightly moist; yellowish brown 10YR 5/6; loamy sand; weak, blocky; friable; few coarse and medium roots; transition not reached.

AND MA & MB, Acric Ferralsol (Dystric) (Cv 1200)

A
0-35cm — Dry; yellowish brown 10YR 5/4; loamy sand; weak, fine blocky; soft; many fine, common medium and very few coarse roots; gradual, smooth transition.

B
35cm+ — Slightly moist; brownish yellow 10YR 6/6; sandy loam; weak, fine-moderate blocky; friable; very few roots; transition not reached.

AXS BA & BB, Hypoluvic Arenosol (Dystric) (Cv 1200)

A
0-50cm — Dry, dark brown 10YR 3/3, loamy sand; weak; blocky, medium and fine; friable; many fine, common medium and few fine roots; gradual smooth transition.

B
50cm+ — Dry; brownish yellow 10YR 6/6; sandy loam; weak; granular, fine and medium; friable; common fine and medium roots; transition not reached.

AXS MA & MB, Haplic Arenosol (Dystric) (Oa 2120)

A	
0-35cm	Dry; dark brown 10YR 3/3; loamy sand; weak; granular, fine and medium; friable; few small, common medium roots; gradual, smooth transition.
B	
35cm+	Dry; brownish yellow 10YR 6/6; sandy loam; weak; granular, fine and medium; friable; very few fine roots; increasing orange mottles with depth; transition not reached

BAM BA + BB, Haplic Acrisol (Chromic) (Tu 1120)

A	
0-20cm	Dry; very dark grey 10YR 3/1; sandy loam; weak, granular fine; friable; many fine roots; abrupt smooth transition;
B	
20cm-70cm	Dry; pale brown 10YR 6/3; sandy loam; weak, granular, fine; friable; many fine and few medium roots; abrupt smooth transition;
‘Potential’ E	
70-90cm	Dry; dark grey 10YR 4/1; sandy loam; weak; granular, fine; friable; few roots; abrupt smooth transition;
B	
90cm+	Dry; pale brown 10YR 6/3; sandy loam; weak, granular, fine; friable; very few roots; transition not reached.

BAM MA & MB, Haplic Acrisol (Chromic) (Tu 1120 transition to Vf)

A	
0-20cm	Dry; very dark grey 10YR 3/1; sandy loam; weak, granular fine; friable; many fine roots; abrupt smooth transition;
B	
20cm-70cm	Dry; pale brown 10YR 6/3; sandy loam; weak, granular, fine; friable; many fine and few medium roots; abrupt smooth transition;
‘Potential’ E	
70-90cm	Dry; dark grey 5 YR 4/1; sandy loam; weak; granular, fine; friable; few roots; abrupt smooth transition;
B	
90cm+	Dry; strong brown 7.5YR 5/8; sandy loam; weak, granular, fine; friable; very few roots; transition not reached.

C01 BA & BB, Cutanic Lixisol (Rhodic) (Sw 2211)

A 0-30cm	Dry; strong brown 7.5YR 5/8; sandy loam; weak to moderate, blocky, medium; soft; common medium, few fine and very few coarse roots; gradual, smooth transition;
B 30-75cm	Dry; light reddish brown 5YR 6/4; sandy clay; moderate, blocky, subangular/ fine angular; slightly hard; few medium roots; gradual, smooth transition;
Saprolite 75cm+	Dry; red 2.5YR 4/6; shale; moderate to strong, prismatic; nearly no roots; transition not reached.

C01 MA & MB, Cutanic Lixisol (Rhodic) (Sw 2211)

A 0-30cm	Dry; strong brown 7.5YR 5/8; sandy loam; weak to moderate, blocky, medium; soft; common medium, few fine and very few coarse roots; gradual, smooth transition;
B 30-75cm	Dry; light reddish brown 5YR 6/4; sandy clay loam; moderate, blocky, subangular/ fine angular; slightly hard; few medium roots; gradual, smooth transition;
Saprolite 75cm+	Dry; red 2.5YR 4/6; shale; moderate to strong, prismatic; nearly no roots; transition not reached.

C02 BA & BB, Acric Ferralsol (Dystric) (Cv 1200)

A 0-20cm	Dry; yellowish brown 10YR 5/6; loamy sand; weak to moderate, blocky, fine and medium; soft; few fine, common medium and no coarse roots; diffuse, smooth transition;
B 20cm+	Moist; brownish yellow 10YR 6/8; sandy clay loam; weak to moderate, blocky, medium; friable to firm; few fine and medium roots; transition not reached.

C02 MA & MB, Acric Ferralsol (Dystric) (Cv 1200)

A 0-20cm	Dry; yellowish brown 10YR 5/6; loamy sand; weak to moderate, blocky, fine and medium; soft; few fine, common medium and no coarse roots; diffuse, smooth transition;
B 20cm+	Moist; brownish yellow 10YR 6/8; sandy clay loam; weak to moderate, blocky, medium; friable to firm; few fine and medium roots; transition not reached.

C03 BA & BB, Haplic Lixisol (Rhodic) (Oa 2120)

A 0-30cm	Dry; dark yellowish brown 10YR 4/4; sandy loam; weak, blocky, fine; soft; many fine and medium, few coarse roots; gradual, smooth transition;
B 30cm+	Dry to slightly moist; reddish yellow 5YR 6/6; sandy clay loam; weak, blocky, medium; hard/firm; almost no roots; transition not reached.

C03 MA & MB, Haplic Lixisol (Rhodic) (Oa 2120)

A 0-30cm	Dry; dark yellowish brown 10YR 4/4; sandy loam; weak, blocky, fine; soft; many fine and medium, few coarse roots; gradual, smooth transition;
B 30cm+	Dry to slightly moist; brownish yellow 10YR 6/8; sandy clay loam; weak, blocky, medium; hard/firm; almost no roots; transition not reached.

C04 BA & BB, (Haplic Lixisol (Rhodic) Oa 2120)

A
0-30cm Dry; brown/dark brown 10YR 4/3; sandy loam; weak, blocky, fine; soft; many fine and medium, few coarse roots; gradual, smooth transition;

B
30cm+ Dry to slightly moist; reddish yellow 7.5YR 6/8; sandy clay loam; moderate, blocky, medium; hard/firm; almost no roots; transition not reached

C04 MA & MB, (Haplic Lixisol (Rhodic) Oa 2120)

A
0-30cm Dry; brown/dark brown 10YR 4/3; sandy loam; weak, blocky, fine; soft; many fine and medium, few coarse roots; gradual, smooth transition;

B
30cm+ Dry to slightly moist; reddish yellow 7.5YR 6/8; sandy clay loam; moderate, blocky, medium; hard/firm; almost no roots; transition not reached

C05 BA & BB, Albic Arenosol (Dystric) (Vf 1220)

A
0-20cm Dry; light yellowish brown 10YR 6/4; loamy sand; weak, granular-blocky, fine and medium; soft; common fine, few medium and no coarse roots; abrupt wavy transition;

E
20-30cm Dry; light grey 10YR 7/2; loamy sand; weak, granular to single grain, fine; soft; almost no roots; abrupt, wavy transition;

B
30cm+ Slightly moist; yellowish red 5YR 5/8; sandy loam; weak, blocky, medium; friable to firm; almost no roots; transition not reached.

C05 MA & MB, Albic Arenosol (Dystric) (Vf 1220)

A 0-20cm	Dry; brownish yellow 10YR 6/8; loamy sand; weak, granular-blocky, fine and medium; soft; common fine, few medium and no coarse roots; abrupt wavy transition;
E 20-30cm	Dry; light grey 10YR 7/2; loamy sand; weak, granular to single grain, fine; soft; almost no roots; abrupt, wavy transition;
B 30cm+	Slightly moist; reddish yellow 5YR 6/6; sandy loam; weak to moderate, blocky, medium; friable to firm; almost no roots; transition not reached.

C06 BA & BB, Cutanic Lixisol (Rhodic) (Sw 1211)

A 0-25cm	Dry; light yellowish brown 10YR 6/4; loamy sand; weak to moderate, blocky, fine; soft; many medium, common fine and few coarse roots; abrupt wavy transition;
B 25cm+	Dry to slightly moist; yellowish red 7.5YR 6/6; sandy loam – sandy clay loam; moderate, blocky, medium; slightly hard/slightly firm; few medium roots; transition not reached.

C06 MA & MB, Acric Ferralsol (Dystric) (Hu 1200)

A 0-25cm	Dry; yellowish brown 10YR 5/6; loamy sand; weak to moderate, blocky, fine; soft; many medium, common fine and few coarse roots; abrupt wavy transition;
B 25cm+	Dry to slightly moist; reddish yellow 7.5YR 6/8; sandy loam – sandy clay loam; weak, blocky, medium; slightly hard/slightly firm; few medium roots; transition not reached.

C07 BA & BB, Acric Nitisol Eutric (Sd 1110)

A
0-30cm Dry; light reddish brown 5YR 6/4; sandy clay loam; weak to moderate, blocky, fine; slightly hard; many fine, medium and coarse roots; gradual, smooth transition;

B
30cm+ Dry; red 2.5YR 4/6; clay loam; moderate, blocky, fine and medium; hard; few medium and coarse roots; transition not reached.

C07 MA & MB, Mollic Fluvisol (Dystric) (Ik 2100)

A
0-80cm Dry; brown/dark brown 10YR 4/3; clay loam; moderate to strong, blocky, medium; hard; many fine, common medium and few coarse roots; 10cm overburden; diffuse, smooth transition;

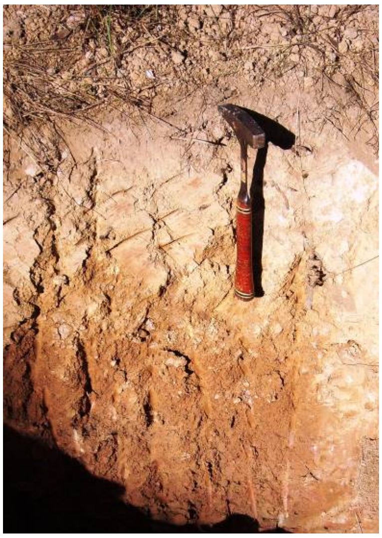
B
80cm+ Dry; yellowish brown 10YR 5/6; clay loam; moderate to strong, blocky, medium; hard; few roots; transition not reached.

C08 MA & MB, Vertic chemozems (clayic) (Bo 1210)

A
0-40cm Dry; dark brown 10YR 3/3; clay loam; strong, blocky, fine and medium; slightly hard; many fine and medium, few coarse roots; gradual, smooth transition

B
40cm+ Dry; light yellowish brown 10YR 6/4; clay loam; strong, blocky, medium; hard; common medium and coarse roots; transition not reached.

C09 BA & BB, Haplic Lixisol (Rhodic) (Sw 2111)

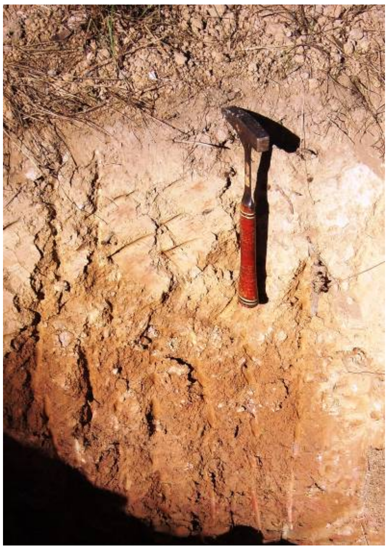


A	
0-40cm	Dry; light yellowish brown 10YR 6/4; sandy clay loam; weak, granular to blocky, fine and medium; soft; common fine, few medium and few coarse roots; gradual, smooth transition;
B	
40-90cm	Dry; yellow 10YR 7/6; clay loam; moderate, blocky, fine and medium; slightly hard; few roots; diffuse, smooth transition;
B	
90cm+	Dry; brownish yellow 10YR 6/6; clay loam; moderate to strong, blocky and platy, fine and medium; slightly hard; no roots; transition not reached.

C09 MA & MB, Haplic Lixisol (Rhodic) (Sw 2111)

A	
0-25cm	Dry; light yellowish brown 10YR 6/4; sandy clay loam; weak to moderate, blocky, fine and medium; soft; common medium and fine roots, no coarse roots; gradual, smooth transition;
B	
25-160cm	Dry; yellow 10YR 7/6; clay loam; moderate, blocky, medium; slightly hard; few medium, few fine and no coarse roots; quartz stoneline at 50cm; gradual, smooth transition;
C	
160cm+	Slightly moist; shale; signs of wetness present.

C10BA & BB, Haplic Lixisol (Rhodic) (Sw 2111)



A	
0-40cm	Dry; light yellowish brown 10YR 6/4; sandy clay loam; weak, granular to blocky, fine and medium; soft; common fine, few medium and few coarse roots; gradual, smooth transition;
B	
40-90cm	Dry; yellow 10YR 7/6; clay loam; moderate, blocky, fine and medium; slightly hard; few roots; diffuse, smooth transition;
B	
90cm+	Dry; brownish yellow 10YR 6/6; clay loam; moderate to strong, blocky and platy, fine and medium; slightly hard; no roots; transition not reached.

C10 MA & MB, Haplic Lixisol (Rhodic) (Sw 2211)

A	
0-15cm	Dry; light yellowish brown 10YR 6/4; sandy clay loam; weak, blocky, fine; soft; few fine and medium roots, no coarse roots; abrupt, smooth transition;
B	
15-160cm	Dry; yellow 10YR 7/6; clay loam; moderate, blocky, fine and medium; slightly hard; very few medium roots; gradual, smooth transition;
C	
160cm+	Slightly moist; brownish yellow 10YR 6/8; clay loam; moderate, blocky, fine; friable to slightly firm; no roots; quartz coarse fragments; transition not reached.

C11 BA & BB, Haplic Lixisol (Rhodic) (Sw 2211)

A	
0-40cm	Dry; brown 10YR 5/3; loamy sand; weak, blocky, fine; soft; many fine and medium, few coarse; gradual, wavy transition;
B	
40-120cm	Dry; brownish yellow 10YR 6/6; sandy clay loam; moderate, blocky, medium; hard; common medium, few coarse and common fine roots; gradual, smooth transition;
B	
120cm+	slightly moist; yellowish brown 10YR 5/8; clay loam; moderate, blocky, medium; friable to firm; few medium roots; transition not reached.

C11 MA & MB, Haplic Lixisol (Rhodic) (Sw 2211)

A	
0-40cm	Dry; brown 10YR 5/3; loamy sand; weak, blocky, fine; soft; common fine and medium, few coarse roots; gradual, smooth transition;
B	
40-150cm	Dry; brownish yellow 10YR 6/6; sandy loam; moderate, blocky, fine and medium; few coarse and medium roots; gradual, smooth transition;
B	
150cm+	Slightly moist; purple seams and yellowish brown10YR 5/6 matrix; moderate, blocky, medium; no roots; transition not reached.

C12 BA & BB, Haplic Lixisol (Se1110)

A	
0-35cm	Dry; yellowish brown 10YR 5/4; sandy silt loam; weak, blocky, fine; soft; few coarse, common fine and few medium roots; abrupt, smooth transition;
B	
35cm+	Moist; yellowish brown 10YR 5/6; clay loam; moderate, blocky, medium; friable; few coarse and medium roots; transition not reached.

C12 MA & MB, Haplic Lixisol (Se1110)

A	
0-35cm	Dry; yellowish brown 10YR 5/4; sandy silt loam; weak, blocky, fine; soft; few coarse, common fine and few medium roots; abrupt, smooth transition;
B	
35cm+	Moist; yellowish brown 10YR 5/6; clay loam; moderate, blocky, medium; friable; few coarse and medium roots; transition not reached.

C13 BA & BB, Haplic Lixisol (Rhodic) (Sw 2211)

A	
0-20cm	Dry; light yellowish brown 10YR 6/4; sandy loam; weak, blocky, fine; soft; few fine and medium and very few coarse roots; gradual, wavy transition;
B	
20-80cm	Dry; yellow 10YR 7/6; clay loam; moderate, blocky, medium and fine; soft; very few medium roots; gradual, smooth transition;
C	
80cm+	Moist; yellowish red 5YR 5/6; clay loam; moderate, blocky, medium; friable; no roots; transition not reached.

C13 MA & MB, Haplic Lixisol (Rhodic) (Sw 2211)

A	
0-20cm	Dry; light yellowish brown 10YR 6/4; sandy loam; weak, blocky, fine; soft; few fine and medium and very few coarse roots; gradual, wavy transition;
B	
20-80cm	Dry; yellow 10YR 7/6; clay loam; moderate, blocky, medium and fine; soft; very few medium roots; gradual, smooth transition;
C	
80cm+	Moist; yellowish red 5YR 5/6; clay loam; moderate, blocky, medium; friable; no roots; transition not reached.

C14 BA & BB, Acric Ferralsol (Dystric) (Cv 1200)

A	
0-45cm	Dry; brown/dark brown 7.5YR 4/4; sand; weak, crumb to granular, fine; many soft; fine and medium, few coarse roots; gradual, smooth transition;
B	
45cm+	Dry; yellowish red 5YR 6/6; loamy sand; weak, blocky, fine; soft; common medium and few coarse roots; transition not reached.

C14 MA & MB, Acric Ferralsol (Dystric) (Cv 1200)

A	
0-15cm	Dry; brown/dark brown 7.5YR 4/4; sand; weak, single grain, massive; soft; common fine, medium and few coarse roots; gradual, smooth transition;
B	
15cm+	Dry; brown/dark brown 10YR 4/3; loamy sand; weak to apedal, blocky, fine; soft; common medium and very few coarse roots; red clay bricks in lower part of horizon from previous disturbance; transition not reached.

C15 BA & BB, Acric Ferralsol (Dystric) (Cv 1200)

A 0-45cm	Dry; brown/dark brown 7.5YR 4/4; sand; weak, crumb to granular, fine; many soft; fine and medium, few coarse roots; gradual, smooth transition;
B 45cm+	Dry; yellowish red 5YR 6/6; loamy sand; weak, blocky, fine; soft; common medium and few coarse roots; transition not reached.

C15 MA & MB, Albic Arenosol (Dystric) (Vf 1220)

A 0-40cm	Dry; brown/dark brown 7.5YR 4/4; loamy sand; weak, single grain to granular, fine; soft; many fine and medium, few coarse roots; gradual, smooth transition;
E 40-80cm	Dry; light grey 10YR 7/2; loamy sand; weak, blocky, fine; soft; few medium roots; gradual, smooth transition;
B 80cm+	Dry; strong brown 7.5YR 5/6; sandy loam; weak, blocky, fine; soft; nearly no roots; transition not reached.

C16 BA & BB Acric Ferralsol (Dystric) (Cv 1200)

A 0-45cm	Dry; brown/dark brown 7.5YR 4/4; sand; weak, crumb to granular, fine; many soft; fine and medium, few coarse roots; gradual, smooth transition;
B 45cm+	Dry; yellowish red 5YR 6/6; loamy sand; weak, blocky, fine; soft; common medium and few coarse roots; transition not reached.

C16 MA & MB, Acric Ferralsol (Dystric) (Cv 1200)

A	
0-35cm	Dry; brown/dark brown 7.5YR 4/4; loamy sand; weak, granular, fine and medium; soft; many medium, common fine and few coarse roots; gradual, smooth transition;
B	
35cm+	Dry; dark yellowish brown 7.5YR 4/4; sandy loam; weak, blocky, fine; soft; few coarse and common medium roots; transition not reached.

C17 BA & BB, Acric Nitisol (Rhodic) (Sd 1210)

A	
0- 20cm	Dry; yellowish brown 10YR 5/6; sandy loam; weak to moderate, blocky, fine and medium; soft; many medium and coarse, few fine roots; gradual, wavy transition;
B	
20cm+	Dry; strong brown 7.5YR 5/8; clay loam; moderate, blocky, medium; slightly hard; common medium and coarse, few fine roots; transition not reached.

C17 MA & MB, Acric Nitisol (Rhodic) (Sd 1210)

A	
0-10cm	Dry; yellowish red 5YR 4/6; sandy loam; weak to moderate, blocky, medium; soft; common fine and medium, few coarse roots; abrupt, wavy transition;
B	
10cm+	Dry to slightly moist; red 2.5YR 5/8; clay loam; moderate to strong, blocky, medium; soft to slightly hard; few coarse and medium roots; transition not reached.

C18 BA & BB, Haplic Lixisol (Sd 1210)

A 0- 20cm	Dry; yellowish brown 10YR 5/6; sandy loam; weak to moderate, blocky, fine and medium; soft; many medium and coarse, few fine roots; gradual, wavy transition;
B 20cm+	Dry; strong brown 7.5YR 5/8; clay loam; moderate, blocky, medium; slightly hard; common medium and coarse, few fine roots; transition not reached.

C18 MA & MB, Haplic Lixisol (Se 1110)

A 0-40cm	Dry; yellowish brown 10YR 5/6; loamy sand; weak, blocky to granular, fine and medium; soft; many fine, few medium and very few coarse roots; gradual, smooth transition.
B 40cm+	Dry; strong brown 7.5YR 5/8; sandy clay loam; moderate, blocky, fine; soft to slightly hard; common medium and very few fine roots; brown and orange mottles increasing with depth; transition not reached.

C19 BA & BB, Acric Nitisol (Rhodic) (Sd 1210)

A 0- 20cm	Dry; yellowish brown 10YR 5/6; sandy loam; weak to moderate, blocky, fine and medium; soft; many medium and coarse, few fine roots; gradual, wavy transition;
B 20cm+	Dry; red 2.5YR 5/8; clay loam; moderate, blocky, medium; slightly hard; common medium and coarse, few fine roots; transition not reached.

C19MA & MB, Haplic Lixisol (Se 2110)

A	
0-25cm	Dry; dark yellowish brown 5YR 4/4; loamy sand; weak, blocky, medium; soft; many fine, few medium and coarse roots; few fine pieces of charcoal; gradual, smooth transition;
B	
25cm-80cm	Dry; yellowish red 5YR 5/8; sandy loam; moderate, blocky, fine and medium; slightly hard; few fine, common medium to 20cm, then no roots; gravel content starts at 35cm; abrupt, smooth transition;
Stondline	
80cm+	Slightly moist; red 2.5YR 4/6; sandy clay loam; moderate, blocky, medium; firm; no roots; transition not reached

C20 BA & BB, Haplic Arenosol (Dystric) (Oa 2120)

A	
0-35cm	Dry; brown/dark brown 10YR 4/3; sand to loamy sand; weak, granular, fine and medium; soft; many fine and medium, few coarse roots; gradual, smooth transition;
B	
35cm+	Dry; light yellowish brown 10YR 6/4; loamy sand; weak to apedal, blocky, fine; soft; few coarse and common medium roots; transition not reached.

C20 MA & MB, Haplic Arenosol (Dystric) (Oa 2120)

A	
0-35cm	Dry; brown/dark brown 10YR 4/3; sand to loamy sand; weak, granular, fine and medium; soft; many fine and medium, few coarse roots; gradual, smooth transition;
B	
35cm+	Dry; light yellowish brown 10YR 6/4; loamy sand; weak to apedal, blocky, fine; soft; few coarse and common medium roots; transition not reached.

C21 BA & BB, Haplic Arenosol (Dystric) (Oa 2120)

A	
0-35cm	Dry; brown/dark brown 10YR 4/3; sand to loamy sand; weak, granular, fine and medium; soft; many fine and medium, few coarse roots; gradual, smooth transition;
B	
35cm+	Dry; light yellowish brown 10YR 6/4; loamy sand; weak to apedal, blocky, fine; soft; few coarse and common medium roots; transition not reached.

C21 MA & MB, Acric Ferralsol (Dystric) (Cv 1200)

A	
0-15cm	Dry; dark greyish brown 10YR 4/2; sand to loamy sand; weak to moderate, granular, medium; soft; common medium and fine, few coarse roots; gradual, smooth transition;
B	
25-75cm	Dry; yellowish brown 10YR 5/6; loamy sand; apedal to weak, blocky, fine; soft; few coarse and medium roots; gradual, smooth transition;
B	
75cm+	Slightly moist; brown/dark brown 10YR 4/3; sandy loam; weak, blocky, fine; friable; few coarse roots; transition not reached.

C22 BA & BB, Haplic Arenosol (Dystric) (Oa 2120)

A	
0-35cm	Dry; brownish yellow 10YR 6/8; sand to loamy sand; weak, granular, fine and medium; soft; many fine and medium, few coarse roots; gradual, smooth transition;
B	
35cm+	Dry; light yellowish brown 10YR 6/4; loamy sand; weak to apedal, blocky, fine; soft; few coarse and common medium roots; transition not reached.

C22 MA & MB, Haplic Arenosol (Dystric) (Oa 2220)

A
0-45cm — Dry; brownish yellow 10YR 6/8; sand to loamy sand; weak, granular, fine and medium; soft; few medium and coarse, common fine roots; gradual, smooth transition;

B
45cm+ — Dry; reddish brown 7.5YR 5/4; loamy sand; weak, blocky, fine; soft; few coarse roots; matrix colour reddening with depth; transition not reached.

C23 BA & BB, Haplic Lixisol (Se 2110)

A
0- 15cm — Dry; yellowish red 5YR 4/6; sandy loam; weak to moderate, blocky, fine; soft; many medium, few fine and coarse roots; abrupt, smooth transition;

B
15cm+ — Dry; red 2.5YR 4/8; sandy clay loam; weakly moderate, blocky, medium; slightly hard; common medium and few coarse roots; transition not reached.

C23 MA & MB, Haplic Lixisol (Se 2110)

A
0-15cm — Dry; yellowish red 5YR 4/6; loamy sand; weak to apedal, blocky, fine; soft; few roots; abrupt, smooth transition;

B
25cm+ — Dry; red 2.5YR 4/8; sandy clay loam; weak to moderate, blocky, fine and medium; slightly hard; few coarse roots; transition not reached.

C24 BA & BB, Acric Ferralsol (Dystric) (Hu 1200)

A	
0-30cm	Dry; dark brown 10YR 3/3; loamy sand; weak, blocky, fine and medium; soft; many fine, medium and few coarse roots; gradual, smooth transition;
B	
30cm+	Dry; dark red 2.5YR 3/6; sandy loam; weak, single-grain/blocky, fine and medium; soft to slightly hard; few fine, medium and coarse roots; transition not reached.

C24 MA & MB, Acric Ferralsol (Dystric) (Hu 1200)

A	
0-15cm	Dry; dark reddish brown 2.5YR 3/4; loamy sand; weak to moderate, granular, fine and medium; many fine and medium, few coarse roots; some fine charcoal; diffuse, smooth transition;
B	
15cm+	Dry; red 2.5YR 4/6; sandy loam; apedal to weak, blocky, fine; soft; common medium and few fine roots; transition not reached.

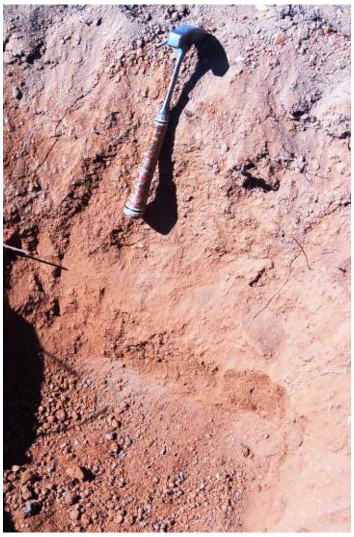
C25 BA & BB, Acric Ferralsol (Dystric) (Hu 1200)

A	
0-30cm	Dry; dark brown 10YR 3/3; loamy sand; weak, blocky, fine and medium; soft; many fine, medium and few coarse roots; gradual, smooth transition;
B	
30cm+	Dry; dark red 2.5YR 3/6; sandy loam; weak, single-grain/blocky, fine and medium; soft to slightly hard; few fine, medium and coarse roots; transition not reached.

C25 MA & MB Acric Ferralsol (Dystric) (Hu 1200)

A 0-15cm	Dry; dark reddish brown 2.5YR 3/4; loamy sand; weak to moderate, granular, fine and medium; many fine and medium, few coarse roots; some fine charcoal; diffuse, smooth transition;
B 15cm+	Dry; red 2.5YR 4/6; sandy loam; apedal to weak, blocky, fine; soft; common medium and few fine roots; transition not reached.

CBS GA + GB, Acric Ferralsol (Dystric) (Hu 1200)



A 0 – 3 cm	Dry; yellowish red 5YR 4/6; sand; weak, fine, single grain; loose; few fine and medium pores; few fine roots; clear smooth transition.
B 3 cm +	Dry; red 2.5YR 4/8; sandy loam; apedal; loose; few fine and coarse pores; few coarse roots; few fine black mottles; Iron concretions from 30cm increasing with depth transition not reached.

CFN MA + MB, Acric Ferralsol (Dystric) (Cv 1200)

A 0-40 cm	Dry; yellowish brown 10YR 5/4; loamy sand; weak, fine, crumb; loose; few fine and medium pores; common fine roots; few, fine, faint black mottles; clear smooth transition.
B 40 cm+	Moist; strong brown 7.5YR 5/8; loamy sand; weak, fine, single grain; loose; common fine and medium pores; few coarse roots; few medium, distinct brown mottles; burnt roots at 1m; transition not reached.

CHBS GA + GB, Acric Ferralsol (Dystric) (Hu 1200)

A 0-30 cm	Dry; greyish brown 10YR 5/2; sand; weak, fine single grain; loose; common fine and few coarse pores; few fine roots; diffuse tonguing transition.
B 30 cm+	Dry; yellowish red 5YR 5/6; sandy loam; weak, fine single grain; loose; few fine, very fine and medium pores; few coarse roots; few medium, distinct black and orange mottles in transition from A to B; transition not reached.

CHIEF BA & BB, Haplic Arenosol (Dystric)   (Oa 2120)

A 0-35cm	Dry; brown/dark brown 10YR 4/3; sand; weak, granular, fine and medium; soft; many fine, common medium and few coarse roots; gradual, smooth transition;
B 35cm+	Slightly moist; brownish yellow 10YR 6/8; loamy sand; weak, blocky, fine; friable; common medium and coarse, few fine roots; transition not reached.

CHIEF MA & MB, , Haplic Arenosol (Dystric)   (Oa 2120)

A 0-10cm	Dry; brown 10YR 5/3; sand; weak, blocky, fine to medium; soft; few fine and medium roots; gradual, smooth transition;
B 10cm+	Dry, increasing moisture with depth; brownish yellow 10YR 6/8; loamy sand; weak; blocky, fine – towards apedal; very few roots; transition not reached.

CKY MA + MB, Haplic Arenosol (Dystric) (Oa 2220)

A 0 – 15 cm	Dry; 10YR 5/3 brown; sand; weak, coarse, single grain; loose; common fine and coarse pores; common fine and coarse roots; diffuse, smooth transition.
B 15 cm+	Dry; strong brown 7.5YR 5/6; loamy sand; weak, coarse, single grain; loose; few fine and medium pores; few coarse roots; few medium, faint black and brown mottles; transition not reached.

CSA BA & BB, Acric Ferralsol (Dystric) (Cv 1200)

A 0-10cm	Dry; dark yellowish brown 10YR 4/4; loamy sand; weak; granular, very fine and fine; friable; few fine roots; gradual smooth transition;
B 10cm+	Dry; yellowish brown 10YR 5/6; sandy clay loam; weak-moderate; blocky; fine and medium; friable; common medium and coarse roots; iron concretions increasing with depth; transition not reached

CSA MA & MB, Acric Ferralsol (Dystric) (Cv 1200)

A 0-12cm	Dry; yellowish brown 10YR 5/4; sand; weak; granular, fine and very fine; loose; many fine and few medium and coarse roots; gradual smooth transition;
B 12cm+	Dry; yellowish brown 10YR 5/6; sandy loam; weak; granular fine and medium; friable; few medium and coarse roots; transition not reached.

CVAG MA + MB, Nitic Lixisol (Rhodic) (Sd 1120)

A 0 – 15cm	Dry; reddish brown 5YR 5/3; sandy clay loam; weak, fine crumb; loose; many fine and common coarse pores; many fine roots; gradual smooth transition.
B 15cm+	Dry; yellowish red 5YR 5/6; sandy clay; moderate, medium subangular blocky; few fine and coarse pores; few coarse roots; lumps of quartz at 750mm, transition not reached.

ELK BA & BB, Acric Ferralsol (Dystric) (Cv 1200)

A 0-50cm	Dry; dark brown 10YR 3/3; loamy sand; weak; blocky, fine and very fine; friable; many fine and medium roots; gradual smooth transition.
B 50cm+	Dry; brownish yellow 10YR 6/6; sandy loam; weak; blocky, fine and medium; friable; many medium, common coarse and fine roots; transition not reached.

ELK MA & MB, Petroplinthic Acrisol (Chromic) (Gc 1200)

A 0-20cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak; granular, fine and medium; friable; few fine, common medium and no coarse roots; gradual smooth transition;
B 20cm-120cm	Dry; brownish yellow 10YR 6/6; sandy loam; weak; granular, fine and medium; friable; few medium roots; common light brown and dark brown mottles; some iron concretions forming, and increasing with depth; abrupt smooth transition;
B 120cm+	Dry; brownish yellow 10YR 6/6; sandy loam; weak; blocky, medium; hard; transition not reached.

ESI BA & BB, Acric Ferralsol (Dystric)(Tu 1120)

A
0-30cm Dry; dark greyish brown 10YR 4/2; sandy loam; weak; granular, fine and medium; loose; many fine and medium, few coarse roots; diffuse, smooth transition;

B
30cm+ Dry; very pale brown 10YR 7/3; sandy loam; weak; granular, fine; friable; few fine, common medium and coarse roots; transition not reached.

ESI MA & MB, Haplic Acrisol (Rhodic) (Tu 2110)

A
0- 35cm Dry; very dark greyish brown 10YR 3/2; sand; weak; single grain, fine and medium; loose; common fine and few medium roots; gradual smooth transition;

B
35cm+ Dry; light yellowish brown 10YR 6/4; sandy loam; weak; granular, fine and medium; loose; common medium and few coarse roots, few past 50cm; transition not reached

FAN BA & BB, Acric Ferralsol (Dystric) (Cv 1200)

A
0-45cm Dry; dark yellowish brown 10YR 4/4; sand; weak; granular, fine; loose; common fine, many medium and few coarse roots; abrupt/gradual, smooth transition;

B
45cm+ Dry; reddish yellow 7.5YR 6/8; sandy loam; weak; granular, fine; loose; few fine and medium roots; transition not reached.

FAN MA & MB, Acric Ferralsol (Dystric) (Hu 1200).

A 0-30cm	Dry; brown/dark brown 10YR 4/3; sandy loam; weak; granular fine and medium; friable; few fine, common medium and few coarse roots; abrupt, smooth transition;
B 30cm+	Dry; strong brown 7.5YR 5/8; loamy sand; weakly moderate; granular, fine and medium; friable; few fine and medium roots; transition not reached.

FAT BA & BB, Haplic Arenosol (Dystric) (Oa 1120)

A 0-40cm	Dry; brown/dark brown 10YR 4/3; loamy sand; weak; granular; fine and medium; loose; many fine, medium and coarse roots; gradual smooth transition;
B 40cm+	Dry; reddish brown 7.5YR 5/4; loamy sand; weak; granular, fine and medium; friable; many

FAT MA & MB, , Haplic Arenosol (Dystric) (Oa 2220)

A 0-20cm	Dry; dark brown 7.5YR 3/2; sand; weak; granular, very fine and fine; loose; many fine, common medium and few coarse roots; gradual smooth transition;
B 20cm+	Dry; reddish brown 7.5YR 5/4; loamy sand; weak; crumb, fine and medium; loose; nearly no roots; Manganese concretions evident in horizon from 150cm; transition not reached.

FERG01 A & B, Albic Arenosol (Dystric) (Vf, 2120)

A 0 – 20 cm	Dry; brown 10YR 5/3; sand; weak, fine single grain, loose; few fine, medium and coarse pores; common fine roots; diffuse smooth transition.
E 20 – 30 cm	Dry; light yellowish brown 10YR 6/4, sand; weak, crumb; gradual smooth transition.
B 30 cm +	Dry; brownish yellow; sand; weak, fine single grain, loose; few fine medium and coarse pores; few coarse roots; transition not reached.

FERG02 A & B, Haplic Arenosol (Dystric) (Oa, 2120)

A 0 – 35 cm	Dry; dark grayish brown 10YR 4/2; sand; weak fine, single grain; loose; few fine, many medium and coarse pores; common fine roots; diffuse smooth transition.
B 35cm–180cm	Dry; yellowish brown 10YR 5/6; sand; weak; fine, single grain; loose; few coarse and medium pores; common coarse roots; gradual smooth transition.
B 180 cm+	Dry; strong brown 7.5YR 5/8; loamy sand; weak to moderate, granular; loose; few coarse and medium pores; few fine and medium roots; transition not reached.

FERG03 A & B, Haplic Arenosol (Dystric) (Oa 1220)

A 0 – 25cm	Dry; very dark grayish brown 10YR 3/2; sand; weak, fine single grain; loose; common fine and medium pores; common fine roots; diffuse smooth transition.
B 25 cm +	Dry; brown 10YR 4/4; loamy sand; weak, fine single grain; loose; few fine, common medium pores; few coarse roots; common fine and medium faint brown mottles (OM); transition not reached.

FERG04 A & B, Haplic Arenosol (Dystric) (Oa 2120)

A 0 – 25cm	Dry; black 7.5YR 2.5/1; sand; moderate, medium, granular; friable; many very fine and fine and coarse pores; many fine roots; gradual smooth transition.
B 25cm+	Moist; dark brown 10YR 3/3; loamy sand; weak, fine, single grain; friable; few fine and medium pores; common coarse roots; transition not reached.

FERG05 A & B, Haplic Arenosol (Dystric) (Oa 2120)

A 0 – 20cm	Dry; black 7.5YR 2.5/1; sand; weak, fine, single grain; common fine and medium pores; common fine roots; diffuse smooth transition.
B 20cm+	Moist; dark brown 10YR 3/3; loamy sand; weak, fine, single grain; few fine, common medium pores; few coarse roots; transition not reached.

FERG06 A & B, Haplic Areonosol (Dystric) (Oa 1120)

A 0-30cm	Dry; very dark brown 10YR 2/2; sand; weak, fine, single grain; loose; common fine and medium pores; common very fine and fine roots; gradual, smooth transition.
B 30cm+	Dry; yellowish brown 10YR 5/6; loamy sand; weak, fine, single grain; friable; few fine and medium pores; few coarse roots; common, medium, faint, black, black and brown and brown mottles (OM); transition not reached.

FERG07 A & B, Haplic Arenosol (Dystric) (Oa 1120)

A 0-35cm	Dry; very dark grayish brown 10YR 3/2; sand; weak, fine, single grain; loose; many fine and medium pores; many fine roots; gradual, smooth transition.
B 35cm-85cm	Moist; dark brown 10YR 3/3; loamy sand; weak, fine, single grain; friable; few fine and common medium pores; few coarse roots; transition not reached.

FERG08 A & B, Mollic Fluvisol (Eutric) (Ik 2100)

A 0-25cm	Dry; black 10YR 2/1; sand; weak, fine, single grain; loose; many fine and coarse pores; common fine roots; diffuse, smooth transition.
B 25cm+	Moist; yellowish brown 10YR 5/4; sand; weak, medium, single grain; friable; few fine and medium pores; few coarse roots; common medium, distinct, red mottles; transition not reached.

FERG09 CA & CB, Haplic Areonosol (Dystric) (Oa 2220)

A 0-15cm	Dry; brown 10YR 4/3; sand; weak, fine, single grain; loose; common fine and few medium and coarse pores; common fine and coarse roots; diffuse smooth transition.
B 15cm+	Dry; strong brown 10YR 4/6; sand; weak, fine, single grain; few fine and common medium and coarse pores; common coarse and few fine roots; few, coarse, distinct, brown mottles; transition not reached.

FISH02 BA & BB, Haplic Ferralsol (Dystric) (Cv 1200)

A	
0-60cm	Dry; dark brown 10YR 3/3; sandy loam; weak; coarse blocky; loose; many fine, medium and coarse roots; few dark charcoal pieces; diffuse smooth transition;
B	
60cm+	slightly moist; yellow 10YR 7/6; sandy loam; weak; blocky; friable; few fine, many medium and few coarse roots; charcoal fragments to 150cm from bioturbation of tree fall; transition not reached.

FISH02 MA & MB, Haplic Ferralsol (Dystric) (Cv 1200)

A	
0-60cm	Dry; dark brown 10YR 3/3; sandy loam; weak; coarse blocky; loose; many fine, medium and coarse roots; few dark charcoal pieces; diffuse smooth transition;
B	
60cm+	slightly moist; yellow 10YR 7/6; sandy loam; weak; blocky; friable; few fine, many medium and few coarse roots; charcoal fragments to 150cm from bioturbation of tree fall; transition not reached.

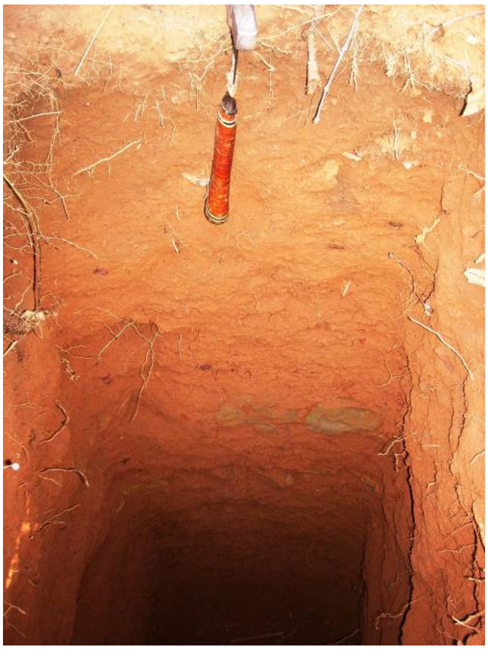
FISH BA & BB, Haplic Arenosol (Fw 2210)

A	
0-30cm	Dry; dark greyish brown 10YR 4/2; sandy loam; very weak; medium/coarse blocky; soft; abundant coarse and fine roots; few charcoal fragments; diffuse smooth transition (porous);
E	
30-60cm	slightly moist; light yellowish brown 10YR 6/4; sandy loam; apedal/very weak blocky; friable; abundant fine roots; few charcoal fragments; diffuse smooth transition (porous);
E	
60-90cm	slightly moist; light yellowish brown 10YR 6/4; fine sandy loam; apedal massive – coarse blocky; friable; many fine roots; very few small charcoal fragments; few darker channelled infilling from faunal activity; diffuse smooth transition (porous);
E	
90-120cm	moist; Yellow 10YR 7/6; fine sandy loam; apedal massive breaking to weak coarse, blocky; many fine roots, decreasing with depth; friable; few dark charcoal pieces; abundant fine porous faunal channels; few localised zones of bleached sand grains; transition not reached.

FISH BA & BB, Haplic Acrisoll (Fw 2210)

A 0-30cm	Dry; dark greyish brown 10YR 4/2; sandy loam; very weak; medium/coarse blocky; soft; abundant coarse and fine roots; few charcoal fragments; diffuse smooth transition (porous);
E 30-60cm	slightly moist; light yellowish brown 10YR 6/4; sandy loam; apedal/very weak blocky; friable; abundant fine roots; few charcoal fragments; diffuse smooth transition (porous);
E 60-90cm	slightly moist; light yellowish brown 10YR 6/4; fine sandy loam; apedal massive – coarse blocky; friable; many fine roots; very few small charcoal fragments; few darker channelled infilling from faunal activity; diffuse smooth transition (porous);
E 90-120cm	moist; Yellow 10YR 7/6; fine sandy loam; apedal massive breaking to weak coarse, blocky; many fine roots, decreasing with depth; friable; few dark charcoal pieces; abundant fine porous faunal channels; few localised zones of bleached sand grains; transition not reached.

FIX BA & BB, Haplic Ferralsol (Dystric) (Bv 1200)



A 0-15cm	Dry; yellowish brown 10YR 5/8; loamy sand; weak, blocky, medium and fine; slightly hard; many fine, medium and coarse roots; gradual, smooth transition;
B 15-120cm	Dry; strong brown 7.5YR 5/8; sandy loam; weak to moderate, blocky, medium; slightly hard; common fine, many medium and few coarse roots; gradual, smooth transition;
B 120-160cm	slightly moist; strong brown 7.5YR 5/8; sandy loam; moderate, blocky, coarse; slightly hard; common fine, many medium and few coarse roots; abrupt, smooth transition;
Stone line 160-180cm	Moist; large stone layer, quartzitic; abrupt, smooth transition.
B 180cm+	Moist; Yellowish red 5YR 4/6; sandy clay loam; moderate, blocky, medium; friable; few roots; increasing iron concretions with depth; transition not reached.

FIX MA & MB, Haplic Ferralsol (Dystric) (Av 1200)

A 0-25cm	Dry; light yellowish brown 10YR 6/4; loamy sand; weak, blocky, fine; soft; many fine and medium roots, common coarse roots; diffuse, smooth transition.
B 25-120cm	Dry; reddish yellow 5YR 7/6; sandy clay loam; weak-apedal; blocky, fine; slightly hard; few fine, medium and coarse roots; gradual, smooth transition.
B 120cm+	Slightly moist; Yellowish red 7.5YR 6/8; sandy clay loam; moderate, blocky, coarse; very few medium roots; deep red and black concretions (some magnetic) increasing with depth; transition not

GUI BA & BB, Posic Ferralsol (Dystric) (Cv 1200)

A 0-50cm	Dry; dark yellowish brown 10YR 4/4; loamy sand; weak, tending towards moderate, blocky; soft; many fine, medium and coarse roots; diffuse, smooth transition;
B 50cm+	slightly moist; yellowish brown 10YR 5/6; loamy sand; weak, blocky; friable; few coarse and medium roots; transition not reached.

GUI MA & MB, Haplic Arenosol (Dystric) (Oa 2220)

A 0-30cm	Dry; dark brown 10YR 3/3; sand; weak, blocky, medium/coarse; soft; very few fine, many medium and few coarse roots; gradual, wavy transition;
B 30cm+	Slightly moist; yellowish brown 10YR 5/6; weak, blocky, fine; friable; few fine, common medium and very few coarse roots; transition not reached.

HEB BA & BB, Haplic Arenosol (Dystric) (Tu 1120)

A	
0-30cm	Dry; dark greyish brown 10YR 4/2; sandy loam; weak; granular, fine and medium; loose; many fine and medium, few coarse roots; diffuse, smooth transition;
B	
30cm+	Dry; very pale brown 10YR 7/3; sandy loam; weak; granular, fine; friable; few fine, common medium and coarse roots; transition not reached.

HEB MA & MB, Haplic Arenosol (Dystric) (Tu 2120)

A	
0-40cm	Dry; brown 10YR 5/3; loamy sand; granular, fine and medium; many fine, few medium and coarse roots; gradual smooth transition;
B	
40cm+	Dry; brown 10YR 5/3; loamy sand; granular, fine and medium; few coarse and fine roots; common yellow and dark brown mottles; transition not reached.

HEL BA & BB, Posic Ferralsol (Dystric) (Ct 2100)

A	
0-40cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak, granular, fine; soft; many fine and medium roots; abrupt, smooth transition;
E	
40-50cm	Dry; greyish brown 10YR 5/2; loamy sand; weak, blocky, fine; soft; few fine roots; abrupt, smooth transition;
B	
50cm+	Slightly moist; yellow 10YR 7/6; sandy loam; weal, blocky, fine to medium; very few roots; transition not reached

HEL MA & MB,Posic Ferralsol (Dystric) (Ct 2100)

A	
0-40cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak, granular, fine; soft; many fine and medium roots; abrupt, smooth transition;
E	
40-50cm	Dry; greyish brown 10YR 5/2; loamy sand; weak, blocky, fine; soft; few fine roots; abrupt, smooth transition;
B	
50cm+	Slightly moist; yellow 10YR 7/6; sandy loam; weal, blocky, fine to medium; very few roots; transition not reached

IBS BA & BB, Posic Ferralsol (Dystric) (Cv 1200)

A	
0-15cm	Dry; dark brown 10YR3/3; sandy loam; weak; granular, fine; loose; many fine, common medium and coarse roots; abrupt, smooth transition;
B	
15cm+	Dry; yellowish brown 10YR 5/6; loamy sand; weak; granular, fine; friable; common fine, medium and coarse roots; transition not reached.

IBS MA & MB, Posic Ferralsol (Dystric) (Cv 1200)

A	
0-35cm	Dry brown/dark brown; 10YR 4/3; sandy loam; weak; granular, fine; loose; few fine and coarse roots; diffuse, smooth transition;
B	
35cm+	Dry; yellowish brown 10YR 5/8; loamy sand; weak; blocky, fine; friable; few fine roots; transition not reached.

IVW BA & BB, Haplic Ferralsol (Dystric) (Bv 1200)

A 0-30cm	Dry; brown/dark brown 7.5YR 4/4; loamy sand; weak, blocky, fine to medium; soft; many coarse, common fine and medium roots; gradual, smooth transition;
B 30-110cm	Dry; strong brown 7.5YR 5/8; sandy loam; weak-apedal, blocky, fine; soft to slightly hard; few coarse and medium roots; gradual, smooth transition;
B 110cm+	Moist; Yellowish red 5YR 5/8; sandy loam; weak to moderate; blocky, medium to coarse; friable; few fine roots; transition not reached.

IVW MA & MB, Haplic Ferralsol (Dystric) (Bv 1200)

A 0-30cm	Dry; brown/dark brown 7.5YR 4/4; loamy sand; weak, blocky, fine to medium; soft; many coarse, common fine and medium roots; gradual, smooth transition;
B 30-110cm	Dry; strong brown 7.5YR 5/8; sandy loam; weak-apedal, blocky, fine; soft to slightly hard; few coarse and medium roots; gradual, smooth transition;
B 110cm+	Moist; Yellowish red 5YR 5/8; sandy loam; weak to moderate; blocky, medium to coarse; friable: few fine roots: transition not reached

JANE BA & BB, Posic Farralsol (Dystric) (Cv 1200)

A 0-20cm	Dry; dark yellowish brown 10YR 4/4; loamy sand; weak, blocky, fine; soft; many fine, common medium and few coarse roots; gradual, smooth transition;
B 20cm+	Dry to slightly moist; reddish yellow 7.5YR 7/6; sandy loam; apedal – weak, blocky, fine; soft-friable; few fine, medium and coarse roots; transition not reached

JANE MA & MB, Haplic Arenosol (Dystric) (Oa, 2220)

A	
0-30cm	Dry; yellowish brown 10YR 5/4; sand; weak, blocky, fine; soft; common fine, medium and coarse roots; gradual, smooth transition;
B	
30cm+	Dry; yellowish red 7.5YR 6/6; loamy sand; weak, blocky, fine and medium; soft to slightly hard; common coarse, few medium roots; yellow brown apedal reworked to neocutanic; transition not reached.

JCH BA + BB, Hypoluvic Arenosol (Dystric) (Cv 1200)

A	
0-50cm	Dry; 10YR 3/3 dark brown; loamy sand; weak; blocky, fine and very fine; friable; many fine and medium roots; gradual smooth transition.
B	
50cm+	Dry; 10YR 6/6 brownish yellow; sandy loam; weak; blocky, fine and medium; friable; many medium, common coarse and fine roots; transition not reached.

JCH MA/MB – Albic Arenosol (Dystric) (Vf 2120)

A	
0-20cm	Dry; brown 10YR 5/3; sand; weak; fine, single grain; loose; common fine and very few medium pores; gradual, smooth transition;
E	
20-30cm	Moist; light yellowish brown 10YR 5/3, sand; weak; fine, single grain; friable; common fine, med and coarse pores; gradual, smooth transition;
B	
30cm+	Dry; light yellowish brown 10YR 6/4; sandy loam; weak-moderate; granular, fine and very fine; firm few medium and coarse pores; transition not reached.

JEC BA & BB, Posic Ferralsol (Dystric) (Hu 1200)

A	
0-40cm	Dry; brown/dark brown 10YR 4/3; sand; weak, granular fine and medium; loose; many fine and medium, common coarse roots; gradual smooth transition;
B	
40cm+	Dry; strong brown 7.5YR 5/6; loamy sand; weak; granular, medium; friable; few fine, many medium and few coarse roots; transition not reached.

JEC MA & MB, Posic Ferralsol (Dystric) (Hu 1200)

A	
0-35cm	Dry; brown/dark brown 7.5YR 4/4; loamy sand; weak, granular, fine and medium; friable; many fine, medium and few coarse roots; gradual wavy transition;
B	
35cm+	Dry; strong brown 7.5YR 5/8; loamy sand; weak; granular, medium; friable; common medium and few coarse roots; transition not reached.

JKG BA & BB, Posic Ferralsol (Dystric) (Cv 1200)

A	
0-50cm	Dry; dark yellowish brown 10YR 4/4; loamy sand; weak, tending towards moderate, blocky; soft; many fine, medium and coarse roots; diffuse, smooth transition;
B	
50cm+	slightly moist; yellowish brown 10YR 5/6; loamy sand; weak, blocky; friable; few coarse and medium roots; transition not reached.

JKG MA & MB, Acric Ferralsol (Dystric) (Ct, 2100)

A	
0-15cm	Dry; brown 10YR 5/3; loamy sand; weak-moderate, blocky; soft; many fine and few medium roots; abrupt transition;
E	
15-25cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak, blocky; soft; common medium and few fine roots; abrupt transition;
B	
25cm+	slightly moist; yellowish brown 10YR 5/8; loamy sand; apedal-weak, blocky; few roots; very few yellow mottles; transition not reached.

JOM BA & BB, Haplic Arenosol (Dystric) (Oa 2120)

A	
0 – 50cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak; granular, fine and medium; friable; common fine and medium roots; diffuse, smooth transition;
B	
50cm+	Dry; light yellowish brown 10YR 6/4; sandy loam; weak; granular, fine and medium; friable; few fine, common medium and few coarse roots; transition not reached.

JOM MA & MB, Haplic Arenosol (Dystric) (Oa 2120)

A	
0-40cm	Dry; brown 10YR 5/3; sand; weak; granular fine and medium; loose; many fine, few medium and coarse roots; gradual smooth transition;
B	
40cm+	Dry; light yellowish brown 10YR 6/4; loamy sand; granular, medium; friable; few medium roots; transition not reached.

JON BA & BB, Haplic Lixisol (Se 1110)

A	
0-20cm	Dry; yellowish brown 10YR 5/4; loamy sand; weak, granular, fine and medium; soft; many fine, medium and few coarse roots; gradual, smooth transition;
B	
20cm+	Dry; yellow 10YR 7/6; sandy clay loam; moderate, blocky, medium and coarse; common coarse and few medium roots; transition not reached.

JON MA & MB, Haplic Lixisol (Se 1110)

A	
0-25cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak to moderate, blocky, coarse; soft; many fine and medium, few coarse roots; gradual, smooth transition.
B	
25cm-120cm	Dry to slightly moist; yellow 10YR 7/6; sandy clay loam; moderate, blocky, medium; friable to firm; few fine, medium and coarse roots; diffuse, smooth transition;
B	
120cm+	Moist; Yellowish red 7.5YR 6/8; sandy clay loam; moderate, blocky, fine and medium; firm; transition not reached.

KABS GA & GB, Acric Ferralsol (Dystric) (Hu 1100)

A	
0-35cm	Dry; brown 10YR 5/3; sand; weak, fine, crumb; loose; few fine, medium and coarse pores; few fine and coarse roots; some shiny fragments of quartz; abrupt, tonguing transition.
B	
35cm+	Dry; reddish brown 5YR 4/4; loamy sand; apedal; hard; few fine, medium and coarse pores; few coarse roots; few medium, distinct black mottles; transition not reached

KABS MA & MB, Albic Arenosol (Dystric) (Vf 2120)

A 0 – 20cm	Dry; brown 10YR 4/2; sand; weak, fine, single grain; loose; common fine and few medium and coarse pores; common fine roots; clear smooth transition.
E 20-33cm	Dry; light brown 10YR 6/4; sand; weak, fine, single grain; loose; gradual smooth transition.
B 33cm +	Dry; brown 10YR 5/4; loamy sand; weak, fine, single grain; slightly hard; few fine and medium pores; few coarse roots; going into quartz rock, transition not reached.

KAS MA & MB, Acric Ferralsol (Dystric) (Ct 2100)

A 0-35cm	Dry; very dark gray 10YR 3/1; sand; weak, fine, single grain; loose; common fine and many medium and coarse pores; common fine roots; few coarse, distinct, black mottles (charcoal); gradual smooth transition.
E 35-45cm	Dry; light yellowish brown 10YR 6/4; sand; weak, fine, single grain; loose; gradual smooth transition.
B 45cm+	Dry; yellowish brown 10YR 5/6; sand; apedal; loose; few fine, medium and coarse pores; few coarse roots; transition not reached.

KCON BA & BB, Haplic Acrisol (Chromic) (Oa 1220)

A 0– 35cm	Dry; brown 10YR 4/4; sand; weak, coarse, single grain; loose; many fine and coarse pores; many fine and coarse roots; gradual, smooth transition.
B 35cm+	Moist; strong brown 7.5YR 4/6; loamy sand; weak, coarse, single grain; friable; common fine and coarse pores; many medium and coarse roots; transition not reached.

KHS GA & GB, Haplic Acrisol (Humic) (Sr 2120)

A 0 – 40cm	Dry; black 10YR 2/1; sand; weak, fine single grain; loose; few very fine and common fine pores; few very fine and many fine roots; gradual smooth transition.
B 40cm +	Dry; dark yellowish brown 10YR 4/4; loamy sand; weak, fine single grain; slightly hard; few medium pores; few fine and medium roots; layer of bricks from redundant kiln at 700mm; transition not reached.

KIC BA & BB, Haplic Arenosol (Dystric) (Tu 2120)

A 0-50cm	Dry; dark brown 10YR 3/3; sand; weak; granular, fine and medium; loose; many fine and medium roots; diffuse smooth transition;
B 50cm+	Dry; pale brown 10YR 6/3; loamy sand; weak; granular, fine and medium; friable; common coarse and few fine roots; transition not reached.

KIC MA & MB, Haplic Arenosol (Dystric) (Tu 2120)

A 0-35cm	Dry; dark greyish brown 10YR 4/2; sand; weak; granular, fine and medium; friable; many fine and common medium roots; diffuse smooth transition;
B 35cm+	Dry; brown 10YR 5/3; loamy sand; weak; granular, fine and medium; friable; common medium roots, with roots stopping at 65cm; transition not reached.

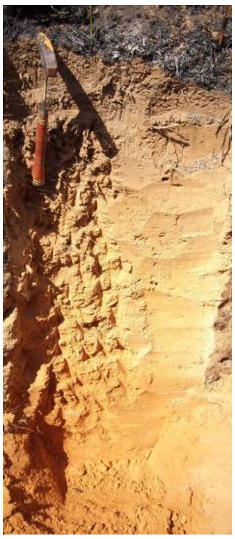
KNG MA + MB, Nitic Acrisol (Rhodic) (Sd 1210)

A	
0 – 4cm	Dry; dark brown 7.5YR 3/3; loamy sand; weak, medium, single grained; loose; few fine and few medium pores; few fine roots; clear, smooth transition.
B	
4cm+	Moist; yellowish red 5YR 4/6; sandy clay; moderate, medium, massive; firm; few fine and few coarse pores; few very coarse roots.

KSM BA & BB, Haplic Ferralsol (Dystric) (Av 1100)

A	
0-40cm	Dry; yellowish brown 10YR 5/4; sandy loam; weak; granular, fine; loose; many fine, medium and coarse roots; gradual smooth transition;
B	
40cm+	Dry; yellow 10YR 7/8; sandy loam; weak; granular, fine and medium; friable; common fine, many medium and coarse roots; transition not reached.

KSM MA & MB, Haplic Ferralsol (Dystric) (Av 1200 Wo 1100)



A	
0-35cm	Dry; brown 10YR 5/3; loamy sand; weak; granular, fine and medium; loose; many fine and medium, few coarse roots; gradual smooth transition;
B	
35-120cm	Dry; yellow 10YR 7/6; loamy sand; weak; granular, medium; friable; few fine and medium roots; gradual smooth transition;
B	
120cm+	Dry; yellow 10YR 7/6; sandy loam; weak; granular, medium and fine; friable; few roots; transition not reached.

KUDU MA & MB, Posic Ferralsol (Dystric) (Hu 1200)

A	
0 – 10cm	Dry; brown 7.5YR 4/4; sand; weak, coarse, single grained; loose; common fine and medium pores; few fine roots; diffuse, smooth transition.
B	
10cm +	Moist; yellowish red 5YR 4/6; clay loam; moderate, fine, single grained; slightly firm; few fine and few coarse pores; few coarse roots; transition not reached.

KYB MA & MB, Posic Ferralsol (Dystric) (Hu 1200)

A	
0-15cm	Dry; dark reddish brown 7.5YR 3/3; sand; weak, coarse, single grained; loose; common fine and many coarse pores; common fine pores; diffuse, smooth transition.
B	
15cm+	Dry; yellowish red 5YR 4/6; loamy sand; weak, coarse, single grained; loose; few fine and common medium pores; few coarse roots; few medium, faint brown mottles; transition not reached.

LIC BA & BB, Acrix Ferralsol Dystric (Ct 2100)

A	
0-35cm	Dry; dark grey 10YR 4/1; sand; moderate; blocky; friable; many fine and medium, few coarse roots; abrupt smooth transition;
E	
35-50cm	Dry; grayish brown 10YR 5/2; sand; weak; granular, fine; friable; few roots; gradual smooth transition;
B	
50cm+	Dry; yellow 10YR 7/8; loamy sand; weak – moderate; blocky, fine; friable; very few roots; transition not reached.

LIC MA & MB, Posic Ferralsol Dystric (Hu 1200)

A	
0-20cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak; single fine grained; friable; many fine, few medium and few coarse roots; gradual, smooth transition;
B	
20cm+	Dry; pale brown 10YR 6/3; sandy loam; weak; granular, fine and medium; firm; few roots; transition not reached.

LWN GA + GB, Posic Ferralsol (Dystric) Hu 1200)

A	
0-10cm	Dry; dark gray 7.5YR 4/1; sand; weak, fine granular; loose; common fine and few medium and coarse pores; few coarse roots; few fine and medium distinct black, orange, red and red-brown mottles; clear smooth transition.
B	
10cm+	Dry; reddish brown 5YR 4/4; loamy sand; weak, single grain); hard; few fine, medium and coarse pores; few coarse roots; transition not reached.

MABS MA + MB, Posic Ferralsol (Dystric) (Hu 1200)

A	
0-15cm	Dry; dark gray 7.5YR 4/1; loamy sand; weak fine, single grain; loose; few fine and many coarse pores; few fine roots; few medium distinct black mottles; clear smooth transition.
B	
15cm+	Moist; strong brown 7.5YR 4/6; loamy clay; weak, granular; few medium and coarse pores; few coarse roots; common fine, medium and coarse distinct black, brown red and yellow mottles; transition not reached.

MCH BA & BB,Haplic Arenosol (Dystric) (Oa 1220)

A 0-30cm	 Dry; dark brown 10YR 3/3; sandy loam; weak; granular, fine and medium; loose; common fine and few coarse roots; gradual wavy transition;
B 30cm+	 Dry; yellowish red 5YR 5/6; loamy sand; weak; blocky, medium; friable; many fine roots; concretions (7.5YR 6/8 yellowish red) increasing with depth; transition not reached.

MCH MA & MB, Albic Arenosol (Dystric) (Vf 2120)

A 0-25cm	 Dry; dark brown 10YR 3/3; sandy loam; weak; subangular fine; loose; many fine and medium, few coarse roots; few charcoal pieces; gradual, smooth transition.
E 25-35cm	 Dry; yellow 10YR 6/4; sand; weak; fine, single grain; friable; common fine, med and coarse pores; gradual, smooth transition;
B 35cm+	 Dry; light yellowish brown 10YR 6/4; loamy sand; weak; granular fine and medium; many fine and medium, few coarse roots; transition not reached.

MMB MA & MB, Haplic Arenosol (Dystric) (Oa 2120)

A 0-20cm	 Dry; dark grayish brown 10YR 4/2; loamy sand; weak, fine, single grained; loose; common fine and coarse pores; many fine roots; diffuse, smooth transition.
B 20cm +	 Moist; yellowish brown 10YR 5/6; silty loam; weak, fine, single grained; friable; few fine and medium pores; few coarse roots; few organic cutans; few, coarse, prominent, brown and grey mottles; transition not reached.

MPU BA & BB, (Acric Ferralsol (Dystric) Hu 1200)

A 0-15cm	Dry; yellowish brown 10YR 5/8; loamy sand; weak, blocky, medium and fine; slightly hard; many fine, medium and coarse roots; gradual, smooth transition;
B 15-160cm	Dry; strong brown 7.5YR 5/8; sandy loam; weak to moderate, blocky, medium; slightly hard; common fine, many medium and few coarse roots; abrupt, smooth transition;
Stone line 160-180cm	Moist; large stone layer, quartzitic; abrupt, smooth transition.
B 180cm+	Moist; Yellowish red 5YR 4/6; sandy clay loam; moderate, blocky, medium; friable; few roots;

MPU MA & MB, Acric Plinthosol (Dystric) (Gc 1200)

A 0-20cm	Dry; yellowish brown 10YR 5/4; loamy sand; weak, blocky, fine; soft; many fine, few medium and coarse roots; gradual, smooth transition;
B 20cm-110cm	slightly moist; brownish yellow 10YR 6/8; sandy loam; weak – apedal, blocky, fine; friable; few medium and coarse roots; Black concretions increasing with depth, not associated with mottling; gradual, smooth transition;
B 110cm+	moist; Yellowish red 5YR 5/8; weak to moderate, blocky, fine and medium; firm; few medium roots; transition not reached.

MUBS PA & PB, Albic Arenosol (Dystric) (Vf 2220)

A 0 – 30cm	Dry; very dark grayish brown 10YR 3/2; sand; weak, fine, single grain; loose; many fine and few coarse pores; many fine roots; gradual, smooth transition.
E 30-40cm	Dry; light yellowish brown 10YR 6/4; sand; weak, fine, single grain; loose; gradual smooth transition.
B 35cm +	slightly moist; strong brown 6.5YR 4/6; sand; weak, coarse, single grain; friable; few fine and few coarse pores; few fine roots; transition not reached.

MUMPU MA & MB, Posic Ferralsol (Dystric) (Pn 1100)

A
0-20cm Dry; very dark grayish brown 10YR 3/2; sand; weak, fine, crumb; loose; few fine, medium and coarse pores; few fine roots; gradual smooth transition.

B
20cm+ Moist; yellowish brown 10YR 5/4; sand; weak, fine, crumb; friable; few fine, medium and coarse pores; common coarse roots; many medium and coarse, distinct and prominent orange, red and reddish brown mottles; transition not reached.

NDS A & B, Mollic Fluvisol (Eutric) (Ik 2100)

A
0-12cm Dry; black 10YR 2/1; sand; weak, fine, crumb; loose; few fine, common medium and coarse pores; many fine roots; gradual smooth transition.

B
12cm+ Moist; yellow 10YR 7/6; sand; weak, medium, single grain; friable; few with signs of fine medium and coarse pores; many coarse roots; distinct orange, red, reddish brown mottles; transition not reached.

NGOM MA & MB, Haplic Arenosol (Dystric) (Oa 2220)

A
0-15cm Dry; very dark gray 7.5YR 3/1; sand; weak, fine crumb; loose; common fine medium and coarse pores; many fine roots; few medium distinct dark brown mottles; gradual smooth transition.

B
15cm+ Dry; strong brown 7.5YR 5/6; loamy sand; weak, fine single grain; loose; few medium pores; few medium and coarse roots; few medium distinct dark brown mottles; transition not reached.

Ntbs CA & CB, Posic Ferralsol (Dystric) (Cv 1200)

A	
0-15cm	Dry; black 10YR 2/1; sand; moderate, medium, crumb; loose; many fine, medium and coarse pores; many fine and few coarse roots; abrupt smooth transition.
B	
15cm+-	Moist, very dark grayish brown 10YR 3/2(dyed by OM) to brownish yellow 10YR 6/6; loamy sand; moderate, medium, single grain; loose; common fine and few medium and coarse pores; common coarse roots; few increasing to common black and brown, red and red and yellow mottles; transition not

Ntbs – GA & GB, Albic Arenosol (Dystric) (Vf 2120)

A	
0-35cm	Dry; dark gray 10YR 4/1; sand; weak, fine, crumb; loose; common fine, medium and coarse pores; many, fine roots; few, fine, taint black mottles; gradual, wavy transition.
E	
35-45cm	Dry; light yellowish brown 10YR 6/4; sand; weak; loose; gradual smooth transition.
B	
45cm+	Moist; yellowish brown 10YR 5/8; loamy sand; weak, medium, single-grain; friable; few medium and coarse pores; common coarse roots; common, medium and coarse, prominent orange and red mottles, increasing with depth; transition not reached.

Ntbs – MA & MB, Albic Arenosol (Dystric) (Vf 2120)

A	
0-30cm	Dry; dark gray 10YR 4/1; sand; weak, medium, loose; few fine, medium and coarse pores; many fine roots; few fine black mottles; diffuse wavy transition.
E	
30-40cm	Dry; light yellowish brown 10YR 6/4; sand; weak; loose; gradual smooth transition.
B	
40cm+	Moist; yellowish brown 10YR 5/8; loamy sand; weak, single grain; few fine pores; common coarse roots; few, medium distinct brown mottles; transition not reached.

NTD GA & GB, Acric Ferralsol (Dystric) (Ct 2100)

A
0-20cm — Dry; dark gray 10YR 4/1; sand; weak, fine, single grain; loose; many fine and common medium and coarse pores; common fine roots and few coarse roots; clear smooth transition.

E
20-30cm — Dry; light yellowish brown 10YR 6/4; sand; weak; loose; gradual smooth transition.

B
30cm+ — Dry; yellowish brown 10YR 5/6; loamy sand; weak, fine, single grain; soft; few fine, medium and coarse pores; common coarse roots; transition not reached.

OKAN MA & MB, Mollic Fluvisol (Eutric) (Ik 2100)

A
0-35cm — Dry; dark greyish brown 10YR 4/2; sand; weak, granular, fine; soft; many fine, medium and few coarse roots; abrupt, smooth transition;

E
35-50cm — Dry; greyish brown 10YR 5/2; loamy sand; weak, blocky, fine; soft; common medium roots; gradual, smooth transition;

B
50cm+ — Slightly moist; brownish yellow 10YR 6/8; loamy sand; weak, blocky, fine and medium; friable; few coarse roots; transition not reached

PEF BA & BB, Acric Ferralsol (Dystric) (Ct 2100)

A
0-65cm — Dry; ; black 10YR 2/1; sand; weak, fine, single grain; loose; few fine and medium and coarse pores; many fine roots; gradual smooth transition.

B
65cm+ — Moist;; yellowish brown 10YR 5/4sand; weak, fine single grain; loose; few fine and common coarse pores; few coarse roots; common medium distinct orange, red and reddish brown mottles; transition not reached.

PEF MA & MB, Posic Ferralsol (Dystric) (Cv 1200)

A 0-40cm	Dry; dark grey 10YR 4/1; sand; weak, granular, fine and medium; soft; many fine, common medium and few coarse roots; diffuse, smooth transition;
B 40cm+	Slightly moist; Yellow 10YR 7/8; sandy loam; weak, blocky, fine; friable; few fine and common medium and few coarse roots; transition not reached.

PSK BA & BB, Albic Arenosol (Dystric) (Vf 2120)

A 0-35cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak-moderate, blocky; soft; abundant fine, medium and coarse roots; gradual smooth transition;
E 35-50cm	Dry; light yellowish brown 10YR 6/4; loamy sand; weak; fine, single grain; friable; common fine, med and coarse pores; gradual, smooth transition;
B 50m+	slightly moist; yellowish brown 10YR 5/4; loamy sand; weak, blocky; friable; common fine, medium and coarse roots; transition not reached.

PSK MA & MB, Haplic Arenosol (Dystric) (Oa 2120)

A 0-25cm	Dry; dark brown 10YR 3/3; loamy sand; weak to moderate, blocky; soft; many fine and medium and few coarse roots; abundant organic matter applied to surface; diffuse smooth transition;
B 25cm+	slightly most; brown 10YR 5/3; sandy loam- sandy clay loam; weak-moderate blocky; friable; common medium and coarse roots; iron concretions forming in lower slope areas of field; transition not reached.

SAL BA & BB, Haplic Acrisol (Tu 2120)

A
0 – 50cm Dry; dark greyish brown 10YR 4/2; loamy sand; weak; granular, fine and medium; friable; common fine and medium roots; diffuse, smooth transition;

B
50cm+ Dry; light yellowish brown 10YR 6/4; sandy loam; weak; granular, fine and medium; friable

SAL MA & MB, Haplic Acrisol (Tu 2120)

A
0-35cm Dry; dark brown 10YR 3/3; loamy sand; weak; granular, fine and medium; loose; few fine and common medium roots; gradual smooth transition;

B
35cm+ Dry; yellowish brown 10YR 5/4; loamy sand; granular, medium; friable; very few medium roots; transition not reached.

SIP BA & BB, Haplic Ferralsol (Dystric) (Bv 1200)

A
0-15cm Dry; yellowish brown 10YR 5/8; loamy sand; weak, blocky, medium and fine; slightly hard; many fine, medium and coarse roots; gradual, smooth transition;

B
15-120cm Dry; strong brown 7.5YR 5/8; sandy loam; weak to moderate, blocky, medium; slightly hard; common fine, many medium and few coarse roots; gradual, smooth transition;

B
120-160cm slightly moist; strong brown 7.5YR 5/8; sandy loam; moderate, blocky, coarse; slightly hard; common fine, many medium and few coarse roots; abrupt, smooth transition;

Stone line
160-180cm Moist; large stone layer, quartzitic; abrupt, smooth transition.

B
180cm+ Moist; Yellowish red 5YR 4/6; sandy clay loam; moderate, blocky, medium; friable; few roots; increasing iron concretions with depth; transition not reached.

SIP MA & MB, Haplic Ferralsol (Dystric) (Hu 1200)

A 0-25cm	Dry; yellowish brown 10YR 5/6; loamy sand; weak, blocky, fine; slightly hard; many fine, medium and coarse roots; gradual, smooth transition;
B 25cm+	Dry; reddish yellow 7.5YR 6/8; sandy loam; weak, blocky, fine to medium; few roots; borderline luvic soil; abundant termite activity; transition not reached.

SKY BA & BB, Haplic Arenosol (Dystric) (Tu, 2120)

A 0-30cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak, granular/blocky; soft; many fine, medium and coarse roots; gradual, wavy transition;
B 30cm+	Moist; greyish brown 10YR 5/2; sandy loam; weak, blocky; friable; few coarse and medium roots; common black and orangey yellow mottles from 180cm; transition not reached.

SKY MA & MB, Haplic Arenosol (Dystric) (Oa 2120)

A 0-30cm	Dry; yellowish brown 10YR 5/4; loamy sand; weak, granular/blocky; soft; many fine, medium and coarse roots; gradual, wavy transition;
B 30cm+	Moist; greyish brown 10YR 5/2; sandy loam; weak, blocky; friable; few coarse and medium roots; common black and orangey yellow mottles from 180cm; transition not reached.

SSK BA & BB, Haplic Arenosol (Dystric) (Oa 2120)

A	
0-45cm	Dry; dark yellowish brown 10YR 4/4; sand; weak, blocky, fine; soft; many fine, medium and coarse roots; gradual, smooth transition;
B	
45cm+	Slightly moist; brownish yellow 10YR 6/8; loamy sand; weak, blocky, coarse; friable; common coarse and few medium roots; transition not reached.

SSK MA & MB, Albic Ferralsol (Dystric) (Vf 1120)

A	
0-40cm	Dry; yellowish brown 10YR 5/4; loamy sand; weak, fine and medium granular; soft; many fine and medium and few coarse roots; gradual, smooth transition;
E	
40-50cm	Dry; greyish brown 10YR 5/2; loamy sand; weak, fine, blocky; soft; common fine and few medium roots; abrupt, smooth transition;
B	
50cm+	Slightly moist; brownish yellow 10YR 6/6; sandy loam; weak, medium blocky; friable; few roots; transition not reached.

STW BA & BB, Acric Ferralsol (Dystric) (Cv 1200)

A	
0-15cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak, granular/crumb; soft; many fine, common medium and few coarse roots; gradual, smooth transition;
B	
15cm+	slightly moist; very pale brown 10YR 7/4; loamy sand; weak-apedal, blocky; friable; common medium and few coarse roots; transition not reached.

STW MA & MB, Albic Arenosol (Dysrtic) (Ct 2100)

A	
0-10cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak, blocky/granular; soft; common fine and medium roots; abrupt, wavy transition;
E	
10-25cm	Dry; light yellowish brown 10YR 6/4; loamy sand; weak, fine blocky; soft; few medium and fine roots; abrupt wavy transition;
B	
25cm+	Slightly moist; very pale brown 10YR 7/4; sandy loam; weak, blocky; friable; nearly

TIS BA & BB, Acric Ferralsol ((Dystric) (Cv 12000

A	
0-15cm	Dry; 10YR3/3 dark brown; sandy loam; weak; granular, fine; loose; many fine, common medium and coarse roots; abrupt, smooth transition;
B	
15cm+	Dry; 10YR 5/6 yellowish brown; loamy sand; weak; granular, fine; friable; common fine, medium and coarse roots; transition not reached.

TIS MA & MB, Haplic Arenosol (Dystric) (Oa 2220)

A	
0-40cm	Dry; brown/dark brown 10YR 4/3; loamy sand; weak; granular, fine and medium; friable; few fine, medium and no coarse roots; few dark brown mottles; gradual, smooth transition;
B	
40cm+	Dry; reddish yellow 7.5YR 6/8; loamy sand; weak; granular, medium; friable; few medium roots; common brown and dark brown mottles; transition not reached.

TRH BA & BB, Hypoluvic Arenosol (Dystric) (Cv 1200)

A	
0-45cm	Dry; dark yellowish brown 10YR 4/4; sand; weak; granular, fine; loose; common fine, many medium and few coarse roots; abrupt/gradual, smooth transition;
B	
45cm+	Dry; reddish yellow 7.5YR 6/8; sandy loam; weak; granular, fine; loose; few fine and medium roots; transition not reached.

TRH MA & MB, Hypoluvic Arenosol (Dystric) (Cv 1200)

A	
0-30cm	Dry; dark yellowish brown 10YR 4/4; sandy loam; weak; blocky, fine; friable; few fine roots; gradual, smooth transition;
B	
30cm+	Dry; strong brown 7.5YR 5/8; loamy sand; weak; blocky, fine; friable; common coarse and medium roots; transition not reached.

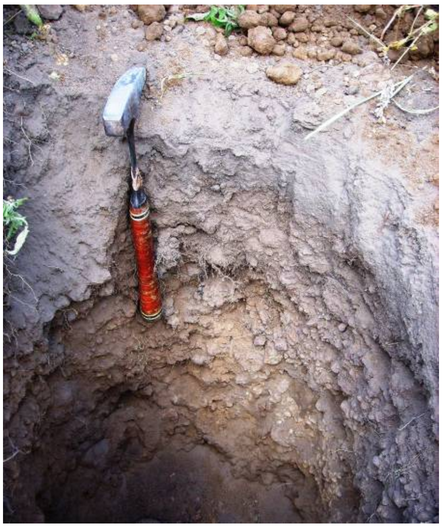
TYN BA & BB, Haplic Arenosol (Dystric) (Tu 2120)

A	
0-50cm	Dry; dark brown 10YR 3/3; loamy sand; weak; granular and crumb; fine and medium; loose; many fine and medium, few coarse roots; diffuse smooth transition.
B	
50cm+	Dry; pale brown 10YR 6/3; loamy sand; weak; granular, fine and medium; common coarse and few fine roots; transition not reached.

TYN MA & MB, Haplic Arenosol (Dystric) (Tu 2120)

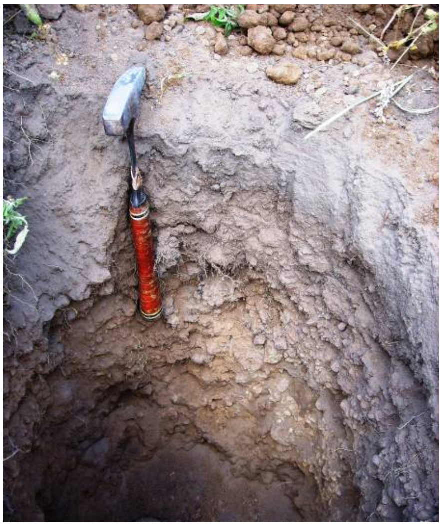
A	
0 – 50cm	Dry; dark greyish brown 10YR 4/2; loamy sand; weak; granular, fine and medium; friable; common fine and medium roots; diffuse, smooth transition;
B	
50cm+	Dry; light yellowish brown 10YR 6/4; sandy loam; weak; granular, fine and medium; friable; few fine, common medium and few coarse roots; transition not reached.

VIX BA & BB, Plinthic Acrisol (Ferric) (We 2000)



A	
0-20cm	Dry; dark brown 10YR 3/3; loamy sand; weak, blocky, coarse; soft; many fine and common medium and coarse roots; abrupt, smooth transition;
B	
20cm+	Dry; yellowish brown 10YR 5/6; sandy clay loam; weak to moderate, blocky, coarse; hard; common medium roots; increasing iron concretions (concretion inside =2.5YR 4/6 red, outside = 7.5YR 6/8 reddish yellow) with depth; transition not reached.

VIX MA & MB, Plinthic Acrisol (Ferric) (We 2000)



A	
0-20cm	Dry; dark brown 10YR 3/3; loamy sand; weak, blocky, coarse; soft; many fine and common medium and coarse roots; abrupt, smooth transition;
B	
20cm+	Dry; yellowish brown 10YR 5/6; sandy clay loam; weak to moderate, blocky, coarse; hard; common medium roots; increasing iron concretions (concretion inside =2.5YR 4/6 red, outside = 7.5YR 6/8 reddish yellow) with depth; transition not reached.

WIBS MA, MB1 + MB2, Haplic Lixisol (Rhodic) (Sw 2211)

A	
0-15cm	Dry; very dark gray 7.5YR 3/1; sandy clay loam; weak, fine single grain; loose; common fine and medium pores; common fine roots; few, fine faint black mottles; clear smooth transition.
B	
15-70cm	Moist; strong brown 7.5YR 5/8; sandy clay; moderate, medium subangular blocky; slightly hard; few fine, medium and coarse pores; few coarse roots; gravel layer at 450mm to 700mm; common medium, distinct brown mottles; clear smooth transition.
C	
70cm+	Moist; red 2.5YR 4/6; shale and weathered shale; moderate medium, platy; firm; few fine, medium and coarse pores; few coarse roots; many coarse prominent black, red and white mottles; transition not reached

Appendix 6: Analytical data for granite pot trial.

Table 6.1: Soil data

Sample number	pH KCl	Acidity mmol/kg	Yield g	Ca	Mg mg/kg	Na	K	Sum bases	ECEC mmolc/kg	Acid sat %
K1L1G0R1	5.16	0	3.77	1211	257	377	379	108.1	108.1	0
K1L1G0R2	5.4	0	2.48	1229	284	401	361	111.8	111.8	0
K1L1G0R3	5.38	0	3.98	1259	278	413	428	115.0	115.0	0
K1L1G1R1	5.29	0	3.36	1248	258	403	314	109.5	109.5	0
K1L1G1R2	5.39	0	3.65	1264	276	418	423	115.2	115.2	0
K1L1G1R3	5.33	0	3.29	1235	295	459	418	117.0	117.0	0
K1L1G2R1	5.2	0	3.98	1267	267	379	378	111.8	111.8	0
K1L1G2R2	5.26	0	3.05	1254	264	389	297	109.2	109.2	0
K1L1G2R3	5.43	0	2.86	1167	251	389	460	108.0	108.0	0
K1L1G3R1	5.36	0	2.92	1308	273	425	434	117.8	117.8	0
K1L1G3R2	5.54	0	2.8	1275	267	399	496	116.1	116.1	0
K1L1G3R3	5.29	0	2.16	1301	268	406	420	115.8	115.8	0
K0L1G0R1	5.03	0	3.27	1142	258	402	39	97.1	97.1	0
K0L1G0R2	5.22	0	3.11	1206	327	550	42	112.5	112.5	0
K0L1G0R3	5.12	0	3.12	1013	242	388	38	88.7	88.7	0
K0L1G1R1	5.01	0	3.38	1137	271	435	42	99.4	99.4	0
K0L1G1R2	5.31	0	2.34	1164	272	435	49	101.0	101.0	0
K0L1G1R3	5.21	0	2.96	1091	245	369	41	92.1	92.1	0
K0L1G2R1	5.11	0	3.38	1096	248	392	42	93.6	93.6	0
K0L1G2R2	5.44	0	2.8	1168	248	384	42	96.8	96.8	0
K0L1G2R3	5.6	0	2.58	1157	256	437	45	99.3	99.3	0
K0L1G3R1	5.41	0	3.79	1160	275	452	60	102.1	102.1	0
K0L1G3R2	5.52	0	1.71	1155	265	448	55	100.7	100.7	0
K0L1G3R3	5.43	0	3.25	1146	285	456	65	102.5	102.5	0
K1L0G0R1	3.6	9.581	1.71	370	278	393	430	69.8	79.4	12
K1L0G0R2	3.67	8.978	2.73	362	279	402	461	70.6	79.6	11
K1L0G0R3	3.56	8.978	2.78	362	243	364	341	62.9	71.9	12
K1L0G1R1	3.75	8.509	2.16	393	325	469	559	81.5	90.0	9
K1L0G1R2	3.64	10.854	3.02	380	253	376	380	66.2	77.0	14
K1L0G1R3	3.72	9.916	2.58	408	279	416	456	73.4	83.3	12
K1L0G2R1	3.76	9.38	1.84	407	333	495	538	83.4	92.8	10
K1L0G2R2	3.85	8.576	1.25	386	300	439	571	78.0	86.6	10
K1L0G2R3	3.74	8.911	2.87	391	272	402	484	72.1	81.0	11
K1L0G3R1	3.93	8.978	2.19	470	281	426	476	77.6	86.6	10
K1L0G3R2	3.79	10.251	2.4	433	303	436	451	77.4	87.7	12
K1L0G3R3	3.9	9.246	2.64	398	280	415	504	74.2	83.4	11
K0L0G0R1	3.77	7.169	1.44	453	274	437	50	65.8	72.9	10
K0L0G0R2	3.74	7.035	1.32	438	268	432	57	64.5	71.5	10
K0L0G0R3	3.71	7.37	0.87	456	260	424	54	64.3	71.7	10
K0L0G1R1	3.73	7.906	1.51	467	271	423	57	65.8	73.7	11
K0L0G1R2	3.75	7.236	1.1	443	243	362	50	59.4	66.7	11
K0L0G1R3	3.82	6.834	1.91	455	268	420	56	64.8	71.6	10
K0L0G2R1	3.88	6.767	1.25	480	269	428	61	66.6	73.4	9
K0L0G2R2	3.83	7.169	2.2	471	250	393	60	63.0	70.2	10
K0L0G2R3	3.87	7.236	1.65	475	261	416	57	65.0	72.3	10
K0L0G3R1	3.86	7.169	1.8	498	269	426	72	67.7	74.9	10
K0L0G3R2	3.86	7.437	1.63	517	274	439	76	69.7	77.2	10
K0L0G3R3	3.86	7.303	1.72	507.5	271.5	432.5	74	68.7	76.0	10

Table 6.2: Plant data

Sample number	Ca	Mg	K	Na
	mg/kg			
K1L1G0R1	4869	2767	54273	1419
K1L1G0R2	4572	2765	52984	1601
K1L1G0R3	4732	2714	58476	1635
K1L1G1R1	4677	2670	55427	1025
K1L1G1R2	4236	2720	57726	1548
K1L1G1R3	4436	3021	54886	1651
K1L1G2R1	3902	3201	55865	1194
K1L1G2R2	4761	2450	58390	1488
K1L1G2R3	4684	3315	56633	1645
K1L1G3R1	3874	2657	54290	1257
K1L1G3R2	4021	2914	56414	1210
K1L1G3R3	4602	3388	53800	1876
K0L1G0R1	5070	2758	59498	1224
K0L1G0R2	4783	2759	60912	1541
K0L1G0R3	6975	9413	8230	1650
K0L1G1R1	5143	9019	9482	1367
K0L1G1R2	5845	8154	13207	1257
K0L1G1R3	5280	10093	8957	1404
K0L1G2R1	4567	9078	10017	1572
K0L1G2R2	5459	8583	16265	1392
K0L1G2R3	5201	9656	13282	1320
K0L1G3R1	4054	8426	10981	1415
K0L1G3R2	4648	5474	22223	1476
K0L1G3R3	4034	5640	9150	1395
K1L0G0R1	1824	3769	59103	1085
K1L0G0R2	1865	3712	58705	748
K1L0G0R3	1981	3630	56249	661
K1L0G1R1	1834	3087	55777	1072
K1L0G1R2	1849	3159	58933	777
K1L0G1R3	1752	3787	56991	691
K1L0G2R1	1851	3753	59810	1286
K1L0G2R2	2021	3558	58105	2261
K1L0G2R3	1898	3884	55878	588
K1L0G3R1	1770	2898	59588	1169
K1L0G3R2	1435	2827	64140	552
K1L0G3R3	1596	3231	61458	741
K0L0G0R1	3007	8016	16101	1019
K0L0G0R2	2463	7010	16683	715
K0L0G0R3	1528	3690	10144	838
K0L0G1R1	2760	8011	18709	818
K0L0G1R2	1629	3787	11318	690
K0L0G1R3	2381	6399	16326	1260
K0L0G2R1	2331	5768	26133	1421
K0L0G2R2	2579	8993	16990	678
K0L0G2R3	2468	6442	22596	1951
K0L0G3R1	2422	6600	24153	2396
K0L0G3R2	2304	5878	24909	1066
K0L0G3R3	2363	6239	24530	1731

Appendix 7: **Statistical data from Anova relating to the pulverised granite pot trial in Chapter 3.**

Table 7.1

	Univariate Tests of Significance for pH (DATA20061110.sta) Sigma-restricted parameterization Effective hypothesis decomposition				
Effect	**SS**	**Deg of Freedom**	**MS**	**F**	**p**
Intercept	990.36	1.00	990.36	94095.57	0.00
Granite	0.28	3.00	0.09	8.93	0.00
Potassium	0.00	1.00	0.00	0.04	0.83
Lime	28.29	1.00	28.29	2687.89	0.00
Granite vs Potassium	0.03	3.00	0.01	0.97	0.42
Granite vs Lime	0.00	3.00	0.00	0.10	0.96
Potassium vs Lime	0.04	1.00	0.04	3.82	0.06
Granite vs Potassium vs Lime	0.08	3.00	0.03	2.46	0.08
Error	0.34	32.00	0.01		

Table 7.2

	Granite vs Potassium vs Lime; LS Means (DATA20061110.sta) Current effect: F(3, 32)=2.4610, p=.08053 Effective hypothesis decomposition							
Cell no.	**Granite (g)**	**Potassium**	**Lime**	**Ph Mean**	**Ph Std Error**	**Ph - 95%**	**Ph +95%**	**n**
1	0	Absent	Absent	3.74	0.06	3.62	3.86	3
2	0	Absent	Present	5.12	0.06	5.00	5.24	3
3	0	Present	Absent	3.61	0.06	3.49	3.73	3
4	0	Present	Present	5.31	0.06	5.19	5.43	3
5	7.5	Absent	Absent	3.77	0.06	3.65	3.89	3
6	7.5	Absent	Present	5.18	0.06	5.06	5.30	3
7	7.5	Present	Absent	3.70	0.06	3.58	3.82	3
8	7.5	Present	Present	5.34	0.06	5.22	5.46	3
9	15	Absent	Absent	3.86	0.06	3.74	3.98	3
10	15	Absent	Present	5.38	0.06	5.26	5.50	3
11	15	Present	Absent	3.78	0.06	3.66	3.90	3
12	15	Present	Present	5.30	0.06	5.18	5.42	3
13	30	Absent	Absent	3.86	0.06	3.74	3.98	3
14	30	Absent	Present	5.45	0.06	5.33	5.57	3
15	30	Present	Absent	3.87	0.06	3.75	3.99	3
16	30	Present	Present	5.40	0.06	5.28	5.52	3

Table 7.3

Granite additions effect on pH. LS Means (DATA20061110.sta)
Current effect: F(3, 32)=8.9345, p=.00019
Effective hypothesis decomposition

Cell no.	Granite (g)	pH Mean	pH Std. Err.	pH - 95%	pH +95%	n
1	0	4.45	0.03	4.39	4.51	12
2	7.5	4.50	0.03	4.44	4.56	12
3	15	4.58	0.03	4.52	4.64	12
4	30	4.65	0.03	4.59	4.71	12

Table 7.4

Bonferroni test; variable pH (DATA20061110.sta)
Probabilities for Post Hoc Tests
Error: Between MS = .01052, df = 32.000

Cell no.	Granite	{1} 4.4467	{2} 4.4958	{3} 4.5808	{4} 4.6458
1	0		1.00	0.02	0.00
2	7.5	1.00		0.30	0.01
3	15	0.02	0.30		0.78
4	30	0.00	0.01	0.78	

Table 7.5

Bonferroni test; variable pH
Homogenous Groups, alpha = .05000
Error: Between MS = .01052, df = 32.000

Cell no.	Granite (g)	pH Mean	1	2	3
1	0	4.45	****		
2	7.5	4.50	****	****	
3	15	4.58		****	****
4	30	4.65			****

Table 7.6

Effect of Lime on pH; LS Means
Current effect: F(1, 32)=2687.9, p=0.0000
Effective hypothesis decomposition

Cell no.	Lime	pH Mean	pH Std Error	pH - 95%	pH +95%	n
1	Absent	3.77	0.02	3.73	3.82	24
2	Present	5.31	0.02	5.27	5.35	24

Table 7.7

Effect of Lime on yield
Current effect: F(1, 32)=54.466, p=.00000
Effective hypothesis decomposition

Cell No.	Lime	Yield (g)Mean	Yield Std. Err.	Yield -95.00%	Yield +95.00%	n
1	Absent	1.94	0.11	1.72	2.16	24
2	Present	3.08	0.11	2.86	3.31	24

Table 7.8

Effect of K on yield (g)
Current effect: F(1, 32)=11.103, p=.00219
Effective hypothesis decomposition

Cell No.	Potassium	Yield (g) Mean	Yield Std. Err.	Yield -95.00%	Yield +95.00%	n
1	Absent	2.25	0.11	2.03	2.48	24
2	Present	2.77	0.11	2.55	2.99	24

Table 7.9

Univariate Tests of Significance for Yield (g)
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. Of Freedom	MS	F	p
Intercept	302.80	1	302.80	1052.92	0.0
Granite	0.24	3	0.08	0.28	0.84
Potassium	3.19	1	3.19	11.10	0.00
Lime	15.66	1	15.66	54.46	0.00
Granite vs Potassium	0.78	3	0.26	0.90	0.44
Granite vs Lime	0.95	3	0.31	1.10	0.36
Potassium vs Lime	1.06	1	1.06	3.71	0.06
Granite vs Potassium vs Lime	0.56	3	0.18	0.65	0.58
Error	9.20	32	0.28		

Table 7.10

Effect	SS	Degr. Of Freedom	MS	F	p
	Univariate Tests of Significance for Soil-Ca Sigma-restricted parameterization Effective hypothesis decomposition				
Intercept	31807050	1	31807050	27330.17	0.00
Granite	20082	3	6694	5.75	0.00
Potassium	4850	1	4850	4.17	0.04
Lime	6925501	1	6925501	5950.73	0.00
Granite vs Potassium	1624	3	541	0.47	0.70
Granite vs Lime	813	3	271	0.23	0.87
Potassium vs Lime	108633	1	108633	93.34	0.00
Granite vs Potassium vs Lime	889	3	296	0.25	0.85
Error	37242	32	1164		

Table 7.11

Effect	SS	Degr. Of Freedom	MS	F	p
	Univariate Tests of Significance for Soil-Acidity Sigma-restricted parameterization Effective hypothesis decomposition				
Intercept	1352.38	1.00	1352.38	2924.61	0.00
Granite	2.18	3.00	0.73	1.57	0.22
Potassium	5.38	1.00	5.38	11.64	0.00
Lime	1352.38	1.00	1352.38	2924.61	0.00
Granite vs Potassium	0.81	3.00	0.27	0.58	0.63
Granite vs Lime	2.18	3.00	0.73	1.57	0.22
Potassium vs Lime	5.38	1.00	5.38	11.64	0.00
Granite vs Potassium vs Lime	0.81	3.00	0.27	0.58	0.63
Error	14.80	32.00	0.46		

Table 7.12

Effect	SS	Degr. Of Freedom	MS	F	p
		Univariate Tests of Significance for Soil -Mg Sigma-restricted parameterization Effective hypothesis decomposition			
Intercept	3539546	1.00	3539545.63	9052.67	0.00
Granite	374	3.00	124.60	0.32	0.81
Potassium	1795	1.00	1794.63	4.59	0.04
Lime	634	1.00	634.38	1.62	0.21
Granite vs Potassium	1425	3.00	475.05	1.21	0.32
Granite vs Lime	1640	3.00	546.63	1.40	0.26
Potassium vs Lime	846	1.00	845.88	2.16	0.15
Granite vs Potassium vs Lime	374	3.00	124.69	0.32	0.81
Error	12512	32.00	390.99		

Table 7.13

Effect	SS	Degr. Of Freedom	MS	F	p
		Univariate Tests of Significance for Soil -sum of bases Sigma-restricted parameterization Effective hypothesis decomposition			
Intercept	369894.35	1.00	369894.35	17404.65	0.00
Granite	164.37	3.00	54.79	2.58	0.07
Potassium	1532.88	1.00	1532.88	72.13	0.00
Lime	15720.79	1.00	15720.79	739.71	0.00
Granite vs Potassium	63.35	3.00	21.12	0.99	0.41
Granite vs Lime	90.09	3.00	30.03	1.41	0.26
Potassium vs Lime	94.48	1.00	94.48	4.45	0.04
Granite vs Potassium vs Lime	34.49	3.00	11.50	0.54	0.66
Error	680.08	32.00	21.25		

Table 7.14

Bonferroni test; variable Plant - K
Probabilities for Post Hoc Tests
Error: Between MS = 6519E4, df = 32.000

Cell No.	Granite (g)	Potassium	Lime	{1} 2332.5	{2} 5609.3	{3} 1889.8	{4} 4724.2	{5} 2256.3	{6} 5422.3	{7} 1811.5	{8} 4449.5	{9} 2459.0	{10} 5075.3	{11} 1922.8	{12} 4448.5	{13} 24530.	{14} 4244.8	{15} 1600.2	{16} 4165.3
1	0	Absent	Absent		0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
2	0	Absent	Present	0.00		0.00	1.00	0.00	1.00	0.00	0.44	0.00	1.00	0.00	0.44	0.00	0.10	0.00	0.06
3	0	Present	Absent	1.00	0.00		0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
4	0	Present	Present	0.00	1.00	0.00		0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
5	7.5	Absent	Absent	1.00	0.00	1.00	0.00		0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
6	7.5	Absent	Present	0.00	1.00	0.00	1.00	0.00		0.00	1.00	0.00	1.00	0.00	1.00	0.00	0.39	0.00	0.22
7	7.5	Present	Absent	1.00	0.00	1.00	0.00	1.00	0.00		0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00
8	7.5	Present	Present	0.00	0.44	0.00	1.00	0.00	1.00	0.00		0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00
9	15	Absent	Absent	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00		0.00	1.00	0.00	1.00	0.00	1.00	0.01
10	15	Absent	Present	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00		0.00	1.00	0.00	1.00	0.00	1.00
11	15	Present	Absent	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00		0.00	1.00	0.00	1.00	0.00
12	15	Present	Present	0.00	0.44	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00		0.00	1.00	0.00	1.00
13	30	Absent	Absent	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00		0.00	1.00	0.00
14	30	Absent	Present	0.00	0.10	0.00	1.00	0.00	0.39	0.00	1.00	0.00	1.00	0.00	1.00	0.00		0.00	1.00
15	30	Present	Absent	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00	1.00	0.00		0.00
16	30	Present	Present	0.00	0.06	0.00	1.00	0.00	0.22	0.00	1.00	0.01	1.00	0.00	1.00	0.00	1.00	0.00	

Table 7.15

Granite vs Potassium vs Lime on plant Ca Current effect: F(3, 32)=1.1114, p=.35889 Effective hypothesis decomposition								
Cell No.	**Granite (g)**	**Potassium**	**Lime**	**P-Ca Mean**	**P-Ca Std. Err.**	**P-Ca - 95.00%**	**P-Ca +95.00%**	**n**
1	0	Absent	Absent	2332.50	261.79	1799.25	2865.75	3
2	0	Absent	Present	5609.33	261.79	5076.08	6142.59	3
3	0	Present	Absent	1889.83	261.79	1356.58	2423.09	3
4	0	Present	Present	4724.17	261.79	4190.91	5257.42	3
5	7.5	Absent	Absent	2256.33	261.79	1723.08	2789.59	3
6	7.5	Absent	Present	5422.33	261.79	4889.08	5955.59	3
7	7.5	Present	Absent	1811.50	261.79	1278.25	2344.75	3
8	7.5	Present	Present	4449.50	261.79	3916.25	4982.75	3
9	15	Absent	Absent	2459.00	261.79	1925.75	2992.25	3
10	15	Absent	Present	5075.33	261.79	4542.08	5608.59	3
11	15	Present	Absent	1922.83	261.79	1389.58	2456.09	3
12	15	Present	Present	4448.50	261.79	3915.25	4981.75	3
13	30	Absent	Absent	2363.00	261.79	1829.75	2896.25	3
14	30	Absent	Present	4244.83	261.79	3711.58	4778.09	3
15	30	Present	Absent	1600.17	261.79	1066.91	2133.42	3
16	30	Present	Present	4165.33	261.79	3632.08	4698.59	3

Table 7.16

Bonferroni test; variable Plant -Ca Probabilities for Post Hoc Tests Error: Between MS = 2056E2, df = 32.000					
Cell No.	**Granite (g)**	**{1} 3639.0**	**{2} 3484.9**	**{3} 3476.4**	**{4} 3093.3**
1	0		1.00	1.00	0.04
2	7.5	1.00		1.00	0.25
3	15	1.00	1.00		0.28
4	30	0.04	0.25	0.28	

Table 7.17

Univariate Tests of Significance for Soil -K
Sigma-restricted parameterization
Effective hypothesis decomposition

Effect	SS	Degr. Of Freedom	MS	F	p
Intercept	2872876	1	2872876	1645.33	0.00
Granite	12052	3	4017	2.30	0.10
Potassium	1753763	1	1753763	1004.40	0.00
Lime	21126	1	21126	12.10	0.00
Granite vs Potassium	4596	3	1532	0.88	0.46
Granite vs Lime	8612	3	2871	1.64	0.20
Potassium vs Lime	9605	1	9605	5.50	0.03
Granite vs Potassium vs Lime	8142	3	2714	1.55	0.22
Error	55875	32	1746		

Table 7.18

Bonferroni test; variable Plant K
Probabilities for Post Hoc Tests
Error: Between MS = 6519E4, df = 32.000

Cell No.	Granite (g)	Potassium	Lime	{1} 14309.	{2} 42880.	{3} 58019.	{4} 55244.	{5} 15451.	{6} 10548.	{7} 57233.	{8} 56013.	{9} 21906.	{10} 13188.	{11} 57931	{12} 56962.	{13} 24530.	{14} 14118.	{15} 61729.	{16} 54835.
1	0	Absent	Absent		0.02	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00
2	0	Absent	Present	0.02		1.00	1.00	0.03	0.00	1.00	1.00	0.39	0.01	1.00	1.00	1.00	0.02	0.89	1.00
3	0	Present	Absent	0.00	1.00		1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00
4	0	Present	Present	0.00	1.00	1.00		0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.01	0.00	1.00	1.00
5	7.5	Absent	Absent	1.00	0.03	0.00	0.00		1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00
6	7.5	Absent	Present	1.00	0.00	0.00	0.00	1.00		0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00
7	7.5	Present	Absent	0.00	1.00	1.00	1.00	0.00	0.00		1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00
8	7.5	Present	Present	0.00	1.00	1.00	1.00	0.00	0.00	1.00		0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00
9	15	Absent	Absent	1.00	0.39	0.00	0.00	1.00	1.00	0.00	0.00		1.00	0.00	0.00	1.00	1.00	0.00	0.00
10	15	Absent	Present	1.00	0.01	0.00	0.00	1.00	1.00	0.00	0.00	1.00		0.00	0.00	1.00	1.00	0.00	0.00
11	15	Present	Absent	0.00	1.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00		1.00	0.00	0.00	1.00	1.00
12	15	Present	Present	0.00	1.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00		0.00	0.00	1.00	1.00
13	30	Absent	Absent	1.00	1.00	0.00	0.01	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00		1.00	0.00	0.01
14	30	Absent	Present	1.00	0.02	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00		0.00	0.00
15	30	Present	Absent	0.00	0.89	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00		1.00
16	30	Present	Present	0.00	1.00	1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	1.00	0.01	0.00	1.00	